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EFFECTIVE UTILIZATION OF BATTERY-SUPERCAPACITOR HYBRID ENERGY STORAGE SYSTEMS IN DC NANO-GRIDS

by

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I want to dedicate this dissertation to an exceptionally important individual in my life, my spouse, Sara Rassa, for her unwavering support throughout this long journey.
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I express my heartfelt gratitude to Dr. Ali Bidram, my advisor and dissertation chair, for his unwavering support throughout these years. I also extend my appreciation to my committee members for their valuable time and guidance in reviewing my dissertation. Furthermore, I am grateful to my parents, Mr. Hossein Ghorashi Khalil Abadi and Mrs. Sakineh Beik, for providing my siblings and me with opportunities that they never had.

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This PhD dissertation proposes novel control strategies to improve the flexibility and reliability of DC nanogrids by utilizing battery-supercapacitor hybrid energy storage systems (HESSs). The dissertation is divided into five sections, each addressing a specific challenge in DC nanogrids and proposing unique control strategies to overcome them. The proposed strategies include an adaptive control system for multiple nanogrids, a distributed power management strategy for a grid-connected DC nano-grid, a model predictive control strategy to improve voltage quality and stability in islanded DC nanogrids, a cloud HESS technology to improve voltage stability in clustered DC nanogrids, and a method of electric vehicle (EV) charging to utilize internal supercapacitors to improve battery lifetime and voltage quality of DC nanogrids. The proposed methods aim to improve power quality, flexibility, and efficiency of DC nanogrids, reduce power fluctuations, and enhance the lifetime of battery energy storage systems.
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Chapter 1: Introduction

1.1 Motivation

DC nanogrids are emerging as a promising solution for distributed energy systems, particularly in the context of the increasing penetration of renewable energy sources. These systems consist of different types of distributed energy resources (DERs) such as photovoltaic (PV) panels, and energy storage systems (ESS) connected to a DC bus. DC nanogrids have a number of advantages over traditional AC grids, including higher efficiency, simpler design, and improved reliability. They also offer greater flexibility for integrating DERs into the grid and enabling bi-directional power flow. Given their potential, DC nanogrids are expected to play a crucial role in the development of future grids.

To realize the full potential of DC nanogrids, it is essential to ensure their performance, reliability, and flexibility. One of the key challenges in this regard is the effective utilization of energy storage systems. ESS can play a critical role in smoothing out the fluctuations in renewable energy sources and ensuring a stable and reliable power supply. However, the performance of ESS depends on several factors, such as their capacity, response time, and efficiency. In addition, the choice of the storage technology and its configuration can have a significant impact on the overall system performance.

Hybrid energy storage systems (HESSs) that combine batteries and supercapacitors have emerged as a promising solution for DC microgrids. Batteries can provide high energy density, while supercapacitors can offer high power density and fast response time. The combination of these two technologies can enhance the performance and reliability of the ESS and improve the overall system efficiency. Furthermore, HESSs can provide better
utilization of the available storage capacity and increasing the battery lifetime, thereby reducing the overall system cost.

The motivation for this dissertation is to address the challenges associated with the effective utilization of HESSs in DC nanogrids. The main objective is to improve the performance and reliability of DC nanogrids by developing advanced control strategies for the HESSs. The proposed strategies will enable efficient use of the available storage capacity and enhance the overall system performance in terms of stability, response time, and efficiency.

The proposed research is expected to make a significant contribution to the development of DC nanogrids and their effective utilization in the future grids. The results of this dissertation will provide insights into the performance and reliability of DC nanogrids and enable the development of advanced control strategies for HESS. The research will contribute to the design of efficient and cost-effective energy storages for DC microgrids, thereby accelerating the transition to a sustainable and reliable energy future.

1.2 Dissertation Structure

The topics discussed in each of the chapters are briefly described as follows:

1.2.1 Chapter 2

Chapter 2 of this dissertation studies the structure and control challenges of DC nanogrids and clustered DC nanogrids. The increasing deployment of distributed generation and renewable energy sources in power systems has led to the emergence of nanogrids, which are capable of operating autonomously and independently from the main grid. However, the implementation of nanogrids presents new challenges such as voltage
stability issues, which can affect the performance and reliability of the system. To address these challenges, a multiagent-based adaptive control and management structure is proposed. The technique is aimed at improving the voltage quality and reliability of DC nanogrids by controlling the voltage and power of multiple nanogrids in an islanded microgrid system. The proposed technique is expected to provide flexible and effective control and management of nanogrids, leading to improved overall system performance. This chapter is based on the authors work entitled “Adaptive control and management of multiple nano-grids in islanded DC microgrid systems” published in [1].

1.2.2 Chapter 3

Chapter 3 proposes a distributed rule-based power management strategy for a photovoltaic (PV) system with a hybrid energy storage system (HESS) based on an active compensation filtering technique. The objective is to improve the power quality and efficiency of the system during grid-connected mode of a DC nano-grid. The proposed method utilizes the HESS to absorb the instantaneous renewable power and load variations by the supercapacitor (SC) while providing ancillary services for the upstream grid. The active compensation filter is employed to smooth out the power variations of the battery energy storage system (BESS) while controlling the charge-level of the SC in a specific range, resulting in a significant improvement in the efficiency and power quality of the system. The proposed power management strategy is designed to be implemented in a distributed manner, allowing for scalability and flexibility in the system. The effectiveness of the proposed strategy is demonstrated through extensive simulations under various operating conditions. The results show that the proposed method achieves improved power quality and efficiency, as well as effective utilization of the HESS for load management.
and grid support. This chapter provides valuable insights into the potential of utilizing
HESS in PV systems to enhance their performance and contribute to the sustainable
development of the power grid. This chapter is based on the authors work entitled “A
distributed rule-based power management strategy in a photovoltaic/hybrid energy storage
system based on an active compensation filtering technique” published in [2].

1.2.3 Chapter 4

Chapter 4 proposes a model predictive control (MPC) strategy for improving the
performance and voltage quality of DC nanogrids during islanded operation. The proposed
approach employs an MPC controller that supervises the filtration-based power allocation
system of the hybrid energy storage to achieve switchless operation of the grid-forming
HESS unit. As a result, the dynamic stability and power quality of the islanded DC nano-
grid are improved. In addition, the prediction model of the MPC controllers only requires
the charge capacity of the SC and it does not require the dynamic model of the DC power
distribution system or power electronic converters. As a result, the proposed control
structure is highly scalable, and it can be used in DC nanogrids with different topologies
or larger scale DC distribution system such as multiple bus DC microgrids.

The proposed approach is demonstrated through simulations and experimental
results, highlighting its ability to enhance the performance of the DC nano-grid during
islanded operation. The findings of this chapter show that the MPC controller is an effective
solution for improving the performance and voltage quality of DC nanogrids during
islanded operation by utilizing hybrid energy storage systems. This chapter is based on the
authors work entitled “A model predictive control strategy for performance improvement
of hybrid energy storage systems in DC microgrids” published in [3].
1.2.4 Chapter 5

Chapter 5 of this dissertation presents a novel battery-SC HESS technology for improving the transient stability, voltage quality, and battery lifetime of an islanded clustered DC nano-grid system. The proposed technology uses an optimized combination of local and community batteries as well as central supercapacitor to improve the performance of the system during sudden load or renewable energy fluctuations. The battery-SC HESS technology can also reduce the required size of the SC compared to the conventional distributed HESS architecture, thereby increasing the system efficiency and reducing the initial cost of the system.

The proposed battery-SC HESS technology is developed based on a cloud HESS concept, which includes a grid-forming power electronic converter and an energy management system (EMS). To provide an effective coordination between local BESSs and the community SC the current control structure of the gateway converters is also modified. The proposed cloud HESS technology is evaluated using simulation studies, and the results demonstrate its effectiveness in improving the transient stability, voltage quality, and battery lifetime of the islanded clustered DC nano-grid system. The use of a single central or community SC helps to reduce the instantaneous power variations of the local and community BESSs which increases the system efficiency and lifetime. In addition, it enhances the dynamic response of the voltage control system in all the DC nano-grids improving the voltage quality of the system in all the DC buses. This chapter is based on the authors work entitled “Effective utilization of grid-forming cloud hybrid energy storage systems in islanded clustered dc nano-grids for improving transient voltage quality and battery lifetime” published in [4].
1.2.5 Chapter 6

Chapter 6 of this dissertation proposes a new method for charging electric vehicles with battery-supercapacitor hybrid energy storages (HESS) to improve the voltage quality and extend the lifetime of the central battery energy storage of the HESS. The chapter develops the idea of utilizing the internal supercapacitor (SC) of modern electric vehicles (EVs) with HESS technologies to improve the transient voltage quality in islanded building-level DC microgrids (MGs) without degrading the internal battery energy storage system (BESS) of the EVs.

The proposed method utilizes an online system identification technique to estimate the internal power allocation strategy of EVs based on the parametric identification of an ARX model. The estimation is then used to provide effective coordination between the central battery energy storage system (CBESS) of the MG and the internal SC of EV. A filtration-based current allocation between the EV and the MG’s CBESS is also proposed to assign high-frequency power variations of renewable energy sources (RESs) and loads to the SC of the EV while the internal BESS of the EV is charging with its standard current profile.

The chapter also presents a small signal stability analysis to investigate the impact of the proposed EV charging method on the transient voltage stability of the DC MG. The simulation results show an 86% reduction in the CBESS power variation and an 87% reduction in the amplitude of the transient voltage deviations in a specific load change scenario. Moreover, the experimental results demonstrate that the proposed EV charging method leads to better transient response and voltage quality in the MG. Overall, this chapter provides a comprehensive solution to improve the performance of DC MGs by
integrating EVs with HESS technologies. This chapter is based on the authors work entitled “A method for charging electric vehicles with battery-supercapacitor hybrid energy storage systems to improve voltage quality and battery lifetime in islanded building-level DC microgrids” published in [5].

1.2.6 Chapter 7

The concluding chapter of this dissertation presents the findings and outcomes derived from all the previous chapters. The main aim of this research was to propose innovative techniques to enhance the flexibility, efficiency, and reliability of DC nanogrids using HESSs in different operational modes. The chapter highlights the significance of the proposed methods and their contributions towards the development of advanced DC nanogrids. Moreover, potential areas for future research in this field are also suggested to improve the performance of DC nanogrids further.
Chapter 2: Adaptive Control and Management of Clustered DC Nano-grids

2.1 Motivation

The increasing deployment of distributed generation and renewable energy sources in power systems has led to the emergence of nanogrids as an attractive solution for providing electricity to isolated communities and remote areas. Nanogrids are capable of operating autonomously and independently from the main grid, providing a reliable and sustainable power supply to consumers. However, the implementation of nanogrids presents new challenges such as voltage stability issues, which can affect the performance and reliability of the system.

The objective of this chapter is to study the structure and control challenges of DC nanogrids and clustered DC nanogrids and propose an adaptive control and management structure to address these challenges. The proposed technique is aimed at improving the voltage quality and reliability of DC nanogrids by controlling the voltage and power of multiple nanogrids in an islanded microgrid system. The proposed multi-agent-based adaptive control and management structure is expected to provide flexible and effective control and management of nanogrids, leading to improved overall system performance.

This chapter is based on the paper titled "Adaptive Control and Management of Multiple Nano-Grids in an Islanded DC Microgrid System" published in the IET Generation, Transmission & Distribution. The proposed technique is expected to contribute to the development of sustainable and reliable nano-grid systems, which are crucial for the electrification of remote and isolated areas. The results of this study can also be used as a reference for future research in the field of nanogrids and distributed energy systems.
Overall, the chapter aims to provide valuable insights into the structure and control challenges of nanogrids and offer a solution to address these challenges, which will pave the way for the widespread implementation of nanogrids in power systems.

2.2 Introduction

Micro-grids (MGs) are independent active distributed energy systems that can improve the performance of traditional power systems through increasing consumer participation, sustainable energy resources penetration, grid resiliency, and power system stability [6]. Designing MGs by connecting multiple nano-grids (MNGs) promotes the modularity of MGs which in turn results in higher flexibility, resiliency, and scalability [7]. Nano-grids (NGs) can be defined as power distribution systems consisting of local power generation and consumption units which conventionally include a local energy storage system (ESS), a gateway (GW) module, and a dedicated control system [8]. NGs share lots of features with MGs such as operation in isolated or grid connected mode. However, they have smaller scale and simpler structure, typically, supplying a building or a single load [8,9]. While NGs can be AC, more recently, DC NGs have gained much attention to minimize power conversion losses and reduce the system complexity [7]. MNGs have a different structure compared to conventional DC MGs requiring control and management strategies which are well-suited for their structural features.

2.2.1 Power Management Strategies in DC MNGs

In islanded DC MGs, typically, there are multiple distributed energy resources (DERs) which are connected in parallel to the MG common DC bus through power electronic converters and they are responsible for regulating the DC bus voltage as well as maintaining the stability of the system (i.e., grid forming units) [10]. The efficient and
reliable operation of these parallel grid forming units requires appropriate power sharing strategies that can be achieved using centralized, decentralized, or distributed control approaches. However, the conventional control and power management techniques designed for parallel connected DERs may not be feasible in islanded MNGs due to their different structure. Fig. 1 Structure of DC MGs: (a) a typical DC MG with parallel grid forming units; (b) a DC MG that consists of multiple DC NGs (i.e., a DC MNG system).

compares the structure of a typical islanded DC MG with an MNG system. As seen, in an MNG system, there is one grid forming unit at each NG (e.g., a battery energy storage system) that regulates the NG local DC bus voltage, and the GW module is responsible for power exchange with the upstream grid. In this structure, the local grid forming units are connected to different DC buses to supply their local loads. Consequently, in an MNG, local grid forming units cannot directly coordinate, and the effective power sharing of MNG requires an advanced coordination among the GW modules of different NGs. On the other hand, the plug and play (PnP) operation of NGs is a vital requirement for reliable and scalable operation of an MNG system. Therefore, the effective operation of clustered NGs requires a highly flexible and adaptive control and management system to provide a desirable power sharing among different NGs without affecting their PnP ability [11–13].

To address the discussed challenges, a variety of centralized, decentralized, and distributed control schemes have been suggested in the literature for MNG systems. In centralized control architectures, typically one NG or a cloud energy storage (e.g., the community BESS) operates as a master unit to control the voltage of the MG common DC bus using its GW converter (i.e., the MG grid forming unit) and the other NGs operate as grid following units and exchange power with each other through their GW modules [14].
Despite simplicity, this approach may put considerable stress on the master unit when the number of NGs is high, and/or the NGs’ power generation and load fluctuate a lot. Reference [15] proposes a modified centralized control scheme for multiple NGs in an AC MG. The proposed system contains a photovoltaic (PV)/battery energy storage system (BESS) as a master unit and three other NGs. In this approach, to reduce the burden on the master unit, the grid following NGs demand constant active power. However, if the active power demand inside each NG varies significantly over time, the accurate power sharing among the NGs cannot be provided.

Alternatively, the decentralized and distributed control structures can be deployed to increase the flexibility and scalability of the control system. Reference [16] proposes a
A decentralized control strategy in an islanded cluster of NGs to provide flexible power sharing and voltage regulation inside the system. In this method, power exchange among the NGs is based on the variation of the common DC bus voltage, and the participation of BESSs in voltage regulation of local DC buses is related to their available capacity or state of charge (SoC). A decentralized power sharing strategy between DC NGs based on a nonlinear $I-V$ droop control technique is also proposed in [17]. This method improves the power sharing in the DC MNG systems and provides less steady-state voltage deviation compared to the conventional power sharing methods with linear droop characteristic.

Reference [18] also proposes a distributed voltage control and power sharing strategy in an MNG system using a consensus control protocol. The ability of the proposed control algorithm in realizing the global power objective and voltage profile, while mitigating different types of attacks has been studied. However, neither [16] nor [18] has addressed the battery SoC balancing performance in different NG units.

Effective SoC balancing is of paramount value in MGs with multiple ESSs to increase their efficiency and MG’s reliability [19]. The SoC balancing control strategies in DC microgrids with parallel distributed ESSs have been widely discussed in the literature [20–22]. In these methods, the contribution of an ESS to voltage regulation of the MG DC bus is conventionally related to its available capacity or SoC. However, as discussed before, the ESSs are connected to different DC links (i.e., each ESS is responsible for voltage regulation of its local DC bus) in MNG systems and the direct coordination among the ESSs is not available. In addition, the local loads and generation units in different NGs may have considerably different power profiles. This can provide situations in which a BESS in one NG is charging while a BESS in another NG is discharging. Moreover, the
NGs should be able to safely disconnect and connect to the MG DC bus at any time (i.e., PnP operation) [12]. When an NG is connected to MG common DC bus, it can share power with other NGs through its GW module to balance the SoC of its BESS with them. But, if the NG is isolated, it may still continue to supply its local loads without the ability of power exchange with its neighboring NGs. So, the battery SoC balancing strategies in MNGs should be highly adaptable to the operational modes of the NGs to ensure the PnP operation of them. In conclusion, due to the different structure of MNGs, the conventional power sharing methods designed for parallel BESSs in conventional DC MGs are not feasible for battery SoC balancing in MNG systems [23,24]. To address this issue, an additional control layer (e.g., a supervisory control system) is suggested to improve the flexibility of the system by adjusting the control setting of the NGs based on the system conditions [23]. For instance, a decentralized adaptive droop control strategy is proposed in [23] which provides a communication-less coordination among NGs to balance the SoC of BESSs. The NGs contain a PV, household loads, and a BESS that regulates the NG local DC bus voltage. In this method, there is a supervisory controller that selects the operational mode of the NGs with respect to the SoC of their local BESS and common DC bus voltage. Despite the high level of scalability and flexibility, this approach has the following drawbacks: The proposed $I-V$ droop control approach may cause relatively high voltage deviation on the MG DC link (i.e., \%5) as well as inaccurate power sharing among NGs which are the intrinsic limitations of the decentralized droop control techniques [25,26].
2.2.2 Voltage Regulation of Local DC Buses

In addition to the importance of incorporating a flexible battery SoC balancing and power sharing strategy among NGs, designing an effective control technique for regulating NG’s local DC bus voltage is of paramount value. Generally, there is one grid forming unit at each NG (e.g., a BESS) that regulates the NG local DC bus voltage (i.e., the local grid forming unit). The NG local DC bus voltage control system generally consists of two cascaded proportional-integral (PI) controllers and a pulse width modulator (PWM) which is similar to the conventional primary control layer of DC MGs. In this structure, the reference voltage for the PI voltage controller is typically a constant value (i.e., the nominal voltage of the NG DC bus). However, when a DC MG that consists of multiple NGs (i.e., an MNG system) is islanded, at least one of the NGs should regulate the MG common DC bus voltage through its GW module to maintain the stability of the islanded MG. In this case, the GW module is seen as a constant power load (CPL) or a constant power source (CPS) from its NG local DC bus point of view based on the direction of its output current. Consequently, the DC NGs intrinsically face with CPL issue that cannot be effectively addressed with the conventional PI voltage regulators [27–29]. Due to the small size of NGs, this CPL issue does not usually destabilize the NG. But it may cause low marginal stability and some voltage oscillations on the NG local DC bus specially if the DC NG contains some local CPLs [30]. This voltage oscillations can produce large current ripples of the local grid forming DER. Knowing that the local grid forming unit in DC NGs is typically a BESS, these current ripples can significantly reduce BESS lifetime [2,31]. Therefore, a more advanced NG voltage control strategy is desirable to increase the system efficiency and reliability.
To tackle this challenge, model predictive controllers (MPC) can be utilized to regulate the NG’s local DC bus voltage. MPC techniques are among the alternatives of PI controllers in systems with CPLs that can provide an optimal trade-off between voltage variation, modification of load impedance, and the current ripples of energy storages [32,33]. Thus, implementation of an appropriate MPC algorithm can improve the transient response and dynamic stability of the NGs as well as increasing the lifetime of the BESS.

Fig. 2. Control Structure of the local grid-goring DER in DC MGs: (a) conventional PI control structure; (b) direct or FCS-MPC method; (c) the proposed AMPC-PI method.
compared to the regular PI controllers. The key idea of the MPC is to utilize a dynamical model of the system to predict its future response and apply it to compute a sequence of future control input actions. To this end, typically, the linearized model of the system around an operating point is utilized to predict the future responses [32]. Among many available MPC techniques, direct MPC with reference tracking which is also known as finite control set MPC (FCS-MPC) is the most popular method in the literature for DC power applications because of its intuitive design procedure and straightforward implementation [34,35]. This approach does not incorporate any modulator (e.g., Pulse Width Modulation (PWM) unit) and it aims to achieve the regulation of output variables (e.g., output voltage or current) along their reference trajectories by directly manipulating the converter switches. However, this method may lead to computationally interactable optimization problems due to its computational complexity [36]. Additionally, due to the removal of PWM unit, the direct MPC method suffers from a variable switching frequency which complicates the design of converter’s output filters [37]. Moreover, as illustrated Fig. 2, the required sampling time for the direct MPC approach is in the range of few microseconds which demands significantly more sophisticated hardware for real-time applications compared to the conventional PI voltage regulators. Consequently, the implementation of this technique requires a major restructuring of the local grid forming control and measurement systems that may not be always viable. Furthermore, because the output power of the GW module varies significantly over time, the DC NG has a nonlinear time-varying dynamic behavior. Thus, the effective and reliable operation of the DC NG may not be ensured using linear control (e.g., PI controllers) or conventional MPC techniques. To tackle this issue and improve the performance of the NG voltage control
system, adapting the NG voltage controller is needed with respect to the system changes [38].

2.2.3 Contribution and Scope

To address the discussed challenges, this work proposes an adaptive and flexible distributed control framework for a cluster of NGs in an islanded DC microgrid. The contributions of this work are threefold:

1) To increase the flexibility of the MG voltage control and power management system, ensure the PnP operation of the NGs, maximize PV power generation, and avoid battery SoC violation, an advanced rule-based supervisory control system (a decision-making module) is designed for each DC NG. The supervisory controller adjusts the operational mode of the NG components (e.g., GW, BESS, PV, and load) with respect to system conditions (or based on some predefine rules) to achieve the system objectives. The discrete logic of the supervisory controller is designed using a unified modeling language (UML) state diagram. This framework has the ability to represent the nested states and concurrent operation of the NG components that significantly reduces the complexity of system design compared to conventional finite state machines with sequential Boolean logics. In another word, the proposed UML structure facilitates the design of more advanced logic for the NG management systems, thereby improving the flexibility and adaptability of the NGs in a distributed and scalable manner. As a result, the proposed NG management strategy supports a variety of features such as autonomous PnP operation of NGs, maximizing PV power generation and BESS SoC management.

2) An adaptive distributed power sharing strategy is proposed based on a smart switching averaging consensus protocol to promote the system flexibility and efficiency
by offering an accurate battery SoC balancing among different NGs while maintaining the PnP operation of NGs. In this method, the BESSs of all NGs that are not isolated maintain the same SoC value at their steady state operation. Thereby, the BESSs imitate the behavior of a single cloud energy storage which its capacity is equal to the summation of all the

<table>
<thead>
<tr>
<th>Structure</th>
<th>Method</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centralized</td>
<td>Centralized management for optimal operation [9].</td>
<td>Optimal/Economical power sharing.</td>
<td>Low scalability, low reliability, high stress on the master unit.</td>
</tr>
<tr>
<td></td>
<td>Modified centralized method with constant active power exchange [10].</td>
<td>Reduced stress on the master unit.</td>
<td>Inaccurate power/current sharing</td>
</tr>
<tr>
<td>Decentralized</td>
<td>Self-sustained decentralized power exchange [12]</td>
<td>Reliable, communication-less, easily scalable.</td>
<td>Steady state voltage deviation, Inaccurate current sharing</td>
</tr>
<tr>
<td></td>
<td>Adaptive decentralized power sharing for battery SoC balancing [19]</td>
<td>PnP operation of NGs is provided, reliable, communication-less</td>
<td>High steady state voltage deviation</td>
</tr>
<tr>
<td></td>
<td>Decentralized nonlinear I-V droop technique for power exchange in clustered DC NGs [13]</td>
<td>PnP operation of NGs, reliable, communication-less</td>
<td>Degraded performance in large scale systems.</td>
</tr>
<tr>
<td>Distributed</td>
<td>Secured consensus-based distributed control of clustered DC NGs [14]</td>
<td>Reliable, robust against cyber-attack, accurate current sharing.</td>
<td>PnP operation of NGs is not provided.</td>
</tr>
<tr>
<td></td>
<td>This work proposed adaptive distributed power sharing and battery SoC balancing method.</td>
<td>Flexible to system changes, autonomous PnP operation of NGs, accurate current sharing, high-quality voltage.</td>
<td>Relatively complex decision logic</td>
</tr>
</tbody>
</table>

Table 1. Different power sharing and battery SoC balancing strategies in MNG systems.
BESSs’ energy storage capacities. Moreover, this approach provides a significantly less voltage deviation on the MG’s common DC bus compared to the decentralized adaptive droop control techniques. One of the main differences of the proposed smart switching consensus algorithm with other switching consensus techniques is that in this method the communication network is fixed but the signals that agents transfer via the communication network are changed based on predefined rules using a rule-based supervisory controller to track the changes on the electrical network and system objectives. Therefore, the communication network is less complex, but it is smart and more flexible.

3) Table 1 clarifies the advantage of the proposed adaptive distributed SoC balancing method and compared it with the discussed power sharing strategies in DC MNG systems.

4) An adaptive model predictive control (AMPC) algorithm is utilized to regulate the voltage of the NGs’ local DC bus in the presence of time varying and nonlinear behavior of the GW modules as well as the local CPLs. This method maintains the structure of the

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Switching Frequency</th>
<th>Sampling Rate</th>
<th>Flexibility</th>
<th>CPL Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cascaded PI</td>
<td>Fixed (Simple filtering)</td>
<td>0.1 to 1ms</td>
<td>Relatively flexible to system changes</td>
<td>Poor transient response or instability</td>
</tr>
<tr>
<td>FCS-MPC</td>
<td>Variable (Complex filtering)</td>
<td>&lt;50 µs</td>
<td>Prediction model cannot be updated (inflexible)</td>
<td>Accurate response for CPLs around nominal operating point. The performance can be affected if the CPLs significantly varies overtime.</td>
</tr>
<tr>
<td>Proposed AMPC-PI</td>
<td>Fixed (Simple filtering)</td>
<td>0.1 to 1ms</td>
<td>Prediction model is updated based on system changes (flexible)</td>
<td>Acceptable transient response for different CPL/CPS values.</td>
</tr>
</tbody>
</table>
conventional NG voltage control system, but the PI voltage regulator is replaced by an AMPC controller. In this approach, the AMPC controller is cascaded with a PI current regulator, and indirectly regulates the NG local DC voltage by computing a reference trajectory for the current regulator. In addition, the required sampling time for the AMPC controller is in the range of a millisecond which is approximately similar to the sampling time of the conventional digital PI voltage regulators in DC NG applications. In addition, the design of converter output filter remains similar to the conventional cascaded PI controllers with PWM techniques. Consequently, the implementation of this technique does not require a noticeably more sophisticated hardware or a major restructuring of the conventional NG voltage control systems. Finally, the simulation results show that the proposed control strategy can reduce the stress on the BESS module compared to the regular PI voltage controllers as well as improving the transient response of the system. Table 2 clarifies the advantage of the proposed AMPC method and compared it with the conventional control structure of grid-forming DERs in DC MNG systems.

### 2.3 Control Challenges in Islanded DC MNGs

This section discusses the specific control challenges in islanded DC MNGs including the GW behaviour as a CPL or a CPS in local DC buses as well as the flexible power sharing challenges. The rest of this work will focus on addressing these challenges.
2.3.1 CPL and CPS Behaviour of the GW in Local DC buses

As illustrated in Fig. 1b, there is a local grid-forming DER (e.g., a BESS) at each NG that is responsible for regulating the local DC bus voltage. In addition, the DC NGs can share/exchange power in the MNG network through their GW modules. In another word, the GW converters connect the local DC buses to MG common DC to support the power sharing between DERs of different NGs. Moreover, in islanded DC MNGs, at least one of the NGs should operate as the network grid-forming unit to regulate the MG common DC bus voltage through its GW module. Therefore, the GW units play two different roles at the same time. From the MG DC link point of view (see Fig. 1 Structure of DC MGs: (a) a typical DC MG with parallel grid forming units; (b) a DC MG that consists of multiple DC NGs (i.e., a DC MNG system).
On the other hand, from their local DC buses, they operate like a current source that demands or injects power regardless of the transient voltage variation at the NG local DC bus. Therefore, from the local DC bus point of view, the GW module behaves as a CPL, or a CPS based on the direction of its output power. Fig. 3 shows the schematic model of the GW from local and common DC buses point of view. Based on this model, and assuming the line inductance is negligible, the output power of the GW is obtained as:

\[
P_{GW} = \frac{v_{j}^{MG}(v_{j}^{MG} - v_{j-1}^{MG})}{R_m} + \frac{v_{j}^{MG}(v_{j}^{MG} - v_{j+1}^{MG})}{R_m}
\]  

(2.1)

where \(v_{j}^{MG}\) represents the output voltage of the GW converter of NG_j and \(R_m\) is the line resistance. Also, \(v_{j-1}^{MG}\) and \(v_{j+1}^{MG}\) show the output voltage of the GW modules of the neighboring NGs. Equation (1) clearly shows that the power transferred by GW from the NG local DC bus to the MG DC link is not related to the local DC bus voltage. This means that, from the local DC bus point of view, the GW module is seen as a CPL if \(P_{GW} > 0\) and it will be seen as a CPS if \(P_{GW} < 0\). It should be noted that the output power of the GW which also represents the amount of power exchanged among NGs, is typically controlled by adjusting the reference voltage of the GW converters (i.e., \(v_{j}^{ref}\)) through the MNG energy management or power sharing system (Note: at steady state \(v_{j}^{ref} = v_{j}^{MG}\)).

The discussed behavior of the GW modules may cause some major voltage stability issues in local DC buses that are explained as follows:

- In the case of CPL operation of GWs, they significantly reduce the marginal voltage stability of their local DC bus due to their negative incremental resistance, thereby
impacting the functionality of conventional PI controllers. This means that voltage control techniques should be utilized that can effectively address the CPL issue.

- The GW modules cause a significant variations on the nominal operating point of DC NGs. For instance, they may operate as a CPS when they are transferring power to the local DC bus and a few hours later they may behave like a CPL when they are sending power to the MG DC link. Therefore, due to the fact that the CPL units and CPS units have opposite impacts on the dynamic behavior of DC power systems, the voltage control techniques that utilize the linear approximation of the system’s model around a fixed nominal point (i.e., linear controllers or conventional MPC methods) will be dysfunctional. This means that voltage control techniques should be implemented which can adapt themselves to the ever-changing behavior of the system.

2.3.2 Flexible Power Sharing and PnP operation of NGs

As discussed in Section 2.2, due to the fact that the local BESSs of different NGs are connected to different DC buses, the conventional droop-based techniques cannot achieve desirable power sharing among BESSs to balance their SoC values (see the MNG structure in Fig.1). To effectively balance the SoC of BESSs additional information exchange among NGs such as SoC of BESSs and connection status of NGs are required. Typically, this coordination can be achieved using centralized control architectures in which all DC NGs inside the system communicate with the centralized supervisory control and energy management system (EMS). However, the centralized technologies cause low reliability, lack of scalability, and vulnerability to a single point of failure. The decentralized DC bus signalling methods can also provide a seam-less coordination between the NGs, but they generate a large voltage deviation on the MG common DC link (e.g., 2%-5%) [18].
other hand, the conventional averaging consensus algorithms with fixed network topology, which are widely used for distributed control techniques in DC MGs, are not suitable for SoC balancing of BESSs in DC MNGs because the available NGs for power sharing or the number of grid-forming GW units can be changed during the system operation. To address this issue, communication network topology of the system should be able to follow the system changes and switches to the new configurations according to the system conditions. Therefore, consensus-based algorithms with switching topologies are needed. Yet, changing the network topology is not the only issue in DC MNG systems. The power sharing and BESS SoC balancing can be more complicated in these systems if the PnP operation of NGs is an objective of the control system. The reason is that the distributed power sharing among NGs is realized by adjusting the reference voltage of the grid-forming GW modules based on the SoC value of BESSs. However, assume a case that an isolated DC NG immediately reconnects to the MG common DC link. If the BESS’s SoC of that NG significantly differs from the other NGs who are currently connected to the MG DC link, which is highly probable, the distributed power sharing algorithms may compute a large voltage deviation that can destabilize the system or activate the protection relays. Therefore, an additional intelligent control layer (i.e., a real-time decision-making module) at each NG is required to not only change the operating mode of the NG components but also adjust the switching consensus algorithm based on the sequence of previous actions of the NG components and neighbouring agents as well as the current system conditions. In another word, to guarantee the smooth PnP operation of NGs, the distributed consensus algorithm and NG management system needs some intelligence with high-level adaption. On the other hand, due to the concurrent behaviour of NG components,
designing the required advanced logic of the decision-making system by standard techniques such as FSMs or state flow charts can be a tedious task. Therefore, it is highly desirable to use heuristic techniques to reduce the complexity of designing the logic of the NGs’ real-time decision-making systems.

**2.4 Overview of the Case Study System**

As seen in Fig. 4, the islanded DC MG is considered as a cluster of DC NGs (i.e., an MNG system) with a ring topology\(^1\) architecture. The structure of a single NG is also shown in Fig. 5. The NG contains a gateway (GW) unit, a PV unit, a BESS, and a group of AC and DC CPLs. In this work, NGs are designed as intelligent reactive agents that can

---

\(^1\) The ring topology architecture is not a necessary requirement in this work. The DC MG can have any other single bus topologies.

25
change their dynamic behaviour and control objectives upon satisfying a predefined condition. Here, every single NG has a control unit containing two level of controllers and a data processing module. The data processing module (see Fig. 5) receives internal data from local measurements and external data through communication with neighbouring NGs. The higher-level controller is a decision-making module (i.e., a supervisory controller). This module is responsible for identifying the operational mode of NG (e.g., MG voltage control, SoC balancing, etc.) and helps with avoiding SoC violation in BESSs, maximizing the PV power generation, and providing PnP capability for NGs. The lower level contains a group of controllers that compute references for the current regulators of

Fig. 5. The schematic model of a DC NG in this work.
power electronic converters to achieve the system objective at each operating mode. The NG control system is discussed in what follows.

**2.5 NG’s Decision-Making Module**

To increase the flexibility and adaptability of the system, each NG is designed as an intelligent reactive agent that can change the dynamic behavior of its components (e.g., control objective, communication, or electrical connection) with respect to the system conditions. To this end, a discrete-event supervisory controller (i.e., decision making module) is designed for each DC NG that selects the operational mode of the NG subsystems (e.g., PV, GW, BESS, load) based on predefined rules.

**2.5.1 Communication and GW Module Sequence of Actions**

Let assume an NG (e.g., NG\(_j\)) has two neighboring NGs (e.g., NG\(_{j-1}\), NG\(_{j+1}\)) that can share some information with them. The external inputs that NG\(_j\) receives from its neighbors is defined as:

\[
U_j = \{y_{(j-1,j)}, y_{(j+1,j)}, m_{j-1}^{GW}, m_{j+1}^{GW}\} \tag{2.2}
\]

where \(y_{(j-1,j)}\) and \(y_{(j+1,j)}\) are the output signals of NG\(_{j-1}\) and NG\(_{j+1}\) sent to NG\(_j\). \(m_{j-1}^{GW}\) and \(m_{j+1}^{GW}\) also represent the operating mode of the GW of the neighboring NGs. The output signals of the NG\(_j\) are also defined as:

\[
Y_j = \{y_{(j,j-1)}, y_{(j,j+1)}, m_j^{GW}\} \tag{2.3}
\]

where \(y_{(j,j-1)}\) and \(y_{(j,j+1)}\) are the signals sent by NG\(_j\) to NG\(_{j-1}\) and NG\(_{j+1}\), respectively. \(m_j^{GW}\) is also the operating mode of the GW in NG\(_j\). The NG sends its consensus protocol state (i.e., \(\psi_j\)) to the neighbouring NGs when its GW is in MG voltage control mode (i.e.,
In this operating mode, the GW operates as a MG grid forming unit and regulates the MG common DC bus voltage. Once the GW module of the NG leaves this mode of operation, the NG passes the output signals of its neighbouring agents to each other (i.e., \( y_{(j,j-1)} = y_{(j+1,j)} = \psi_j \)). So, the output signals of the NG depend on the operational mode of the GW converter. It will be shown in Section 2.6 that by implementing this smart switching communication technique, the consensus protocols’ value (i.e., \( \psi_j^* \)) becomes always equal to the average SoC of the BESSs in NGs whose GW is in MG voltage control mode (i.e., grid forming NGs) regardless of the operating mode of NGs. Additionally, \( S \) represents the connection status of the NG, with “0” denoting isolated mode and “1” denoting MG-connected mode. When NG becomes islanded (i.e., \( S = 0 \)), GW switches to the idle mode. In addition, to return to the grid forming mode (i.e., MG voltage control mode), the GW first switches to a transient operational mode (i.e., battery charging or discharging) and operates as a grid following unit to charge/discharge the battery and reduce the difference between the BESS’s SoC and the consensus value (i.e., \( |SoC_j - \psi_j^*| \)). Once this value becomes very small (i.e., less than 0.01), the GW module returns to the MG voltage control mode. It will
be discussed later that this strategy is essential to maintain the smooth PnP operation of the NGs. In addition, to guarantee that at least half of the NGs which are connected to the MG common DC bus operate as MG grid forming units\(^2\), NG\(_j\) cannot switch to the transient

\(^2\) MG grid forming units (or grid forming NGs) are the NGs whose GW converter regulates the MG common DC bus voltage.
modes (i.e., battery charging or discharging) if its neighbouring NGs are in a transient mode (see $e_1$ and $e_2$ in Fig. 6)

2.5.2 PV, BESS, and Load Sequence of Actions

The proposed logic can accommodate maximum PV power generation in the NGs. As seen in Fig. 6, PV unit only leaves MPPT mode to balance the PV power generation and load if there is no capacity to store the extra generated power. This can occur when the NG$_j$ is isolated, and its BESS is fully charged or NG$_j$ is connected to the MG common DC bus and all the BESS of the MG grid forming NGs are fully charged. The latter can be recognized by an individual NG since the power sharing strategy among NGs proposed in Section 5.2 provides the same SoC value for all the BESSs in NGs whose GW is in MG voltage control mode (i.e., MG grid forming units). Moreover, when the SoC of BESS becomes lower than a specific value (i.e., $soC_j < 0.25$) the load unit switches to the load shedding mode by disconnecting the noncritical loads. If the load shedding action is not sufficient for maintaining the SoC of BESS higher than a minimum threshold value (i.e., $soC_j < 0.20$), to maintain the system’s stability the loads are disconnected and the system switches to the recovery (i.e., no load) mode to charges the batteries.

2.5.3 Evaluating the Complexity and Flexibility of the Decision Logic

As discussed in the previous section, the UML-based logic design provides a framework that can capture the concurrent behaviour of the NG components including communication system, GW, BESS, PV, and loads. Therefore, it intrinsically supports the process of the system states and switching conditions in a parallel manner, so that facilitates the design of the supervisory controller. It can be easily shown that under the proposed method, each
NG may react to the system changes by performing 72 different operating modes representing a high flexibility and adaptability of the NG control systems. To design this logic in UML framework, it is just needed to define 13 substates for NG components which includes 3 substates for loads, 3 substates for PV, a single substate for BESS, 4 substates for GW, and 2 substates for the communication system. However, in the case of designing this logic with classical sequential frameworks such as FSMs or state-flow charts, it is required to define 72 states which is equal to the number of operating modes of the NGs. In addition, to design and represent the proposed logic in classical FSMs it is needed to define 160 state transitions while the proposed UML method just requires defining 15 state transitions. Moreover, due to the modular representation of states, the UML methods support distributed or parallel execution of states, thereby increasing the scalability of the supervisory controller. Table 3 summarizes the advantages of the proposed UML strategy over the classical FSM methods.

### 2.6 Low-level Controllers

The low-level controllers of the NGs calculate reference values for the current regulators of the converters to achieve the system objectives at each operating mode. In the

<table>
<thead>
<tr>
<th>Framework</th>
<th>Processing Method</th>
<th>State Definition</th>
<th>$N_T^2$</th>
<th>$N_S^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSM</td>
<td>Sequential</td>
<td>Single layer, unscalable.</td>
<td>160</td>
<td>72</td>
</tr>
<tr>
<td>UML</td>
<td>Parallel – concurrent computation</td>
<td>Hierarchical, modular, and scalable.</td>
<td>15</td>
<td>13</td>
</tr>
</tbody>
</table>

1 Each NG may perform 72 different operational modes under the proposed rule-based supervisory controller (in both FSM and UML).
2 $N_T$ is the total number of state-transition required to represent/implement the logic of the supervisory controller in each framework.
3 $N_S$ is the total number of substates required to represent/implement the logic of the supervisory controller in each framework.
following, first, the proposed control strategies in PV and BESS are discussed. Then, the control structure of GW unit is proposed.

2.6.1 PV and BESS Control Systems

As discussed in Section 2.5, the BESS is responsible for regulating the voltage of the NG local DC bus. From the NG local DC bus side, the other units (i.e., PV, load, and GW) operate as a CPL or a CPS according to the direction of their output current. Without loss of generality, it is assumed that BESS utilizes a bidirectional DC-DC buck converter. Fig. 7 shows the circuit model of the NG form the point of view of BESS power electronic converter (i.e., the local grid forming unit) that is adopted from [39]. In this model, only the averaged dynamics are considered, and the high frequency switching dynamics are ignored. In addition, the impedance of the NG DC link is neglected. The overall current of the parallel connected load/source converters in an NG (i.e., PV, load, and GW) is represented by \( i_o \) that is obtained as:

\[
    i_o = \frac{P_{CP}}{v_{NG}}
\]  

(2.4)

where \( P_{CP} \) is the total power of the constant power units (i.e., load/source converters) and it is obtained as

\[
    P_{CP} = P_{GW} + P_{Load} - P_{PV}
\]  

(2.5)

where \( P_{Load} \), \( P_{PV} \), \( P_{GW}^m \) are the power of the load, PV, and GW units at a given operating point, respectively. Thus, if \( P_{CP} < 0 \), the buck converter is supplied by a CPS. Alternatively, if \( P_{CP} > 0 \), the power electronic converter is
loaded by a CPL that can cause some stability issues due to the negative incremental impedance of CPLs [32]. The equivalent linearized model of the constant power units at a given operating point can be also obtained as

\[ i_o = \left( -\frac{P_{CP}}{V_{NG}^2} \right) v_{NG} + 2 \frac{P_{CP}}{V_{NG}} \]  

(2.6)
where \( V_{NG} \) is the voltage of NG DC bus at that given operating point. Equation (2.6) indicates that, at a given operating mode, the constant power units can be approximated by a resistance parallel with a constant current source as follows

\[
\begin{align*}
I_{CP} &= 2 \frac{P_{CP}}{V_{NG}} \\
R_{CP} &= -\frac{V_{NG}^2}{P_{CP}}
\end{align*}
\] (2.7)

Fig. 7(b) shows the equivalent circuit model of the NG. Therefore, the averaged dynamic model of the NG, at a given operating point, can be obtained as follows

\[
\begin{align*}
L \frac{di_b}{dt} &= v_m \cdot \text{Duty} - Ri_b - v_{NG} \\
C \frac{dv_{NG}}{dt} &= i_b - \frac{v_{NG}}{R_{CP}} - I_{CP}
\end{align*}
\] (2.8)

where \( i_b \) is the output current of the BESS (see Fig. 7) and \( V_{NG} \) is the voltage of the NG local DC bus. \( R \), \( L \), and \( C \) are also the resistance, inductance, and capacitance of the converter’s output filter, respectively. Fig. 8 shows the control structure of the BESS unit. To regulate the voltage of the NG local DC bus (i.e., \( V_{NG} \)) an AMPC algorithm is employed to compute a reference signal (i.e., \( i_{ref} \)) for the current regulator of the DC-DC converter of BESS unit. The current regulator is a PI controller that calculates the duty cycle (i.e., \( \text{Duty} \)) of the converter to regulate its output current (i.e., \( i_b \)) to the reference value (i.e., \( i_{ref} \)). By adding the dynamics of the current regulator to equation (2.8) and
defining \( \text{Duty} = k_p (i_{\text{ref}} - i_b) + k_i \int (i_{\text{ref}} - i_b) dt \), where \( k_p \) and \( k_i \) are the proportional and integral gain of the PI current regulator, the linear time varying (LTV) dynamic model of the NG can be obtained in a state space form as

\[
\begin{align*}
\dot{x}(t) &= A(t)x(t) + B(t)u(t) \\
y(t) &= Cx(t)
\end{align*}
\]

(2.9)

where \( x = [i_b, v_{\text{NG}}, e_{\text{int}}]^T \), \( u = [u_{\text{mv}}, u_{\text{md}}]^T \). \( e_{\text{int}} \) is defined as the integral of the error (i.e., \( e_{\text{int}} = \int (i_{\text{ref}} - i_b) dt \)). Also, \( u_{\text{mv}}(t) = i_{\text{ref}} \) is the control input (or manipulated variable) and \( u_{\text{md}}(t) = I_{\text{CP}} \) is the measured disturbance. \( A \), \( B \), and \( C \) are defined as

\footnote{In practice, the current regulator is a digital controller that has a much lower sampling time than its higher-level discrete-time NG voltage regulator. So, from the NG voltage controller point of view, it can be approximated by a continuous-time system.}
As seen, the NG system has a time-varying dynamic behavior. Specially, the \( P_{CP} \) (or \( R_{CP} \)) may vary in a wide range during the NG operation. Consequently, the typical MPC techniques that employs the linear time invariant (LTI) approximation of the system cannot achieve the desired operation of the NG due to the inaccurate prediction model. However, AMPC control techniques have an interesting feature which is updating the prediction model at each control interval. As a result, the LTI approximation of the system at each control interval is more accurate. Also, AMPC is intrinsically a discrete-time controller. So, the AMPC requires a discrete-time approximation of the system (e.g., a discrete-time predictive model). Consequently, after updating the model parameters (e.g., \( r_{cp} \), \( v_{in} \)) at each control interval, the AMPC controller utilizes the following discrete-time approximation of the system:

\[
\begin{align*}
x_d(k+1) &= A_d x_d(k) + B_d u_d(k) \\
y_d(k) &= C x_d(k)
\end{align*}
\]

(2.13)

where \( x_d \), \( u_d = [u_{dmv} \ u_{dmd}]^T \), and \( y_d \) are discrete time approximation of the system states, inputs, and output, respectively. Also, \( A_d \) and \( B_d \) are directly computed as
\[ A_d = e^{AT_s}, B_d = \left( \int_{\tau=0}^{T_s} e^{A\tau} d\tau \right) B = A^{-1}(A_d - I)B \]  

(2.14)

where \( T_s \) is the AMPC sampling time. Then, the AMPC algorithm solves a quadratic programming (QP) formulation using an active set optimization method to compute the sequence of future control actions (i.e., the reference current). To this end, it minimizes the following cost function, at each time step (i.e., \( k \)).

\[
J = \sum_{i=1}^{H_p} \eta_e \left( v_{\text{ref}}(k+i\mid k) - y_d(k+i\mid k) \right)^2 \\
+ \sum_{i=1}^{H_c} \eta_c \left( u_{\text{mv}}(k+i\mid k) - u_{\text{mv}}(k+i-1\mid k) \right)^2
\]

(2.15)

subject to

\[
-i_{b,\text{nom}} \leq \frac{u_d(k+i\mid k)}{1.1} \leq i_{b,\text{nom}}, \quad i \in \{1, \ldots, H_c\}
\]

(2.16)

where \( H_p \) and \( H_c \) are the prediction and control horizon and \( H_c < H_p \). \( v_{\text{ref}} \) is the reference voltage and \( \forall k, v_{\text{ref}}(k) = v_{\text{nom}} \). \( u_{\text{mv}} \) is the manipulated variable and \( u_{\text{mv}}(k) = i_{\text{ref}}(k) \). \( \eta_e \) and \( \eta_c \) are also the weights of the error and manipulated variable move, respectively. So, by adjusting \( \eta_e / \eta_c \), one can provide an optimal tradeoff between voltage regulation of the NG local DC bus and current ripples of the BESS. Finally, after computing the sequence of future control actions, the AMPC imposes the first one and goes for the next time step.

As seen, the proposed AMPC controller indirectly regulates the output voltage of the BESS converter (or NG local DC bus voltage) by calculating a reference trajectory for its lower-hand PI current regulator. This structure is relatively similar to the conventional NG
control strategies in which a PI voltage controller computes a reference value for its cascaded PI current regulator. Therefore, the AMPC control interval (or sampling time) can be similar to the sampling time of conventional PI voltage regulators in NG applications which is in the range of a millisecond. However, the conventional direct MPC techniques (e.g., FCS-MPC), typically require a sampling time in the range of a few microseconds. Thus, the direct MPC methods should carry out approximately a same number of computations in a significantly shorter time frame compared to the proposed AMPC technique. Hence, in terms of hardware requirements, the proposed approach is considerably less demanding than the direct MPC methods and it may be more comparable with the conventional NG PI voltage controllers. In addition, the proposed approach maintains the structure of the conventional NG voltage control systems (i.e., two cascaded controllers and a PWM). Consequently, the implementation of this technique does not require a major restructuring of the conventional NG voltage control system.

Fig. 9 shows the control structure of the PV unit. The PV unit has three different operating modes including an MPPT, an idle, and a load following mode. During the load following mode, the output power of the PV is approximately equal to the demanded power by the GW and load (i.e., \( P_{\text{PV}} \approx P_{\text{GW}}^{\text{in}} + P_{\text{load}} \)). Thus, when PV switches to this mode, the output current of the BESS becomes nearly zero to avoid battery SoC violation. In addition,
the PV module will switch to the idle mode if the available solar irradiance power becomes less than a threshold value (i.e., \( P_{in} < P_{min} \)).

2.6.2 GW Control Systems

The GW converter of an NG has four different operating modes including an MG voltage control (i.e., MG grid forming mode), two transient modes, and an idle mode. Fig. 10 illustrates the structure of the parallel connected NGs in the MNG system where \( V_{j}^{MG} \) and \( I_{GW}^{out} \) are the output voltage and current of the NG\( _j \). \( R_{m} \) and \( L_{m} \) are also resistance and inductance of the DC link between two neighbouring NGs. During MG voltage control mode, the NGs communicate with each other based on a consensus protocol to regulate the voltage of the MG common DC bus (i.e., \( V_{j}^{MG} \)) as well as sharing power. In this approach, all the grid forming NGs balance the SoC of their BESS unit with each other. The agents have an undirected ring communication network topology illustrated in Fig. 11(a) Define \( \mathcal{A} \) as the set of all agents, and \( \mathcal{A}_{G} \subseteq \mathcal{A} \) as the set of grid forming NGs. Also, consider \( \mathcal{N}_{j} \) as the set of neighbours of NG\( _j \) that can be obtained as:

![Diagram of MG Common DC Bus]
So, \( \forall j \in \mathcal{A} \), the number of elements in \( N_j \) is two (i.e., \( |N_j| = 2 \)). The protocol state of the NG\( j \) (i.e., \( \psi_j \)) is defined as follows:

\[
\dot{\psi}_j(t) = -2\lambda \psi_j + \lambda \sum_{i \in N_j} y(i, j) \tag{2.18}
\]

where \( y(i, j) \) is the output signal of the NG\( i \) sent to the NG\( j \), and \( \lambda \) is the gain of communication network.

First, assume that all the GW units are in MG voltage control mode (i.e., \( \mathcal{A}_{0} = \mathcal{A} \)). As discussed in Section 2.5, when the GW unit of NG\( j \) is in grid forming mode, it sends its protocol state to the neighbouring agents (i.e., \( y(f, i) = \psi_j, i \in N_j \)). Consequently, \( \forall j \in \mathcal{A} \), (2.18) is reformulated as

\[
\dot{\psi}_j(t) = -2\lambda \psi_j + \lambda \sum_{i \in N_j} \psi_i \tag{2.19}
\]
Equation (2.19) can be represented in state space form as

$$\dot{\psi}(t) = -L\psi(t) \tag{2.20}$$

where $\psi = [\psi_1, \psi_2, \ldots, \psi_n]^T$ and $L = [l_{ji}]_{n \times n}$ is the graph Laplacian matrix of the network that is obtained as

$$l_{ji} = \begin{cases} -\lambda, & i \in N_j \\ 2\lambda, & i = j \end{cases} \tag{2.21}$$

Equations (2.19) to (2.21) represent a standard static averaging consensus algorithm. By reinitializing $\psi_j(0) = SoC_j(kT_s')$ at each sampling time (i.e., $k$), it can be shown if $\lambda$ is enough large, all the protocol states will converge to a consensus value [40] (i.e., $\forall j \in A, \psi_j^* = SoC^*$) that is obtained

$$SoC^* = \frac{1}{|A|} \sum_{j \in A} SoC_j(kT_s') = \frac{1}{n} \sum_{j=1}^{n} SoC_j(kT_s') \tag{2.22}$$

where $|A| = n$ is the total number of NGs and $T_s'$ is the sampling period. So, if $A_G = A$ and $\lambda$ is enough large, the steady state values of protocol states at each sampling period (i.e., $\psi_j^*$) is equal to the average SoC of all BESSs.

Now, assume that an NG (e.g., NG$_1$) switches to one of the transient or idle modes (i.e., $A_n = A - \{1\}$). So, the communication module of NG$_1$ switches to the message passing mode (see Fig. 6). In this case, NG$_1$ passes the outputs of its neighbouring agents (i.e., $\{n, 2\} \in N_1$) to each other (i.e., $y(1, 2) = \psi_n, y(1, n) = \psi_2$). Fig. 11(b) shows the equivalent communication network when NG$_1$ is in the message passing mode. In this case, the protocol states can be obtained as
\[
\dot{\psi}(t) = -L'\psi(t) \tag{2.23}
\]

where the new Laplacian matrix, \( L' \), is obtained as

\[
L' = \begin{bmatrix}
2\lambda & -\lambda & 0 & \cdots & -\lambda \\
0 & l'_{ji} & 0 & \cdots & 0 \\
\vdots & \ddots & \ddots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & l'_{ji} \\
0 & 0 & 0 & \cdots & 0
\end{bmatrix}_{n\times n} \tag{2.24}
\]

where \( \forall ij \in \mathcal{A}_G \), \( l'_{ji} = l'_{ij} \) and \( \sum_{i \in \mathcal{A}_G} l'_{ji} = 0 \). Thus, by reinitializing \( \psi_j(0) = SoC_j(kT'_s) \) at each sampling time, the protocol states of all the MG grid forming units converge to a consensus value (i.e., \( \forall j \in \mathcal{A}_G, \psi_j = SoC^* \)) that is obtained as follows:

\[
SoC^* = \frac{1}{|\mathcal{A}_G|} \sum_{j \in \mathcal{A}_G} SoC_j(kT'_s) = \frac{1}{n-1} \sum_{j=2}^{n} SoC_j(kT'_s) \tag{2.25}
\]

where \( |\mathcal{A}_G| = n - 1 \) is the total number of grid forming NGs. Also, based on (2.24), \( \psi^*_1 \) is obtained as

\[
\psi^*_1 = \frac{1}{2} \sum_{j \in \mathcal{A}_G} \psi^*_j = \frac{\psi^*_2 + \psi^*_n}{2} = SoC^* \tag{2.26}
\]

So, based on the proposed approach, the protocol states of all NGs always reach a consensus value that is equal to the average SoC of all the batteries in the grid forming NGs regardless of the NGs operating mode. This can be represented as follows

\[
\forall j \in \mathcal{A}, \psi^*_j = \frac{1}{|\mathcal{A}_G|} \sum_{j \in \mathcal{A}_G} SoC_j(kT'_s) \tag{2.27}
\]

\( \psi^*_j \) is then used by the GW units of the NGs to balance the SoC of the BESSs with each other.
Fig. 12 shows the control structure of the GW module in NGj. When the GW is in MG voltage control mode, it measures the error between the SoC of its BESS and the average SoC of all the grid forming units (i.e., $\psi^*_{j}$) and then sends the error to the proportional derivative (PD) controller. In this case, if the error (i.e., $\psi^*_{j} - SoC_{j}$) increases, the PD controller slightly reduces the voltage reference of the GW module (i.e., $\psi_{ref}$) to deliver more electrical power to the NG and charges the battery. On the other hand, if the SoC of BESS becomes higher than the average SoC of the grid forming NGs, the outputs of the PD controller (i.e., $\delta_{j}$) decreases to increase the output power of the NG and discharge the battery. It will be shown in section 6 that this technique can balance the SoC of the BESSs in all grid forming units. In addition, when NG is isolated, the GW module switches to the idle mode and delivers no power. In this mode, the NG cannot balance the SoC of BESS with other NGs. Thus, if the NG directly switches from the isolated mode to the MG voltage control mode, the error between the consensus value and SoC of BESS
(i.e., $\psi_j^* - SoC_j$) will be large. Consequently, the PD controller’s output may be very large (i.e., $|\delta_j| \gg 0$) that can cause a significant voltage deviation on the MG common DC bus. In addition, it may deliver a significant power to the NG which may destabilize the system. To improve the PnP ability of the NGs and provide a bump less transition to the grid forming mode, the NG firstly switches to a transient mode (see the internal logic of NGs in Fig. 6). In the transient mode, the GW operates as a grid following unit and delivers power to the NG so that charges/discharges the BESS with its nominal value (i.e., $\zeta_\omega$). Once the error becomes very low (i.e., $|\psi_j^* - SoC_j| \leq 0.01$) the GW switches to the MG voltage control mode. It should be noted there is not any community load or CPL on the MG common DC link, so the conventional cascaded PI controllers can provide a good voltage regulation at MG common DC link.

In conclusion, the system computes the average SoC of all the batteries that are in grid forming NGs using a switching averaging consensus protocol regardless of the NGs’ operating mode representing a high-level flexibility. The consensus value is then used as a reference SoC by the GW module of the MG grid forming units to balance the SoC of their batteries with each other. The consensus value is also used by the supervisory controllers of all units to select the operational mode of the system and ensure the safe automatic connection of the NGs to the MG common DC bus. It will be shown in section 6 that the proposed adaptive distributed power sharing technique can accurately balance the SoC of the BESS in different NGs while maintaining the PnP ability of NGs.
2.7 Simulation Result

The performance of the proposed control system is evaluated by simulating a test system using MATLAB/Simulink. The test system is an islanded MNG which consists of four similar DC NGs. The BESSs are also similar, and they are lithium-ion type. The system parameters are illustrated in Table 4.
## Table 4. System parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{NG}^{nom}$</td>
<td>Nominal voltage of NGs’ DC bus</td>
<td>100 V</td>
</tr>
<tr>
<td>$v_{MG}^{nom}$</td>
<td>Nominal voltage at MG DC bus</td>
<td>750 V</td>
</tr>
<tr>
<td>$i_{b}^{nom}$</td>
<td>Nominal output current of the BESSs</td>
<td>100 A</td>
</tr>
<tr>
<td>$Q$</td>
<td>Nominal charge time of the batteries</td>
<td>3 hours</td>
</tr>
<tr>
<td>$P_{load}^{nom}$</td>
<td>Nominal load power at each NG</td>
<td>10 kW</td>
</tr>
<tr>
<td>$P_{PV}^{nom}$</td>
<td>Nominal PV power generation</td>
<td>10 kW</td>
</tr>
<tr>
<td>$P_{b}^{nom}$</td>
<td>Nominal power of BESS</td>
<td>10 kW</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Gain of communication network</td>
<td>5</td>
</tr>
<tr>
<td>$k_{PD}^{P}$</td>
<td>Proportional gain of the PD controller</td>
<td>400</td>
</tr>
<tr>
<td>$k_{PD}^{D}$</td>
<td>Derivative gain of the PD controller</td>
<td>10</td>
</tr>
<tr>
<td>$N_{d}$</td>
<td>Filter coefficient of the PD controller</td>
<td>1</td>
</tr>
<tr>
<td>$R_{m}$</td>
<td>Resistance of the MG DC link</td>
<td>10mΩ</td>
</tr>
<tr>
<td>$L_{m}$</td>
<td>Inductance of the MG DC link</td>
<td>5mH</td>
</tr>
<tr>
<td>$k_{p}^{c}$</td>
<td>Proportional gain of current regulator</td>
<td>0.8</td>
</tr>
<tr>
<td>$k_{i}^{c}$</td>
<td>Integral gain of current regulator</td>
<td>4</td>
</tr>
<tr>
<td>$K_{p}^{V}$</td>
<td>Proportional gain of voltage regulator</td>
<td>4</td>
</tr>
<tr>
<td>$k_{i}^{v}$</td>
<td>Integral gain of voltage regulator</td>
<td>50</td>
</tr>
<tr>
<td>$T_{s}$</td>
<td>AMPC controllers’ sampling time</td>
<td>1 ms</td>
</tr>
<tr>
<td>$H_{p}$</td>
<td>Prediction horizon of AMPC</td>
<td>10</td>
</tr>
<tr>
<td>$H_{c}$</td>
<td>Control horizon of AMPC</td>
<td>2</td>
</tr>
<tr>
<td>$\eta_{e}$</td>
<td>Weight of error minimization</td>
<td>0.75</td>
</tr>
<tr>
<td>$\eta_{c}$</td>
<td>Weight of manipulated variable move</td>
<td>0.066</td>
</tr>
</tbody>
</table>
2.7.1 AMPC Performance Evaluation

Fig. 13 illustrates the performance of the proposed AMPC technique compared to a conventional NG voltage control system (i.e., a regular PI voltage controller represented in Fig. 2). It is believed that this comparison is reasonable because both control systems have the same structure in which the voltage controllers (i.e., AMPC and PI) calculate a reference signal for the current regulator of the bidirectional DC-DC converter (i.e., the current controller of the BESS unit). They also have a similar saturation limit that is equal to \( 1.1 i_{\text{nom}} \) (i.e., \( i_{\text{ref}} < 1.1 i_{\text{nom}} \)) and a same sampling time (i.e., \( T_s = 1\text{ms} \)). In addition, they utilize an exactly similar PWM technique and use similar converter output filters. To consider the operational saturation limits, the PI voltage controller uses a back calculation anti-windup technique. On the other hand, the AMPC minimizes the proposed cost function in (15) subject to the saturation constraint (see (2.15) and (2.16)). As discussed before, \( P_{cp} \) represents the total power of the constant power units that is defined in (5). If \( P_{cp} > 0 \), the DC-DC converter of the BESS unit will supply a CPL that can provide some stability concerns caused by the negative incremental impedance of CPLs [6,27]. In the case study...
Fig. 13. The performance of the proposed AMPC technique compared to a PI voltage controller, (a) $P_{cp}$ changes, (b) voltage variation of the NG local DC bus, (c) output current of the BESS (i.e., $i_b$).
system, the maximum CPL is 10 kW (i.e., $|P_{cp}| < 10\text{kW}$). Fig. 13(a) represents the variation of $P_{cp}$ in the test system. Fig. 13(b) shows the transient voltage variation of the NG local DC bus during $P_{cp}$ changes. The conventional PI controller causes more voltage variation on the NG local DC bus compared to the proposed AMPC technique. Particularly, at maximum CPL (i.e., $t \in T_1$), the PI controller has a small marginal stability that causes a poor transient response and significant voltage oscillation on the NG local DC bus. Fig. 13(b) also shows that in higher CPL values, the system experiences significantly worse transient response in the PI voltage control technique while the AMPC performance is not affected by the large CPL values. Fig. 13(c) represents the output current of the BESS in both control techniques. The AMPC provides fewer current ripples compared to the PI controller. So, due to the limited life cycle of the BESSs, the AMPC algorithm can also increase the efficiency of the system by increasing the lifetime of the BESSs. In conclusion, the proposed AMPC approach considerably overperformed the regular PI voltage controller results in more reliability (i.e., better voltage regulation) and more efficiency (i.e., increasing the lifetime of the BESSs).
2.7.2 Battery SoC Balancing (Power Sharing)

The battery SoC balancing performance of the proposed approach is studied in this section. The net power is defined as the difference between generation power and load consumption in each NG (i.e., \( P_{net} = P_{PV} - P_{Load} \)). Fig. 14 shows the so-called net power profiles in the DC MG system during the 5-hours simulation interval. The PV power generation in NG2 is higher than the load consumption (i.e., \( P_{PV} > P_{Load} \)) while the net power in the other NGs has a negative value. Fig. 15 illustrates the SoC of BESSs in two different scenarios. In both scenarios, all the NGs initially have a same SoC value. In the first scenario, all the NGs are isolated and share no power with each other. In the second scenario, it is assumed that all the NGs are connected to the MG common DC bus and all the GW modules are in MG grid forming mode (i.e., grid forming NGs). Due to the similar power generation and load values (i.e., similar net power), the average SoC of BESSs in both scenarios are the same. However, as seen in Fig. 15 (b), in the second scenario, the SoCs of all BESSs are balanced with each other that verifies the effectiveness of the distributed power sharing approach. Consequently, the BESSs altogether behave similar to a cloud energy storage system (e.g., a community BESS). This BESS aggregation is highly beneficial that results in maximum

Fig. 14. The net power profile in different NGs during the simulation interval.
utilization of BESSs capacities and increase the MNG reliability. Fig. 16 also represents
the voltage deviation of the MG DC common DC bus and the output current of the GW
units (i.e., $i_{GW}^m$) under the proposed control approach (i.e., second scenario). As seen, the
voltage deviation on MG common DC link is very low, and it can be negligible. Thus, the
proposed distributed power sharing method does not affect the voltage regulation of the
MG common DC bus. However, the decentralized droop-based techniques usually generate
2% to 5% steady state voltage deviations.

2.7.3 PnP Operation of NGs
This section investigates the PnP ability of the DC NGs. Fig. 17(a) shows the sequence of actions in PnP operation of an NG. In this test case, all the NGs are initially connected to the MG common DC bus and all the GW units are in MG voltage control mode (i.e., grid forming NGs). In addition, the net power at each NG is like the test cases in Section 6.2. At $t = t_i$, NG4 becomes isolated, and its GW module switches to the idle mode. During the isolated mode, NG4 does not share power and its SoC value cannot be balanced with other NGs. In this mode, instead of its protocol state (i.e., $\psi_4$), NG4 sends the state of NG3.

\footnote{Remember that the grid forming NGs (or MG grid forming NGs) are those whose GW module regulates the MG common DC bus voltage.}
Fig. 17. Plug and play operation of NG. (a) Sequence of actions, (b) SoC variation of the NGs, (c) voltage variation of MG common DC bus at $t = t_2$, (d) voltage variation of MG common DC bus at $t = t_3$. 
(i.e., $\psi_3$) to NG1 and $\psi_1$ to NG3. Thus, the protocol states of all NGs converge to the average SoC of grid forming NGs (i.e., NG1, NG2, and NG3). Therefore, the grid forming NGs balance their SoC value with each other. At $t = t_2$, the NG4 becomes connected to the MG DC link. So, its GW module switches to the battery charging transient mode (i.e., grid following) to charge the BESS with its nominal power (i.e., $i_b^{\text{nom}}$) during $T = [t_2, t_3]$ time interval. Since at $t = t_3$, the difference between the battery SoC and the consensus value (i.e., $\psi_4^*$) becomes very small (i.e., $|\psi_4^* - \text{SoC}| < 0.01$), the GW unit of NG4 switches to the MG voltage control mode and balances the SoC of its BESS with other NGs. The SoC variation of all BESS is illustrated in Fig. 17(b).

The transient voltage variation on the MG common DC bus in $t_2$ and $t_3$ switching instances is also illustrated in Fig. 17(d), respectively. This voltage variations in both switching instances are insignificant compared to the nominal voltage of the MG common DC bus (i.e., 750 V). In conclusion, each NG can be isolated and then safely connected to MG common DC bus without any manual modification on the voltage control system and power sharing algorithm, representing PnP ability of the NGs.

### 2.8 Discussion

The proposed adaptive battery SoC balancing strategy provides the same SoC value for all the BESSs inside the MG. Consequently, the BESSs altogether behave like a community BESS or a cloud energy storage system which its capacity is equal to the summation of all the BESSs capacities. Consequently, the proposed approach can improve the overall efficiency of the system by utilizing the maximum energy storage capacity of batteries. Compared to the centralized cloud energy storages, the proposed distributed
technique can enhance the resiliency and flexibility of the system by enabling the DC NGs to utilize their local BESS in the isolated mode. However, it may increase the initial cost of the system. Thus, based on the system objectives, further cost-benefit analysis should be applied to compare the centralized cloud energy storage technologies with the proposed distributed technique in different clustered NG applications.

2.9 Conclusion

An adaptive multiagent-based control strategy is presented to provide effective and flexible voltage regulation and power sharing in an MNG system. The performance of the proposed approach is validated using MATLAB/Simulink. Each NG is designed as a reactive agent that has a hierarchical control system. The top level is a discrete-event supervisory controller that selects the operational mode of the agent based on predefined rules. The supervisory control layer ensures the PnP ability of the NGs as well as the effective operation of the system. The low-level controllers are responsible for power sharing and voltage regulation with respect to the operational mode of the agent. To regulate the voltage of the NGs local DC bus, an adaptive model predictive controller is deployed providing better transient response, and fewer current ripples compared to regular PI voltage controllers. Additionally, a switching consensus control algorithm is presented that strongly regulates the voltage of MG common DC bus as well as offering accurate power sharing among the NGs by balancing the SoC of all BESS in different NGs while maintaining the PnP operation of them. Consequently, the proposed adaptive multi-agent control strategy provides effective cooperation of the clustered NGs as well as maintaining the scalability and flexibility of the system.
Chapter 3: A Distributed Rule-based Power Management Strategy in a Photovoltaic/Hybrid Energy Storage System based on an Active Compensation Filtering Technique

4.1 Motivation

Renewable energy sources, such as photovoltaic (PV) systems, are becoming increasingly popular due to their environmentally friendly nature and potential for reducing dependence on fossil fuels. However, the variability of renewable energy sources can pose challenges to the power grid, particularly in terms of power quality and efficiency. The integration of energy storage systems, such as hybrid energy storage systems (HESS), can address these challenges by absorbing the variations in renewable power and load, while also providing ancillary services for the grid.

This work proposes a distributed rule-based power management strategy for a PV system with a HESS based on an active compensation filtering technique. The aim is to enhance the power quality and efficiency of the system during grid-connected mode of a DC nano-grid. The proposed method utilizes the HESS to absorb the instantaneous renewable power and load variations by the supercapacitor (SC) while providing ancillary services for the upstream grid. The active compensation filter is employed to smooth out the power variations of the battery energy storage system (BESS) while controlling the charge-level of the SC in a specific range, resulting in a significant improvement in the efficiency and power quality of the system.

This chapter provides valuable insights into the potential of utilizing HESS in PV systems to enhance their performance and contribute to the sustainable development of the power grid. The proposed power management strategy is designed to be implemented in a distributed manner, allowing for scalability and flexibility in the system. The effectiveness
of the proposed strategy is demonstrated through extensive simulations under various operating conditions, indicating that it can achieve improved power quality and efficiency, as well as effective utilization of the HESS for load management and grid support. The research presented in this chapter provides an important contribution to the field of renewable energy systems, particularly in terms of enhancing the performance of PV systems through the integration of HESS.

3.2 Introduction

The deployment of renewable energy technologies in modern power systems is growing rapidly to reduce the carbon emissions and alleviate global energy crisis by decreasing the dependency on fossil fuels [31]. Photovoltaic (PV) systems use a clean, free, and unlimited source of energy with relatively low maintenance costs. Because of these desirable features, PV systems play an important role in the transformation of the global electricity sector [41]. Photovoltaic systems also enable an economical sustainable solution for remote rural areas in which there is no access to the utility grid [42]. However, balancing the PV’s generated power and load is challenging due to the limitation on the availability of power and intermittency of generation. This challenge can be tackled by utilizing energy storage systems (ESSs) as well as implementing effective dynamic power and energy management systems [43,44].

Among many available ESS devices on the market, battery energy storages systems (e.g., lithium-ion or lead acid batteries) have been known as one of most widespread energy storages for various applications including residential buildings, renewable energy
Fig. 18. Classification of Energy Management Strategies in HESSs with active topologies.
systems and microgrids. The battery energy storages (BESSs) are highly dispatchable, and they have low energy losses and relatively low costs. In addition, they have a large energy density that makes them suitable for peak shaving and steady state power balancing. However, the BESSs may have inoperative performance during sudden load variations or rapid changes of PV power due to their relatively low power capacity and slow dynamic response. In addition, the BESSs have a limited life cycle. Thus, the instantaneous changes of the PV power generation or load power fluctuations may cause frequent charge/discharge of the battery that reduces the BESS’s lifetime [45,46].

The aforementioned limitations of the BESSs can be tackled by effective hybridization of BESSs with supercapacitors (SCs) [47]. SCs have a higher power density and faster dynamic response compared to the BESSs which enables them to provide more energy for a considerably shorter time. In addition, they have significantly higher lifecycle than the BESSs. So, the frequent charge/discharge of the SCs does not affect their lifetime [48]. However, the SCs are not suitable for long-term energy storage due to their limited energy density. Considering the underlying limitations and capabilities of the BESSs and SCs, a SC is utilized in tandem with a BESS in battery/supercapacitor hybrid energy storage systems (HESSs) to improve the transient response of the system as well as increasing the lifetime span of the BESSs. To this end, the BESS is utilized for steady state power balancing while the SC absorbs high frequency power fluctuation from the PV and loads [46].
Battery-supercapacitor HESSs may have different topologies including passive, semi-active, and active topologies. Among them, active topologies are superior due to their higher level of controllability. In addition, the energy storage capacity and power dispatch capability of the HESS components (i.e., BESS and SC) can be fully utilized in active topologies. In these topologies each of the HESS components is individually connected to system bus voltage through a power electronic converter and has an independent control system. Nevertheless, an efficient control and power management strategy is essential to justify the additional cost of the active components [49].

The effective integration of PV/battery-supercapacitor HESSs depends on optimal sizing as well as appropriate power management and supervision of BESSs and SCs. The optimal sizing of the HESSs can minimize the likelihood of load shedding actions as well as PV power curtailment due to the lack/excess of power generation while considering the cost of components. On the other hand, the power management and supervision techniques aim to perform power allocation of BESSs and SC for effective utilization of their storage capacity and operational capabilities while ensuring the reliability of the system.

The power management strategies of HESSs can be categorized into optimization-based, filtration-based, and rule-based methods [50]. Fig. 18 shows the classification of energy management strategies in HESS with active topologies. The optimization-based methods can be categorized into model-based and intelligent approaches. The model-based approaches typically include online algorithms (e.g., model predictive controllers) for real time applications or offline algorithms (e.g., multi-objective or dynamic programming) for long-term planning. The intelligent methods also include data-driven approaches such as machine learning-based and artificial neural networks (ANN), and evolutionary
algorithms. While these methods can be implemented through both offline and online algorithms, in practice, their high computational complexity may limit their real-time applications [51,52].

On the other hand, the rule-based methods have lower computational complexity and are more suitable for real-time applications. The rules-based methods can be categorized into finite state machines (FSMs) and fuzzy rule-based approaches. In these methods, the rules can be designed by an expert or based on mathematical models [52].

Due to the simple and powerful structure of FSMs, they are widely used in rule-based dynamic energy management systems for various applications. FSMs or their equivalent finite state automata (FSA) are mathematical models of computation that are widely used in computer science and control for modeling, analysis, and supervisory control of discrete-event dynamic systems. A discrete-event dynamic system (DEDS) is an event-driven system that consists of a set of discrete states and transitions among them. In these systems, the evolution of states (or state transitions) depends on the occurrence of events at discrete instants of time. In FSM-based power management techniques, each operational mode of the system is associated with a discrete state of an FSA model; the transitions are defined based on the switching rules. The application of FSMs in designing centralized supervisory control and energy management systems has been studied in [53–55]. Furthermore, hybrid automata have been introduced to model and evaluate the interaction between transient response and discrete logic of a dynamic rule-based system. To this end, the discrete logic and continuous-time dynamics of the system are represented in one frame. This is achieved by labeling continues-time dynamics on the discrete state of an FSA. Hybrid automata modeling has been used in [56–58] to design centralized
supervisory control and dynamic energy management systems.

Despite the advantages of FSA techniques to model systems with sequential Boolean logics, they have an intrinsic limitation in modeling concurrent operation of the subsystems. In these models, the number of discrete states grows exponentially with the number of processes which is an obstacle in developing highly flexible and adaptive supervisory control systems [59]. To reduce the complexity, modular modeling techniques can be used to develop an FSA model for each module as well as designing a distributed supervisory control system or use a coordinator agent to manage the appropriate coordination among them [60,61].

In most microgrid (MG) applications, power management of HESSs is implemented using filtration-based methods [50]. These methods are typically deployed by decomposing the input current (or power) of the HESS into high-frequency and low-frequency components and allocating the high-frequency components into SC. Generally, the implementation of power smoothing filters using linear time invariant (LTI) low pass filters (LPF) results in less system complexity but lower efficiency. On the other hand, to increase the system efficiency, one can use advanced filtering techniques such as wavelet transformations with the cost of increasing the computational complexity of the charge control system [52,62].

In practice, using non-ideal filters may result in full charging or discharging the SC. In addition, sudden changes in the input power of the HESS (e.g., a sudden load variation) may impose a considerable stress on the SC module that can immediately fully charge or discharge the SC. To avoid state of charge (SOC) violation of SC and increase the system efficiency adaptive filtering techniques can be applied [44,63,64]. In adaptive rule-based
filters, typically a rule-based supervisory controller is utilized to relax or deactivate the filter if the SOC of SC violates a certain limit. In this case, more of high frequency components of the HEES input power is sent to BESS to avoid SC SOC violation. Therefore, the size of the SC should be designed appropriately regarding the bandwidth of the filter and net power fluctuations. Otherwise, the filter is frequently deactivated that may lessen the system’s efficiency. An adaptive SOC-based linear time-varying filter is also presented in [64] for smoothing the output power of wind turbine/battery-supercapacitor HESS. This approach improves the power smoothing capabilities of the HESS by adjusting the time constants of the filters based on SOC variations of the ESSs. However, this technique is basically designed for power smoothing applications, and it is not appropriate for dynamic power balancing purposes.

To address these challenges and improve the efficiency, and reliability, this work creates a control framework for a PV/HESS system. The case study system contains a group of interconnected loads, a PV power generation system, and a battery-supercapacitor HESS with parallel active topology. The contributions of this work are as follows:

- An active compensation technique is proposed that improves the efficiency of the power smoothing filter. This approach reduces the minimum required size of the SC for smoothing the input power of the BESS. In addition, it does not increase the computational complexity of the charge control system that makes it suitable for real-time applications.

- Based on the active compensation technique, a hybrid dynamic adaptive filter is designed that ensures reliable operation of the HESS by avoiding SOC violation of SC.

- A distributed supervisory control strategy has been implemented. In this approach, the
duties of centralized supervisory controller are distributed among the PV, load, and HESS agent. This technique reduces the computational complexity of the supervisory control system and increase its scalability.

- To analyze the hybrid dynamical behavior of the agents and design the supervisory control system, the agents are modelled in a standard hybrid dynamical framework (i.e., hybrid automata). This approach facilitates designing a reliable and efficient hybrid supervisory control system for the PV/HESS system.

The rest of the work is organized as follows: Section 3.3 introduces the hybrid automata and section 3.4 provides preliminaries of power allocation in HESSs. Section 3.5 describes the system architecture and components. Section 3.6 proposes the active compensation technique and presents the designed distributed supervisory control strategy as well as the hybrid automaton model of the agents. The proposed hybrid control strategy is verified through simulation in Section 3.7. Section 3.8 concludes the work.

### 3.3 Preliminaries on Hybrid Automata

Hybrid automata are standard frameworks to model, analyze, and design supervisory controllers for hybrid dynamical systems. Hybrid dynamical systems are defined as the systems in which an interaction between continuous-time and discrete-event dynamics exists (e.g., switching systems). In such systems, a discrete event may change the dynamical behavior of the system. A hybrid automaton with inputs and outputs can be described with a nine-tuple as:

$$\mathcal{H} = \{Q, X, F, E, Inv, U, Y, H, Init\}$$  \hspace{1cm} (3.1)
where $\mathcal{Q}$ is a finite set of discrete modes. $X \subseteq \mathbb{R}^n$ is a finite set of real-valued variables associated with the continuous-time states of the system. $\mathcal{r}$ denotes a set of vector fields $f_q$ that represent the evolution of continuous-time dynamics of the system at each discrete mode. Each vector field is a Lipchitz function as $f_q : X \times U \rightarrow \mathbb{R}^m$. $\mathcal{E}$ is the set of all transitions $e_{ij}$. A transition is a four-tuple as $(q_i, g_{ij}, r_{ij}, q_j)$ where $q_j$ and $q_j$ are the source and target modes, and $g_{ij}$ is the guard condition. A guard condition is a Boolean expression which is evaluated dynamically based on its associated value. $\eta_{ij} : \mathbb{R}^m \rightarrow \mathbb{R}^m$ is the reset or update of the transition. $\mathcal{U}$ is the finite set of inputs and $\mathcal{Y}$ is the finite set in which is the set of outputs of the system. $\mathcal{H}$ also represents the set of output functions of the system associated with each operational mode and $\mathcal{Inv}$ is the set of invariants. $\mathcal{Init}$ is also the set of initial states.

**Example:** Consider a hybrid dynamical system containing two reactive agents $(a, b)$ that have asynchronous mode transitions. Assume that the agent $a$ has three different operational modes (i.e., $\mathcal{Q}^a = \{q^a_1, q^a_2, q^a_3\}$) and $b$ has two modes (i.e., $\mathcal{Q}^b = \{q^b_1, q^b_2\}$). Consequently, the global system has $n(\mathcal{Q}_{ab}) = n(\mathcal{Q}_a) \times n(\mathcal{Q}_b) = 6$ different operational modes. The dynamical behaviour of these agents changes if they switch to a new operational mode. The dynamics of this system are defined as:
Fig. 19. State transition diagram of hybrid automata models of two coordinated reactive agents. 
(a) distributed supervisory control approach (b) centralized approach (hybrid automata with sequential logic).
\[
\begin{align*}
\dot{x}_a &= \alpha(q^a_j) x_a + x_b \\
\dot{x}_b &= x_a + \beta(q^b_j) x_b + u_c
\end{align*}
\] (3.2)

with \(\alpha(q_j^a) \in \{-1, -2, -3\}\) and \(\beta(q_j^b) \in \{-1, -2\}\). \(u_c\) is an external control input and \((x_a, x_b)\) are the continuous time dynamics of agents \(a\) and \(b\), respectively.

First, consider that each agent has a supervisory control system that selects the operational mode of that agent, and the agents can communicate with each other (i.e., there is a distributed supervisory control architecture.). Fig. 19 (a) shows a state transition diagram that visually represents the hybrid automata models of the two coordinated reactive agents. Both agents send the value of their continuous state to each other (i.e., \(y_a = x_b\) and \(y_b = x_a\)). Agent \(a\) is initially in \(q^a_1\) operational mode with \(x_a(0) = x_0\). The other agent also operates in \(q^b_1\) operational mode with \(x_b(0) = x_0\). In this mode, \(\alpha(q_1^a) = -1\) and the continuous dynamics of the agent \(a\) evolves based on \(\dot{x}_a = -x_a + u_a\). Similarly, Agent \(b\) initially operates in \(q^b_1\) operational mode and its continuous dynamic state evolves as \(\dot{x}_b = -x_b + u_b + u_c\). Once the state of \(b\) (i.e., \(x_b\)) exceeds a certain value (i.e., \(G_2\)) the guard condition \(G_1(1,2) : u_a > G_2\) is satisfied and \(e^a(1,2)\) is being activated. So, Agent \(a\) switches to \(q^a_2\) operational mode and changes its dynamical behaviour. In addition, before completing the transition, the initial value of agent \(a\) is specified based on the defined reset map (i.e., \(\eta^a_{(1,2)} : x_a(t_0) = x(t^-)\)). Similarly, Agent \(b\) can react to system changes by switching its dynamical behaviour upon stratifying a guard condition.

Alternatively, consider an equivalent system that has a centralized supervisory controller that selects the operational mode of these agents. Fig. 19(b) shows the hybrid...
automaton model of the global system. To design the equivalent centralized supervisory controller using a hybrid automaton with sequential logic, it is required to define $n(Q_{ab}) = n(Q_a) \times n(Q_b) = 6$ discrete modes and identify the transitions among them. However, in the distributed approach $n(Q_a) + n(Q_b) = 5$ discrete modes are defined.

Now, let assume a system containing $N$ coordinated reactive agents with asynchronous mode transitions that each has $M$ discrete modes. To design a centralized supervisory control system for the global hybrid system using a hybrid automaton with sequential logic, it is required to define $M^N$ discrete modes and identify the transitions among them. Consequently, the complexity of hybrid modelling and supervisory control of the system exponentially increases with the number of agents. However, by utilizing a hybrid automaton framework (with inputs and outputs), the equivalent distributed supervisory control system can be designed by just defining $M \times N$ discrete modes (i.e., $M$ discrete modes for each agent). Thus, the complexity of modelling, and supervisory control of the system can decrease remarkably.

### 3.4 System Description

Fig. 20 shows the schematic model of the PV/HESS system in this work. The PV module consists of a group of PV panels that are connected to the point of common coupling (PCC) through a DC-DC converter. The HESS module includes a SC and a BESS which are also connected in parallel to the PCC using DC-DC converters (i.e., parallel active topology). The PV/HESS system supplies a group of loads in a stiff AC grid which is connected to the PCC through an AC-DC converter. The voltage of the PCC is also regulated by the AC-DC converter through connection to the AC stiff grid. So, the HESS module is assumed to operate in current control mode. The AC stiff grid can be considered
as an AC microgrid that a portion of its power demand is supplied by the PV/HESS system. Knowing the fact that energy management and supervision level has by far slower dynamics, for the sake of simplicity, the dynamics of the power electronic converters and low-level controllers (LLC) (e.g., current controllers) are neglected in the rest of this work.

In HESS power management systems, the net power, i.e., $P_{\text{net}}$, is typically defined as the difference between generated and demanded power by the load. In the case of having a PV system as a single source of generation, the net power can be formulated as:

$$P_{\text{net}} = P_{\text{PV}} - P_{\text{load}}$$

(3.3)

where $P_{\text{PV}}$ represents the PV power generation and $P_{\text{load}}$ is the demanded power by the load. The net power is used by the HESS to maintain the power balance between the demand and generation. Alternatively, the net power can be written as:

$$P_{\text{net}} = P_{\text{HESS}} = V_{dc}I_{\text{HESS}} = V_{dc}(I_b + I_{SC})$$

(3.4)

where $I_b$ and $I_{SC}$ are the input currents of BESS and SC from the DC bus side, respectively. $V_{dc}$ is also the voltage of the DC bus.

In practice, the BESSs have limited life cycle. For instance, the estimated life of a Lithium-ion battery may vary between 400 to 800 charge cycles. Thus, the instantaneous changes of the net power in a PV power generation system may cause frequent charge/discharge of the battery that reduces the BESS’s lifetime. Typically, to increase the BESS lifetime and improve the system efficiency a filtration-based power allocation algorithm is designed that decomposes the net power into high frequency and low frequency components and allocates the high frequency components into SC. Fig. 21 shows a conventional centralized energy management system in a PV/HESS for MG applications.
In this method, the input reference current of the HESS module (i.e., $I_{\text{HESS}}$) passes from an LPF and then is sent to the current regulator of the BESS. The difference between the HESS and BESS input current ($I_{\text{HESS}} - I_b$) is also sent to the SC. Assuming the system is in normal operation (i.e., $I_{\text{SC}} = I_{\text{SC}}^{\text{in}}$, and $I_b = I_b^{\text{in}}$) and using an LTI low-pass filter (LPF), $I_b$ and $I_{\text{SC}}$ can be obtained as:

$$I_b(s) = G_F(s)I_{\text{HESS}}(s) \quad (3.5)$$

$$I_{\text{SC}}(s) = (1 - G_F(s))I_{\text{HESS}}(s) \quad (3.6)$$

where $G_F(s)$ represents the transfer function of the low pass LTI filter. In practice, using none-ideal filters and/or severe variations of the net power may result in SOC violation of the SC. To avoid this, the energy management system (EMS) deactivates the filter based on predefined rules to avoid SOC violation of the SC module. For example, when the SOC of SC exceeds from a certain value, the filter is deactivated and the EMS sends the HESS current to the BESS ($I_b = I_{\text{HESS}}, I_{\text{SC}} = 0$) to prevent SC from being over charged [63]. Thus, more of the high frequency components of the net power are sent to the BESS in this mode. Consequently, the size of the SC should be designed properly regarding the bandwidth of the filter and the net power fluctuations. Otherwise, the filter is frequently turned off that reduces the system’s efficiency.

Moreover, If the SOC of BESS violates its upper limit (i.e., $SOC_b > SOC_{\text{max}}$) the PV power generation should be cut down (i.e., $I_{\text{PV}} = I_{\text{load}} < I_{\text{MPP}}$) to avoid the BESS’s SOC violation. Similarly, if the BESS’s SOC reaches to its minimum allowable value, the EMS or supervision system disconnects unnecessary loads to avoid the instability of the MG. It
should be mentioned that optimal sizing of the PV/HESS (e.g., long-term planning) or using advanced load and PV power forecasting methods can reduce the likelihood of PV power curtailment as well as load shedding actions that results in more system efficiency. However, to guarantee the reliable operation the PV/HESS system, it is still necessary to design a real-time supervisory control and energy management system to avoid SOC violation of the BESS and SC.

This work focuses on designing an efficient and reliable real-time energy management and supervision system. To this end, it proposes a hybrid adaptive filtering approach based on the so-called active compensation technique to increase the system efficiency and improve its reliability. To this end, a compensation term will be added to the power smoothing filter that indirectly regulates the SOC of the SC. This technique reduces the SOC variation of the SC that results in reducing the minimum required size of the SC for a same filter bandwidth compared to the conventional method. In addition, a flexible supervisory control system will be designed in a hybrid automaton framework that

Fig. 20. The schematic model of the PV/HESS system.
provides smooth transitions between operational modes of the HESS and ensures the reliability of the PV/HESS system.

3.5 Proposed Control and Management Strategy

The supervision system is illustrated in Fig. 22. In this structure, every single module of the system (i.e., PV, HESS, and load) has a dedicated energy management system. The coordination among these EMSs forms the global energy management system. Here, PV, load, and HESS can be considered as reactive agents that have asynchronous mode transitions. The coordination of these agents is as follows:

- The HESS agent receives the generation and demanded power (i.e., \( P_{PV}, P_{load} \)) from the PV and load agents. \( P_{PV} \) and \( P_{load} \) is then used by the HESS’s EMS to determine the input currents of the BESS and SC (i.e., \( I_{b}, I_{SC} \)). To avoid SC SOC violation, The HESS supervisory controller selects the operational mode of the HESS agent with respect to the SOC of SC.
The PV agent receives the demanded power (i.e., $P_{\text{load}}$) and SOC value of the BESS (i.e., $SOC_b$) from the load and HESS agents. The PV supervisory controller selects the operational mode of the PV with respect to available solar irradiance power (i.e., $P_{ir}$) and $SOC_b$ to avoid over charging of the BESS as well as ensuring the reliability of the system.
• The load module receives the SOC value of BESS (i.e., $SO_{CB}$) from the HESS agent.

This value is then used by the load supervisory controller To avoid BESS SOC violation and ensure the stability of the MG.

The following subsections represent the designed control structure and the distributed hybrid automaton model of the controlled system. First, an active compensation filtering technique is proposed that increases the system efficiency without increasing the computational complexity of charge control system. Then, by modelling each agent in a hybrid automaton framework, a distributed supervisory control technique will be applied to ensure the safe and reliable operation of the system.

3.5.1 Proposed Active Compensation Technique

3.5.1.1 Mathematical Formulation and Analytical Studies: SOC and the stored energy in an SC (i.e., $E_{SC}$) can be obtained by (3.7) and (3.8) as:

$$SOC_{SC}(t) = \frac{1}{Q_{n}} \int_{t_0}^{t} I_{SC}^d dt + SOC_{SC}(t_0)$$  \hspace{1cm} (3.7)

$$E_{SC} = \frac{1}{2} CV_{SC}^2$$ \hspace{1cm} (3.8)

where $V_{SC}$ and $I_{SC}^d$ are the input current and the voltage of the SC from the SC side $Q_{n}$ and $C$ are also the nominal charge and capacitance of the SC. Knowing $I_{SC}^d = C \frac{dV_{SC}}{dt}$, and using (3.7), the SOC of an SC can be represented as:

$$SOC_{SC}(t) = \frac{C}{Q_{n}} V_{SC}$$ \hspace{1cm} (3.9)
Thus, from (3.8) and (3.9) one can obtain:

$$\text{SOC}_{SC} \propto \sqrt{E_{SC}}$$  \hspace{1cm} (3.10)

Therefore, by regulating the $E_{SC}$ in a certain range, one can prevent SOC violation in SC.

To this end, a compensating term is added to filter that indirectly controls the SOC of the SC. The compensator term is defined as:

$$I_C = k_p(E_{ref} - E_{SC}(t)) - k_d \left( \frac{dE_{SC}}{dt} \right)$$  \hspace{1cm} (3.11)

where $k_p$ and $k_d$ are the proportional and derivative terms of the active compensator and $E_{ref}$ is the reference signal for $E_{SC}$ and it has a constant value (i.e., $\dot{E}_{ref} = 0$). Fig. 23 shows the conceptual model of the proposed active compensation technique and its equivalent closed form model. Assuming the filter is linear time invariant (LTI), $i_b$ and $I_{SC}$ are obtained as:

$$I_b(s) = G_F(s)I_{HESS}(s) - G_F(s)I_C(s)$$  \hspace{1cm} (3.12)

$$I_{SC}(s) = (1 - G_F(s))I_{HESS}(s) + G_F(s)I_C(s)$$  \hspace{1cm} (3.13)

where $I_{HESS} = I_b + I_{SC}$ and $G_F$ represents the transfer function of the low pass LTI filter.

Therefore, if $I_C > 0$ (e.g., $E_{SC} < E_{ref}$ and $\dot{E}_{SC} < 0$) the input current of the BESS decreases and that of SC increases to charge the SC with a slight amount of low frequency components. Implementing the proposed filtering technique with the conceptual model in Error! Reference source not found. requires the computation of $k_p$ and $k_d$ using a trial-
and-error approach as well as measuring \( E_{SC} \) which may not be feasible. To avoid this, the discussed approach can be implemented in a closed form as follows. To this end, \( E_{SC} \) is defined as:

\[
E_{SC} = \int_{t_0}^{t} V_{dc} I_{SC} dt + E(t_0)
\]  
(3.14)

Using (3.14), the compensator term can be represented as:

\[
I_C = k_p (E_{ref} - \int_{t_0}^{t} V_{dc} I_{SC} dt - E(t_0)) - k_d (V_{dc} I_{SC})
\]  
(3.15)

Knowing \( E_{ref} \) has a constant value, the compensator term is obtained in the frequency domain as:

\[
I_C(s) = -G_C(s) I_{SC}(s) + \frac{k_p \Delta E}{s}
\]  
(3.16)

where \( \Delta E = E_{ref} - E(t_0) \) and \( G_C(s) \) is the transfer function of the active compensator which is defined as:

\[
G_C(s) = \frac{k_p s + k'_p}{s}
\]  
(3.17)

where \( k'_p = k_p V_{dc} \) and \( k'_p = k_d V_{dc} \). Using (3.12), and (3.16) can be reformulated as:

\[
I_b(s) = G_F(s) I_{HESS}(s) + G_C(s) G_F(s) I_{SC}(s) - k_p G_F(s) \frac{\Delta E}{s}
\]  
(3.18)

By replacing \( I_{SC} \) with \( I_{HESS} - I_b \), and \( k_p \Delta E = \gamma \), (3.16) can be represented in a closed form as:
where $G_F'(s)$ and $G_F''(s)$ are defined as:

\[
G_F'(s) = \frac{G_F + G_C G_F}{1 + G_C G_F} \tag{3.20}
\]

\[
G_F''(s) = \frac{G_F}{1 + G_C G_F} \tag{3.21}
\]

Similarly, $I_{SC}$ can be represented in a closed form as:

\[
I_{SC} = (1 - G_F'(s)) I_{HESS} + G_F''(s) \frac{\gamma}{s} \tag{3.22}
\]

Thus, the compensated filter is a multi-input-multi-output (MIMO) LTI filter. Finally, using (3.19) and (3.22) the compensated filter is obtained as:

\[
\begin{bmatrix}
I_b(s) \\
I_{SC}(s)
\end{bmatrix} = \begin{bmatrix}
G_F'(s) & -G_F''(s) \\
1 - G_F'(s) & G_F''(s)
\end{bmatrix} \begin{bmatrix}
I_{HESS}(s) \\
\frac{\gamma}{s}
\end{bmatrix} \tag{3.23}
\]
Using (3.20) to (3.24), $\gamma$ can be also defined as:

$$\gamma = \rho(SOC_{ref}^2 - SOC_{SC}^2(t_0))$$  \hspace{1cm} (3.24)

where $\rho$ is the charging coefficient defined as $\rho = \left( k_i Q_n^2 \right) / (2 \nu_{dc} C)$. Equation (3.24) shows that $\gamma$ is a function of the reference SOC (i.e., $SOC_{ref}$) as well as the initial SOC value of the SC. This definition facilitates regulating the SOC of SC when its initial value is different from the reference SOC.

It should be mentioned that to model the system in a hybrid automaton framework and design the supervisory controller, it is required to define the dynamics of the compensated filter in the state space form. Here, assume that the original LPF is a second order LTI filter defined as:

$$G_F = \frac{1}{\left( \alpha s + 1 \right)^2}$$  \hspace{1cm} (3.25)

where $\alpha$ is the filter coefficient. Using (3.20) and (3.21), the transfer functions of the filter with using active compensation technique is obtained as:

$$G_F^c = \frac{(1 + k'_p)s + k'_i}{\alpha^2 s^3 + 2\alpha s^2 + (1 + k'_p)s + k'_i}$$  \hspace{1cm} (3.26)

$$G_F^c = \frac{s}{\alpha^2 s^3 + 2\alpha s^2 + (1 + k'_p)s + k'_i}$$  \hspace{1cm} (3.27)

Using (3.23) to (3.27), the dynamics of the compensated filter can be represented in the state space form as:
\[
\begin{align*}
\dot{x}_F(t) &= A_F x_F(t) + B_F u_F(t) \\
y_F(t) &= C_F x_F(t) + D_F u_F(t)
\end{align*}
\] (3.28)

where \(x_F = [x_1, x_2, x_3]^T\), \(u_F(t) = [I_{HESS}, \gamma]^T\), and \(y_F(t) = [I_b, I_{SC}]^T\). \(A_F, B_F, C_F,\) and \(D_F\) are also obtained as:

\[A_F = \begin{bmatrix}
0 & 0 & -k_i'/\alpha^2 \\
1 & 0 & -(1+k_p')/\alpha^2 \\
0 & 1 & -2/\alpha
\end{bmatrix}\] (3.29)

\[B_F = \begin{bmatrix}
k_i'/\alpha^2 & (1+k_p')/\alpha^2 & 0 \\
0 & -1/\alpha^2 & 0
\end{bmatrix}^T\] (3.30)

\[C_F = \begin{bmatrix}
0 & 0 & 1 \\
0 & 0 & -1
\end{bmatrix}\] (3.31)

\[D_F = \begin{bmatrix}
0 & 0 \\
1 & 0
\end{bmatrix}\] (3.32)

The dynamical equation of the compensated filter represented in (3.28) to (3.32) will be used later in Section 5.2.2 to analyse the performance of the proposed active compensation technique and in Section 5.3.1 to design the hybrid supervisory controller of the HESS module. In addition, these equations show that the proposed active compensation technique does not require any additional information or measurements and it does not increase the computational complexity of the charge control system making it suitable for real-time applications. While this method can be utilized for both nonlinear and linear filters, in the case of using an LTI filter, the closed form formulation enables the system designer to select the parameters of the filter in an analytical manner considering the dynamic stability and the bandwidth of the filter.
3.5.1.2 Empirical analysis: Considering (3.28) to (3.32) the performance of the proposed active compensation technique is illustrated in Fig. 24. The case study system is a SC with 4 seconds charge time and 30KW nominal power and $V_{dc} = 300\,\text{V}$. The BESS also has 30 KW nominal power and 2 hours charge time. The filter parameters are $\alpha = 0.12$, $\kappa_i = 0.003$, $\kappa_p = 0.5$, and the initial SOC of SC is 0.45 (i.e., $SOC_{SC}(t_0) = 0.45$).
As seen, by defining \( \gamma \) using (3.24), the compensated filter smoothly charges the SC to increase its SOC to the reference value (i.e., \( SOC_{\text{ref}} = 0.5 \)) after around 15 seconds. On the other hand, without compensation technique the SOC of SC does not reach to the desired point (i.e., \( SOC_{\text{ref}} = 0.5 \)). At \( t = 40s \), a sudden load change happens. This load change imposes a high stress on the HESS that charges the SC with \( I_{SC} = I_{\text{HESS}} - I_h \) during a short time interval represented by \( \tau_1 \). The load change results in SOC violation of the SC when there is no active compensation. However, the active compensation technique generates an overshoot current during \( \tau_2 \) interval that discharges SC to prevent its SOC violation and regulates its SOC to the reference value. Thus, the proposed active compensation technique lessens the SOC variation of the SC that reduces the minimum required size of SC and increases the system efficiency. It should be noted that the proposed technique can have similar impact on the other types of linear and nonlinear filters.

In the proposed rule-based approach, the supervisory control system is designed to avoid SOC violation of the HESS components (i.e., BESS and SC) while maintaining the balance between generation and load. To reduce the computational complexity and improve the scalability, the tasks of a centralized supervisory control system are distributed among the PV, load, and HESS agent. To this end, the HESS supervisory controller is responsible for the efficient and reliable operation of HESS as well as avoiding SOC violation of the SC. On the other hand, avoiding BESS SOC violation is dedicated to the PV and load supervisory controllers. In addition, the cooperation between supervisory controllers ensures the balance between generation and load in all operating modes. In what
follows, the supervisory controller of each agent and its hybrid automaton model will be discussed.

3.5.1 HESS Agent

To avoid SC SOC violation, a hybrid adaptive filtering technique is utilized in the HESS module. The filter is compensated using the proposed technique in Section 3.5.1. Fig. 25 shows the structure of the proposed hybrid adaptive filtering technique. In this approach, if the SOC of SC exceeds a certain value, the bandwidth of the filter increases to lessen the stress on the SC. To this end, the HESS supervisory controller changes the dynamics of the filter by adjusting the filter parameters (i.e., $\alpha$, $k_p$’, and $k_i$’). In addition, it updates the value of $\gamma$ and specifies the initial states of the filter (i.e., $x_F(t_0)$) before switching to the new operational mode for regulating the SOC of the SC as well as ensuring the stability of the system after switching instances.

Fig. 25. The proposed hybrid adaptive filtering technique.
Fig. 26 represents the hybrid automaton model of the HESS agent where \( x_F = [x_1, x_2, x_3]^T \) is the continuous dynamics of the filter and \( u_F = [I_{\text{HESS}}, \gamma]^T \) represents the inputs (See (3.28)). To balance the power generation and load \( I_{\text{HESS}} \) is defined as:

\[
I_{\text{HESS}} = \frac{P_{\text{net}}}{V_{dc}} = \left( \frac{P_{PV} - P_{load}}{V_{dc}} \right) 
\]

(3.33)

where \( P_{PV} \) is the photovoltaic power generation and \( P_{load} \) is the load power. The state space parameters of the dynamical model of the compensated filter in \( q_1 \) and \( q_2 \) or \( q_3 \) operational modes are respectively defined as:

\[
\{ A, B, C, D \} = \{ A_F, B_F, C_F, D_F \} \bigg|_{\ell = \ell_0, \alpha = \alpha_0} 
\]

(3.34)

\[
\{ A', B', C', D' \} = \{ A_F, B_F, C_F, D_F \} \bigg|_{\ell = \ell_0', \alpha = \alpha_0'} 
\]

(3.35)

where \( A_F, B_F, C_F, \) and \( D_F \) are defined in (3.29) to (3.32). \( \{ \ell_0, \ell_1, \ell_2 \} \) also represent the filter parameters in \( q_1 \) operating mode and \( \{ \ell_0', \ell_1', \ell_2' \} \) are the filter parameters in \( q_2 \) and \( q_3 \) modes. In Fig. 6, \( e_{(i,j)} = [q_i, q_j, r_{(i,j)}, q_j] \) represents a transition from operational mode \( q_i \) to \( q_j \).
the normal operation of the HESS agent. The agent switches to \( q_2 \) or \( q_3 \) operational modes when the SOC of SC violates some threshold values (i.e., \( SOC_{SC} > 0.7 \) or \( SOC_{SC} < 0.3 \)). In these modes, the supervisory controller changes the dynamics of the filter and increases the filter bandwidth to reduce the stress on the SC module. If this mode changing is not effective enough to control the SOC of SC, the agent will switch to the SC recovery modes represented by \( q_4 \) and \( q_5 \) to protect the HESS’s devices. In these modes, the supervisory controller deactivates the filter and SC is smoothly charged or discharged by 20% of its nominal power. Once the SOC of SC reaches to a predefined value, the filter switches back to the normal operation.

In hybrid dynamical systems, the switching resets (or initialization) have a significant impact on the transient response and stability of the system after switching instances [66]. In the proposed hybrid filtering method, any transient current oscillation on after switching instances can affect the performance of the power smoothing filter by charging or discharging the SC. In one hand, after switching to \( q_2 \) operating mode (i.e. \( SOC_{SC} > 0.7 \)), to discharge the SC and return to normal operating mode (i.e., \( SOC_{SC} \leq 0.5 \)), it is required to send a negative transient current to SC. Similarly, after switching to \( q_3 \) mode, it is necessary to send a positive transient current to SC, in order to charge it and switch back to \( q_1 \). On the other hand, when the HESS switches back to normal operation a
bump less transition (i.e., transition with no current fluctuation) is needed to maintain the
SOC of SC to the reference value.

Assume a hybrid system that has a stable equilibrium at each mode. If the initial
states of this system in each discrete mode are equal to their steady state value (i.e.,
equilibrium point) the system will not experience any transient oscillation after switching
instances. Using (3.29) to (3.32), the steady state values of the filter dynamics (i.e.,
\( x_F^* = [x_1^*, x_2^*, x_3^*]^T \) in \( q_j \in \{q_1, q_2, q_3\} \) operating mode can be obtained as:

\[
\dot{x}_F = 0 \rightarrow x_1^* = \frac{\gamma}{\alpha_j}, x_2^* = \frac{2}{\alpha_j}I^*_{\text{HESS}}, x_3^* = I^*_{\text{HESS}} \tag{3.36}
\]

where \( \alpha_j \) is the filter coefficient in \( q_j \) mode defined in (3.29) to (3.32). Consequently, by
properly defining the reset maps, one can manage the transient current oscillations to
regulate the SOC of SC and ensure the reliable operation of HESS after switching
instances. To this end, using (3.24) and (3.36), the reset maps (i.e., \( r(i,j), j \in \{1,2,3\} \) ) are
defined as:

\[
\begin{align*}
r_{(i,j)} &= \{x_1(t_0) = 0, x_2(t_0) = \frac{2}{\alpha_j}x_3(r^-), x_3(t_0) = x_3(r^-)\}, \\
\gamma(t_0) &= \rho_j(SOC^{2}_{\text{ref}} - SOC^{2}_{\text{SC}}(r^-))
\end{align*}
\tag{3.37}
\]

<table>
<thead>
<tr>
<th>Guard</th>
<th>Expression</th>
<th>Guard</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta_{(1,2)} )</td>
<td>( SOC_{\text{SC}} &gt; 0.7 )</td>
<td>( \delta_{(1,3)} )</td>
<td>( SOC_{\text{SC}} &lt; 0.3 )</td>
</tr>
<tr>
<td>( \delta_{(2,1)} )</td>
<td>( SOC_{\text{SC}} \leq 0.5 )</td>
<td>( \delta_{(2,4)} )</td>
<td>( SOC_{\text{SC}} &gt; 0.8 )</td>
</tr>
<tr>
<td>( \delta_{(3,1)} )</td>
<td>( SOC_{\text{SC}} \geq 0.5 )</td>
<td>( \delta_{(3,5)} )</td>
<td>( SOC_{\text{SC}} &lt; 0.2 )</td>
</tr>
<tr>
<td>( \delta_{(4,1)} )</td>
<td>( SOC_{\text{SC}} \leq 0.5 )</td>
<td>( \delta_{(5,1)} )</td>
<td>( SOC_{\text{SC}} \geq 0.5 )</td>
</tr>
</tbody>
</table>
where \( t \) is the time when the transition is activated and \( t_0 \) is the time at which the transition is completed. \( \alpha_j \) and \( \rho_j \) are also the value of filter coefficient and charging coefficient (see (3.24) to (3.29)) at the new operational mode (i.e., \( q_j \)). With this definition, when the system switches back to normal operation (i.e., \( q_1 \)), \( \gamma \) is updated to zero (i.e., \( \gamma(t_0) = 0 \)).

So, the initial states of the filter become equal to their steady state value (i.e., \( x_F(t_0) = x_F^* \)) and the HESS experiences a bump less transition to \( q_1 \). On the other hand, if the system switches to \( q_2 \) or \( q_3 \), \( \gamma \) will be updated to a negative or positive value, respectively. Consequently, \( x_F(t_0) \neq x_F^* \) and the charge control system generates a transient current fluctuation that discharges/charges the SC and regulates its SOC to the reference value (i.e., \( SOC_{ref} \)). It should be mentioned that in SC recovery modes (i.e., \( q_4, q_5 \)) the filter is deactivated, so the initial states do not have any impact on the outputs of the filter. Thus, \( r(i,j), j \in \{4,5\} \) are not specified.

The impact of the switching resets on SOC regulation of the SC as well as system’s stability has been studied in two testcases. Table 6 represents the characteristics of the filters used in these testcases. In both cases, the study system is similar to the study system of the example in Section 5.2.2.

<table>
<thead>
<tr>
<th>Testcases</th>
<th>Filters</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Adjusting</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \alpha, \gamma )</td>
</tr>
<tr>
<td>Case 1</td>
<td>Filter1</td>
<td>Off</td>
</tr>
<tr>
<td></td>
<td>Filter2</td>
<td>On</td>
</tr>
<tr>
<td></td>
<td>Filter3</td>
<td>On</td>
</tr>
<tr>
<td>Case 2</td>
<td>Filter1</td>
<td>On</td>
</tr>
<tr>
<td></td>
<td>Filter2</td>
<td>On</td>
</tr>
</tbody>
</table>

Table 6. Characteristics of the tested filters.
Case 1 highlights the performance of the proposed hybrid adaptive filtering technique as well as the necessity of resetting $\gamma$ after mode transitions. Fig. 27 illustrates the performance of the three tested filters in this testcase with $SOC_{SC}(0) = 0.52$ and $SOC_{ref} = 0.5$. 

All the filters initially have a small negative value for $\gamma$ (i.e., $\gamma(0) = -1.6$) to slightly discharge the SC and regulate its SOC to the reference value. Then, a sudden load change happens at $t = 40s$. As seen, Filter 1 is not able to respond to the load change and fails to maintain the SOC of the SC within the allowable range (i.e., $0.2 < SOC_{SC} < 0.8$). On the other hand, in Filter 2 and Filter 3, once the SOC of SC exceeds 0.7 (at $t = 41.7s$), the supervisory controller increases the bandwidth of the filter by switching to the $q_2$ operational mode at $t_0 = 41.7^+s$. Consequently, the SOC of the SC remains in the allowable range for both filters. However, in Filter 2, $\gamma$ is not updated (i.e., $\gamma(41.7^-) = \gamma(41.7^+) = -1.6$) and the SOC of SC remains equal to 0.7. So, the HESS agent is locked in $q_2$ operational mode and it cannot switch back to normal operation. On the other hand, Filter 3 discharges SC by updating $\gamma$ to a larger negative value when it switches to $q_2$ (i.e., $\gamma(41.7^-) = -1.6, \gamma(41.7^+) = -48$). Thus, it regulates the SOC of SC to the reference value and switches back to $q_1$ at $t_0 = 51.5^+s$. In addition, at $t_0 = 51.5^+s$, Filter 3 pushes $\gamma$ to zero (i.e., $\gamma(51.5^+) = 0$) to ensure a bump less transition to $q_1$. Similarly, if the system switches to $q_1$, $\gamma$ will be updated to a positive value that results in charging the SC. Here, resetting $\gamma$ to a
positive/negative value is similar to intentionally generating a pulse shape current that charges/discharges the SC to regulate its SOC to the reference value. It should be noted that in all the operating modes the input current of the SC is equal to difference between HESS and BESS current (i.e., \( I_{SC} = I_{HESS} - I_b \)). So, this pulse shape current does not have any impact on the power balancing performance of the system and (3.33) is always satisfied.

Case 2 highlights the necessity of precisely resetting the initial states (i.e., \( x_F(t_0) \)) to avoid unintentional transient current oscillations after switching instances. In this testcase, the first HESS agent employs a typical gain scheduling adaptive filter (i.e., Filter 1). This

Fig. 27. The performance of the filters in Case 1. (\( \ell_0 = 2, \ell_1 = 0.2, \ell_2 = 0.01, \ell'_0 = 0.1, \ell'_1 = 0.5, \ell'_2 = 0.005 \)) (a) Input current of the HESS and battery (b) SOC variation of the SC.
filter maintains its previous states as the initial values for the new operational mode (i.e., \(x_F(t_0) = x_F(t^-)\)). On the other hand, the second agent is designed based on the proposed hybrid adaptive approach (i.e., Filter 2) and it resets the initial values before completing the transitions. The performance of the two tested filters is illustrated in Fig. 28. In this testcase a sudden load change happens at \(t = 40s\). Consequently, to avoid SOC violation, both filters switch to \(q_2\) operational mode at \(t_0 = 42.8^+s\) and increase their bandwidth. In addition, both HESS agents update \(\gamma\) before completing the transition (i.e., \(\gamma(42.8^+) = -48\)) to regulate the SOC of the SC to the reference value (i.e., \(SC_{ref} = 0.5\)). Then, the guard condition \(g_{(2,1)}\) is satisfied at \(t^- = 51.8s\) and both HESSs switch to the normal operation and update \(\gamma\) (i.e., \(\gamma(51.8^+) = 0\)). However, the first HESS that uses Filter 1 experiences a significant uncontrolled current fluctuation after switching back to normal operation (i.e., \(q_1\)). This current fluctuation is beyond the nominal value of the BESS current, and it may damage or destabilize the system. In addition, it charges SC again and the HESS switches back to the \(q_2\) at \(t_0 = 52.4^+s\) to avoid SC SOC violation. Consequently, this agent cannot switch back to the normal operation to smooth the input current of the BESS. However, by defining the switching resets as (3.37) one can eliminate the uncontrolled current fluctuation after switching instances.

In conclusion, if the SOC of SC violates a certain range (i.e., \(SOC_{SC} > 0.7\) or \(SOC_{SC} < 0.3\)), the HESS agent switches to \(q_1\) or \(q_3\) operational modes. Once the agent switches to these modes, the charge control system generates a controlled transient current to regulate the SOC of SC to the reference value (i.e., \(SC_{ref} = 0.5\)). Then, once the SOC
of SC reaches to its reference value, the HESS switches back to $q_1$ operational mode. Then, the HESS experiences a bump less transition (i.e., transition with no current oscillation) to maintain the SOC of SC to the reference value. The proposed supervisory control approach is achieved by modelling and analysing the system behaviour in a standard hybrid dynamical framework (i.e., a hybrid automaton) as well as properly defining the guard conditions and reset maps.

Fig. 28. The performance of the filters in Case 2. \( \varepsilon_0 = 2, \varepsilon_1 = 0.2, \varepsilon_2 = 0.01, \varepsilon'_0 = 0.1, \varepsilon'_1 = 0.5, \varepsilon'_2 = 0.005 \) (a) Input current of the HESS and battery (b) SOC variation of the SC
3.5.1 PV and Load Agents

The automaton model of the PV supervisory controller is illustrated in Fig. 29(a) the PV agent has three operational modes, including maximum power point tracking (MPPT), load following, and idle modes. The system is initially in MPPT mode (i.e., $q_1$ and $P_{PV} = P_{MPPT}$). If the SOC of BESS reaches to its maximum value (i.e., $SOC_h > 0.8$), to avoid battery SOC violation, PV reduces its power generation and switches to the load following mode (i.e., $P_{PV} = P_{load} < P_{MPPT}$). In addition, if the available solar irradiance power is less than the threshold value (i.e., $P_{ir} < P_{min}$) the PV switches to the idle mode. Fig. 29(b) shows the automaton model of the load module. This agent has three operational modes including full load, load shedding, and system recovery modes. When the SOC of BESS decreases from a saturation value (i.e., $SOC_h < 0.25$), the load module switches to the load shedding operational mode by disconnecting the noncritical loads. If this load shedding action is not
sufficient to increase the SOC of BESS, the system will be forced to switch to the recovery mode by disconnecting all the loads. This action is necessary to maintain the stability of system and protect the system’s devices. The load module switches back to the full load mode if the SOC of BESS exceeds 0.3 (i.e., $SOC_b \geq 0.3$).

In this work, PV, load, and HESS agents have asynchronous mode transitions. As discussed in Section 2, utilizing a distributed approach for designing the supervisory control system can reduce the computational complexity compared to an equivalent centralized structure. In the proposed distributed supervisory control approach the HESS agent has five operational modes. PV and load modules also have three operational modes. Thus, the total number of discrete modes is equal to the summation of the operational modes, i.e., eleven. On the other hand, to design an equivalent centralized supervisory controller using the hybrid automata with sequential logic, it is required to define $5 \times 7$ discrete modes and identify the transitions among them that can be a tedious task. In addition, any change (e.g., adding new devices) to the system requires a significant reconfiguration of the centralized controller. Therefore, the proposed distributed strategy reduces the computational complexity of the supervisory control system and increases its scalability.

### 3.6 Simulation Results

This section analyses the performance of proposed multi-agent based supervisory control and power management system using MATLAB/Simulink. The BESS nominal power and energy is 30 KW/60 kWh. The SC has also 30 KW nominal power and 4 seconds
of charge time. The PV and load module have 30 KW nominal power and the voltage of PCC is 300 V (i.e., \( V_{dc} = 300 V \)). The filter parameters are defined as 
\[
\ell_0 = 4, \ell_1 = 0.04, \ell_2 = 0.004, \ell'_0 = 0.5, \ell'_1 = 0.5, \text{ and } \ell'_2 = 0.05.
\]

Fig. 30 represents the power sharing and battery SOC balancing performance of the system. Initially, the PV module is in the MPPT mode and BESS’s SOC is 0.52 (i.e., \( SOC_b(0) = 0.52 \)). Then, the SOC of BESS reaches to its maximum allowable value (i.e., \( SOC_{max} = 0.8 \)) at \( t = 6507s \). At this time, the guard condition \( g_{(1,2)} : SOC_b \geq 0.8 \) is satisfied and the PV agent switches to the load following mode (i.e., \( P_{PV} < P_{load} \)). Consequently, the net power becomes zero (i.e., \( P_{net} = 0 \)) and the SOC of BESS remains the same. During this time (i.e., \( t \in T_1 \)), the available solar power gradually decreases while that of load demand increases. At \( t = 11450s \), the demanded power becomes more than the maximum power generation of the PV module (i.e., \( P_{load} > P_{MPPT} \)). So, the PV switches to the MPPT mode and the BESS releases power to maintain the balance between generation and load. Fig. 31 illustrates the input current of the HESS module (i.e., \( I_{HESS} \) and \( I_b \)). The power smoothing filter charges/discharges the BESS with low frequency components of the net power. As seen, when the PV is in load following mode (i.e., \( t \in T_1 \)), the input current of the HESS is approximately zero.
The SOC variation of the SC module of the HESS is illustrated in Fig. 31. At five instances (i.e., $t = 513s$, $t = 2680s$, $t = 6509s$, $t = 12586s$, and $t = 15300s$), the guard condition $g_{(1,3)}: SOC_{SC} < 0.3$ is satisfied and the system switches to the $q_1$ mode to avoid SC SOC violation. Consequently, the SOC of SC always remains in the allowable range during
Before switching to $q_i$, the BESS generates a pulse shape current to regulate the SOC of SC to the reference value (i.e., $SOC_{ref} = 0.5$). These generated pulse shape currents at switching instances are shown in Fig. 31. It should be noted that the input current of SC is always equal to difference between HESS and BESS currents (i.e., $I_{SC} = I_{HESS} - I_b$), consequently, the SC absorbs these pulse shape currents which satisfies (33). In another word, charging or discharging the SC by the BESS does not affect the power balancing performance of the PV/HESS system.

Fig. 33 represents the SOC variation of HESS when the supervisory controller is deactivated. So, the agent cannot change its operational mode. In this case, the SOC of the SC is violated which can damage the system. Fig. 32 shows the SOC variation of the SC when there is no active compensation during the normal operation (i.e., $q_i$). In this case, there are frequent transitions to the $q_2$ and $q_3$ operational modes (i.e., fifty instances) which is ten times higher than the case when the filter is compensated using the proposed approach. Consequently, the proposed hybrid adaptive filtering method increases the reliability and the efficiency of the system.
In this chapter, a distributed rule-based supervisory control and power management technique in a PV/HESS system is presented. The case study system consists of a PV, a load, and a HESS that contains a BESS and a SC. Each module is an intelligent agent that can react to the environment by changing its dynamical behavior and/or operational mode. First, an active compensation filtering technique is proposed that improves the system’s efficiency by controlling the SOC variation of the SC. Then, to design the distributed supervisory control system, the hybrid automaton modeling approach is employed. The proposed hybrid modelling framework facilitates designing a hybrid adaptive filter for the HESS agent that can manage the current oscillations after switching instances. The distributed supervisory control approach provides efficient the reliable operation of PV/HESS system by preventing the SCs and BESSs from SOC violation. In addition, the proposed distributed power management technique reduces the computational complexity of the supervisory control system compared to its equivalent centralized method. Finally, the performance of the proposed rule-based power management strategy is verified by simulating the PV/HESS system in MATLAB/Simulink.

Fig. 33. SOC variation of HESS 1 when there is no active compensation in normal operation (i.e., $\ell_1 = \ell_2 = 0$).

3.7 Conclusion

In this chapter, a distributed rule-based supervisory control and power management technique in a PV/HESS system is presented. The case study system consists of a PV, a load, and a HESS that contains a BESS and a SC. Each module is an intelligent agent that can react to the environment by changing its dynamical behavior and/or operational mode. First, an active compensation filtering technique is proposed that improves the system’s efficiency by controlling the SOC variation of the SC. Then, to design the distributed supervisory control system, the hybrid automaton modeling approach is employed. The proposed hybrid modelling framework facilitates designing a hybrid adaptive filter for the HESS agent that can manage the current oscillations after switching instances. The distributed supervisory control approach provides efficient the reliable operation of PV/HESS system by preventing the SCs and BESSs from SOC violation. In addition, the proposed distributed power management technique reduces the computational complexity of the supervisory control system compared to its equivalent centralized method. Finally, the performance of the proposed rule-based power management strategy is verified by simulating the PV/HESS system in MATLAB/Simulink.

4.1 Motivation

The motivation behind this chapter is to address the challenges faced by DC nanogrids during islanded operation, where the grid is disconnected from the main power source and relies solely on the energy stored in the HESS. DC nanogrids face voltage instability, frequency fluctuations, and power quality issues, leading to reduced efficiency and reliability.

The proposed MPC strategy aims to enhance the performance of DC nanogrids during islanded operation by utilizing the HESS and an MPC controller. The MPC controller supervises the filtration-based power allocation system of the HESS, ensuring switchless operation of the grid-forming HESS unit. This approach improves the dynamic stability and power quality of the DC nano-grid, enhancing its efficiency and reliability.

The proposed MPC strategy is highly scalable and can be implemented in DC nanogrids with different topologies or larger scale DC distribution systems, promoting their adoption in various applications such as microgrids, data centers, and electric vehicles. Additionally, the prediction model of the MPC controller only requires the charge capacity of the HESS, eliminating the need for a dynamic model of the DC power distribution system or power electronic converters, making the proposed approach cost-effective and easily implementable.
Overall, the motivation behind this chapter is to provide an efficient control strategy for DC nanogrids during islanded operation, enhancing their performance and promoting their adoption in various applications.

4.2 Introduction

Microgrids (MGs) are independent active distribution networks that can enhance the performance of traditional power systems through increasing consumer participation, sustainable energy resources penetration, power system stability, and grid resiliency [67,68]. Recently, DC MGs have gained significant attention because of their lower power conversion losses and less control complexity compared to the AC MGs. DC MGs can be considered as viable solutions for rural electrification, resilience enhancement of power grids, and supporting local energy communities [69]. However, control of DC MGs can be challenging in the presence of constant power loads (CPLs) and pulsed power loads (PPLs) which require a fast dynamic response and a large stability margin of the control system [28,70,71]. To tackle this challenge, highly-dispatchable distributed energy resources (DERs) as well as advanced control and management techniques are required to improve the transient response, stability, and flexibility of the system [6].

Battery energy storage systems (BESSs) are one of the most popular energy storages devices for MG applications. BESSs are dispatchable, with low energy losses, and comparatively low costs. Moreover, they have a high energy density that makes them suitable for peak shaving and steady-state power balancing [31,47]. However, the BESSs may have relatively poor transient response during fast load changes due to their low power density [6,48]. Consequently, grid-forming BESSs may not provide acceptable performance and voltage quality for a DC MG in the presence of PPLs. In addition, BESSs
have a limited lifecycle. Therefore, the instantaneous variations of the renewable power
generation or load power fluctuations may result in frequent charge/discharge of the
batteries that lessens the BESSs’ lifetime [48,50].

The above-mentioned limitations of BESSs can be addressed by an effective
combination of BESSs with supercapacitors (SCs) [6,43]. In comparison to the BESSs, the
SCs have a higher power density and faster dynamic response. So, they can release/absorb
more energy for a significantly shorter time frame. Furthermore, they have a much higher
lifecycle than BESSs. Thus, the frequent charge/discharge of SCs does not affect their
lifetime. However, SCs are not appropriate for long-term energy storage applications
because of their low energy density [64]. Considering the structural capabilities and
limitations of BESSs and SCs, an SC is utilized in tandem with a BESS in battery-
supercapacitor hybrid energy storage systems (HESSs) to improve the dynamic
performance of the system and expand the lifespan of the BESSs. To this end, the BESS is
used for steady-state power balancing while the SC absorbs transient power fluctuation
from loads (e.g., PPLs) or renewable resources (e.g., PV or wind) [48]. The HESSs
consisting of a BESS and SC can be designed with different topologies including passive,
semi-active, and active topologies among which the active topologies are more desirable
because of their higher controllability. In addition, the full dispatch capacity of BESS and
SC can be utilized in active topologies [50]. In these topologies, each of the HESS
components (i.e., the BESS and SC) is connected to the MG DC bus through a power
electronic converter and has an independent current control system. However, a more
advanced control and energy management system (EMS) should be implemented to justify
the additional costs of the active components (e.g., power electronic converters) [49].
The effective and reliable operation of the HESSs requires the design of suitable offline and online management and control algorithms. In offline methods, different optimization algorithms (e.g., stochastic programming or genetic algorithms) can be implemented to compute the suitable size of the SC, BESS and other DERs, based on the availability of renewable energy sources (e.g., wind or PV), cost of system’s equipment, and the demanded power by the loads. On the other hand, online algorithms are necessary to ensure efficient and reliable real-time operation of the system. The real-time management and control strategies can be implemented in different control layers of the MG for different purposes. For instance, they can be implemented in the tertiary level of the MG for the optimal (or economic) state of charge (SoC) management of the BESSs or they can be employed in the secondary control layer of the MG for real-time power sharing between the HESS components (i.e., the BESS and SC) and other DERs. They can be also implemented in the primary control layer for effective current sharing between the BESS and SC to improve the transient voltage stability and voltage quality of the MG.

In DC MG applications, a HESS operates as a grid-following unit if the DC MG is connected to the utility grid, or it may operate as a grid-forming unit when the DC MG is islanded. In grid-connected mode of the MG, the voltage of the DC MG is regulated through connection to the upper hand AC grid using a bidirectional AC to DC converter. In this case, the HESS operates in power (or current) control mode, so its operation does not impact the transient voltage stability of the MG. In this operating mode, the EMS (i.e., the tertiary control layer) of the MG computes a reference power for the BESS and SC to charge the BESS with a steady power and absorb the instantaneous power fluctuations by SC. To this end, real-time optimization-based energy management strategies can be applied
at the tertiary level of the MG to perform optimal power allocation between the HESS components as well as minimizing the operational cost of the MG. To this end, the real-time optimal EMS strategies usually considers the mid-term operation of the system (e.g., within a few hours’ time interval) while the fast dynamics of the system related to primary-level controllers and power electronic converters are neglected [50,72].

In grid-forming operation (i.e., the islanded mode of the MG), the HESS module is responsible for maintaining the dynamic stability and voltage quality of the DC MG. In this case, the HESS receives a reference current signal that is typically computed by a proportional-integral (PI) voltage controller to regulate the voltage of the MG DC bus. So, the HESS power/current allocation system may interact with the primary-level controllers including the voltage controller and current regulators of the BESS and SC converters. As a result, the HESS actions may indirectly affect the voltage quality and transient response of the system. Thus, compared to grid-following operation, the HESS power/current allocation system should have a significantly faster dynamic response to effectively share the HESS reference current computed by the MG voltage controller between the SC and BESS [6,73,74].

Filtration-based (FB) power/current allocation of HESSs is the most common approach in MG applications that can be implemented for both grid-following and grid-forming HESS units. FB strategies have low computational complexity making them a feasible solution for real-time applications, e.g., for grid-forming HESS units [50,65]. In this approach, the HESS control system utilizes a low-pass, or a high pass filter to split the HESS reference current/power into high frequency and low-frequency components and then allocates the high-frequency parts into SC and the low-frequency components to
BESS (i.e., “BESS-SC” operating mode). Considering the fact that SC has a low energy density and a small charge time (e.g., in the range of a few seconds), it can be immediately fully charged/discharged after a sudden load variation. However, the conventional FB strategies cannot automatically limit the SoC variation of SC (and its terminal voltage) in a predefined range. So, they typically employ a rule-based supervisory controller that may deactivate the filter and send the HESS reference current to the BESS (i.e., “BESS-only” operation) if the SoC of SC violates a predefined range [65]. Consequently, the continuous operation of SC is not guaranteed, and the HESS may frequently switch between different operating modes to limit the SC SoC variation in a predefined range. However, these switching instances may trigger some transient voltage deviations during the system operation and affect the voltage quality of MG. Moreover, this work investigates that when a grid-forming HESS performs the “BESS-SC” mode, the MG voltage control system has higher marginal stability compared to the “BESS-only” operation. Thus, because of the destabilizing effect of CPLs, it is essential to guarantee the continuous operation of SC, particularly, if the grid-forming HESS is loaded by a large CPL.

In practice, to ensure the continuous operation of SC, the size of SC should be enough large to handle the significant power/current variations which in turn increases the initial cost of the system; or the cut-off frequency of the filter should be reduced, thereby decreasing the BESS’s lifetime. To address this issue, the previous work of authors [2] was to develop an active compensation filtering technique that automatically recovers the SoC (or terminal voltage) of SC to significantly reduce the required number of switching instances. However, that approach still needs a rule-based EMS that may deactivate the SC to guarantee its SoC variation in a predefined range. The proposed work in [75]
also suggests a virtual capacitance droop method that can automatically recover the SoC of SC to a reference value. It is also shown that this approach can slightly improve the marginal stability of MG given that the droop parameters are selected appropriately. However, this approach may cause a steady-state voltage deviation which is one of the intrinsic limitations of the droop control techniques [76]. Also, the right choice of droop coefficients can be a tedious task in DC MGs with multiple loads or DERs.

Recently, model predictive control (MPC) strategies have gained significant attention in HESS applications. The main idea of MPC is to utilize the dynamical model of the system to predict the system’s outputs (i.e., prediction step) within a moving horizon

Fig. 34. A comparison between different real-time control and management strategies of HESSs with respect to the standard hierarchical control structure of DC MGs.
(i.e., prediction horizon) and then compute a sequence of future control actions to minimize a predefined cost function (i.e., optimization step) \[34,77\]. One of the interesting features of MPC controllers is their ability to directly apply the operational constraints in their real-time optimization step. Consequently, MPC strategies can automatically limit the SoC variation of the HESS components in a predefined range. However, they have considerably higher computational complexity compared to the rule-based approaches.

In DC MGs with HESS technologies, the MPC strategies can be applied in different control layers for different purposes. For instance, the references \[78–82\] propose MPC-based EMS of HESSs in which the MPC controllers are located at the tertiary level of the MG, and they are responsible for optimal (or economic) energy management and scheduling of different DERs including the HESS units. In such applications, the sampling time or action time of the MPC controller is typically in the range of a few minutes. So, the MPC prediction model (i.e., the prediction step) does not consider the fast dynamics of the system (e.g., primary controllers, power electronic converters, and circuit dynamics). Therefore, these methods focus on improving the steady state performance of the system and they don’t address the voltage stability or transient response of the MG. In addition, at this layer, the MPC controllers typically have centralized architectures which need the information of all DERs to ensure the optimal operation of MG. Alternatively, The MPC controllers can be utilized in the primary controller layer of MG (e.g., direct MPC methods) to control the output voltage and currents of the power electronic converters \[77\]. For example, the reference \[83\] proposes a finite control set MPC (FCS-MPC) approach to improve the transient response and resiliency of a grid-forming HESS unit in a DC MG. In this approach, the FCS-MPC is located at the primary control layer of the MG, and it
directly manipulates the converters’ switches to regulate the output current of the BESS and SC to their reference values which are both computed by a FB power/current allocation system. However, the FCS-MPC strategies may intrinsically lead to intractable optimization problems due to their high computational complexity [34]. They also cause variable frequency switching that complicates the design of the converter’s output filters [37,84]. Additionally, the implementation of them for DC MG applications requires a major reconfiguration of the inner loop converter controllers which may not be always feasible. Fig. 34 compares the discussed real-time control and management strategies of HESSs concerning the standard control hierarchy of DC MGs.

To address the discussed challenges and improve the performance of a grid-forming HESS unit in regulating the MG DC bus voltage (i.e., enhancing the performance of the MG primary control layer), this work has the following contributions:

1) This work develops a detailed state-space dynamic model of an islanded DC MG in which a grid-forming HESS supplies a CPL. It is also assumed that the HESS utilizes a conventional FB power/current allocation strategy with a rule-based supervisory controller.

2) It provides a small-signal stability analysis to compare the marginal stability of the MG in “BESS-SC” and “BESS-only” operating modes of the HESS. The stability analysis shows that the DC MG has significantly higher marginal stability in the “BESS-SC” operating mode. This means that if the HESS only performs the “BESS-SC” operating mode, the MG PI voltage controller can work with significantly larger gain values and remain stable for larger communication delays.
3) An FB-MPC approach is proposed in which an MPC control system works in tandem with a linear time-invariant (LTI) filter to perform the current assignment between the BESS and SC. In this approach, the MPC module automatically restores the SoC of SC after sudden load changes and ensures its SoC variation in a predefined range. As a result, the grid-forming HESS is able to always work in “BESS-SC” operating mode, so the continuous operation of SC is guaranteed. Consequently, the MG’s PI voltage controller can operate with higher gain values which results in a better transient response and voltage quality, particularly, if the DC MG is loaded by large CPLs.

4) Compared to the existing MPC strategies in DC MG applications, the proposed MPC controller is unique in the sense that it is located at the primary control layer of the MG (i.e., interacts with voltage and current regulators of power electronic converters) but it is not responsible for regulating the output voltage or current of the power electronic converters. Instead, it is responsible for managing the SC SoC variation by computing a compensation term and adding/subtracting that value to/from the reference current of the BESS and SC power electronic converters. Due to this feature, it does not require to be as fast as the direct MPC methods (e.g., FCS-MPC). For instance, the action time of the proposed MPC controller can be in the range of a few milliseconds or more while the direct MPC methods action time should be less than a millisecond. So, the optimization step is less complex in this method (i.e., more suitable for real-time applications). Moreover, its prediction model does not need the dynamics of the MG circuit model or the power electronic converters. In addition, it does not require the information of other DERs including their output currents or voltages. Instead, it just requires the filter model and the nominal current and charge capacity of the SC. Consequently, it has a
considerably less complex prediction model. In addition, it can be easily adapted for the multi-generation/multi-bus DC MGs due to its decentralized architecture.

It should be noted that the proposed FB-MPC approach aims to improve the performance of the MG’s primary control layer. Because the primary control layer of MG has very fast dynamic responses, this work focuses on the short-term operation of the system (i.e., in the range of a few seconds) to study the transient response and voltage stability of the system under rapid load changes. So, the SoC management of BESSs that typically requires long-term (or mid-term) EMS and power sharing strategies and demands the appropriate actions of the secondary and tertiary control layer of the MG, is not discussed in this work. Fig. 34 compares the scope and contribution of this research with the discussed literature with respect to control hierarchy of DC MGs. MG voltage control system and why implementing the proposed FB-MPC method can be advantageous.

4.3 System Analysis

This section investigates the impact of an FB power/current allocation system on the dynamic stability of MG. Fig. 35 shows an islanded DC MG containing a PV power generation system, a HESS module, and a CPL where $i_{\text{HESS}}$, $i_{\text{Load}}$, and $i_{\text{PV}}$ represent the HESS, load and PV currents, respectively. $i_{\text{CP}}$ also represents the difference between the load and PV currents (i.e., $i_{\text{CP}} = i_{\text{Load}} - i_{\text{PV}}$). The case study system in this work is based on the standard single bus islanded DC MG proposed in [65,74] in which the HESS controls the common DC bus voltage. As seen, the HESS module contains a BESS and SC which are both connected in parallel to the MG DC bus through bidirectional boost converters.
The CPL is considered as a DC load connected to the MG DC bus through a power electronic converter (i.e., a load converter) and it demands a steady power under varying voltage at MG side. Here, it is assumed that the PV is in maximum power point tracking (MPPT) mode and operates as a constant power source\(^5\) (CPS). The HESS also operates as a grid-forming unit to regulate the MG DC bus voltage.

Fig. 36 shows the equivalent circuit model of the islanded DC MG where \(v_b\) and \(v_{sc}\) are the terminal voltages of the BESS and SC. \(i_{L1}\) and \(i_{L2}\) are the output currents of the BESS and SC, and \(v_{dc}\) is the DC bus voltage. \(P_{cp}\) is also the difference between the demanded power by the CPL (i.e., \(P_{load}\)) and the generated power by the CPS (i.e., \(P_p\)). Consequently, when the PV power generation becomes larger than the demanded power by the load (i.e., \(P_{cp} < 0\)), the grid-forming HESS module charges by a CPS. On the other hand, if the demanded power by the load converter is higher than the PV generation power (i.e., \(P_{cp} > 0\)) the HESS

---

\(^5\) In MPPT mode, the PV module generates its maximum available power regardless of the varying voltage at MG DC bus. So, it performs as a constant power source at each operating point.
is loaded by a CPL. It is worth noting that CPLs may degrade the dynamic stability of DC MGs due to their negative incremental resistance \([27,85]\). Consequently, the DC MGs that contain large CPLs require high marginal stability of control system to ensure the reliable operation of them.

Fig. 37 illustrates the conventional FB power allocation strategy in a grid-forming HESS unit. In this structure, the voltage regulator is a proportional-integral (PI) controller that computes a reference current (i.e., \(i_{\text{ref}}\)) for the HESS module to regulate the DC bus voltage. Next, the HESS power allocation module extracts the high frequency components of the HESS reference current (i.e., \(i_{\text{ref}}\)) using a high-pass filter (HPF). Then, to ensure the safe and reliable operation of system, the HESS current allocation system performs two modes of operation called “BESS-SC” and “BESS-only”. During the “BESS-SC” operating mode (i.e., \(S=1\)), the system allocates the high frequency components of the

![Circuit model of the case study DC MG system.](image)
HESS reference current (i.e., \( i_{HPF} \)) to the SC (i.e., \( i_{ref}^{SC} = i_{HPF} \)) and the remaining low frequency components to the BESS (i.e., \( i_{ref}^{b} = i_{ref} - i_{HPF} \)). On the other hand, to avoid SC SoC violation, the supervisory controller may deactivate the filter (or SC) and switch to the “BESS-only” operating mode (i.e., \( S = 0 \)). In this case, the system allocates all the reference current to the BESS (i.e., \( i_{ref}^{b} = i_{ref} \), \( i_{ref}^{SC} = 0 \)). So, the HESS operates like a single BESS when the power allocation filter is deactivated (i.e., “BESS-only” mode). The simplified logic of the rule-based supervisory controller for SC SoC management is represented in Fig. 38. Finally, at each operating mode, the current controllers calculate the duty of cycle of BESS and SC converters, i.e., \( d_1 \) and \( d_2 \), to regulate their output currents to their reference values, i.e., \( i_{ref}^{b} \) and \( i_{ref}^{SC} \).

In what follows, section 4.3.1 develops the state space dynamical model of the closed-loop system. Then, using the developed dynamical model, section 4.3.2 analyzes the small-signal stability of the system to compare the marginal stability of DC MG in the two different modes of operation, i.e., “BESS-SC” and “BESS-only”. It will also discuss the
impact of the filter’s time constant (or bandwidth) on the stability of the closed-loop system.

4.3.1 Dynamic Modelling

Based on the circuit model shown in Fig. 36, and dynamic equation of single-bus DC MGs with CPLs proposed in [86] the state space averaged dynamic model of the open-loop system (i.e., the islanded single-bus DC MG) is obtained as
\[
\begin{align*}
L_1 \frac{di_{L1}}{dt} &= v_b - R_i i_{L1} - v_{dc}(1 - d_1) \\
L_2 \frac{di_{L2}}{dt} &= v_{SC} - R_i i_{L2} - v_{dc}(1 - d_2) \\
C_{bus} \frac{dv_{dc}}{dt} &= i_{L1}(1 - d_1) + i_{L2}(1 - d_2) - \frac{P_{cp}}{v_{dc}} \tag{4.1}
\end{align*}
\]

where \(C_{bus}\) is the total capacitance of the MG DC bus. \(d_1\) and \(d_2\) are the duty cycle of the BESS and SC boost converters that are calculated by the PI current regulators. \(P_{cp}\) is also the difference between the generated power by the CPL and CPS (i.e., \(P_{cp} = P_{load} - P_{pv}\)). Considering the proposed control structure in Fig. 37, \(d_1\) and \(d_2\) are derived as

\[
\begin{align*}
d_1 &= k_{p1}(i_{ref}^b - i_{L1}) + k_{i1} e_{int1}, \quad e_{int1} = \int (i_{ref}^b - i_{L1})dt \\
d_2 &= k_{p2}(i_{ref}^{SC} - i_{L2}) + k_{i2} e_{int2}, \quad e_{int2} = \int (i_{ref}^{SC} - i_{L2})dt \tag{4.2}
\end{align*}
\]

where \(i_{ref}^b\) and \(i_{ref}^{SC}\) are the reference values of the current regulators. \((k_{p1}, k_{i1})\) and \((k_{p2}, k_{i2})\) are the proportional and integral gains of the BESS’s and SC’s PI current controllers, respectively. \(e_{int1}\) and \(e_{int2}\) represent the integral of the errors (i.e., \(i_{ref}^b - i_{L1}\) and \(i_{ref}^{SC} - i_{L2}\)), respectively. Assuming power/current allocation module utilizes a first order linear time invariant (LTI) filter \(i_{ref}^b\) and \(i_{ref}^{SC}\) are derived in Laplace form as

\[
\begin{align*}
i_{ref}^b(s) &= \left(\frac{1}{1 + \tau_s s}\right) i_{ref}(s) \\
i_{ref}^{SC}(s) &= \left(\frac{\tau_s s}{1 + \tau_s s}\right) i_{ref}(s) \\
i_{ref} + i_{ref}^b &= i_{ref} \tag{4.3}
\end{align*}
\]
where $\tau_f$ is the filter’s time constant and $i_{ref}$ is the HESS reference current. Based on (4.3), the performance of the current allocation system can be also explained as: if $\tau_f = (\omega_c)^{-1}$ the filter will pass the reference current (i.e., $i_{ref}$) from a high-pass filter with cut-off frequency to absorb the high frequency components by SC and send the remaining low-frequency components to BESS. Equation (4.3) can be also represented in a state space form as

$$
\begin{align*}
\tau_f & \frac{dx_f}{dt} = -x_f + i_{ref} \\
i_{ref}^{SC} & = x_f \\
i_{ref}^{b} & = i_{ref} - x_f 
\end{align*}
$$

(4.4)

where $x_f$ is the dynamical state of the LTI filter. The reference current, i.e., $i_{ref}$, is calculated by MG voltage controller and it can be represented as

$$
\begin{align*}
i_{ref} & = k_{p3}(v_{ref} - \hat{v}_{dc}) + k_{i3}e_{int3} \\
e_{int3} & = \int (v_{ref} - \hat{v}_{dc}) dt 
\end{align*}
$$

(4.5)

where $v_{ref}$ is the reference voltage of the MG DC bus and $e_{int3}$ is the integral of the voltage error. $k_{p3}$ and $k_{i3}$ are the proportional and integral gains of the PI voltage controller. $\hat{v}_{dc}$ is also the measured DC bus voltage at the feedback loop. By assuming the feedback loop has $\tau_d$ time delay and considering a first order Padé approximation of the delay [87] (i.e., $e^{-\tau_d s} \simeq (1 - 0.5 \tau_d s) / (1 + 0.5 \tau_d s)$), $\hat{v}_{dc}$ is obtained as
\[
\begin{align*}
\frac{1}{\tau_d} \frac{dx_d}{dt} &= -x_d + v_{dc} \\
\frac{2}{\tau_d} \frac{dx_d}{dt} &= -x_d + v_{dc} \\
\hat{v}_{dc} &= 2x_d - v_{dc}
\end{align*}
\] (4.6)

where \( v_{dc} \) is the MG DC bus voltage. Thus, based on (1) to (5), the nonlinear dynamical model of the closed-loop system can be obtained as

\[
\dot{x} = f(x, u)
\] (4.7)

where \( x \) represents the dynamic states of the MG (i.e., \( x = [i_{L1}, i_{L2}, v_{dc}, x, x_f, e_{int1}, e_{int2}, e_{int3}]^T \)) and \( u = [v_{ref}, P_{cp}]^T \) is the input vector of the system. \( f \in \mathbb{R}^8 \) is a vector showing the evolution of states, and it is defined as \( f = [\frac{1}{L_1}f_1, \frac{1}{L_2}f_2, \frac{1}{C_{bus}}f_3, \frac{1}{\tau_f}f_4, \frac{2}{\tau_d}f_5, f_6, f_7, f_8]^T \) where \( f_1, f_2, f_3, f_4, f_5, f_6, f_7 \) and \( f_8 \) are defined in (4.8) to (4.15).

\[
f_1 = v_b - R_1 i_{L1} - v_{dc} + k_{p1} v_{dc} x_f - k_{p1} v_{dc} i_{L1} + k_{f1} v_{dc} e_{int1}
\] (4.8)

\[
f_2 = v_{sc} - R_2 i_{L2} - v_{dc} + k_{p2} k_{p3} v_{ref} v_{dc} - 2k_{p2} k_{p3} v_{dc} x_d + k_{p2} k_{p3} v_{dc}^2 + k_{p2} k_{i3} v_{dc} e_{int3} - k_{p2} v_{dc} x_f - k_{p2} v_{dc} i_{L2} + k_{i2} v_{dc} e_{int2}
\] (4.9)

\[
f_3 = i_{L1} - k_{p1} i_{L1} x_f + k_{p1} i_{L1}^2 - k_{i1} i_{L1} e_{int1} + i_{L2}
\]

\[
- k_{p2} k_{p3} v_{ref} i_{L2} + 2k_{p2} k_{p3} x_d i_{L2} - k_{p2} k_{p3} v_{dc} i_{L2}
\]

\[
- k_{p2} k_{i3} i_{L2} e_{int3} + k_{p2} i_{L2} x_f + k_{p2} i_{L2}^2
\]

\[
- k_{i2} i_{L2} e_{int2} - (P_{cp} / v_{dc})
\]

\[
f_4 = -x_d + v_{dc}
\] (4.10)

\[
f_5 = -x_F + k_{p3} v_{ref} - 2k_{p3} x_d + k_{p3} v_{dc} + k_{i3} e_{int3}
\] (4.11)

\[
f_6 = x_f - i_{L1}
\] (4.12)

\[
f_7 = k_{p3} v_{ref} - 2k_{p3} x_d + k_{p3} v_{dc} + k_{i3} e_{int3} - x_f - i_{L2}
\] (4.13)
\[ f_8 = v_{ref} - 2x_d + v_{dc} \]  \hspace{1cm} (4.15)

Equations (4.7) to (4.15) represent the nonlinear dynamical model of the closed-loop system in a state space form which will be used for analytically evaluating the system’s stability in different modes of operation.

### 4.3.2 Stability Analysis

This section analyzes the small-signal stability of the MG based on the Eigen-value analysis of the linearized system [87]. The mathematical proofs of the eigen value analysis of time-delay systems are also discussed in [36]. To this end the linearized model of the closed-loop system is obtained at each equilibrium point (i.e., Jacobian linearization). The choice of this method is justified due to high complexity of the nonlinear model. Using the nonlinear state-space equation of the system defined in (4.7) to (4.15), the stationary point of the system (i.e., \((\bar{x}, \bar{u})\)) is obtained as

\[ \dot{\bar{x}} = 0 \iff f(\bar{x}, \bar{u}) = 0 \]  \hspace{1cm} (4.16)

Then, by using a first order Taylor series expansion of \(f\) and defining \(\Delta x = x - \bar{x}\) and \(\Delta u = u - \bar{u}\), one can obtain:

\[ \Delta \dot{x} = \dot{x} - \dot{\bar{x}} = f(x, u) = A_{\frac{\partial f(x, u)}{\partial x}}(\Delta x) + B_{\frac{\partial f(x, u)}{\partial u}}(\Delta u) \]  \hspace{1cm} (4.17)

where \(A\) and \(B\) are defined in (4.18) and (4.19), respectively.

\[ A_{\frac{\partial f(x, u)}{\partial x}}(\bar{x}, \bar{u}) = \frac{\partial f(x, u)}{\partial x} \bigg|_{(x, u)} \]  \hspace{1cm} (4.18)
Consequently, to find the closed-loop poles of the linearized system at each operating point, it is required to calculate the eigenvalues of the Jacobian matrix, i.e., $A$, which is obtained as:

$$Eig(A) = \{ \lambda \mid \det (\lambda I - A) = 0 \}$$

In this section, firstly the marginal stability of the DC MG in “BESS-SC” and “BESS-only” operating modes is evaluated, then the reason that the system has more stability margin in “BESS-SC” operation will be discussed. To this end, two different test cases are evaluated. The parameters of the case study system are shown in Table 7. In the first test case, it is assumed that the grid-forming HESS supplies 50kW constant power load (i.e., $P_{CP} = 50kw$). Then, the closed-loop poles of the system are obtained with respect to different values of proportional and integral gains of the MG PI voltage controller (i.e., $k_{p3}$ and $k_{i3}$). As seen in Fig. 39, the closed-loop poles of the MG are very sensitive.
Fig. 39. Dominant poles of the closed-loop system with respect to the proportional gain of the MG voltage controller (i.e., $k_{P3}$). Also, $k_3 = 20$, $\tau_f = 2s$, $\tau_d = 1ms$, and $P_{dc} = 50kW$. (a) “BESS-only” operation; (b) “BESS-SC” operation.

value when the DC MG is in “BESS-only” operating mode. In addition, the DC MG will be destabilized if $k_{P3} > 0.49$. On the other hand, the MG remains stable for significantly larger values of $k_{P3}$ in “BESS-SC” operation.

Fig. 40 also represents the closed-loop poles of the system with respect to $k_{I3}$ changes. As seen, the dominant poles of the closed-loop system are not very sensitive to $k_{I3}$ values in both of the operational modes. However, the DC MG will be unstable for relatively large value of integral gain (i.e., $k_{I3} > 44.3$) in “BESS-only” operation while the
Fig. 40. Dominant poles of the closed-loop system with respect to the integral gain of the MG voltage controller (i.e., $k_{i3}$). Also, $k_{p3} = 0.38$, $T_f = 2s$, $\tau_d = 1ms$, and $P_{cpp} = 50kW$. (a) “BESS-only” operation (b) “BESS-SC” operation.

The system remains stable in “BESS-SC” for larger gains (i.e., $k_{i3} = 120$).

Fig. 41 represents the closed-loop poles of the system with respect to communication delay (i.e., $\tau_d$). As seen, by increasing the communication delay the dominant poles of the closed-loop system move to the unstable region in both “BESS-only” and “BESS-SC” operation of the HESS. As seen in Fig. 41(a), the DC MG will be unstable for the delays larger than 5 milliseconds (i.e., $\tau_d \geq 5ms$) in “BESS-only” operation and it will be destabilized for delays larger than 13.5 milliseconds (i.e., $\tau_d \geq 13.5ms$) in “BESS-SC” operation. Consequently, compared to “BESS-only” operation, the DC MG can
tolerate considerably larger communication delays in “BESS-SC” operation due to its higher marginal stability at this mode.

The reason that the MG voltage controller has higher marginal stability in “BESS-SC” operating mode is directly related to the impact of current decomposition filter (i.e., the HPF) and SC operation. As seen in Fig. 37, when the HESS performs the “BESS-SC” operation, the SC is responsible for absorbing the transient power/current fluctuations to regulate the MG DC bus voltage while the BESS absorbs/releases the steady state power. To this end, the reference current calculated by the voltage controller firstly passes from

Fig. 41 Dominant poles of the closed-loop system with respect to the communication delay (i.e., \( \tau_d \)). Also, \( k_{r1} = 0.38 \), \( k_{r2} = 20 \), \( \tau_r = 2s \), and \( P_{CP} = 50kW \). (a) “BESS-only” operation (b) “BESS-SC” operation.
the HPF, then it is sent to the SC current regulator. The HPF causes a positive phase shift (e.g., like a lead compensator) that pushes the closed-loop poles of the system to the left-side of the $j\omega$ axis (i.e., the stable region). As a result, the current decomposition filter (i.e., the HPF) improves the marginal stability of the system by acting like an active compensator. Fig. 42 illustrates the impact of the HPF time constant (i.e., $\tau_f$) on the dynamic stability of the MG given that the HESS is loaded by a large CPL (i.e., $P_{cpp} = 50kW$). In this case, based on equation (4.3), when the filter time’s constant is very small (i.e., $\tau_f \approx 0$), the current allocation filter (i.e., the HPF) is approximately deactivated, hence all the HESS reference current is absorbed by the BESS and the SC reference current is approximately zero ($i_{ref}^{bess} = i_{ref}^{SC} = 0$). So, the HESS operation is similar to the “BESS-only” operating mode. On the other hand, when the filter’s time constant increases, the HPF provides a wider positive phase shift, and the SC absorbs a larger portion of the HESS reference current. As seen in Fig. 42, the closed-poles of the system are pushed to the stable region and the marginal stability of system is improved by increasing the time constant of the HPF.
Regarding the provided results by small-signal stability analysis of the system one can conclude:

1) The current decomposition filter (i.e., the HPF) acts like an active compensator that improves the marginal stability of system when the HESS performs the “BESS-SC” operation. In another word, the HPF not only performs the current assignment between the BESS and SC but also improves the marginal stability of the system.

2) The system has considerably higher stability margin when SC is active (i.e., in “BESS-SC” operating mode) compared to the “BESS-only” operation. However, to ensure the voltage stability during the entire system operation, the gains of MG voltage controller should be small; otherwise, the MG may experience an unstable DC bus voltage after switching to “BESS-only” operation. On the other hand, the very low gains of the MG voltage controller may adversely affect the transient response of the system and reduce the voltage quality. Thus, the discontinuous operation of SC limits the marginal stability of the voltage controller and indirectly declines the transient response of the system.

Based on the provided results, this work proposes an MPC strategy that works in tandem with an FB current allocation system (i.e., an HPF) to improve the performance of a grid-forming HESS. In this method, the HPF performs the current assignment between the BESS and SC as well as improving the marginal stability of the system and the MPC controller recovers the SoC of SC after sudden load changes and guarantees the continuous operation of SC. As a result, the HESS will always operate in “BESS-SC” operating mode, so the MG voltage controller can operate with higher gain values that results in a better
transient response and voltage quality. Fig. 43 illustrates the justification of the proposed FB-MPC approach.

### 4.4 Proposed FB-MPC Method

Fig. 44 shows the proposed FB-MPC technique. In this method, similar to the FB approach, the voltage controller located at the primary control layer of the MG computes a reference current to regulate the MG common DC bus voltage. This reference current is then sent to the FB-MPC power/current allocation system. In the proposed method, the rule-based supervisory controller used in the conventional FB approach (see Fig. 37) is replaced by an MPC module (see Fig. 44), so that guarantee the continuous operation of the SC and filter. In this approach, the MPC module regulates the SoC of SC to a reference value while considering the SoC constraints of the SC. To this end, at each time step, the MPC controller employs the discretized dynamical model of the system to predict the
future error between the SoC of SC and its reference value within a moving horizon, i.e., prediction horizon. Then, to minimize the error, it computes a sequence of compensation currents (i.e., $i_{com}$) within a moving horizon (i.e., control horizon) and applies the first one.

As a result, based on the SoC variation of SC and the HESS reference current (i.e., $i_{ref}$), the MPC compensator sends a compensation term to the HPF. After passing from the HPF, the compensation term is added to the reference current of the SC and subtracted from the reference current of the BESS. As a result, the MPC compensator provides an additional coordination between the BESS and SC in which the BESS gradually charges/discharges the SC. Consequently, the proposed FB-MPC can control the SoC variation in a predefined range which in turn ensures the continuous operation of the SC and filter. In what follows, section 4.4.1 develops the prediction model of the MPC controller, section 4.4.2 introduces the MPC objective function, section 4.4.3 discusses the MPC tuning parameters, 4.4.4 discusses the functionality of the MPC compensator, and 4.4.5 discusses the dynamic stability of the MG under the proposed FB-MPC approach.

Fig. 44. The structure of a grid-forming HESS unit with the proposed FB-MPC power/current allocation system.
4.4.1 Prediction Model

The prediction model represents the dynamical relationship between the HESS reference current (i.e., $i_{ref}$) and the SoC of SC. The percentage value of SC’s SoC can be represented as

$$SoC_{sc}(t) = \frac{-100I_n}{Q_n^{sc}} \int_{t_0}^{t} i_{SC(p.u)} dt + SoC_{sc}(t_0)$$ (4.21)

where $Q_n^{sc}$ is the nominal capacity of the SC. Also, $I_n$ and $i_{SC(p.u)}$ are the nominal and per unit value of SC’s discharge current, respectively. This per unit representation is applied here for better scaling the model parameters. Assuming there is no leakage current and considering the circuit model of the system shown in Fig. 36 the discharge current is equal to the inductor current of the boost converter, i.e., $i_{SC} = i_{L2}$. In addition, knowing the fact the power electronic converter and the current regulator has by far faster dynamics than $SoC_{SC}$, $i_{L2}$ can be considered equal to its reference value, i.e., $i_{L2} \simeq i_{ref}^{SC}$. So, (4.21) can be reformulated as

$$SoC_{sc}(t) = \frac{-100I_n}{Q_n^{sc}} \int_{t_0}^{t} i_{ref}^{SC(p.u)} dt + SoC_{sc}(t_0)$$ (4.22)

where $i_{ref}^{SC(p.u)}$ is the per unit value of the SC’s reference current. Assuming the HESS uses a first order LTI filter, $i_{ref}^{SC(p.u)}$ can be represented in Laplace form as

$$i_{ref}^{SC(p.u)}(s) = \frac{1}{I_n} \left( \frac{\tau S}{\tau S + 1} i_{ref} + \frac{\tau S}{\tau S + 1} i_{com} \right)$$ (4.23)

where $\tau_f$ is the filter’s time constant and $i_{com}$ is the compensation current applied by the
MPC compensator (see Fig. 44). Equation (4.23) can be also represented in a state space form as

\[
\begin{align*}
\tau_f \frac{dx_f'}{dt} &= -x_f' + i_{\text{com}} + \left(\frac{1}{I_n}\right)i_{\text{ref}} \\
i_{\text{ref}(p,u)}^{\text{SC}} &= \left(\frac{1}{I_n}\right)i_{\text{ref}} + i_{\text{com}} - x_f' \tag{4.24}
\end{align*}
\]

where \( x_f' \) represents state variable of the filter’s model. Using (4.22) and (4.24), the dynamical model of SC’s SoC is obtained as

\[
\begin{align*}
\frac{d\text{SoC}_\text{SC}}{dt} &= \frac{100I_s}{Q_n^{\text{SC}}} (x_f' - i_{\text{com}}) - \frac{100}{Q_n^{\text{SC}}} i_{\text{ref}} \\
\frac{dx_f'}{dt} &= -\frac{1}{\tau_f}(x_f' - i_{\text{com}}) + \frac{1}{\tau_f I_n} i_{\text{ref}} \tag{4.25}
\end{align*}
\]

The MPC compensator is naturally a discrete-time controller. So, it utilizes the discretized dynamical model of the SC’s SoC. Based on (4.25), the MPC prediction model is represented as

\[
\begin{align*}
x_m(k+1) &= (I + T_s A)x_m(k) + T_s B_1 u(k) + T_s B_2 d(k) \\
y_m(k) &= C x_m(k) \tag{4.26}
\end{align*}
\]

where \( x_m(k) = [\text{SoC}_\text{SC}(k), x_f'(k)]^T \) are the states of the prediction model, \( u(k) = i_{\text{com}}(k) \) is the manipulated variable (i.e., control input), \( d(k) = i_{\text{ref}} / I_n \) is the measured disturbance, \( I \) is a 2 by 2 identity matrix, and \( T_s \) is the sampling period of the MPC. Matrices \( A, B_1, \) and \( B_2, \) and vector \( C \) are

\[
A = \begin{bmatrix} 0 & 100I_s / Q_n^{\text{SC}} \\ 0 & -1/\tau_f \end{bmatrix}, \quad B_1 = B_2 = \begin{bmatrix} -100I_s / Q_n^{\text{SC}} \\ 1/\tau_f \end{bmatrix}, \quad C = [1, 0] \tag{4.27}
\]
4.4.2 Objective Function

In optimization step, the MPC compensator solves a quadratic programming (QP) problem to compute the manipulated variable (i.e., compensation current) using an active set optimization method. In this QP formulation, the cost function is quadratic while the constraints have to be linear. The MPC objective function is defined as

$$
\min : \sum_{i=1}^{H_p} \psi_c \left( \text{SCSoC}_{ref}(k+i | k) - y_m(k+i | k) \right)^2 \\
+ \sum_{i=1}^{H_p} \psi_c (u(k+i | k) - u(k+i-1 | k))^2 + \rho \varepsilon(k)^2
$$

subject to the constraints:

$$
\begin{cases}
\text{SoC}_{\text{min}} - \lambda \varepsilon(k) \leq y_m(k+i | k) \leq \text{SoC}_{\text{max}} + \lambda \varepsilon(k), \\
i \in \{1, \ldots, H_p\}
\end{cases}
$$

where $u$ is the manipulated variable, $y_m$ is the model’s output represented in (28), and $\varepsilon$ is the slack variable for constraint softening. $\psi_c$ and $\psi'_c$ are the tuning weights on the tracking error and manipulated variable move, and $\rho$ is constraint violation penalty weight. $H_p$ and $H_c$ are the prediction and control horizons and $\lambda$ is equal concern for relaxation (ECR) value. It is assumed that $\lambda > 0$, $H_p > H_c$ and $u(k+i | k) - u(k+i-1 | k) = 0$ for $i \geq H_c$

4.4.3 Tuning MPC Parameters

The desirable operation of the MPC compensator requires appropriately tuning the MPC parameters. In (4.28), the first term penalizes the deviation of the SC’s SoC (i.e., $\text{SCSoC}_{\text{sc}}$)
from its reference value (i.e., $ref_{SoC}$) and the second term penalizes the rapid changes on the control input (i.e., $i_{con}$). The third term also penalizes a tolerable soft constraint violation compared to the other cost function terms. The tracking error has the minimum priority compared to the other terms. So, $\psi_e$ should be considered much smaller than the $\psi_c$ and $\rho$.

Although a relatively large value of $\rho$ increases the likelihood of having a very small optimal slack variable ($\varepsilon(k)$), it may result in significantly rapid manipulated variable move if the SoC constraints are violated. This rapid manipulate variable move can cause a relatively large voltage sag on the MG DC bus. Also, it may put a high stress on the BESS for charging the SC when a violation of constraints is predicted. So, the weights on the manipulated variable move should be much larger than the other cost function terms (i.e., $\psi_e \ll \rho \ll \psi_c$). Consequently, in contrast to the rule-based SC SoC compensation.
methods, the proposed approach can guarantee the continuous operation of SC without affecting the transient voltage of the MG (i.e., no voltage sags) by effectively tuning the MPC parameters.

4.4.4 Functionality of the MPC Compensator

As seen in Fig. 44, the MPC compensator receives the HESS reference current (i.e., $i_{ref}$) that is computed by the voltage controller as well as the SoC of SC (i.e., $SoC_{SC}$) to control the SC SoC variation in a predefined range. To this end, at the prediction step, the MPC controller employs the dynamic model of the FB current allocation system and the dynamic relationship between the SC’s current and its SoC value. In this respect, the MPC controller applies the dynamic model of FB current allocation system to estimate how much of the HESS reference current will be allocated to the SC and then predicts the SC SoC variation during its prediction interval (i.e., the prediction horizon). Then, at the optimization step, the MPC controller computes a sequence of compensation terms, i.e., $i_{con}$ (see (25) to (29)), in order to minimize the error between the SoC of SC (i.e., $SoC_{SC}$) and its reference value (i.e., $SoC_{ref}$) by considering the SC SoC constraints defined in (29). Then, the MPC controller applies the first value in the sequence and goes for the next time step. The flowchart of the MPC compensator is shown in Fig. 45.

The compensation term is then sent to the HPF. Accordingly, by assuming the DC MG including the HPF and MG voltage controller have similar dynamics to the examined case study system in section 4.3, the reference currents of the BESS, and SC represented in (3), are reformulated in the FB-MPC method as
\[
\begin{align*}
    i_{ref}^b(s) &= \frac{1}{1+\tau_f s} i_{ref}^b(s) - d_{com} \\
    i_{ref}^{SC}(s) &= \frac{\tau_f s}{1+\tau_f s} i_{ref}^b(s) + d_{com} \\
    i_{ref}^{SC}(s) + i_{ref}^b(s) &= i_{ref}
\end{align*}
\]

where \( i_{ref} \) is defined in (5). \( d_{com} \) is also obtained as

\[
d_{com} = \left( I_n \right) \left( \frac{\tau_f s}{1+\tau_f s} \right) i_{com}
\]

where \( i_{com} \) is the compensation term computed by the MPC controller. As a result, the MPC controller adds a compensation term to the reference current of the SC and subtract that value from the BESS reference current. (Note: sum of the BESS and SC currents should be always equal to HESS reference current. Please also compare (4.3) and (4.30)). Consequently, the proposed FB-MPC method provides an additional coordination between the BESS and SC in which the BESS can gradually charge/discharge the SC based on the compensation term (i.e., \( d_{com} \)) that is adjusted by the MPC compensator.

It should be also noted that, fundamentally, the MPC controllers have an interesting feature which is their ability in applying the input and output constraints in their optimization step. So, they can certify that the output or input constraints will not be violated. However, this interesting feature is not available in classical linear or nonlinear controllers. So, they cannot be as functional as the MPC methods for this application. For instance, in the proposed FB-MPC method, if the MPC compensator predicts a violation of constraints (i.e., SC SoC violation) during its prediction horizon (e.g., the MPC computes a nonzero slack variable), it can quickly adjust the \( d_{com} \) to prevent the SC SoC
violation in a switching-less manner. Thus, the MPC compensator can guarantee the continuous operation of the SC and filter. In addition, the MPC compensator can limit the fast movement of the manipulated variable (i.e., \( i_{\text{com}} \)), so that reduce the stress on the BESS for charging the SC if a violation of constraints is predicted (see (4.28)). Consequently, from the voltage controller point view, the compensation term (i.e., \( d_{\text{com}} \)) has very slow and smooth variations which does not affect the transient voltage quality of the system.

4.4.5 Voltage Stability of the MG with FB-MPC Method

As discussed in section II, the conventional FB power/current allocation strategy cannot guarantee the continuous operation of the SC and filter. Hence, the HESS may switch between two modes of operation, i.e., “BESS-only” and “BESS-SC”. Then, the proposed small-signal stability analysis in II.B shows that the MG voltage control system has significantly higher marginal stability in “BESS-SC” operating mode compared to the “BESS-only” operation. Consequently, to guarantee the continuous operation of the SC and filter, an MPC controller is utilized that limits the SoC variation of SC in a predefined range. As a result, the HESS will always operate in “BESS-SC” operating mode. To this end, the MPC controller computes a compensation term (i.e., \( i_{\text{com}} \)) and sends it to the HPF (see Fig. 44). Accordingly, the MPC controller provides an additional coordination between the BESS and SC by adding the \( d_{\text{com}} \) to the reference current of the SC and subtract that value form the reference current of the SC.

Practically, due to the fact that the SC SoC variation has significantly slower dynamics compared to DC bus voltage, the MPC action time (or MPC sampling time) is
significantly larger than the MG voltage controller (e.g., the MPC sampling time can be twenty to fifty times larger than the sampling time of the voltage controller). In addition, the variation of the MPC compensation current (i.e., the manipulated variable move) is limited in the MPC cost function (see equation (28)). As a result, from the point of view of MG voltage controller, the compensation term (i.e., $d_{com}$) is seen as a small disturbance that has extremely slow variations. Consequently, $d_{com}$ does not directly change the dynamic model (e.g., the close-loop poles of the linearized model) of the MG voltage control system. Hence, in terms of dynamic stability, under the proposed FB-MPC technique, the system behaves similar to the discussed case study system in section 4.3 (i.e., a grid forming HESS with conventional FB current allocation), but it always works in “BESS-SC” operating mode. In another word, the MPC compensator just ensures the continuous operation of SC (i.e., “BESS-SC” operation) in which the system has a higher marginal stability, and it does not directly affect the dynamics of the MG voltage control system.

It is also worth mentioning that the MPC control system regulates the SoC variation of the SC that impacts the terminal voltage of the SC. Hence, the MPC controller may slightly change the stationary operating point of the system (see (16) to (19)) for a specific load condition. However, $V_{SC}$ does not appear in the small-signal model of the system, so the Jacobian Matrix and Eigen-values at similar stationary points remains unchanged. Consequently, because the range of stationary points (e.g., the allowable range for SoC of SC and $V_{SC}$ variation) is equal in the FB-MPC and FB methods, the proposed stability
Table 8. HESS parameters.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{Q}^c$</td>
<td>charge capacity of the SC</td>
<td>0.22 A.h</td>
</tr>
<tr>
<td>$Q_{n}^b$</td>
<td>charge capacity of the BESS</td>
<td>800 A.h</td>
</tr>
<tr>
<td>$C_{SC}^c$</td>
<td>capacitance of the SC</td>
<td>4.21 F</td>
</tr>
<tr>
<td>$I_{n}$</td>
<td>nominal current of the SC and BESS</td>
<td>400 A</td>
</tr>
<tr>
<td>$R_{SC}^c$</td>
<td>internal series resistance of the SC</td>
<td>2 m$\Omega$</td>
</tr>
<tr>
<td>$R_{SC}^b$</td>
<td>internal series resistance of the BESS</td>
<td>5.3 m$\Omega$</td>
</tr>
<tr>
<td>$v_{h}^n$ max</td>
<td>nominal terminal voltage of the BESS</td>
<td>55 V</td>
</tr>
<tr>
<td>$v_{SC}^c$ max</td>
<td>nominal terminal voltage of the SC</td>
<td>190 V</td>
</tr>
</tbody>
</table>

analysis related to the “BESS-SC” operation of the HESS in FB approach (see section 4.3.2), will be also valid for the FB-MPC method. Therefore, in the FB-MPC method, the voltage control system has the same stability margin compared to the “BESS-SC” operation in FB approach.

Table 9. Controller parameters.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi_{c}$</td>
<td>tracking error’s weight</td>
<td>$8 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\psi_{c}$</td>
<td>manipulated variable move’s weight</td>
<td>0.1</td>
</tr>
<tr>
<td>$\rho$</td>
<td>slack variable’s weight</td>
<td>0.002</td>
</tr>
<tr>
<td>$H_{p}$</td>
<td>prediction horizon</td>
<td>50</td>
</tr>
<tr>
<td>$H_{c}$</td>
<td>control horizon</td>
<td>10</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>ECR value</td>
<td>1</td>
</tr>
<tr>
<td>$t_{s}$</td>
<td>sampling time</td>
<td>2 ms</td>
</tr>
<tr>
<td>$SoC_{min}^c$</td>
<td>minimum allowable SoC of SC (output constraint)</td>
<td>20%</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>ECR value</td>
<td>1</td>
</tr>
<tr>
<td>$t_{s}$</td>
<td>sampling time</td>
<td>2 ms</td>
</tr>
<tr>
<td>$SoC_{min}^c$</td>
<td>minimum allowable SoC of SC (output constraint)</td>
<td>20%</td>
</tr>
<tr>
<td>$SoC_{max}^c$</td>
<td>maximum allowable SoC of SC (output constraint)</td>
<td>80%</td>
</tr>
</tbody>
</table>
4.5 Simulation Results

This section evaluates the performance of the proposed FB-MPC technique and compares it with the conventional FB current allocation strategy by simulating these systems in MATLAB/Simulink. To this end, two test systems are compared with each other in three different load change scenarios. The test case systems have the following characteristics:

- The first system (i.e., Case 1) utilizes a conventional FB strategy represented in Fig. 37.
- The second system (i.e., Case 2) employs the proposed FB-MPC technique. The control structure of this system is illustrated in Fig. 44. The parameters of the MPC compensator are also shown in Table 9.
- The circuit parameters and the gain of PI current regulators are similar to the test cases in section 4.3. Also, they use a similar LTI filter with $\tau_f = 2s$ and the communication delay is 1ms. In addition, the MG PI voltage controllers in both cases have 0.1ms sampling time while the MPC compensator has 2ms sampling time.
- For both systems, the BESS is a Lithium-Ion type. Also, the SC consists of an ideal capacitor with a series internal resistance. It is assumed that the SC has no leakage current. Also, it is assumed that the HESS components (i.e., SC and BESS), and PV are efficiently sized. The parameters of BESS and SC are represented in Table 8. In this experiment, the BESS has 2 hours charge time and SC’s charge time is 2 seconds.
- In both test cases, it is assumed that the PV module is in MPPT mode, and it operates as a CPS. Moreover, it is assumed the DC MG supplies a power electronic load (i.e., a load converter) that demands constant power under the varying voltage at MG side, so it operates as a CPL. Thus, the difference between load and PV power (i.e., $P_{cp} = P_L - P_{pv}$) represents the
equivalent CPL/CPS (or the net power) that is supplied/absorbed by the HESS. Hence, 
\( P_{CP} > 0 \) implies that the HESS is loaded by an equivalent CPL that demands identical power to \( P_{cp} \) and tends to destabilize the system [86] (see the dynamics of the MG in (1) and (10)).

- It is assumed that the HESS nominal power and maximum \( P_{CP} \) are both 20kW (i.e., \( P_{CP}^{max} = 20 \text{ kW} \)). Accordingly, based on the stability analysis provided in section II, in Case 1, the MG voltage controller suffers from low-marginal stability when it operates the “BESS-only” operation. So, the gains of the MG voltage controller are selected as \( k_{p3} = 0.75, k_{i3} = 35 \) to guarantee the stability of the MG at the nominal CPL (i.e., \( P_{CP}^{nom} \)). However, based on the stability analysis in section II, the gains of MG voltage controller can be larger in Case 2 (i.e., FB-MPC), so they are defined as \( k_{p3} = 1.9, k_{i3} = 72 \).

As discussed in section 4.2, the sudden load variations or rapid PV power fluctuations (i.e., fast \( P_{cp} \) changes), adds a considerable stress on the grid-forming HESSs which may cause over charging/discharging of the SC. So, to evaluate the performance of the FB-MPC method and compare it with conventional FB power allocation strategies, the dynamical behavior of Case 1 (i.e., FB) and Case 2 (i.e., FB-MPC) systems are assessed in three different rapid load (or \( P_{cp} \)) variation scenarios. The first scenario contains a sharp shift of \( P_{cp} \) from 10kW to 15kW at \( t=10s \) and then sharp load reduction from 15kW to 10kW at \( t=25s \). In the second situation, the DC MG experiences a fast and periodic pulsed-shape variation of \( P_{cp} \). In the last condition, \( P_{cp} \) sharply increases from 10kW to 19kW at \( t=70s \) and then decreases from 19kW to 10 kW at \( t=90s \). Fig. 46 illustrates the \( P_{cp} \) profile in these three load scenarios. It should be noted that, practically, the first and the third load
change scenarios may happen during adding/losing a load/source converter and the second load change scenario is caused by the PPLs (e.g., electric propulsion or laser guns) inside the DC MG.

Fig. 46. The load change scenarios in the test systems.

Fig. 47. The output power of the HESS components in the test cases (a) Case 1 (i.e., conventional FB), (b) Case 2 (i.e., the proposed FB-MPC).

Fig. 48. Transferred power from BESS to SC because of the MPC actions in the FB-MPC method.
Fig. 50. The SC and BESS SoC variation (a) SoC of SC, (b) SoC of BESS.

Fig. 49. The performance of the current allocation systems in the case study MGs (i.e., Case1 and Case 2). (a) HESS reference current (i.e., $i_{ref}$), (b) The SC and BESS currents (i.e., $i_{k1}, i_{k2}$).
Fig. 47 shows the output power of the BESS and SC in Case 1 (i.e., FB) and Case 2 (i.e., FB-MPC) systems during the discussed load change scenarios where $P_{SC} > 0$ means that the SC is discharging and $P_{SC} < 0$ shows that the SC is charging. As seen in Fig. 47 (a) and (b), the output power of BESS is smoothed and the high frequency variations of the $P_{CP}$ are allocated to the SC in both FB and FB-MPC methods. Also, the HESS output power (i.e., $P_{HESS} = P_b + P_{SC}$) is equal to the $P_{CP}$ (i.e., $P_{HESS} = P_{CP}$) in both cases that indicates the balance between power generation and load. However, the BESS and SC have slightly different output power profiles in FB-MPC method compared to the FB approach, due to the impact of the MPC compensator.

Fig. 48 represents the transfer power between the BESS and SC in FB-MPC approach due to MPC actions (i.e., compensation power). Fig. 50 also illustrates the SC and BESS SoC variation in Case 1 and Case 2 systems. As seen in Fig. 50(a), in FB-MPC method, MPC compensator provides an additional coordination between BESS and SC in which the BESS gradually charges/discharges the SC and controls its SoC variation in a
predefined range. Due to the significant $P_{cf}$ changes in the third load change scenario a high amount of power is sent to the SC. So, in FB method, the SoC of SC reaches to its minimum allowable value at $t=73.1s$. Thus, the rule-based supervisory controller deactivates the SC and allocates $P_{HESS}$ power to the BESS (i.e., “BESS-only” operation). Then, at $t=90s$, the load power suddenly decreases, so the output of the HPF becomes negative (i.e., $i_{HPF} < 0$). Consequently, the rule-based supervisory controller activates the SC and the HESS switches back to “BESS-SC” operating mode. In addition, as it can be seen in Fig. 49 deactivating the SC (i.e., switching to “BESS-only” mode) forces the BESS to suddenly change its output power which puts a large stress on the BESS and MG voltage control system. On the other hand, in Case 2 (i.e., FB-MPC), because of the sudden load change at $t=70s$, the SoC of SC approximately reaches to its minimum value at $t=74.3s$. At this moment, the MPC compensator predicts that there will be a constraint violation in its prediction horizon. So, it shifts the compensator term (i.e., $d_{com}$), so that force the BESS...
to react more quickly and charge the SC. This relatively faster movement of the $d_{com}$ (or the BESS output power) at $t=74.3s$ is clearly illustrated in Fig. 51 (b). Consequently, the MPC compensator prevents the SC SoC violation in a switching-less manner. In addition, it can be observed that due to the significantly larger charge time of the BESS (i.e., 2hours), the SoC of BESS remains approximately unchanged during the simulation interval in both cases.

Fig. 49 compares the current allocation performance of the conventional FB (i.e., Case 1) with the proposed FB-MPC technique (i.e., Case 2) in which Fig. 49(a) represents HESS reference currents computed by MG voltage controllers and Fig. 49(b) illustrates the output currents of the HESS components in Case 1 (i.e., FB) and Case 2 (i.e., FB-MPC) systems. As seen, the HPF assigns the high frequency components (i.e., sharp changes) of the reference current to SC, so that smooth out the reference current of BESS. In addition, it can be observed that high frequency pulsed-shape load variations in the second scenario are completely absorbed by the SC in both cases (i.e., Case 1 and Case 2).

In the third load scenario, as discussed before, the SC (or filter) is deactivated at $t=73.1s$ in Case 1 and the HESS switches to the “BESS-only” operation to avoid SC SoC violation. As a result, the SC current is swiftly shifted to zero which can cause a
considerable transient voltage sag. However, the proposed FB-MPC method guarantees the continuous operation of SC during the entire system operation by adding a compensation current (i.e., \(d_{com}\) defined in equation (4.31)) to the SC and subtracting that value from the BESS reference current. This value (i.e., \(d_{com}\)) is illustrated in Fig. 51. As seen, the \(d_{com}\) experiences a relatively fast move when the SoC of SC reaches to its minimum value at \(t=74.3\) s. The reason is that, at \(t=73.1\) s, the MPC predicts that its output constraint (i.e., the SC SoC allowable range) is going to be violated which results in a small nonzero slack variable (i.e., \(\varepsilon \neq 0\)) in MPC cost function defined in (28). Considering a large slack variable weight (i.e., \(\rho\)), this nonzero slack variable causes a large value in the third term of the MPC cost function. Thus, the MPC compensator quickly reduces the compensation current to minimize the cost function. As a result, the output current of BESS rapidly increases to charge the SC and control its SoC variation.

Fig. 52 depicts the BESS and SC terminal voltages during the simulation interval. As seen, due to the fact that the BESS has significantly larger charge time (i.e., 2hours), the terminal voltage of the BESS (i.e., \(V_b\)) remains relatively unchanged during the simulation interval. It is also worth mentioning that the proposed FB-MPC technique causes different SoC variation in Case 2 compared to the FB method (i.e., Case 1) that results into a different terminal voltage of the SC (i.e., \(V_{SC}\)). Thereby, the reference currents of HESSs in Case 1 and Case 2 computed by the MG voltage controller, have relatively different profiles during the system operation.

Fig. 53 represents the transient variation of the MG DC bus voltage (i.e., \(v_{dc}\)) during the three load change scenarios. As seen, because the MG voltage controller has higher
marginal stability and higher gain values in Case 2 (i.e., the FB-MPC method), it can provide faster responses to the load changes which in turn reduces the transient voltage deviations and enhances the MG’s voltage quality. In addition, it can be seen that at the switching instance in Case 1 (i.e., $t=73.1$ s), the MG DC bus experiences a significant voltage sag. However, this large transient voltage sag is avoided in the proposed FB-MPC technique, due to its switching/less performance. Instead, under the FB-MPC method, the MG DC bus experiences a very small voltage sag (i.e., $1.7$ V) at $t=74.3$ s because of the relatively quick adjustment of $d_{com}$. This voltage sag is $90\%$ smaller than the voltage sag in FB method and it is fairly negligible. Consequently, the MG DC bus experiences smaller voltage sags (smaller peak and shorter duration) at sudden load changes showing the improvement of the MG voltage quality with the proposed FB-MPC method [89].

Table 10 also compares three voltage quality indexes including the sum of absolute value of voltage changes (SAVC), the integral of the square error (ISE), and the integral of absolute value of error (IAE) which are obtained as

$$
\begin{align*}
ISE &= \int (v_{\text{ref}} - v_{dc})^2 \, dt \\
IAE &= \int |v_{\text{ref}} - v_{dc}| \, dt \\
SAVC &= \sum_k |v_{dc}(kT + T) - v_{dc}(kT)|, \quad T = 0.1\text{ms}
\end{align*}
$$

In (4.32), the lower value of ISE and IAE shows the better voltage regulation performance of the MG voltage control system. In addition, the lower SAVC shows the smaller voltage ripples and flatter voltage profile at MG DC bus. As seen in Table IV, all the indexes (i.e., IAE, ISE, and SAVC) are considerably lower in FB-MPC which indicates the higher voltage quality of MG and better performance of the MG voltage control system under the proposed FB-MPC method.
The simulation results and small-signal stability analysis of this work demonstrates that the proposed FB-MPC approach improves the performance of the primary control layer of a single bus DC MG that contains a grid-forming HESS unit. Consequently, the MG voltage controller can regulate the MG DC bus voltage to its reference value with less transient voltage oscillations at rapid load changes. In this work, the reference voltage for the MG primary controller has a constant value which is exactly equal to the nominal voltage of the single bus DC MG. However, in multi-bus/multi-generation DC MGs, the reference voltages for the primary controllers are typically computed by the secondary control layer of the MG. In such systems, the secondary control layer adjusts the reference voltage of the grid-forming DERs to ensure proportional power sharing between them as well as restoring the steady state voltage of the MG (see the objectives of secondary control layer in Fig. 34). Consequently, reference voltages of the primary controllers may slightly change during the system operation. Nevertheless, the secondary control layer has by far slower dynamics compared to primary control layer, which indicates that the secondary control layer does not considerably impact the transient response of the primary controllers or transient voltage stability of the MG. Consequently, the advantages of the

<table>
<thead>
<tr>
<th>Index</th>
<th>FB (Case 1)</th>
<th>FB-MPC (Case 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISE</td>
<td>235 (V^2)</td>
<td>55.2 (V^2)</td>
</tr>
<tr>
<td>IAE</td>
<td>38.52 (V)</td>
<td>22.46 (V)</td>
</tr>
<tr>
<td>SAVC</td>
<td>0.80 (V)</td>
<td>0.38 (V)</td>
</tr>
</tbody>
</table>

**Table 10. Voltage quality indexes.**

**4.6 Discussion and Future Research Direction**

**4.6.1 The FB-MPC Method in Multiple-bus DC MGs**

The simulation results and small-signal stability analysis of this work demonstrates that the proposed FB-MPC approach improves the performance of the primary control layer of a single bus DC MG that contains a grid-forming HESS unit. Consequently, the MG voltage controller can regulate the MG DC bus voltage to its reference (i.e., v_{ref}) value with less transient voltage oscillations at rapid load changes. In this work, the reference voltage for the MG primary controller has a constant value which is exactly equal to the nominal voltage of the single bus DC MG. However, in multi-bus/multi-generation DC MGs, the reference voltages for the primary controllers are typically computed by the secondary control layer of the MG. In such systems, the secondary control layer adjusts the reference voltage of the grid-forming DERs to ensure proportional power sharing between them as well as restoring the steady state voltage of the MG (see the objectives of secondary control layer in Fig. 34). Consequently, reference voltages of the primary controllers may slightly change during the system operation. Nevertheless, the secondary control layer has by far slower dynamics compared to primary control layer, which indicates that the secondary control layer does not considerably impact the transient response of the primary controllers or transient voltage stability of the MG. Consequently, the advantages of the
The proposed FB-MPC method (i.e., improving the transient response of the primary control layer) will be still valid in a DC MG with multiple grid-forming DERs.

Moreover, due to very fast dynamic response of the primary control layer, typically, there is not any communication between primary controllers of grid-forming DERs in a multi-bus/multi-generation MG. In other words, based on the standard control structure of DC MGs [90], the primary controllers (i.e., convert controllers) just use their local information as well as a reference voltage that is adjusted by the secondary control layer. Consequently, the effective coordination (e.g., power sharing) between the DERs can be provided through the suitable actions of the secondary control layer which may have a centralized or a distributed control architecture. As discussed in section III, the proposed real-time FB-MPC system is located at the primary control layer of MG (i.e., converter controllers) and it does not need the information of other DERs (e.g., PV). Consequently, similar to the conventional control structure of DC MGs, the primary control layer of the HESS unit just requires its local information including the local DC bus voltage, and SC SoC variation. Therefore, the proposed FB-MPC is compatible with the conventional hierarchical control structure of DC MGs, so it can be easily extended into multi-bus/multi-generation systems.

Fig. 54 shows the suggested hierarchical control structure of a DC MG that contains multiple grid-forming DERs including a grid-forming HESS unit. In this structure, the grid-forming HESS utilizes the proposed FB-MPC current allocation system discussed in section 4.4. As seen, similar to the conventional hierarchical control structure of MGs [90],
the secondary controller selects the reference voltage of the primary controller of DERs including the grid-forming HESS (i.e., $V_{ref\ j}$) by adjusting the droop gains and adding a voltage restoration term for each DER (i.e., $\delta V_{j}$).

It should be noted that in multiple bus DC MGs, the line impedance (i.e., the impedance of the DC links between DERs) may slightly affect the marginal stability of the system as well as the choice of appropriate gains for PI voltage controllers. In addition, the number of grid-forming HESS units inside the MG, the topology of the DC MG, and types
of power electronic converters (e.g., boost, buck, buck-boost) can also alter the dynamic model of the system and slightly impact the marginal stability and transient response of the DC MG. Consequently, based on the application and the topology of the DC MG, developing a detailed dynamic model of the system and applying further stability analysis can be beneficial. Consequently, a future research direction of this work is to investigate the impact of the discussed parameters (e.g., the line-impedance, MG topology, and the number of grid-forming HESS units with FB-MPC method) on the dynamic stability of a DC MG with multiple DERs.

4.6.2 Active Damping of CPLs with Proposed FB-MPC Method

The stability analysis results of this work can be discussed from a different perspective. These results show that when the FB current assignment system and SC are activated, the DC MG has higher marginal stability in the presence of CPLs. In addition, increasing the time constant of the filter can improve the transient voltage stability of the DC MG. This means that the instability effect of the CPLs that typically requires active or passive stabilization techniques or more advanced voltage controllers, can be easily addressed by a grid-forming HESS unit in which the size of the filter is appropriately selected, and the continuous operation of SC and filter is guaranteed. Consequently, the other future research direction is to compare the performance of proposed FB-MPC technique with the existing active stabilizers in terms of stability improvement and cost-efficiency for different MG applications.

4.7 Conclusion

FB strategies are widely used in HESS applications to perform the power/current allocation between the BESS and SC. In these methods, typically, an LTI filter is utilized
that splits the HESS reference power/current into high-frequency and low-frequency components and then allocates the high-frequency parts to SC. This work firstly provides a small-signal stability analysis to investigate the impact of the HESS current assignment filter on the dynamic stability of a single bus DC MG in which a grid-forming HESS supplies a CPL. The stability analysis shows that the current assignment filter improves the marginal stability of the MG. So, the continuous operation of the SC and filter enables the MG PI voltage controller to operate higher gain values as well as tolerating higher communication delays. However, the conventional FB strategies cannot ensure the continuous operation of the SC and filter during the sudden load variations. To address this challenge, this work proposes an MPC-based SC SoC restoration technique that works in tandem with an LTI filter to perform the current allocation between the BESS and SC. In this method, the MPC controller maintains the SoC of SC in a predefined range, so that ensures the continuous operation of the SC and filter. As a result, the proposed approach indirectly improves the transient response and voltage quality of the system by enabling the MG voltage controller to work with higher gain values. The performance of the proposed FB-MPC method is then validated by simulating a case study DC MG in MATLAB/Simulink.
Chapter 5: Effective Utilization of Grid-forming Cloud Hybrid Energy Storage Systems in Islanded Clustered DC Nano-grids for Improving Transient Voltage Quality and Battery Lifetime

5.1 Motivation

The integration of renewable energy sources (RES) into isolated DC nano-grids presents significant challenges, particularly in ensuring system stability, maintaining voltage quality and improving the battery lifetime. To address these challenges, this chapter presents a novel battery-SC HESS technology based on a cloud HESS concept. The proposed technology optimizes the combination of local and community batteries and a central supercapacitor to enhance the performance of the system during sudden load or RES fluctuations. The chapter highlights how the proposed battery-SC HESS technology can reduce the required size of the SC compared to conventional distributed HESS architectures, which increases system efficiency and reduces the initial cost of the system.

The motivation for this chapter stems from the need to improve the stability and reliability of isolated DC nano-grids, which are essential in remote and rural areas where grid connection is not feasible. The proposed technology offers an effective solution that improves the transient stability, voltage quality, and battery lifetime of these isolated DC nano-grids, thereby enhancing the efficiency and lifetime of the system. Additionally, the proposed cloud HESS technology, which includes an energy management system and grid-forming power electronic converter, provides an effective coordination between local BESSs and the community SC, thereby enhancing the dynamic response of the voltage control system in all DC nano-grids. The chapter's findings demonstrate the effectiveness
of the proposed battery-SC HESS technology in improving the performance of the system, which can be applied in various isolated DC nano-grid systems, including remote and rural areas.

5.2 Introduction

Microgrids (MGs) are self-sufficient distributed energy systems that can improve the performance of traditional power systems by increasing consumer participation, renewable energy sources (RESs) penetration, power system stability, and grid resiliency [90,91]. Recently, DC MGs have gained a significant attention due to their various benefits compared to AC MGs [92]. These benefits include less power conversion losses, no reactive power issues, no frequency synchronization requirement, and simpler integration with energy storage systems (ESSs). Therefore, DC MGs are considered as viable solutions for applications in which there is no access to the utility grid such as remote rural electrification, shipboard power systems or space crafts. In such applications (i.e., islanded DC MGs), the reliability and flexibility of the system are of vital importance due to the lack of utility grid support [93]. Consequently, the deployment of advanced energy storage systems, as well as modular MG architectures are highly desirable in islanded MG applications [94].

Designing DC MGs by interconnecting multiple nano-grids (MNGs) enhances the modularity of MGs, thereby providing higher flexibility, resiliency, and reliability [8,95]. A nano-grid (NG) is basically a small-scale microgrid that consists of local power generation and consumption units. In addition, NGs have the ability to connect or disconnect from the upstream power distribution system (e.g., the MG DC bus) through a gateway (GW) module [12,24]. Fig. 55 compares the structure of an islanded MNG system
with a conventional single-layer DC MG. As seen, in DC MNG architectures, if a fault occurs on the MG DC bus, the NGs can disconnect from the MG DC bus and continue to work independently to supply their local loads signifying the higher reliability and flexibility of the MNG systems [96].

When DC NGs are supplied by RESs, they can be affected by energy fluctuations and uncertainties, which can be only alleviated by utilizing ESSs to guarantee an uninterruptible power supply to the critical loads and to maintain the power balance in the system [11,97]. Battery energy storage systems (BESSs) are the most common and economical energy storage devices in DC MG applications because of their high energy density and relatively low costs. During the islanded mode of the DC MGs, the BESSs operate as the grid-forming units to control the voltage and stability of the system. Similarly, in islanded DC MNGs, BESSs are connected to the NG local DC buses through bidirectional power electronic converters (e.g., a boost converter) and operate as local grid-forming units to regulate the NG DC bus voltage as well as keeping the balance between power generation and loads. At the same time, the voltage of the MG common DC bus is
usually regulated either using the GW modules of the NGs through a decentralized, centralized, or distributed control algorithm or it can be controlled by a community BESS which is connected to the MG DC link [1]. However, the grid-forming BESS units may provide poor transient responses (e.g., high transient voltage deviations) during sudden load changes (e.g., pulsed power loads) due to their low power density. In addition, BESS units have a limited life cycle. Thus, the instantaneous renewable power fluctuations may gradually degrade the BESSs and reduce their lifetime [50].

To address these issues, hybrid energy storage systems (HESSs) can be applied in which a supercapacitor (SC) is utilized in tandem with a BESS to absorb the instantaneous and rapid power fluctuations, thereby smoothing the output power or current of the BESS and improve the transient response of the voltage control system [2,98]. Compared to the BESSs, SCs have higher power density, so they can release/absorb more energy in a noticeably shorter time. Moreover, SCs have a significantly higher life cycle compared to the BESSs. Thus, instantaneous power fluctuation does not impact their lifetime. Additionally, proper utilization of a HESS with parallel active topology as the local grid-forming unit of the MG can provide higher marginal voltage stability and better voltage quality compared to a single BESS unit [3]. To this end, in grid-forming HESS technologies, usually a filtration-based (FB) current allocation system is utilized in the feedback control loop of the BESS and SC power electronic converters which assigns the high-frequency current variations to the SC and low-frequency parts to the BESS. The bandwidth of this filter is also selected based on the energy storage capacity of the SC and required power smoothing level for the BESS [15]. In conclusion, an effective hybridization of a BESS with a SC promotes the stability and voltage quality of the MG as
well as enhances the lifetime of the BESSs. However, utilization of a HESS in each DC NG (i.e., distributed HESS technologies) complicates the dynamic EMS structure of the NGs due to the very low energy density of SCs [45,47]. In addition, implementing a local HESS at each DC NG (i.e., the distributed HESS architecture) can considerably increase the initial cost of the MNG system.

Deployment of a cloud/community energy storage system (CESS) in MGs is an efficient way to reduce the initial cost of the system and diminish the complexity of the MG control system, especially for residential applications [99,100]. In these methods, the CESS is shared among the community members who are typically located in its close vicinity. Some noticeable benefits of CESSs recognized in the literature are economic scaling of batteries as well as lessening shortage likelihood during the peak demand compared to the distributed ESS technologies [101]. In islanded DC MNG applications, a community/cloud battery energy storage system (CBESS) can be utilized as the CESS unit of the MG [102]. In this architecture, the CBESS operates as the master (i.e., grid-forming) unit to control voltage and power balance at the MG DC bus. On the other hand, the NGs (i.e., their GW modules) operate as the grid-following units to provide optimal and reliable power sharing among different NGs. The CBESS technology in islanded MNG systems can provide additional energy/power support for the local and community loads which in turn eliminates the necessity of utilizing bulky local BESSs at NGs. However, the CBESS technologies still suffer from the intrinsic limitations of the BESSs including the poor transient response and limited life-cycle.

To address the discussed challenges, this work proposes the idea of utilizing a community/cloud SC at the MG common DC bus that works in tandem with the CBESS
of the MNG system. This combination forms a cloud hybrid energy storage system (CHESS) in which the CBESS is responsible for long-term energy storage and steady-state power balancing while the community/cloud SC supplies the high-frequency power fluctuations to lessen the stress on the CBESS and improve the voltage quality and transient...
response of the system at all the NG local DC buses along with the MG DC bus. Fig. 56 shows the structure of a DC MNG containing the proposed CHESS architecture with DC MNGs that use the conventional CBESS and distributed HESSs architectures. As seen, instead of utilizing a local HESS at each DC NG (i.e., distributed HESS technology), this work suggests utilizing the aforementioned CHESS architecture. This technology may enhance the voltage quality and lifetime of all the local BESS units as well as the CBESS given that an effective coordination between local BESSs and the CBESS unit with the community/cloud SC is provided. Though, the effective implementation of this idea (proposed CHESS method) is not feasible using the conventional control structure of DC NGs. The reason is that the effective dynamic coordination between the community SC and the local BESSs cannot be provided with these techniques. Therefore, it is essential to reconfigure the control structure of the DC NGs, so that the desired coordination between the local BESS units and the community SC is provided. In this regard, the contributions of this work are provided as follows:

- This work proposes and develops the idea of implementing a community/cloud SC that works in tandem with a CBESS (i.e., the grid-forming CHESS technology) to enhance the voltage quality and expand the lifetime of the batteries in an islanded DC MNG system.

- This work proposes a modified control scheme for DC NGs that allows an implicit coordination between the community SC and the local BESSs of all the NGs.

- It provides a power smoothing analysis in the DC MNG system which indicates that the proposed CHESS and control strategy can enhance the lifetime of all the local BESS units along with the CBESS by smoothing their output power while maintaining the
power balance between generation and load.

- It formulates the detailed state-space dynamic model of the DC NGs to compare the small-signal voltage stability of the NGs under the proposed control structure with the conventional control method. The small-signal stability analysis shows that the proposed modified control scheme can enhance the marginal voltage stability of DC NGs. Therefore, the voltage controllers of local DC buses can operate with larger gain values which in turn improves the transient voltage quality of the DC NGs.

- It shows that the proposed CHESS technology requires a considerably lower size of the SC and a fewer number of active components (i.e., power electronic converters) compared to an equivalent distributed HESS technology. Hence, the proposed approach can considerably reduce the initial costs of the system.

The rest of this chapter is organized as follows: Section 5.3 overviews the case-study system and introduces the proposed modified control scheme. Section 5.4 proposes a power smoothing analysis to investigate the benefits of the community SC and the modified control scheme in reducing the output power fluctuations of batteries. Section 5.5 develops the state space dynamic model of DC NGs and compares the marginal voltage stability of the system in both conventional and modified control schemes. Section 5.6 discusses the efficiency of the proposed CHESS in terms of the required converters, SC size, and power losses compared to its equivalent distributed HESS architecture. Section 5.7 verifies the results of this work using computer simulations and Section 5.8 discusses the future research direction and application of this work and section 5.9 concludes the chapter.
5.3 System Overview

5.3.1 MNG Architecture

Fig. 57 shows the architecture of the case study MNG system that utilizes a CHESS as the master unit. Therefore, the CHESS is responsible for regulating the MG DC bus voltage. Also, the GW modules of the NGs operate as grid-following units to provide optimal power sharing and energy management inside the MNG system. In addition, the MNG system contains a community constant power load (CPL) that is directly connected to the MG DC bus, and it is supplied by the CHESS and NGs. The case study DC NGs also contain a local BESS unit, a PV system, a group of AC and DC CPLs, and a resistive load. In the DC NGs, the local BESS units operate as the local grid-forming units, and they are responsible for regulating the NG local DC bus voltage and maintaining the power balance at their local DC buses.
5.3.2 Control Structure

5.3.2.1 MG Common DC Bus Control: Fig. 58 shows the circuit model and control structure of the MG DC bus. As seen, the CHESS is responsible for voltage regulation and maintaining the power balance at MG DC bus (i.e., the master or grid-forming unit). To this end, a proportional-integral (PI) voltage controller computes a reference current trajectory for the CHESS unit to regulate the MG DC bus voltage. This reference current is sent to a filtration-based model predictive control (FB-MPC) power/current allocation
system which is adopted from the previous work of the authors in [3]. The FB-MPC current allocation sends the high-frequency current variations to the community SC and assigns the low-frequency parts to the CBESS, so that guarantees the continuous operation of the community SC. The community load converter also operates as a CPL and its output current is obtained as

\[ i_{com}^{CPL} = \frac{P_{com}^{CPL}}{v_{MG}} \]  

(5.1)

where \( P_{com}^{CPL} \) is the demanded power by the community load and \( v_{MG} \) denotes the terminal voltage of the CHESS and CPL converters at the MG side. The GW modules of the NGs operate as grid-following units and \( i_{NGi} \) shows the amount of current that NGi sends out to the MG DC bus. \( P_{ex}^{i} \) is also the output power that NGi should transfer to the MG DC bus to ensure optimal (economical) steady-state energy management of the MNG system. This optimal value is calculated by the EMS of the MNG system using an online optimization-based algorithm which is proposed in [14]. \( v_{MGi} \) is also the terminal voltage of the GW converters at the MG side.

The previous work of authors in [3] shows that the utilization of the FB-MPC current allocation system in a grid-forming HESS unit can considerably improve the voltage quality and voltage stability of a single-bus DC MG. Assuming that DC NGs are in close vicinity of each other, the transmission loss between NGs will be negligible. Therefore, \( R_i = 0 \) and \( \forall i \in \{1,...,n\} \), \( v_{MGi} = v_{MG} \). In this regard, the MG DC bus voltage will have the same dynamic model as the case study single-bus DC MG in [3]. Thus, the stability analysis results of [3] will be also applicable to the MG DC bus of the case-study.
MNG system. This means that the CHESS unit can enhance the voltage quality and transient voltage quality of the MG DC bus using the proposed FB-MPC method proposed in [3]. However, to expand the advantage of utilizing the community SC in improving the marginal voltage stability at local DC buses (i.e., NG DC buses) and increasing the lifetime of local BESSs, the control structure of the local DC buses should be modified. Therefore, the rest of this section proposes and analyses a modified control scheme for DC NGs.

5.3.2.2 NG DC Bus Control: Fig. 59 shows the control structure and circuit model of the DC NGs whereas Fig. 59(a) illustrates the conventional control structure of DC NGs and Fig. 59(b) depicts the proposed modified control scheme. As seen, the local resistive load is represented by a parallel resistance (i.e., $R_L$), and the local CPL is shown by a current source. In addition, the PV is in maximum power point tracking (MPPT), and it operates as a grid-following unit (i.e., a CPS). Also, the GW converter operates in power/current control mode to regulate the output power/current of the NG.

Moreover, the local BESS of each NG is responsible for voltage regulation and power balance at the NG’s local DC bus. In the conventional control structure, the reference current trajectory computed by the NG PI voltage controller (i.e., $I_{ref}$) is directly sent to the current control system of the local BESS unit to regulate the MG DC bus voltage. This reference current may have high-frequency variations which can generate large current ripples on the local BESSs. In addition, it may generate large transient voltage deviations (i.e., voltage sags) at sudden load changes due to the relatively slow response of
the BESS. On the other hand, in the proposed modified control scheme (see Fig. 59(b)), the BESS control system performs two modes of operation based on the connection status of the NG (i.e., $S$). When the DC NG is isolated, the BESS control system is exactly...
similar to the discussed conventional control structure of DC NGs. However, when the DC in connected to the MG DC bus (i.e., \( S = 1 \)), instead of directly sending \( i_{\text{ref}} \) to BESS current control system, \( i_{\text{ref}} \) firstly passes through a low passes filter (LPF), then its low-frequency components will be assigned to the BESS. Simultaneously, the remaining high-frequency part of \( i_{\text{ref}} \) is subtracted from the reference current of the GW. Consequently, the BESS output current is flattened, and the high-frequency current variations generated by RESs, or local loads will be transferred to the MG DC bus. It will be discussed in Section 5.4, that the proposed modified control scheme of the NGs also improves the marginal stability of the NG voltage control system. Hence, when the NG is connected to the MG DC bus, the NG voltage controller can operate with larger gain values which results in faster response and better voltage quality (i.e., less voltage sags). Consequently, the NG PI voltage controller will operate with higher gain values when connected to the MG DC bus.

5.4 Power Smoothing Analysis

This section investigates the transient power allocation among different ESSs inside the MNG system to analytically confirm that the community SC of the CHESS unit absorbs the high-frequency (or zero-energy) power variations generated by the RESs and loads given that the bandwidths of current allocations filters are defined properly in the proposed control structure. In another word, the following power allocation analysis (in frequency-domain) is applied to show that how the energy storage capacity of the community SC is shared among different NGs and the community load as well as discussing how to design the power smoothing filters to achieve the desirable performance of the system.
5.4.1 NG Local DC buses

Consider a DC NG (i.e., NG\textsubscript{i}) and define the NG net power (i.e., \( P\text{\textsubscript{net}}\textsubscript{i} \)) as

\[
P\text{\textsubscript{net}}\textsubscript{i} = P\text{\textsubscript{CPL}}\textsubscript{i} + P\text{\textsubscript{RL}}\textsubscript{i} - P\text{\textsubscript{PV}}\textsubscript{i} + P\text{\textsubscript{loss}}\textsubscript{i}
\]  

(5.2)

where \( P\text{\textsubscript{CPL}}\textsubscript{i} \) is the demanded power by the local CPLs, \( P\text{\textsubscript{RL}}\textsubscript{i} \) is the demanded power by the local resistive loads, \( P\text{\textsubscript{Loss}}\textsubscript{i} \) is the local power conversion losses, and \( P\text{\textsubscript{PV}}\textsubscript{i} \) is the local PV power generation at NG\textsubscript{i}. As seen in Fig. 55, the BESS is the local grid-forming unit of the NG, so it is in control to maintain the voltage stability and power balance of the NG DC bus. To this end, it should absorb all the net power (i.e., \( P\text{\textsubscript{net}}\textsubscript{i} \)) as well as support the output power of GW. Therefore, the output power of the local grid-forming unit (i.e., the BESS) should satisfy the following condition.

\[
P\text{\textsubscript{bat}}\textsubscript{i} = P\text{\textsubscript{net}}\textsubscript{i} + P\text{\textsubscript{GW}}\textsubscript{i}
\]  

(5.3)

where \( P\text{\textsubscript{bat}}\textsubscript{i} \) shows the output power of the BESS at NG\textsubscript{i} and \( P\text{\textsubscript{GW}}\textsubscript{i} \) is the power that is transferred to the upstream grid (i.e., MG DC bus) through the GW converter. As seen in Fig. 58, in the conventional control structure of the NGs, the GW converter is in power/current control mode, and its reference power/current trajectory is determined by the energy management system (EMS) of the MNG system using an optimization algorithm [14]. In this case, the output power of the GW is obtained as

\[
P\text{\textsubscript{GW}}\textsubscript{i} = P\text{\textsubscript{ex}}\textsubscript{i}
\]  

(5.4)
where $P_{\text{ex}}^i$ denotes the power exchange between the NG$_i$ and the MG DC bus determined by the EMS of the MNG system. So, based on (5.3), to maintain the power balance, the output power of the BESS is calculated as

$$P_{\text{bat}}^i = P_{\text{net}}^i + P_{\text{ex}}^i$$  \hspace{1cm} (5.5)

Due to high response time (i.e., slow response) of the EMS, $P_{\text{ex}}^i$ changes slowly. However, the $P_{\text{net}}^i$ may have high-frequency variations because of the instantaneous changes of the PV or load power. These high-frequency components of $P_{\text{net}}^i$ usually provide zero steady-state energy but they can degrade the local BESS of the NG by imposing frequent current/power ripples to the BESS.

To deal with this problem, the proposed control scheme, utilizes an LPF to smooth out the reference current of the BESS. As a result, this filter decomposes the $P_{\text{net}}^i$ into high-frequency and low-frequency components and assigns the low-frequency parts to the BESS. Because the terminal voltage of the battery is approximately unchanged during the short-term operation, the LPF filters the output power and current of the BESS with the same bandwidth. The transfer function of this filter (i.e., $H_{\text{LPF}}$) is defined in the Laplace form as

$$H_{\text{LPF}}(s) = \frac{1}{\tau_i s + 1}$$  \hspace{1cm} (5.6)

where $\tau_i$ is the time constant of power/current decomposition LPF. Therefore, under the proposed control strategy, the output power of the local BESS of the NG$_i$ is obtained in Laplace form as
\[ P_{bat}^i(s) = H_{LPF}(s)\left(P_{net}^i(s) + P_{ex}^i(s)\right) \]
\[ = H_{LPF}(s)P_{net}^i(s) + H_{LPF}(s)P_{ex}^i(s) \]  \(5.7\)

On the other hand, due to the very slow variation of \( P_{ex}^i \), \( H_{LPF}(s)P_{ex}^i(s) \approx P_{ex}^i(s) \). So, (5.7) can be reformulated as

\[ P_{bat}^i(s) \approx H_{LPF}(s)P_{net}^i(s) + P_{ex}^i(s) \]  \(5.8\)

Moreover, the GW output power is obtained as

\[ P_{GW}^i(s) = P_{ex}^i(s) - (1 - H_{LPF}(s))\left(P_{net}^i(s) + P_{ex}^i(s)\right) \]  \(5.9\)

Realizing \( H_{LPF}(s)P_{ex}^i(s) = P_{ex}^i(s) \), (9) is reformulated as

\[ P_{GW}^i \approx P_{ex}^i(s) - (1 - H_{LPF}(s))P_{net}^i(s) \]  \(5.10\)

Consequently, under the proposed approach, the local BESS units only absorb the low-frequency variation of the net power and the high-frequency power variations are transferred to the upstream grid (i.e., the MG DC bus) through the GW module of the NGs, which increases the lifetime of the local BESS units.

### 5.4.2 MG Common DC bus

The CHESS operates as the master (or grid-forming) unit at MG DC bus. So, it is responsible for voltage regulation as well as maintaining the power balance at MG DC bus. To this end, the output power of the CBESS and the community SC should satisfy the following condition:

\[ P_{CBESS} + P_{SC} = P_{net}^{MG} \]  \(11\)
where $P_{\text{CBESS}}$ and $P_{\text{sc}}$ represent the output power of the CBESS and community SC, respectively. Also, $P_{\text{net}}^{MG}$ is the MG net power and it is defined as:

$$P_{\text{net}}^{MG} = - \sum_{i=1}^{n} P_{GW}^i + P_{\text{com}}^{cpl} + P_{\text{loss}}^{MG} \quad (5.12)$$

$P_{\text{com}}^{cpl}$ is the demanded power by the community load and $P_{\text{loss}}^{MG}$ is the power loss at MG DC link and GW converters. As seen in Fig. 59, the CHESS uses an HPF to perform the power/current assignment between the CBESS and community SC. The HPF has the following transfer function

$$H_{\text{HPF}}(s) = \frac{\tau_2 s}{\tau_2 s + 1} \quad (5.13)$$

where $\tau_2$ is the time constant of the HPF. Based on the proposed power/current assignment in [16], the output power of the CBESS and SC are obtained in Laplace form as

$$\begin{align*}
P_{\text{CBESS}}(s) &= \left(1 - H_{\text{HPF}}(s)\right) P_{\text{net}}^{MG}(s) - P_{MPC}(s) \\
P_{\text{sc}}(s) &= H_{\text{HPF}}(s) P_{\text{net}}^{MG}(s) + P_{MPC}(s)
\end{align*} \quad (5.14)$$

where $P_{MPC}$ is the compensation power that is applied when an SC SoC violation is predicted by the MPC compensator to avoid discontinuous operation of the SC [3]. Considering the SC is efficiently sized, $P_{MPC}$ is just applied when there is a sudden loss of a major load or sudden source disconnection. So, during the normal operating mode of the system $P_{MPC} = 0$.

In this regard, assuming the system is in normal condition, based on (5.9) to (5.14), the output power of the CBESS can be calculated in the Laplace form as:
\[ P_{\text{CBESS}}(s) = (1 - H_{\text{HPF}}(s))\left(P_{\text{CPL}}^{\text{com}}(s) + P_{\text{loss}}^{\text{MG}}(s)\right) + \sum_{i=1}^{n} (1 - H_{\text{HPF}}(s))(1 - H_{\text{LPF}}(s))P'_{\text{net}}(s) \]

\[ - \sum_{i=1}^{n} (1 - H_{\text{HPF}}(s))P'_{\text{ex}}(s) \]  

(5.15)

Then, if \( \tau_2 \gg \tau_1 \), one can obtain that \( \forall i \in \{1, \ldots, n\} \), \((1 - H_{\text{HPF}}(s))(1 - H_{\text{LPF}}(s))P'_{\text{net}}(s) = 0 \). Moreover, because of the very slow alterations of \( P'_{\text{ex}} \), one can obtain \( (1 - H_{\text{HPF}}(s))P'_{\text{ex}}(s) = P'_{\text{ex}}(s) \). Therefore, the equation (5.15) can be reformulated as

\[ P_{\text{CBESS}}(s) = (1 - H_{\text{HPF}}(s))\left(P_{\text{CPL}}^{\text{com}}(s) + P_{\text{loss}}^{\text{MG}}(s)\right) - \sum_{i=1}^{n} P'_{\text{ex}}(s) \]  

(5.16)

Also, the output power of the community SC is obtained as

\[ P_{\text{SC}}(s) = \sum_{i=1}^{n} (1 - H_{\text{LPF}}(s))P'_{\text{net}}(s) \]

\[ + H_{\text{HPF}}(s)\left(P_{\text{CPL}}^{\text{com}}(s) + P_{\text{loss}}^{\text{MG}}(s)\right) \]  

(5.17)

Equations (5.16) and (5.17) clearly indicate that the community SC will absorb the high-frequency power components generated by the rapid changes of all the local and community loads as well as the instantaneous power fluctuations of all the RESs (i.e., PVs) given that \( \tau_2 \gg \tau_1 \). In another word, if \( \tau_2 \gg \tau_1 \), the energy storage capacity of the community SC will be shared with all the NGs, and the community loads to absorb the high-frequency power fluctuations created by RESs or loads. It should be noted that if the condition \( \tau_2 \gg \tau_1 \) is not satisfied, then \((1 - H_{\text{HPF}}(s))(1 - H_{\text{LPF}}(s))P'_{\text{net}}(s) \neq 0 \) indicating that some of high-frequency power fluctuations will be absorbed by the CBESS thereby deteriorating the performance of the CHESS unit.
In conclusion, if the time constant of the HPF used for current sharing between SC and CBESS is defined considerably larger (e.g., 5 to 10 times) than the time constant of the LPF utilized for current allocation between GW and local BESSs (see Fig. 5(b)) (i.e., $\tau_2 \gg \tau_1$), the community SC will not only smooth out the output power of the CBESS, but also will implicitly coordinate with all the local BESSs to smooth the output power of all of them which highlights the advantage of this method compared to the conventional control strategy of MNGs. In another word, if $\tau_2 \gg \tau_1$, the proposed control and dynamic power sharing system can guarantee the power smoothing of all the BESSs and the CBESS inside the MNG system by just employing a single SC located at the common DC link (i.e., the community SC).

5.5 Stability Analysis

This section analyzes the impact of the proposed control scheme on the marginal voltage stability of DC NGs. To this end, the small-signal stabilities of the DC NGs in both conventional and modified control schemes are compared based on the time-delay eigenvalue analysis of the linearized system.

It should be mentioned that the impact of utilizing the FB-MPC current assignment (see Fig. 5) in marginal stability of the MG DC bus is discussed in the previous work of authors in [3]. That work shows that utilization of the FB-MPC current assignment can improve the marginal voltage stability of the MG DC bus and enhance the transient voltage quality during sudden load changes. Assuming the transmission line loss is negligible (i.e., $R_t = 0$), the MG DC bus of the MNG system will have the same dynamic model compared to the case-study DC MG in [3]. Therefore, the stability analysis results provided in [3] are also applicable to the MG DC bus in the case-study MNG system.
5.5.1 Dynamic Modelling

This section develops the state-space dynamic model of the DC NGs. To this end, based on the circuit model of the NGs shown in Fig. 58, the averaged dynamic model of the open-loop system is obtained as

\[
\begin{align*}
L_1 \frac{di_{11}}{dt} &= -R_1i_{11} - v_{NG}(1-d_1) + v_{bat} \\
L_1 \frac{di_{12}}{dt} &= -R_2i_{12} + v_{NG} - v_{MG}(1-d_2) \\
C_{bus} \frac{dv_{NG}}{dt} &= i_{11}(1-d_1) - i_{12} - \frac{(P_{CPL} - P_{PV})}{v_{NG}} - \frac{v_{MG}}{R_L}
\end{align*}
\]

(5.18)

where, \(i_{11}\) and \(i_{12}\) are the inductor currents of the BESS and GW converters. Also, \(v_{NG}\) shows the NG DC bus voltage and \(v_{MG}\) represents the MG DC bus voltage. In addition, \(R_i, L_i, i \in \{1, 2\}\) represent the resistance and inductance of the power electronic converters and \(C_{bus}\) is equivalent capacitance of the NG DC bus. \(d_1\) and \(d_2\) also represent the duty cycle of the power electronic converters which are obtained as

\[
\begin{align*}
d_1 &= K_{p1}(i_{ref}^{Bat} - i_{L1}) + K_{i1}(e_{int1}) \\
d_2 &= K_{p2}(i_{ref}^{GW} - i_{L2}) + K_{i2}(e_{int2})
\end{align*}
\]

(5.19)

where \(K_{p1}\) and \(K_{p2}\) are the proportional gains of the PI current regulators of the BESS and GW. Also, \(K_{i1}\) and \(K_{i2}\) are integral gains of the current controllers. \(i_{ref}^{Bat}\) and \(i_{ref}^{GW}\) are the reference currents of the BESS and GW modules. \(e_{int1}\) and \(e_{int2}\) represent the integral of the errors and defined as

\[
\begin{align*}
e_{int1} &= \int (i_{ref}^{Bat} - i_{L1})\,dt \\
e_{int2} &= \int (i_{ref}^{GW} - i_{L2})\,dt
\end{align*}
\]

(5.20)
In the conventional control scheme of DC NGs (see Fig. 59(a)), the reference currents of the BESS and GW are obtained as

\[
\begin{align*}
    i_{\text{ref}}^\text{bat} &= i_{\text{ref}} \\
    i_{\text{ref}}^{\text{GW}} &= \frac{P_{\text{ex}}^i}{V_{\text{NG}}} \\
\end{align*}
\]  

(5.21)

On the other hand, in the proposed modified scheme, by considering dynamic model of the LPF in (6), the reference current of the BESS and GW are obtained as

\[
\begin{align*}
    \tau_i \frac{d i_{LPF}}{dt} &= -i_{LPF}^i + i_{\text{ref}} \\
    i_{\text{ref}}^\text{bat} &= i_{LPF} \\
    i_{\text{ref}}^{\text{GW}} &= i_{LPF} - i_{\text{ref}} + \frac{P_{\text{ex}}^i}{V_{\text{NG}}} \\
\end{align*}
\]  

(5.22)

where \( P_{\text{ex}}^i \) is the amount of power exchange between the NG and MG DC bus. Additionally, \( i_{LPF} \) shows the output current of the LPF. Equation (5.22) also shows that if \( \tau_i \rightarrow 0 \) (i.e., the filter becomes deactivated), the reference currents of the BESS and GW will converge to the reference current values in the conventional control strategy of DC NGs shown in (5.21). So, if \( \tau_i = 0 \), the dynamic model of the system under the proposed approach will be similar to the conventional control strategy of DC NGs. Moreover, \( i_{\text{ref}}^\text{int} \) is the reference current computed PI voltage controller and it is obtained as

\[
\begin{align*}
    i_{\text{ref}} &= K_v (v_{\text{NG}}^* - \hat{v}_{\text{NG}}) + K_i e_{\text{int} v} \\
    e_{\text{int} v} &= \int (v_{\text{NG}}^* - \hat{v}_{\text{NG}}) dt \\
\end{align*}
\]  

(5.23)
where \( K_{Pv} \) and \( K_i \) are the proportional and integral gains of the PI voltage controller and \( e_{intv} \) shows the integral of the error. \( v_{ng}^* \) denotes the nominal voltage of the DC NG. \( \hat{v}_{NG} \) is the measures voltage of the NG DC bus. Assuming that the measurement has \( \tau_i \) communication time delay, and using a first order Padé approximation of the delay [87], \( \hat{v}_{NG} \) can be obtained as:

\[
\begin{align*}
\frac{1}{2 \tau} \frac{dx_d}{dt} &= -x_d + v_{NG} \\
\hat{v}_{NG} &= 2x_d - v_{NG}
\end{align*}
\]  

(5.24)

where \( v_{NG} \) the voltage of the NG DC bus and \( x_d \) is the delay state. Consequently, by considering (5.18) to (5.24), the nonlinear state-space equation of the closed-loop system can be obtained in the following form.

\[
\dot{x} = f(x,u,w)
\]  

(5.25)

where \( x \) is the set of system states, \( u \) is the set of controlled inputs, \( w \) is the set of measured (or known) disturbances, and \( f \) is a set of vector fields that show the evolution of states. Hence, by defining \( w = [P_{PV}, P_{CPL}, v_{MGi}, v_{hat}]^T \) \( u = v_{NG}^* \) and \( x = [I_{L1}, I_{L2}, v_{NG}, i_{LPF}, x_d, e_{int1}, e_{int2}, e_{intv}]^T \), the nonlinear dynamic model of the closed-loop system in the proposed modified control strategy of DC NGs is formulated as (5.26). Similarly, the dynamic model of the DC NG in conventional control structure of DC NGs can be obtained by assuming \( \tau_i = 0 \) and \( i_{LPF} = i_{ref} \) (See (5.21) and (5.22)).
\[
\begin{bmatrix}
\frac{di_{L1}}{dt} \\
\frac{di_{L2}}{dt} \\
\frac{dv_{NG}}{dt} \\
\frac{di_{LPF}}{dt} \\
\frac{dx_d}{dt} \\
\frac{de_{int1}}{dt} \\
\frac{de_{int2}}{dt} \\
\frac{de_{intv}}{dt}
\end{bmatrix}
= 
\begin{bmatrix}
\frac{R_i}{L_i} i_{L1} - \frac{1}{L_i} v_{NG} + \frac{K_{pl}}{L_i} v_{NG} i_{LPF} + \frac{1}{L_i} v_{bus} \\
\frac{R_2}{L_2} i_{L2} - \frac{K_{p2}}{L_2} v_{MG} i_{L2} + \frac{K_{p2}}{L_2} v_{MG} i_{LPF} \\
\frac{1}{C_{bus}} i_{L1} - \frac{K_{pl}}{C_{bus}} i_{L1} i_{LPF} + \frac{K_{pl}}{C_{bus}} i_{L1}^2 - \frac{K_{pl}}{C_{bus}} i_{L1} e_{int1} \\
\frac{1}{C_{bus}} i_{L2} - \frac{1}{R_{c} C_{bus}} v_{NG} - \frac{P_{CPL} - P_{PY}}{C_{bus}} \frac{1}{C_{bus}} v_{NG} \\
-\frac{1}{\tau_1} i_{LPF} + \frac{K_{pv}}{\tau_1} v_{NG} - \frac{2}{\tau_1} x_d + \frac{K_{pv}}{\tau_1} v_{NG} + \frac{K_{pv}}{\tau_1} e_{intv} \\
-\frac{2}{\tau_d} x_d + \frac{2}{\tau_d} v_{NG} \\
i_{LPF} - i_{L1} \\
i_{LPF} - K_{pv} v_{NG}^* + 2K_{pv} x_d - K_{pv} v_{NG} - K_{pv} e_{intv} + \frac{P_{PV}^v}{v_{NG}} - i_{L2} \\
v_{NG} - (2x_d - v_{NG})
\end{bmatrix}
\]
5.5.2 Eigenvalue Analysis

This section evaluates the marginal voltage stability of DC NGs under the proposed modified control scheme and compares it with the conventional control structure of DC NGs. To this end, the small-signal stability of the DC NGs is assessed by analyzing the eigen-values of the linearized systems. The mathematical proofs and theorems related to the time-delay eigen-value analysis are discussed with details in [87,88]. The selection of this method can be justified due to the high complexity of the NGs’ nonlinear model.

Firstly, let consider the nonlinear state-space dynamic model of the DC NGs in (5.25) and (5.26). The equilibrium points of the system (i.e., (, , )) can be obtained as

\[ \hat{x} = 0 \iff f(\bar{x}, \bar{u}, \bar{w}) = 0 \]  \hspace{1cm} (5.27)

Next, by employing a first order Taylor series expansion of \( f \), and defining \( \Delta x = x - \bar{x} \), \( \Delta u = u - \bar{u} \), and \( \Delta w = w - \bar{w} \) one can obtain:

\[ \Delta \dot{x} = \dot{x} - \bar{x} = f(x, u, w) = A_{|x, u, w|} x + B_{|x, u, w|} u + D_{|x, u, w|} w \]  \hspace{1cm} (5.28)

where \( A, B, \) and \( D \) are defined as

\[ A_{|x, u, w|} = \left. \frac{\delta f(x, u, w)}{\delta x} \right|_{(x, u, w)} \]  \hspace{1cm} (5.29)

\[ B_{|x, u, w|} = \left. \frac{\delta f(x, u, w)}{\delta u} \right|_{(x, u, w)} \]  \hspace{1cm} (5.30)

\[ D_{|x, u, w|} = \left. \frac{\delta f(x, u, w)}{\delta w} \right|_{(x, u, w)} \]  \hspace{1cm} (5.31)
Thus, to find the closed-loop poles of the linearized system at each operating point, it is required to determine the eigen-values of the Jacobian matrix (i.e., $A$), that is obtained as

$$\text{Eig}(A) = \{ \lambda | \text{det}(\lambda I - A) = 0 \}$$  \hspace{1cm} (5.32)

Fig. 60 to Fig. 63 compare the transient voltage stability of the DC NG under the proposed modified control scheme with the conventional control technique. The circuit parameters of the case-study DC NG are illustrated in Table 11.

As seen in Fig. 60, the closed-loop poles of the system are highly sensitive to the proportional gain of the PI voltage controller (i.e., $K_v$), and by increasing $K_v$, the closed-loop poles of the system move to the unstable region in both conventional and the proposed approach. However, the DC NG can remain stable for considerably larger gain values (i.e., approximately nine-times larger value of $K_v$) in the proposed modified control approach.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{NG}$</td>
<td>Nominal voltage of the NG DC bus</td>
<td>100V</td>
</tr>
<tr>
<td>$V_{MGi}$</td>
<td>Voltage of the MG DC bus</td>
<td>750V</td>
</tr>
<tr>
<td>$C_{bus}$</td>
<td>Capacitance of the NG DC bus</td>
<td>800μF</td>
</tr>
<tr>
<td>$R_L$</td>
<td>Resistive Load</td>
<td>10Ω</td>
</tr>
<tr>
<td>$L_1, L_2$</td>
<td>Inductance of the GW and BESS power electronic converters</td>
<td>400μH</td>
</tr>
<tr>
<td>$R_1, R_2$</td>
<td>Resistance of the GW and BESS power electronic converter</td>
<td>1mΩ</td>
</tr>
<tr>
<td>$K_{p1}, K_{p2}$</td>
<td>Proportional Gains of the GW and BESS current controllers</td>
<td>400</td>
</tr>
<tr>
<td>$K_{I1}, K_{I2}$</td>
<td>Integral Gains of the GW and BESS current controllers</td>
<td>600</td>
</tr>
</tbody>
</table>
that shows marginal voltage stability improvement of the DC NG. Fig. 61 also depicts the dominant closed-loop poles of the system with respect to the $K_p$ changes. As seen, the dominant poles of the system are not very sensitive to $K_p$ changes. In addition, in the conventional control strategy, the DC NG is destabilized for $K_p > 127$. However, under the proposed approach, the DC bus voltage can remain stable for significantly larger values of $K_p$. Fig. 62 illustrates the dominant poles of the closed-loop system based on different values of communication delay (i.e., $\tau_d$). As seen, the NG voltage control system is destabilized for delays larger than 1.4 ms (i.e., $\tau_d > 1.4$ ms). On the other hand, with the
proposed control scheme, the voltage control system can remain stable for more than two-
times larger time-delays (i.e., \( \tau_d < 3.66\text{ms} \)).

The reason that the NG voltage control system has higher marginal voltage stability in the proposed control scheme is directly because of the performance of the current allocation filter (i.e., the LPF). As seen in Fig. 62(b), the current allocation filter assigns the low-
frequency component of \( i_{ref} \) to the BESS of the NG for steady state power balancing and
sends the high-frequency variation parts to the GW module to ensure transient power balance between generation and load. This technique, as seen in (5.22) to (5.26), changes the dynamic model of the NG voltage control system. Fig. 63 illustrates the impact of the current assignment filter in marginal voltage stability of the DC NG. Based on (5.21) and (5.22), if the filter’s time constant is set to zero (i.e., \( \tau_i = 0 \)), the current assignment filter does not assign any transient current/power to the GW module and the DC NG will have the same dynamic behavior to the conventional control technique. Initially, when the filter
is deactivated (i.e., \( \tau_1 = 0 \)), the closed-loop poles of the NG voltage control system are in the right-hand side of the \( j\omega \) axis (i.e., the unstable region). By increasing the filter time constant, more portion of transient current is allocated to the GW module and the closed-loop poles of the system are pushed to the stable region. As seen in Fig. 63, the voltage controller becomes stable for \( \tau_1 > 0.0012 \). Next, by increasing the filter’s time constant, the marginal voltage stability of the DC NG gradually increases. However, for very large values of the \( \tau_1 \), the closed-loop poles of the system shift back to the unstable region as the DC NG becomes unstable again for \( \tau_1 > 2.3s \). Consequently, it can be interpreted from Fig. 63 that the proposed modified control scheme of the DC NGs can considerably improve the transient voltage stability of the system compared to the conventional control technique, given that the filter’s time constant (i.e., \( \tau_1 \)) is selected properly.
5.5.3 Comparing the Voltage Stability in Different Architectures

The dynamic voltage stability analysis shows that the proposed CHESS technology can provide higher stability margin at local DC buses compared to DC MNGs with CBESS architectures (see the structure of the CBESS, distributed HESS and proposed CHESS technology in Fig. 56). On the other hand, in the previous work of authors in [3], it has been discussed that the utilization of a grid-forming HESS at each DC bus improves the stability of the local DC buses compared to the DC MGs/NGs with a typical grid-forming BESS unit because of the impact of the HESS current allocation filter. Since the stability enhancement of the proposed CHESS technology is also directly related to the current allocation filters (i.e., the HPF and LPF), it can be shown that the stability enhancement of the local DC buses in the proposed CHESS technology is similar to the distributed HESS architectures. However, the stability of the MG common DC bus cannot be improved in the distributed HESS represented in Fig. 56(b) because there is not any grid-forming HESS connected to the MG DC bus. In another word, compared to the CBESS technology, the distributed HESS methods can provide higher stability margin just in local DC buses. While the proposed grid-forming CHESS technology improves the voltage stability of all the local and common DC buses by just utilizing a single community SC.

5.6 Analyzing the Efficiency of the Proposed CHESS Method

This section explains why the proposed CHESS architecture is more efficient compared to its “equivalent” distributed HESS architecture. Here, “equivalent” means that both architectures use same bandwidth in their current allocation systems, so that provide same power smoothing performance, transient response, and battery lifetime improvement. To this end, this section first discusses the number of active components (power electronic
converters) in both technologies. Then, it will be shown that sending the high-frequency power variations to MG common DC link in the proposed approach does not impact the steady state power loss (or energy loss) in the DC MNG system. Finally, empirical and analytical approaches are adopted to show why the proposed CHESS technology can reduce the required size of the SC compared to its “equivalent” distributed HESS technology.

5.6.1 Number of Power Electronic Converters

As shown in Fig. 56(b), in the distributed HESS there is a local grid-forming HESS unit at each DC NG which regulates the NG local DC bus voltage. The grid-forming battery-SC HESS units are basically designed based on parallel active topologies in which both of BESS and SC are connected in parallel with their individual power electronic converters. In other words, two distinct DC to DC converters are needed for a grid-forming HESS unit (i.e., one converter is for BESS and the other one is for SC). Therefore, in a DC MNG system with \( N \) number of DC NGs, the distributed HESS architecture requires \( N - 1 \) more power electronic converters compared to the proposed CHESS method. This means that in MNG systems with large number of NGs, the proposed CHESS technology can noticeably reduce the initial cost of the system by decreasing the required number of power electronic converters.

5.6.2 Comparing the Energy Losses in Different Architectures

This section discusses how the proposed CHESS technology does not impact the power losses of the DC MNG system compared to the “equivalent” distributed HESS architecture (see Fig. 56). Based on (4) the output power of the GW modules (i.e., \( P_{GW}^l \)) in CBESS or
distributed HESS architectures is $P_{\text{ex}}^i$ which is selected by the energy management module of the MNG system. On the other hand, in the proposed approach, the high-frequency variations of the net power are subtracted from the output power of the GW modules (see Fig. 59). Therefore, based on (5.10), the output power of the GW module can be obtained in time-domain as

$$
P_{\text{GW}}^i(t)_{\text{CHESS}} = P_{\text{ex}}^i(t) - \mathcal{L}^{-1}\left\{(1-H_{\text{LPF}}(s))P_{\text{net}}^i(s)\right\} = P_{\text{ex}}^i(t) - P_{\text{hf}}^i(t)
$$

(5.33)

where $P_{\text{hf}}^i(t)$ shows the high-frequency fluctuations of the new power in $i^{th}$ NG. Due to the random variation of RESs or loads, the high-frequency net power variations have approximately zero average during the mid-term or steady state operation of the system [103]. Therefore, the average power transferred to the MG DC link is obtained as:

$$
\begin{align*}
\lim_{T \to \infty} \frac{1}{T} \int_{t_0}^{t_0+T} P_{\text{GW}}^i(t)_{\text{CHESS}} \, dt &= \lim_{T \to \infty} \frac{1}{T} \int_{t_0}^{t_0+T} \left( P_{\text{ex}}^i(t) - P_{\text{hf}}^i(t) \right) \, dt \\
&= \lim_{T \to \infty} \frac{1}{T} \int_{t_0}^{t_0+T} P_{\text{ex}}^i(t) \, dt - \lim_{T \to \infty} \frac{1}{T} \int_{t_0}^{t_0+T} P_{\text{hf}}^i(t) \, dt \\
&\approx P_{\text{ex}}^i \left. \right|_{\text{CHESS}}^{\text{ave}} = P_{\text{ex}}^i \text{ ave}
\end{align*}
$$

(5.34)

Therefore, assuming the GW converters have same power conversion efficiency in CHESS and distributed HESS architectures, the average power and energy loss in MG common DC link and GW converters, which is a proportion of the power transmitted through the MG DC link and GW converters, will be similar in these different architectures.

### 5.6.3 Empirical Analysis of the SC Size

This section explains why the proposed CHESS technology can reduce the required size of the SC compared to the distributed HESS architectures. First, it should be noted that
in battery-SC HESSs, the power that is sent to the SC by the HESS current allocation system has zero average during the mid-term or steady state operation of the system. In addition, the instantaneous power variations of the loads or RESs in different NGs are stochastic and relatively uncorrelated. Therefore, the high-frequency rates of the net power (see the net power equation in (5.2) and (5.3)) in different NGs can be interpreted as uncorrelated signals that approximately have a zero mean during the mid-term operation of the system. For instance, Fig. 64(a) illustrates the high-frequency changes of the net power in three different NGs of an MNG system (each color shows the high-frequency variation of the net power in a different NG). In one hand, as seen in Fig. 56(b), in
distributed HESS technologies, there is a local grid-forming HESS unit at each DC NG. In this structure, the SC unit of each local grid-forming HESS absorbs the high-frequency variations of its NG’s net power to smooth out the output power of the local BESS unit. So, the sharp power fluctuations of the local RESs and loads causes transient energy-level or SoC changes of the local SC. Therefore, each SC should have enough size to not being over charged/discharged by its local transient net power fluctuations at their peak values.

On the other hand, as discussed in Section 5.5, in the proposed CHESS technology each DC NG sends out the high-frequency variations of the net power to the MG DC link, then the total summation of them is absorbed by the community SC of the grid-forming CHESS unit. Since the high-frequency variation of the net powers in different NGs are uncorrelated, the peak value of the instantaneous power fluctuations allocated to the community SC will be less than the maximum value of the summation of power fluctuation allocated to the local SC units. Thereby, the required energy storage capacity for the community SC in CHESS technology will be less than the summation of the required energy capacity of the local SC units in distributed HESS architectures. For example, Fig. 64 compares the energy level changes in the community SC in the proposed CHESS technology with the summation of total energy level changes in an equivalent DC MNG system with the distributed HESS architecture. As seen, the summation of the absolute energy level changes of the SC in the distributed HESS technology is around 47% higher than the absolute energy level changes in a community SC in the proposed CHESS technology showing that the required size of the community SC is remarkably lower than the total required SC size in the distributed HESS technologies, thereby indicating the superiority of the proposed CHESS technology.
5.6.4 Analytical Analysis of the SC Size

Providing an analytical proof for the above discussion can further clarify and generalize it. To this end, without loss of generality, assume there is no community load inside the system for both CHESS and its “equivalent” distributed HESS architectures. In the distributed HESS architecture, the output power of the local SC in NG\textsubscript{i} (i.e., \( P_{SC}^i \)) can be obtained as:

\[
P_{SC}^i(t) = P_{if}^i(t) = \mathcal{L}^{-1}\left\{ \left[ 1 - H_{LPF}(s) \right] P_{net}^i(s) \right\}
\]  

(5.35)

where \( P_{if}^i \) represents the high-frequency fluctuations of the net power (i.e., \( P_{net}^i \)) in NG\textsubscript{i} and \( P_{net}^i(t) \) is defined in (5.1). Consequently, the alterations of the stored energy by each SC unit or energy-level changes of the SC (i.e., \( \Delta E_{SC}^i(t) \)) can be obtained as:

\[
\Delta E_{SC}^i(t) = E_{SC}^i(t) - E_{SC}^i(t_0) = -\int_{t_0}^t P_{if}^i(t)dt
\]  

(5.36)

where \( E_{SC}^i(t) \) is the stored energy in \( i^{th} \) SC and \( \forall t \in \mathbb{R} \geq 0, E_{SC}^i(t) > 0 \). In addition, the stored energy of each SC unit (i.e., \( E_{SC}^i(t) \)) should always satisfy the following condition:

\[
E_{SC}^i(t) \leq E_{max}^i
\]  

(5.37)

where \( E_{max} \) is the maximum energy level or charge capacity of the SC. Based on (5.36) and (5.37), the energy level alteration at each community SC is obtained as \( \Delta E_{SC}^i(t) \leq E_{max}^i - E_{SC}^i(t_0) \). Therefore, higher energy level changes for each SC unit (i.e., \( \Delta E_{SC}^i(t) \)) shows that a higher SC size is required for that SC. In this regard, the total energy level changes of SCs can be used as a measure to compare the required total SC
size in different HESS technologies. Thus, considering an MNG system with \( N \) DC NGs, the total energy-level changes of the SC can be obtained as:

\[
S_{abs}^{dist} = \sum_{i=1}^{N} |\Delta E_{SC}(t)| = \sum_{i=1}^{n} \int_{t_0}^{t} P_{Hf}^{\prime}(t) dt
\]  

(5.38)

It should be noted that to measure the total energy level changes of SCs, considering the absolute value of \( \Delta E_{SC}(t) \) in (5.38) is necessary because energy level changes of different SCs may have opposite signs and the simple summation of them does not provide any information about the required total SC size in the MNG system. On the other hand, in the proposed CHESS technology, there is just a single SC unit located at MG DC bus (i.e., the community SC) that absorbs the high-frequency power variations of all the RESs or loads. Assuming there is no community load in the MG DC link, and based on the (5.17), the output power of the community SC is obtained as:

\[
P_{SC}(t) = \sum_{i=1}^{N} \mathcal{L}^{-1} \left\{ \left(1 - H_{LPF}(s)\right) P_{net}^{i}(s) \right\} + \mathcal{L}^{-1} \left\{ H_{HPF}(s) P_{loss}^{MG}(s) \right\}
\]  

(39)

where \( P_{loss}^{MG} \) is the total power loss at MG common DC link (i.e., high-voltage side). Therefore, the total power absorbed by the community SC is obtained as:

\[
P_{SC}(t) = \sum_{i=1}^{N} P_{Hf}^{i}(t) + P_{Hfloss}^{MG}(t)
\]  

(5.40)

Now, assuming there is no power loss at MG common DC link and GW converters (i.e., \( P_{loss}^{MG} = 0 \)), the power that is absorbed by the community in ideal condition (i.e., \( \psi \)) is obtained:
\[ \psi(t) = \sum_{i=1}^{N} P_{\text{HF}}(t) \]  

(5.41)

Because in the ideal condition all the high-frequency power variations of the RESs and loads transmitted to the community SC without any transmission or power conversion losses, one can obtain \( \forall t \in \mathbb{R}, |\psi(t)| \geq |P_{SC}(t)|. \) This means that the power absorbed/released by the community SC in ideal condition always have a higher absolute value compared to the real condition with power losses. So, if it is shown that in the ideal condition, the community SC experiences less absolute value energy level changes compared to a DC MNG with an equivalent distributed HESS, one can also conclude that the absolute energy level changes of the community SC in real conditions are also smaller than that of distributed HESS architecture. Then, considering (5.36) and (5.41), the energy level changes of the community SC in ideal condition is obtained as:

\[ \Delta E_{\text{SC}}^{\text{com}}(t) \bigg|_{\text{ideal}} = E_{\text{SC}}^{\text{com}}(t) - E_{\text{SC}}^{\text{com}}(t_0) = - \int_{t_0}^{t} \psi \, dt \]

(5.42)

where \( E_{\text{SC}}^{\text{com}}(t) \) stored energy at community SC. Then, the total absolute energy level changes of the community SC are obtained as:

\[ S_{\text{abs}}^{\text{CHESS}} \bigg|_{\text{ideal}} = \left| \int_{t_0}^{t} \sum_{i=1}^{N} P_{\text{HF}}^{i}(t) \, dt \right| \]  

(5.43)

Knowing the fact that \( \forall a, b \in \mathbb{R}, |a + b| \leq |a| + |b|, \) from (5.38) and (5.43), one can obtain

\[ \left| \int_{t_0}^{t} \sum_{i=1}^{N} P_{\text{HF}}^{i}(t) \, dt \right| \leq \sum_{i=1}^{N} \left| \int_{t_0}^{t} P_{\text{HF}}^{i}(t) \, dt \right| \]  

(5.44)
In addition, based on (5.38) and (5.39) as well as knowing $|v(t)| \geq |P_{sc}(t)|$, one can obtain

$$S^{CHESS}_{abs} |_{real} < S^{CHESS}_{abs} |_{ideal}.$$  Therefore, based on (5.36) to (5.42), one can extract

$$S^{CHESS}_{abs} |_{real} < S^{CHESS}_{abs} |_{ideal} \leq S^{dist}_{abs} \leq (5.45)$$

Equation (5.43) shows that the required energy storage capacity for SC(s) is always smaller in the proposed CHESS technology compared to its equivalent distributed HESS. Moreover, in practice, the high-frequency variations of the net power in different DC NGs (i.e., $P_{HF}^{i}$) are uncorrelated. This indicates that if the number of NGs inside the MNG increases (i.e., $N \to \infty$) then $\int_{t_0}^{t} \sum_{i=1}^{N} P_{HF}^{i}(t)dt \approx \sum_{i=1}^{N} \int_{t_0}^{t} P_{HF}^{i}(t)dt$. Therefore, the superiority of the proposed approach over distributed HESS architectures increases when there are lots of NGs in the DC MNG system.

### 5.7 Simulation Results

This section verifies the performance of the proposed CHESS technology in smoothing the output power/current of the batteries as well as improving the voltage quality of the MNG system. To this end, the performance of two case study MNG systems are compared in a 20-minute time interval by simulating the systems in MATLAB/Simulink and simulation time step is 50 $\mu$s. The DC MNGs’ parameters are represented in Table 3. The MNG systems have three NGs. Moreover, these case study MNG systems have the following features:

- The first case study system (i.e., Case 1), is an MNG system that utilizes a CBESS which operates as the only master unit at the MG DC bus (i.e., no community SC is
used). In addition, the DC NGs have the conventional control structure represented in Fig. 56(a).

- The second case study system (i.e., Case 2), is an MNG system that utilizes a community SC in tandem with a CBESS to regulate the MG DC bus voltage (i.e., the proposed CHESS technology shown in Fig. 56). The CHESS control structure is shown in Fig. 58 which is adopted from [3]. The DC NGs utilize the proposed modified control scheme (see Fig. 59(b)) to control their local DC bus voltages.

- Both MNG systems (i.e., Case 1 and Case 2 systems) contain three DC NGs and a community load. The structure of the DC NGs is also illustrated in Fig. 57.

- In both case study systems (i.e., Case 1 and Case 2), the DC MNG systems have the same power generation and load power profiles. In addition, The EMS of both MNG systems are adopted from [14] which has a one hour action time. Thus, \( \forall i \in \{1, 2, 3\}, P_{e,i}^t \)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{NG, nom} )</td>
<td>Nominal voltage level at NGs’ local DC bus</td>
<td>100 V</td>
</tr>
<tr>
<td>( V_{MG, nom} )</td>
<td>Nominal voltage level at MG common DC bus</td>
<td>750 V</td>
</tr>
<tr>
<td>( P_{BESS}^\text{nom} )</td>
<td>Nominal power of the local BESSs</td>
<td>20kW</td>
</tr>
<tr>
<td>( Q_{BESS}^i )</td>
<td>Nominal charge time of the local BESSs</td>
<td>2h</td>
</tr>
<tr>
<td>( P_{CBESS}^\text{nom} )</td>
<td>Nominal power of CBESS</td>
<td>60kW</td>
</tr>
<tr>
<td>( Q_{CBESS}^i )</td>
<td>Nominal charge time of CBESS</td>
<td>4h</td>
</tr>
<tr>
<td>( P_{SC}^\text{nom} )</td>
<td>Nominal power of the SC</td>
<td>60kW</td>
</tr>
<tr>
<td>( Q_{SC}^i )</td>
<td>Nominal charge time of the SC</td>
<td>1 s</td>
</tr>
<tr>
<td>( C_i )</td>
<td>DC buses’ capacitance</td>
<td>800( \mu F )</td>
</tr>
<tr>
<td>( R_i )</td>
<td>Transmission lines’ resistance</td>
<td>5m( \Omega )</td>
</tr>
</tbody>
</table>
is seen unchanged during the 20 minutes simulation interval. They have also similar ESSs’ capacities represented in Table 11.

- The NGs have also the same circuit parameters represented in Table 12.

- It is assumed that, in both cases, the local and community BESSs are Li-ion type.

- The gains of the PI voltage controllers in Case 1 are selected as \( (K_{pv} = 0.8, K_{pv} = 10) \) to ensure the voltage stability of the MNG system. On the other hand, due to the higher marginal stability of the system the gains of PI voltage controllers are selected as \( (K_{pv} = 4, K_{pv} = 40) \) to provide faster response of the voltage control and enhance the voltage quality of the MNG system. Also, the time constant of the LPF in DC NGs (i.e., \( \tau_1 \)) is 1s and the time constant of the HPF (i.e., \( \tau_2 \)) in MG DC bus is 5s.

Both the MNG systems (i.e., Case 1 and Case 2), have the same net power (i.e., \( P_{net} \)) and community load power (i.e., \( P_{com} \)) profile which are illustrated in Fig. 65. The net power of a DC NG is defined in (1) and it shows the difference between local load power demand and local PV power generation in each DC NG. For instance, \( P_{net} > 0 \) means that the local power demand in \( i^{th} \) DC NG is larger than its local PV power generation. Illustrates the performance of the Case 1 system. In the Case 1 DC MNG, the CBESS is utilized as the only grid-forming unit in MG DC bus to control the MG DC bus voltages and maintain the power balance. In addition, the NG voltage controllers utilize the conventional voltage control technique illustrated in Fig. 66(a). As seen in Fig. 65, in Case 1 system, all the high-frequency power fluctuations of the net powers are absorbed by the local BESSs and the GW modules send/receive relatively smooth powers to the MG DC bus which is equal to their reference power (i.e., \( P_{ref} \)) generated by the EMS of the MNG system. Similarly, the
high-frequency community load power fluctuation is absorbed by the CBESS to maintain the transient power balance and voltage stability at the MG DC bus. The EMS of the MNG system is adopted from [23] and it computes the rate of power exchanges between the DC NGs to manage the SoC of the local BESSs and CBESS. The SoC variation of the local BESSs and the CBESS are illustrated in Fig. 66(d). Fig. 67 illustrates the performance of the Case 2 MNG system, that utilizes the proposed CHESS technology, for the same community and net power profile (see Fig. 65). The size of the ESSs is also the same as the ones used in Case 1 system. However, in Case 2, a community SC is utilized in tandem with the CBESS to regulate the MG DC bus voltages and maintain the power balance. In

Fig. 65. The net and community load power variations(a) net powers fluctuations (b) the community loads
addition, the DC NGs’ voltage control systems utilize the proposed modified control scheme illustrated in Fig. 59(b). As seen in Fig. 67, with the proposed CHESS technology, the high-frequency power variations of the net power in DC NGs are sent out to the MG DC bus through the GW modules of the NGs. As a result, the local BESS power is smoothed, and the powers of the GW modules have higher variations (compare Fig. 66 (a) and (b) with Fig. 67 (a) and (b)). This high-frequency power fluctuations are then absorbed by the community SC along with the high-frequency power variations of the community load to smooth out the CBESS power. Therefore, the output powers of all the BESS units are smoothed with the proposed CHESS technology. In addition, because the size of the ESSs and the steady state net power fluctuations are similar to the Case 1, the EMS of the MNG system computes similar optimal rate of power exchange between the NGs, thereby providing the same SoC profile for local and community BESSs.
Fig. 69 and Fig. 70 also show the voltage variation at NG and MG DC buses in Case 1 and Case 2 MNG systems, respectively. As discussed in Section 4, voltage controllers of the MNG system have higher marginal stability with the proposed CHESS technology (i.e., Case 2). Consequently, the PI voltage controllers have higher gains in Case 2, thereby having faster response to the load changes. As a result, the DC bus in Case 2 system (i.e., the proposed CHESS technology) has considerably better voltage quality compared to Case 1 MNG system. Table 13 and Table 14 provide quantitative comparisons between the performance of the case study MNG systems based on the integral of squared voltage error (ISE) and sum of absolute battery power variations (SAPV). As seen, the average voltage at MG DC bus (i.e., $v_{\text{MG}}^{\text{ave}} = \sum_{i=0}^{3} v_{Ci} / 4$) and NG DC bus voltages have considerably less ISE values in Case 2 representing higher voltage quality in this case. Also, the local and community BESSs have remarkably smaller SAPV values in Case 2 indicating significantly smaller output power variations of the local and community BESSs which in turn indirectly shows the lifetime improvement of all the batteries.
Fig. 68. Voltage profiles at DC buses in Case 2 MNG system (i.e., the proposed CHESS technology) (a) MG DC bus voltages (b) voltages of the NGs’ DC buses.

Fig. 69. Voltage profiles at DC buses in Case 1 (i.e., conventional CBESS technology) MNG system (a) MG DC bus voltages (b) voltages of the NGs’ DC buses.
5.8 Discussion and Future Research Direction

As discussed in Sections 5.4 and 5.5, the proposed CHESS technology can provide higher transient voltage stability and less battery variations. In this work, the smoother current/power variation of the BESSs is inferred as the higher improvement of the BESSs’ lifetime. It should be noted that there are other parameters such as temperature, depth of discharge or battery type (e.g., Li-ion or Lead-acid) that can also impact the BESSs lifetime. However, assuming in the different architectures the BESSs are in the same operating condition (e.g., same size, type, and operating temperature) as well as knowing

<table>
<thead>
<tr>
<th>BESS</th>
<th>Power Variation Index (SAPV)</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESS&lt;sub&gt;1&lt;/sub&gt;</td>
<td>$SAPV = \sum_i [P_{bat}^i (kT_i) - (P_{bat}^i (kT_i - T_i))]$</td>
<td>7680W</td>
<td>737W</td>
</tr>
<tr>
<td>BESS&lt;sub&gt;2&lt;/sub&gt;</td>
<td>$SAPV = \sum_i [P_{bat}^2 (kT_i) - (P_{bat}^2 (kT_i - T_i))]$</td>
<td>5689W</td>
<td>541W</td>
</tr>
<tr>
<td>BESS&lt;sub&gt;3&lt;/sub&gt;</td>
<td>$SAPV = \sum_i [P_{bat}^3 (kT_i) - (P_{bat}^3 (kT_i - T_i))]$</td>
<td>5612W</td>
<td>569 W</td>
</tr>
<tr>
<td>CBESS</td>
<td>$SAPV = \sum_k [P_{CBESS} (kT_i) - (P_{CBESS} (kT_i - T_i))]$</td>
<td>10091W</td>
<td>1018W</td>
</tr>
</tbody>
</table>

Table 13. Power variation analysis ($T_i = 0.01s$)

<table>
<thead>
<tr>
<th>DC Bus</th>
<th>Voltage Quality Index (ISE)</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG&lt;sub&gt;1&lt;/sub&gt;</td>
<td>$ISE = \int (v_{NG1} - v_{NG1}^*)^2 dt$</td>
<td>980(V&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>40.8(V&lt;sup&gt;2&lt;/sup&gt;)</td>
</tr>
<tr>
<td>NG&lt;sub&gt;2&lt;/sub&gt;</td>
<td>$ISE = \int (v_{NG2} - v_{NG2}^*)^2 dt$</td>
<td>691(V&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>25.7(V&lt;sup&gt;2&lt;/sup&gt;)</td>
</tr>
<tr>
<td>NG&lt;sub&gt;3&lt;/sub&gt;</td>
<td>$ISE = \int (v_{NG3} - v_{NG3}^*)^2 dt$</td>
<td>656(V&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>25.76(V&lt;sup&gt;2&lt;/sup&gt;)</td>
</tr>
<tr>
<td>MG</td>
<td>$ISE = \int (v_{MG}^* - v_{MG}^*)^2 dt$</td>
<td>221(V&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>53.01(V&lt;sup&gt;2&lt;/sup&gt;)</td>
</tr>
</tbody>
</table>

Table 14. Voltage quality comparison
that the SCs just impact the transient current/oscillations of the BESSs, the main parameter which can affect the BESS lifetime is the output power/current oscillations of the BESSs.

In addition, it is discussed that if the same filter bandwidth is designed for current allocation systems, the proposed CHESS technology can provide same power smoothing performance compared to its equivalent distributed HESS but with a smaller number of converters and less required SC size. This means that the proposed CHESS architecture can be a better economic solution for clustered MG applications. Therefore, providing an accurate cost analysis of the different technologies for real microgrid condition may further justify the advantage of the proposed CHESS technology in practical applications.

Finally, compared to the CBESS technology, it is expected that the proposed CHESS technology provides higher current contribution and less voltage drop during faulty conditions (e.g., line to ground faults) due to the faster response of the community SC and its higher power density compared to the BESSs. This means that for the reliable operation of the CHESS technology, the protection settings of the DC MG should be updated. Thus, one of the future research directions of this work can be analyzing the response of the proposed CHESS technology during faulty conditions.

5.9 Conclusion

This chapter proposes a CHESS technology along with a modified control scheme for DC NGs to improve the voltage quality and battery lifetime in an islanded DC MNG system. Firstly, it provides a frequency-based battery-SC power allocation study which indicates that the proposed CHESS technology can provide fewer power variations for all the community and local BESSs by sending all the high-frequency power variations to the community SC of the CHESS unit which means that, in the proposed CHESS architecture,
the output power of the BESSs experience smoother power variations leading to higher BESSs’ lifetime. Then, the time-delay eigenvalue analysis of the closed-loop system shows that the proposed strategy can also improve the marginal voltage stability of the DC NGs enabling the PI voltage controllers of the grid-forming DERs (i.e., CBESS and local BESSs) to operate with larger gain values thereby enhancing the voltage quality of the MNG system compared to the conventional CBESS architectures. Moreover, it is shown that the CHESS technology requires less SC size compared and a smaller number of power electronic converters to its equivalent distributed HESS technology showing the higher efficiency of this technique. Finally, the advantages of the proposed CHESS technology over the conventional CBESS method are discussed by simulating and comparing two case study MNG systems in MATLAB/Simulink.
Chapter 6: A Method for Charging Electric Vehicles with Battery-supercapacitor Hybrid Energy Storage Systems to Improve Voltage Quality and Battery Lifetime in Islanded Building-level DC Microgrids

6.1 Motivation

The motivation behind this chapter is to address the challenges of charging electric vehicles (EVs) in islanded building-level DC microgrids (MGs) (i.e., DC nano-grids) while improving the voltage quality and extending the lifetime of the central battery energy storage system (CBESS) of hybrid energy storage systems (HESS). HESSs, which combine batteries and supercapacitors (SCs), have been proposed as a solution to mitigate the intermittent and variable nature of renewable energy sources (RESs) and to provide stability to MGs during islanded operation. However, utilizing the internal SC of modern EVs with HESS technologies presents an opportunity to further improve the transient voltage quality without degrading the internal battery energy storage system (BESS) of the EVs.

The proposed method utilizes an online system identification technique to estimate the internal power allocation strategy of EVs based on the parametric identification of an ARX model. The estimation is then used to provide effective coordination between the CBESS of the MG and the internal SC of EV. Additionally, a filtration-based current allocation between the EV and the CBESS is proposed to assign high-frequency power variations of RESs and loads to the SC of the EV while the internal BESS of the EV is charging with its standard current profile.

The simulation and experimental results demonstrate that the proposed EV charging method leads to better transient response and voltage quality in the MG. The findings of this chapter provide a comprehensive solution to improve the performance of
DC MGs by integrating EVs with HESS technologies, which can reduce the dependence on the grid and promote the adoption of sustainable energy solutions.

6.2 Introduction

Microgrids are autonomous distributed energy systems that can promote the reliability, resiliency and flexibility of traditional power systems [104]. Recently, DC MGs have drawn remarkable attention due to their fewer power conversion losses and lower control complexity compared to AC MGs [105]. Besides, DC MGs can be easily adopted to integrate RESs (e.g., photovoltaic and wind), ESSs, and EVs. Therefore, DC MGs are counted as feasible solutions for grid modernization, and effective integration of RESs as well as supplying remote rural areas in which there is no access to the utility grid.

Latterly, developing the DC MGs for building-level applications (i.e., building-level DC MGs) has gained significant interest in both academia and industry [106]. A Building-level DC MG, also called a DC nano-grid, is an autonomous small-scale low-voltage DC distribution system supplying a residential or commercial building. Building-level DC MGs are typically designed based on single bus configurations and contain a group of local loads, local power generation units (e.g., a CBESS, and PV), and an AC to DC bidirectional interlinking converter (BIC) that enables the power exchange with the upstream AC grid [107]. In this configuration, during the grid-connected mode the MG, the BIC system operates as the slack terminal and maintains voltage stability and power balance of the DC MG while the CBESS is in grid-following mode and operates as a power terminal. Consequently, in grid connected mode of the MG, the output power of the CBESS is not usually affected by the instantaneous variations of the PV power or loads [108].
On the other hand, the building-level DC MGs can operate autonomously to supply their local loads when the upstream grid is not available. In the islanded mode of operation, the CBESS of the MG operates as the grid-forming unit to regulate the DC bus voltage and maintain the balance between power generation and loads. So, the output power/current of the CBESS can be affected by the instantaneous power fluctuations of the loads or PV that results in frequent charging and discharging the CBESS. Hence, during the islanded mode, the rapid variations of renewable power or load can degrade the grid-forming CBESS due to the limited life cycle of batteries [109]. In addition, it can increase the battery’s temperature which results in reducing the CBESS lifetime [110].

To expand the lifespan of the BESSs, an SC can be utilized in tandem with the BESSs. This combination forms a battery-supercapacitor HESS [111]. In this technology, due to the almost unlimited life-cycle and noticeably higher power density of SCs, the SC absorbs/releases the high current rates, and the BESS is responsible for long-term energy storage because of its larger energy density [112]. To this end, a low-pass filter is usually applied to perform the power/current assignment between the BESS and SC by decomposing the input power/current of the HESS into low and high-frequency components and allocating the high-frequency parts to SC [113]. For instance, a distributed rule-based power management strategy with an adaptive power smoothing filter was proposed for a residential DC MG that utilizes a PV and a battery-SC HESS unit [2]. In this system, regarding the SoC of the SC, a portion of high-frequency power variations of the PV is absorbed by the SC to smooth out the BESS power profile. Besides, a battery lifetime and life cycle cost analysis for a battery-SC HESS was proposed in [114]. This study shows that a battery-SC HESS that utilizes a rule-based EMS with a power
smoothing filter (i.e., the conventional HESS control structure) can 14.8% extend the lifetime of the battery while it is just 5.36% more expensive than a single lead-acid battery in terms of the life cycle cost. Intelligent control of DC MGs with HESSs was also proposed in [115] which improved the overall efficiency and reliability of the system by ensuring the power balance between RESs and HESS units. Also, the design and stability analysis of DC MGs with HESSs was studied in [74]. This study examined the sensitivity of the DC MG stability to the SC terminal voltage and suggested a method to determine the optimal value of SC voltage for enhancing the voltage stability of the DC MGs with HESS technologies. A model predictive control strategy was also suggested for a grid-forming battery-SC HESS unit in a small-scale residential DC MG [3]. It was shown that this method not only increased the lifetime of the BESS but also improved the marginal voltage stability of the system.

In addition to the renewable power fluctuations and CBESS degradation issue, CPLs can create some challenges for the operation of building-level DC MGs. CPLs are typically electronic loads that utilize a point-of-load converter for power conditioning and voltage control [116]. They demand steady power under varying voltage at the MG side. The main characteristic of CPLs is their negative incremental resistance that tends to destabilize the system [27]. CPLs can create serious voltage stability issues in building-level DC MGs due to the high penetration of electronic loads and point-of-load converters. Consequently, the building-level DC MGs (or DC nano-grids) require large marginal stability of the MG voltage controller [1]. One way to achieve this is to design the PI voltage controller with small gains to guarantee the voltage stability of the MG with nominal values of CPLs [117]. However, the very small gains of the PI voltage controllers
may lead to high transient voltage deviations during the load changes. On the other hand, different active compensation techniques can be implemented to improve the marginal stability of the system [118]. However, these techniques may cause steady-state voltage deviations at MG DC bus and their stability improvement is sometimes insufficient [1]. To tackle the stability issues created by CPLs, the conventional PI voltage controllers can be replaced with a variety of advanced control techniques such as nonlinear controllers [119], adaptive controllers [120], or model predictive controllers [85]. However, the design of advanced controllers may add significant complexity to the primary control layer of the DC MG which in turn affects the flexibility and scalability of the system.

Recently, EVs are spreading rapidly around the world because of their low operation and maintenance costs and no pollution emissions. ESS design is one of the major concerns in EV research and development activities that impact the EV price and range [121]. Similar to the MG applications, battery-SC HESS technologies can be utilized in EVs to expand the lifespan of the EVs’ BESSs. The HESS may have different topologies in EV applications including passive, semi-active and active topologies among which the semi-active topology with a filtration-based current allocation system supervised by a rule-based EMS is the most popular configuration [122]. An experimental study of semi-active battery-SC HESSs for EV applications was performed in [123]. This study revealed that a semi-active HESS that incorporates a filtration-based current sharing system supervised by a fuzzy rule-based EMS can reduce the capacity fade cost of the battery up to almost 50% compared to the conventional standalone BESS configurations.

Bidirectional power flow between EVs and the MG, namely V2G technology, enables the utilization of EVs as distributed energy storage systems. This technology can
provide many services in DC MGs such as steady-state power balancing (e.g., peak shaving) and voltage regulation [124]. In steady-state power balancing, the effective utilization of EVs calls for proper optimal energy management and scheduling technique. On the other hand, in voltage regulation services, EVs are deployed to improve the transient response and voltage quality of MG which in turn requires the implementation of real-time energy management systems (EMSs) and suitable primary controllers [125]. However, the existing methods for short-term utilization of EVs (e.g., for MG voltage regulation), may lead to frequent charge/discharge of the EVs’ internal BESSs, thereby reducing the EV range and diminishing their BESSs lifetime. Besides, in these methods, each EV is considered to be a distributed BESS, so the deployment of the internal SC of modern EVs with HESS technologies cannot be provided.

The goal of this chapter is to effectively employ the internal SC of modern EVs with HESS technologies to not only improve the lifetime of EV’s BESS but also to absorb the instantaneous power variation of the RESs and loads in an islanded building-level DC MG for increasing the lifetime of the MG’s CBESS and to enhance the transient response and voltage stability of the MG. In other words, instead of installing an SC to expand the lifetime of the grid-forming CBESS of the DC MG and improve its performance, this work develops a novel EV charging method to utilize the internal SC of modern EVs to coordinate with CBESS during the islanded mode of the DC MG, so that 1) expand the CBESS’s lifetime, and 2) enhance dynamic stability and voltage quality of the system. The realization of this plan requires to design of effective coordination between the internal SC of EVs and the MG’s CBESS. To provide this coordination, understanding the internal power allocation strategy of each EV is also essential. For instance, if the absorbed power
by an EV contains some high-frequency components which are not filtered by the EV’s power smoothing filter, the BESS of the EV may be degraded. Nevertheless, the internal power allocation strategy of EVs is unknown to the MG control and management system. Therefore, a correct estimation of the EVs’ internal power allocation systems is essential. To address the discussed challenges, this work has the following contributions:

- This work proposes and develops the idea of utilizing the internal SC of modern EVs with HESS technologies to improve the transient voltage quality in islanded building-level DC MGs as well as enhance the lifetime of the MGs’ CBESS without degrading the internal BESS of the EVs.

- An online system identification technique is proposed to estimate the internal power allocation strategy of EVs. This approach is based on the parametric identification of an ARX model. To this end, an RLS algorithm is applied which is governed by a forgetting factor. This estimation is then used to provide effective coordination between the CBESS of the MG and the internal SC of EV.

- A filtration-based current allocation between the EV and MG’s CBESS is proposed in which the high-frequency power variations of RESs and loads are assigned to the SC of the EV while the internal BESS of the EV is charging with its standard current profile. Therefore, the output power/current of the CBESS of the MG is smoothed without impacting the charging profile of the EV’s BESS.

- A small signal stability analysis is proposed to investigate the impact of the proposed EV charging method on the transient voltage stability of the DC MG. The stability analysis results indicate that the marginal voltage stability of the DC MG is improved during the charging process of the EV with the proposed approach. Therefore, when
the EV is charging, the MG voltage controller can operate with considerably larger gain values leading to better transient response and voltage quality. Moreover, using the proposed EV charging method, a conventional PI voltage control can guarantee a high stability margin while the DC MG is loaded by a large CPL. These results are also experimentally verified by deploying a HIL testing.

- The simulation results show that the CBESS power variation is 86% reduced in a case study system by using the proposed EV charging method without impacting the constant charging profile of the EV’s BESS. Also, the HIL testing results show that voltage quality can be improved by reducing 87% of the amplitude and decreasing 56% of the settling time of the transient voltage deviations in a specific load change scenario.

It should be noted that this work only focuses on the islanded operation of the building-level DC MGs (i.e., DC nano-grids) because the CBESS degradation and voltage stability issues are more serious in the islanded mode of the system compared to the grid-connected mode. In this regard, one can assume that the DC MG controllers and EV chargers follow their conventional settings during the grid-connected mode of the system.

The rest of this work is organized as follows: Section 6.3 overviews the structure of the proposed control and management system and summarizes the assumptions and objectives of this work. Section 6.4 proposes the online system identification technique. Section 6.5 discusses the impact of the proposed EV charging on the dynamic voltage stability of the DC MG. Section 6.6 validates the performance of the proposed technique using computer simulation and hardware-in-the-loop (HIL) testing. Section 6.7 discusses the limitation and future research direction, and Section 6.8 concludes the chapter.
6.3 System Overview

Fig. 70 represents the case study system in this work. This system is an islanded low-voltage DC MG that contains a CBESS, a PV module, a resistive load and a group of AC, and DC CPLs. The CBESS operates as the master or grid-forming unit and is responsible for voltage regulation and maintaining the power balance inside the system. The PV module operates in MPPT mode. This work has also the following assumptions:

- The case study system is a small-scale DC MG with a single bus configuration that serves a commercial building with a 100kW nominal load. In this system, the load and DERs (i.e., CBESS, PV, and EVs) are located in close proximity to each other. Therefore, the impact of cable parameters (i.e., line impedances) is fairly negligible.
- It is assumed that each EV utilizes a semi-active battery-supercapacitor HESS which is the common HESS topology in EV applications [122]. Also, it incorporates a conventional power smoothing filter that is supervised by a rule-based EMS to perform the power/current assignment between the EV’s BESS and SC.
- The internal power allocation strategy of EVs (i.e., the bandwidths of the power smoothing filter) is unknown. In addition, the MG control system cannot directly perform the power allocation between the BESS and SC of an EV.
- It is assumed that CBESS is efficiently sized. So, there is no need to employ the energy storage capacity of the EVs’ BESSs to maintain the balance between PV power generation and loads (e.g., for peak shaving). Consequently, the EVs’ BESSs can follow their standard charging profile during the connection to the EV chargers. Hence, this work only focuses on the effective utilization of the internal SC of EVs for absorbing the instantaneous power fluctuation generated by the loads and PV.
• The charging profile of the EV’s BESS is based on a standard constant current-constant voltage (CC-CV) approach represented in Fig. 71 [126]. This charging process begins with a constant current until a certain voltage value, known as the high voltage limit, is reached. Assuming that EV utilizes a Li-ion battery with the cathode materials of cobalt, nickel, manganese, and aluminum, the high voltage limit is selected as 4.20V per cell.

Fig. 72 shows the control structure and circuit model of the case study DC MG. As seen, the CBESS operates as the grid-forming unit of the system to regulate the DC bus voltage. To this end, the PI voltage controller of the MG computes a reference current (i.e., $i_{\text{ref}}$). When there is no EV connected to the charger, the EV charger is in idle mode (i.e., $S=0$). In this case, $i_{\text{ref}}$ is directly sent to the CBESS’s current controller which is similar to the conventional control strategy of DC MGs. On the other hand, when the EV is connected to the EV charger (i.e., $S=1$), $i_{\text{ref}}$ is sent to the current/power allocation system. This system subtracts the high-frequency components of $i_{\text{ref}}$ to smooth out the output current of the CBESS and then adds the high-frequency components to the output current.
of the EV charger. Therefore, the internal SC of the EV is utilized for absorbing transient power fluctuations as well as MG voltage regulation. The cut-off frequency (i.e., $\omega_c$) of the high-pass filter (HPF) is adjusted based on the estimated dynamic model of the power allocation system of the EV’s HESS so that charging the internal BESS of the EV with high-frequency components of $i_{ref}$ is avoided. In another word, the MGs’ current allocation system effectively adjusts the filter’s bandwidth to guarantee that the high-frequency variation of RESs or loads is only absorbed by the internal SC of the EV.

### 6.4 Estimating the Parameters of EV Power Management System

Practically, different brands of EVs may have different internal power management systems. On the other hand, the internal power allocation strategy of an EV is unknown for the MG control system. Therefore, an online estimation of the EVs’ power allocation system is needed to provide effective coordination between the CBESS and EV. To this end, the DC MG utilizes an input-output system identification approach to estimate the internal power allocation strategy of the EV. The structure of this method is illustrated in Fig. 73. This estimation is
based on an online parametric identification of an ARX model. The choice of this method can be justified by the fact that it is simple to implement. In addition, it is assumed that the EV utilizes a conventional semi-active HESS topology in which the BESS is directly connected to the EV DC link and SC is connected through a bidirectional DC to DC converter that is in current control mode (see Fig. 73). In this configuration, the high-frequency current variations of the HESS are assigned to the SC using a power allocation filter through adjusting reference current of the SC’s converter (i.e., $i_{SC-ref}$). In addition, the EV utilizes a rule-based EMS to
avoid overcharging/discharging of the SC during acceleration of the car with very high-power rates. However, it will not react when the EV is charging due to the relatively low amplitudes of high-frequency current variations. Therefore, the purpose of the proposed system identification is to estimate which range of frequencies are filtered by the SC and its power filtering system.

As seen in Fig. 73, the online system identification module measures $P_{EV}$ and $P_{BESS}$ at each sampling time (i.e., $T_s$) in the EV charging spot. Then, an ARX model is fitted to the data as

$$A(q^{-1})y_t = B(q^{-1})u_t + e_t$$  \hspace{1cm} (6.1)$$

where $y_t = P_{EVP}$, $u_t = P_{EV}$, and $e_t$ is the prediction error. Also, $A(q^{-1}) = 1 + a_1q^{-1}$ and

Fig. 73. The structure of the proposed system identification approach.
\[ B(q^{-1}) = b_0 + b_1 q^{-1} \] that yields

\[ G(q^{-1}) = \frac{B(q^{-1})}{A(q^{-1})} = \frac{b_0 + b_1 q^{-1}}{1 + a_1 q^{-1}} \quad (6.2) \]

This model can be written in the linear regression form as

\[ y_t = \lambda^T \varphi_t + e_t \quad (6.3) \]

where \( \varphi^T_t \) and \( \lambda^T \) are

\[ \varphi^T_t = (-y_{t-1}, u_t, u_{t-1}) \quad \lambda^T = (a_1, b_0, b_1) \quad (6.4) \]

To estimate the parameters of the ARX model (i.e., \( a_1 \), \( b_0 \), and \( b_1 \)), a recursive least squares algorithm with a gradient-based forgetting factor is utilized. This approach is discussed in detail in [127]. Consequently, the system identification may continuously update the estimated parameters during system operation that can provide a more accurate linear time-invariant (LTI) approximation of the EV’s internal power allocation system.

Now, consider an LTI first-order analog filter. The transfer function of this filter can be represented in Laplace form as

\[ H_{LFF}^{EV}(s) = \frac{\omega_H}{s + \omega_H} \quad (6.5) \]

where \( \omega_H \) is the corner frequency of the LTI low-pass filter. The equivalent digital filter in the Z-domain can be also obtained as

\[ H_{LFF}^{EV}(z) = \frac{z - 1}{z} Z \left( L^{-1} \left( \frac{H(s)}{s} \right) \right) = \frac{1 - e^{-\omega_H T_s}}{z - e^{-\omega_H T_s}} \quad (6.6) \]

Considering (6.1) to (6.6), the corner frequency of the LTI low-pass analog filter can be approximated as
\[ \omega_{\text{ref}}^* = -\frac{1}{T_s} \ln(-a_i) \]  

(6.7)

where \( a_i \) is the estimated parameter defined in (6.4). Moreover, in the initialization step of the algorithm (i.e., the initial guess of the filter parameters) \( b_0 \) and \( b_1 \) are considered as \( b_0 = 0 \), and \( b_1 = 1 + a_0 \). So, it can be shown that by running the online system identification algorithm, these parameters are computed as \( b_0 = 0 \), \( b_1 \approx 1 - e^{-\omega_s T_s} \). In the next step, to guarantee that the high-frequency variation of \( i_{\text{ref}} \) is not assigned to the internal BESS of the EV, the estimated cut-off frequency should be smaller than the cut-off frequency of the HPF (i.e., \( \omega_{\text{ref}}^* < \omega_c \)). In addition, to reduce transient variations on the HPF bandwidth, the estimated value for the HPF cut-off frequency is smoothed through a low-pass linear filter.

So, the cut-off frequency of the HPF in the MG current allocation system is defined as

\[ \eta \frac{d\omega_c}{dt} + \omega_c = \kappa_c \omega_{\text{ref}}^* , \quad \kappa_c > 1 , \quad \eta > 0 \]  

(6.8)

where \( \kappa_c \) is a constant value (i.e., the filtering constant) that should be defined enough large to guarantee that only the EV’s SC will be charged by high-frequency current variations, and \( \eta \) is the time constant of the LPF.

### 6.5 Stability Analysis

This section discusses the impact of the proposed EV charging method on the transient voltage stability of the system. To this end, the state-space dynamic model of the closed-loop system is developed. Then, the small-signal stability of the system in conventional and proposed EV charging methods is compared using the eigenvalue analysis of the linearized dynamic model of the system.
6.5.1 Dynamic Modelling

Based on the circuit model of the system shown in Fig. 72, and by considering the averaged dynamic model of the power electronic converters, the open-loop dynamic model of the system is obtained as

\[
\begin{align*}
L_1 \frac{di_{L1}}{dt} &= v_{\text{bus}} - R_1 i_{L1} - v_{\text{bus}} (1 - d_1) \\
L_2 \frac{di_{L2}}{dt} &= v_{\text{EV}} - R_2 i_{L2} - v_{\text{bus}} (1 - d_2) \\
C_{\text{bus}} \frac{dv_{\text{bus}}}{dt} &= i_{L1} (1 - d_1) + i_{L2} (1 - d_2) + \frac{(P_{PV} - P_{\text{CPL}})}{v_{\text{bus}}} - \frac{v_{\text{bus}}}{R_L}
\end{align*}
\] (6.9)

where \(i_{L1}\) and \(i_{L2}\) represent the inductor or the output currents of the CBESS and EV’s HESS. \(R_1\) and \(R_2\) are the resistance, and \(L_1\) and \(L_2\) are the inductance of the CBESS and EV charger power electronic converters, respectively. Moreover, \(C_{\text{bus}}\) is the equivalent capacitance of the MG DC bus and \(v_{\text{bus}}\) represents the DC bus voltage. Also, \(R_t\) is the total resistive load of the system and \(P_{\text{CPL}}\) is the demanded power of by CPLs. The PV power generation is also represented by \(P_{PV}\). Assuming the PV unit operates in maximum power point tracking (MPPT) mode, it behaves like a constant power source. Furthermore, \(d_1\) and \(d_2\) are the duty cycle of the CBESS and EV charger converters and they are obtained as

\[
\begin{align*}
\frac{dx_{\text{int1}}}{dt} &= i_{\text{ref}}^{\text{CBESS}} - i_{L1} \\
\frac{dx_{\text{int2}}}{dt} &= i_{\text{ref}}^{\text{EV}} - i_{L2} \\
d_1 &= K_{P1} (i_{\text{ref}}^{\text{CBESS}} - i_{L1}) + K_{I1} x_{\text{int1}} \\
d_2 &= K_{P2} (i_{\text{ref}}^{\text{EV}} - i_{L2}) + K_{I2} x_{\text{int2}}
\end{align*}
\] (6.10)

where \(x_{\text{int1}}\) and \(x_{\text{int2}}\) are the integral of the error between the reference currents and the
inductor currents of the converters. Also, the pairs of \((K_{p1}, K_{i1})\) and \((K_{p2}, K_{i2})\) show the proportional and integral gains of the current controllers. Moreover, \(i_{\text{ref}}^{EV}\) and \(i_{\text{ref}}^{\text{CBESS}}\) show the reference currents of the EV charger and CBESS power electronic converters, respectively, which are computed by the MG voltage control and current sharing system. Then, let us assume that the HPF is a first-order linear-time-invariant (LTI) filter that has the following transfer function in Laplace form.

\[
H_{\text{HPF}}(s) = \frac{\tau_c s}{\tau_c s + 1} \tag{6.11}
\]

where \(\tau_c = (\omega_c)^{-1}\) is the time constant of the HPF and \(\omega_c\) is obtained using (6.1) to (6.8) (also see Fig. 5). Then, \(i_{\text{ref}}^{\text{CBESS}}\) and \(i_{\text{ref}}^{EV}\) are obtained as

\[
\begin{align*}
\frac{dx_{\text{int}}}{dt} &= v_{MG}^{*} - \dot{v}_{\text{bus}} \\
\tau_c \frac{dx_f}{dt} &= -x_f + K_{p}\ x_{\text{int}} + K_{p}\ (v_{bus}^{*} - \dot{v}_{bus}) \\
i_{\text{ref}}^{\text{CBESS}} &= x_f \\
i_{\text{ref}}^{EV} &= K_{v} x_{\text{int}} - x_f + K_{p}\ (v_{bus}^{*} - \dot{v}_{bus}) - i_{s}^{EV}
\end{align*}
\]  

where \(x_{\text{int}}\) and \(x_f\) are the dynamic states of the voltage controller and current assignment filter, respectively, and \(i_{s}^{EV}\) is the standard charging current of the EV. The pair of \((K_{p}, K_{i})\) shows the proportional and integral gains of the PI voltage controller. In addition, \(v_{bus}^{*}\) is the nominal voltage of the MG DC bus and \(\dot{v}_{bus}\) is the measured voltage at the MG DC bus. Assuming the voltage measurements has \(\tau_d\) time delay, and using a first-order Pade approximation of the delay, \(\dot{v}_{\text{bus}}\) is obtained as
\[
\begin{aligned}
\frac{1}{2} \tau_d \frac{dx_d}{dt} &= -x_d + v_{bus} \\
\hat{v}_{bus} &= 2x_d - v_{bus}
\end{aligned}
\] (6.13)

where \( x_d \) is the dynamic state of the delay. Considering (6.9) to (6.13), the dynamic model of the closed-loop system can be represented in a state-space form as

\[
\dot{x} = f(x, u, w)
\] (6.14)

where \( x^T = \left[ i_{L1}, i_{L2}, v_{bus}, x_f, x_d, x_{int1}, x_{int2}, x_{intv} \right] \) is the set of dynamic states of the closed-loop system, \( u = v'_{ini} \) is the reference input and \( w = \left[ P_{CPL}, P_{PV}, i_{st}^{EV}, v_{bat}, v_{EV} \right] \) is the set of disturbances. By considering (6.9) to (6.14), the nonlinear state-space dynamic model of the closed-loop system is obtained as (6.15). It should be noted that based on (6.11), if \( \tau_c \to 0 \), then \( x_f = i_{ref}, \ i_{ref}^{\text{BESS}} = i_{ref} \), and \( i_{ref}^{EV} = i_{st}^{EV} \). This means that the dynamic model of the DC MG with conventional EV charging method can be obtained from (6.12) to (6.15) by considering \( \tau_c = 0 \).
\[
\begin{align*}
\frac{di_{L1}}{dt} &= \frac{1}{L_1}v_{bat} - \frac{R_1}{L_1}i_{L1} - \frac{1}{L_1}v_{bus} + \frac{K_{p1}}{L_1}v_{bus}x_f \\
&\quad - \frac{K_{p1}}{L_1}v_{bus}i_{L1} + \frac{K_{f1}}{L_1}v_{bus}x_{int1} \\
\frac{di_{L2}}{dt} &= \frac{1}{L_2}v_{EV} - \frac{R_2}{L_2}i_{L2} - \frac{1}{L_2}v_{bus} + \frac{K_{p2}K_{pv}}{L_2}v_{bus}^*v_{bus} \\
&\quad - 2\frac{K_{p2}K_{pv}}{L_2}v_{bus}x_d + \frac{K_{p2}K_{pv}}{L_2}v_{bus}^2 + \frac{K_{p2}K_{pv}}{L_2}v_{bus}x_{intv} \\
&\quad - \frac{K_{p2}}{L_2}v_{bus}x_f - \frac{K_{p2}}{L_2}v_{bus}i_{L2} + \frac{K_{f2}}{L_2}v_{bus}i_{L2}x_{int2} - \frac{K_{f2}}{L_2}v_{bus}^*i_{L2} \\
\frac{dv_{bus}}{dt} &= \frac{1}{C_{bus}}i_{L1} - \frac{K_{pl}}{C_{bus}}x_f i_{L1} + \frac{K_{pl}}{C_{bus}}i_{L1}^2 - \frac{K_{f1}}{C_{bus}}i_{L1}x_{int1} + \frac{1}{C_{bus}}i_{L2} \\
&\quad - \frac{K_{p2}}{C_{bus}}v_{bus}^*i_{L2} + \frac{2K_{p2}K_{pv}}{C_{bus}}v_{bus}i_{L2} - \frac{K_{p2}K_{pv}}{C_{bus}}v_{bus}^2i_{L2} \\
&\quad - \frac{K_{f2}}{C_{bus}}i_{L2}x_{intv} + \frac{K_{p2}}{C_{bus}}i_{L2}x_f + \frac{K_{f2}}{C_{bus}}i_{L2}^2 - \frac{K_{f2}}{C_{bus}}i_{L2}x_{int2} \\
&\quad + \frac{K_{p2}}{C_{bus}}i_{L2}i_{EV} + \left(\frac{P_{pv} - P_{cpl}}{C_{bus}v_{bus}}\right) - \frac{1}{C_{bus}R_{L}}v_{bus} \\
\frac{dx_f}{dt} &= -\frac{1}{\tau_c}x_f + \frac{K_{pv}}{\tau_c}v_{bus}^* - \frac{2K_{pv}}{\tau_c}x_d + \frac{K_{pv}}{\tau_c}v_{bus} + \frac{K_{pv}}{\tau_c}x_{intv} \\
\frac{dx_d}{dt} &= -\frac{-2}{\tau_d}x_d + \frac{2}{\tau_d}v_{bus} \\
\frac{dx_{int1}}{dt} &= x_f - i_{L1} \\
\frac{dx_{int2}}{dt} &= \frac{K_{pv}}{v_{bus}^*} - 2K_{pv}x_d + K_{pv}v_{bus} + K_{pv}x_{intv} - x_f - i_{L2} - i_{ST} \\
\frac{dx_{intv}}{dt} &= \frac{v_{bus}^*}{2x_d + v_{bus}} \\
&\quad (6.15)
\end{align*}
\]
6.5.2 Eigenvalue Analysis

This section investigates the marginal voltage stability of DC MG under the proposed EV charging method and compares it with the conventional charging method of EVs in low-voltage DC MGs. To this end, the small-signal stability of the DC MGs is measured by analyzing the eigenvalues of the linearized systems. The theorems related to the time-delay eigenvalue analysis are discussed in details in [88]. The selection of this method can be justified due to the high complexity of the nonlinear model of the closed-loop system.

Let us consider the nonlinear state-space dynamic model of the DC MGs represented in (6.14) and (6.15). The equilibrium points of the system (i.e., \( \bar{x}, \bar{u}, \bar{w} \)) can be found as

\[
\dot{\bar{x}} = 0 \iff f(\bar{x}, \bar{u}, \bar{w}) = 0
\]  
(6.16)

Using a first-order Taylor series expansion of \( f \), and defining \( \delta x = x - \bar{x}, \delta u = u - \bar{u} \), and \( \delta w = w - \bar{w} \) one can obtain:

\[
\delta \dot{x} = \dot{x} - \dot{\bar{x}} = f(x, u, w) = A_{\{x,u,w\}} \delta x + B_{\{x,u,w\}} \delta u + D_{\{x,u,w\}} \delta w
\]  
(6.17)

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<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v_{bus} )</td>
<td>Reference or nominal voltage of the DC bus</td>
<td>200V</td>
</tr>
<tr>
<td>( K_{i1}, K_{i2} )</td>
<td>Proportional gains of the current regulators</td>
<td>200</td>
</tr>
<tr>
<td>( K_{c1}, K_{c2} )</td>
<td>Integral gains of the current regulators</td>
<td>500</td>
</tr>
<tr>
<td>( L_{c1}, L_{c2} )</td>
<td>Inductance of the converter filter</td>
<td>500( \mu )H</td>
</tr>
<tr>
<td>( R_{c1}, R_{c2} )</td>
<td>Resistance of the converter filter</td>
<td>200m( \Omega )</td>
</tr>
<tr>
<td>( C_{bus} )</td>
<td>Total capacitance of the MG dc bus</td>
<td>8mF</td>
</tr>
<tr>
<td>( v_{ref} )</td>
<td>Terminal voltage of CBESS</td>
<td>50V</td>
</tr>
<tr>
<td>( v_{EV} )</td>
<td>Terminal voltage of EV’s BESS (or HESS)</td>
<td>40V</td>
</tr>
<tr>
<td>( v_{EV} )</td>
<td>Terminal voltage of EV’s BESS (or HESS)</td>
<td>40V</td>
</tr>
</tbody>
</table>
where \( A, B, \) and \( D \) are defined as

\[
A_{xw} = \frac{\delta f(x, u, w)}{\delta x}_{xw}
\]

(6.18)

\[
B_{xw} = \frac{\delta f(x, u, w)}{\delta u}_{xw}
\]

(6.19)

\[
D_{xw} = \frac{\delta f(x, u, w)}{\delta w}_{xw}
\]

(6.20)

Therefore, to compute the closed-loop poles of the linearized system at each operating point, it is needed to determine the eigenvalues of the Jacobian matrix (i.e., \( A \)).

Fig. 74. Dominant poles of the closed-loop system with respect to different values of \( \kappa_n \), (a) the conventional technique, (b) the proposed approach. Also, \( P_{c,pu} = 60\text{ kW} \), \( P_{pu} = 10\text{ kW} \), \( i_{st}^{EV} = 40\text{ A} \), \( \tau_c = 0.5s \), \( K_{I_v} = 20 \), and \( \tau_s = 1\text{ms} \).
To evaluate the impact of the proposed EV charging method on the transient voltage stability of the system, two case-study DC MGs are compared. In the first case, the DC MG utilizes a conventional EV charging method. On the other hand, the second case study DC MG uses the proposed EV charging method illustrated in Fig. 72. The parameters of the case study DC MGs are given in Table 15. Because the CPS and resistive load have a positive impact on the marginal voltage stability of the DC MGs [10], it is assumed that the PV power generation is less than 20% of its nominal value (i.e., $P_{pv} = 10kW$) and the resistive load is very small (i.e., $R_L = 100\Omega$), so that the marginal stability of the DC MG in severe stability conditions (i.e., small CPS, low resistive load, and large CPLs) can be evaluated.

![Figure 75](image1.png)

Fig. 75. Dominant poles of the closed-loop system with respect to different values of $\tau_c$, (a) the conventional technique, (b) the proposed approach. Also, $P_{cpl} = 60kW$, $P_{pv} = 10kW$, $i_{E}^c = 40\text{A}$, $\tau_c = 0.5\text{s}$, $K_{pv} = 2.5\downarrow$, and $K_p = 20\uparrow$.

To evaluate the impact of the proposed EV charging method on the transient voltage stability of the system, two case-study DC MGs are compared. In the first case, the DC MG utilizes a conventional EV charging method. On the other hand, the second case study DC MG uses the proposed EV charging method illustrated in Fig. 72. The parameters of the case study DC MGs are given in Table 15. Because the CPS and resistive load have a positive impact on the marginal voltage stability of the DC MGs [10], it is assumed that the PV power generation is less than 20% of its nominal value (i.e., $P_{pv} = 10kW$) and the resistive load is very small (i.e., $R_L = 100\Omega$), so that the marginal stability of the DC MG in severe stability conditions (i.e., small CPS, low resistive load, and large CPLs) can be evaluated.
shows the dominant poles of the closed-loop system in the case study DC MGs based on different values of the proportional gain of the PI voltage controller (i.e., $K_{Pv}$). In this experiment, both DC MGs supply relatively large CPLs. As seen in Fig. 74(a), the closed-loop poles of system move to the unstable region by increasing the $K_{Pv}$ in a DC MG with the conventional voltage control and EV charging method, and the voltage controller will be destabilized for $K_{Pv} > 2.9$. However, using the proposed EV charging method, the DC MG can remain stable for remarkably larger values of $K_{Pv}$ representing the higher stability margin of the MG voltage controller. Similarly, the voltage controller can remain stable for
considerably larger values of the integral gain (i.e., $\mathcal{K}_h$) with the proposed EV charging approach. Fig. 75 studies the impact of the communication delay (i.e., $\tau_c$) in both case study DC MGs. As seen, the MG’s voltage control system will be destabilized for $\tau_c > 3.9\text{ms}$ in DC MG with the conventional EV charging method. However, the DC MG can remain stable for significantly larger delays (i.e., $\tau_c < 30\text{ms}$) in the proposed approach due to the higher stability margin of the voltage controller. Fig. 75 shows the impact of the CPLs on the dynamic voltage stability of the DC MG. As seen, in conventional method, the DC MG will be destabilized for $P_{cpl} > 66\text{kW}$. However, the PI voltage controller can tolerate remarkably larger CPL values in the proposed approach. This means that the instability effect of the CPLs that usually requires advanced voltage control techniques can be easily addressed by using the proposed EV charging technique.

The reason that the MG voltage controller has a higher stability margin in the proposed EV charging technique is indeed related to the impact of the current allocation filter (i.e., the HPF). As seen in Fig. 72 the reference current computed by the voltage controller passes through an HPF and then is added to the reference current of the EV charger to employ the internal SC of
the EV for transient voltage regulation. In this structure, the HPF operates like a lead compensator which shifts the closed-loop poles of the DC MG to the left-hand side of the $j\omega$ axis (i.e., the stable region), thereby improving the marginal stability of the DC MG. This impact is illustrated in Fig. 78. As discussed, if $\tau_c \rightarrow 0$ the DC MG will have the same dynamic behavior to the conventional EV charging method. However, by increasing the filter’s time constant (i.e., $\tau_c$) the HPF provides a larger shift to the stable region and assigns a more portion of transient power fluctuations to the internal SC of the EV. Consequently, increasing the time constant of the HPF provides higher marginal stability for the DC MG.

6.6 Simulation Results

This section analyzes the impacts of the proposed EV charging method on the voltage quality and battery lifetime of the DC MGs. To this end, first, the power smoothing performance of the proposed approach as well as the accuracy of the system identification technique is evaluated using MATLAB/Simulink. Then, the performance of the proposed approach on the transient stability and voltage quality of DC MGs is analyzed using HIL testing.

6.6.1 Power Flow Analysis

To analyze the impact of the proposed approach on the lifetime of the CBESS (i.e., power smoothing performance) and investigate the power flow between the MG’s CBESS and EV, the performances of the case-study DC MGs are compared using MATLAB/Simulink. The case study MGs have the following features:
The first case study MG (i.e., Case 1) is a DC MG that utilizes the proposed EV charging method, and its circuit model and control structure is illustrated in Fig. 73.

The second case study MG has a similar structure to the Case 1 system, but it utilizes a conventional EV charging method (i.e., the HPF is deactivated in Case 2).

The corner frequency of the CBESS power smoothing filter (i.e., the HPF) is defined as 10 time larger than the estimated cut-off frequency of the EV power filtering system (i.e., $\eta/K_f = 10$) to guarantee that the high frequency current/power variations are only assigned to the EV’s SC.

The parameters of the DC MGs are illustrated in Table 15. Also, it is assumed that $R_L = 100\Omega$.

![Fig. 79. The net power profile (i.e., $P_{net}$).](image)

![Fig. 80. The estimated cut off frequency values for CBESS-EV power/current allocation system ($\eta = 5, K_f = 10, \omega_H = 0.02, \tau = 1\text{ms}$).](image)
• In both cases, the CBESS has 100kW nominal power and 2 hours of charge time. The EV’s BESS has 12.8kW nominal charge/discharge power and 4 hours of charge time with 80A nominal charge current. The internal SC of the EV also has 50kW nominal power and 1s charge time.

In this experiment, the PV power generation and load profile in Case 1 are similar to those of Case 2. Fig. 79 shows the net power profile (i.e., $P_{net}$) of the case study systems for 10 minutes. The net power profile shows the difference between demanded power by the resistive load and CPLs and the generated power by the PV sources that can be represented as

$$P_{net} = P_{CPL} + \frac{V_{bus}^2}{R_L} - P_{PV}$$  \hspace{1cm} (6.20)
Fig. 80 shows the estimated cut-off frequency of the EV internal power allocation system by the ARX model and the selected value for EV’s CBESS current allocation system (i.e., the HPF) in Case 1 system. As seen, the proposed system identification provides an accurate estimation of the internal BESS-SC current assignment filter of the EV. As seen, the selected cut-off frequency for the HPF is defined as 10 times larger than the internal filter of the EV to guarantee that the high-frequency variations of the net power are not absorbed by the EV’s BESS. In addition, due to the sudden load changes, the estimated value by the ARX model (i.e., \( \omega'_n \)) has some fast changes which are filtered by the designed first-order linear LPF to avoid undesirable transients. It should be noted that based on the selected cut-off frequency (i.e., \( \omega_c = 0.2 \) ), the HPF assigns almost all the instantaneous current ripples with frequencies

![SoC of ESSs in Case 1 (proposed method)](image)

**Fig. 83.** SoC variation of the ESSs in the proposed EV charging method (i.e., Case 1)

Case 2 is the conventional method.

![SoC of ESSs in Case 2 (conventional method)](image)

**Fig. 84.** SoC variation of the ESSs in the conventional EV charging method (i.e., Case 2).
higher than 1 rad/s or 0.16 Hz (i.e., $\omega > 5\omega_c$ or $f > 5f_c$) to the EV charger.

Table 16. Power smoothing analysis$^1$

<table>
<thead>
<tr>
<th>ESS</th>
<th>SAPV</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBESS</td>
<td>1.6 kW</td>
<td>11.7 kW</td>
<td></td>
</tr>
<tr>
<td>EV’s BESS</td>
<td>0.02 kW</td>
<td>0.014 kW</td>
<td></td>
</tr>
</tbody>
</table>

$^1$Case 1 is the proposed EV charging and Case 2 is the conventional method.

Fig. 81 and Fig. 82 depict the output power of the ESS units in Case 1 and Case 2 systems, respectively. In both cases, the EVs are in Stage 1 of their standard charging profile (see Fig. 71) in which the EV charges with a constant current/power. As seen in Fig. 82 in the conventional EV charging method, the EV’s SC is useless, and it receives no power. However, in the proposed EV charging method (i.e., Case 1), the EV’s SC absorbs the instantaneous power variation of the net power which smooths out the output power of the CBESS. Therefore, as it can be seen in Fig. 81 and Fig. 82, the output power of the CBESS has considerably smoother variations in the proposed EV charging method compared to the conventional approach. Fig. 83 and Fig. 84 illustrate the state of charge (SoC) variation of the ESS units in Case 1 and Case 2 systems, respectively. As seen, the SoC of CBESS and EV’s BESS experience similar profiles in the Case 1 and Case 2 systems which means that the proposed approach does not impact the steady-state power and stored energy in batteries (i.e., CBESS and EV’s BESS). On the other hand, the SoC of SC has completely different behaviors in Case 1 and Case 2 systems. The reason is that, in the conventional EV charging method, the SC does not absorb/release power, so its SoC almost remains unchanged. However, in the proposed EV charging approach the SoC of SC varies over time because it is utilized to absorb the high-frequency variations of the net power.
For quantified power smoothing analysis, the sum of absolute power variations (SAPV) is defined as

\[
SAPV = \sum_{k} \left| P_{\text{CBESS}}(kT_s) - P_{\text{CBESS}}(kT_s - T_s) \right|
\]  

(6.21)

where \( T_s \) is the sampling time of the measurements. Considering \( T_s = 1\text{ms} \), the SAPV can effectively show the CBESS power variations for frequencies less than 100Hz. So, it can cover all the high-frequency power variations caused by instantaneous renewable power fluctuations and sudden load shifts which mostly happen in 0.1 to 10 seconds time intervals (i.e., 0.1 to 10Hz). Then, the SAPVs of both cases are obtained based on the CBESS power profile in Case 1 and 2 shown in Fig. 13 and 14, respectively. This power smoothing comparison is shown in Table II indicating that the proposed EV charging method can reduce the CBESS power variations compared to the conventional technique by 86%. In addition, Table II shows that the power variations of the EV’s BESS remain very small in the proposed approach meaning that EV’s SC absorbs almost all the high-frequency power variations. So, since charging the Li-ion batteries with frequency power variations (or current ripples) can noticeably reduce their lifetime [110,114], one can conclude that the proposed method can improve the CBESS lifetime without degrading the BESS of EVs.

6.6.2 HIL testing

The transient response and dynamic stability of the case study DC MGs (Case 1 and Case 2) are studied in a HIL testbed. The schematic of the HIL testbed is shown in Fig. 85. The testbed includes the real-time digital simulator, Opal-RT, and a microprocessor Raspberry Pi. RT-LAB installed host PC is used to run the DC MG’s power system model in real
time. The plant including the DC bus, power electronic converters, and current controllers is modeled in Simulink (see Fig. 85), and it runs in the Opal-RT via RT-LAB. The MG voltage control and current sharing system in Fig. 73 are developed in a C language script and run on the Raspberry Pi. The communications between all the hardware are established by an Ethernet connection. The MG controller receives the voltage measurement from the plant and calculates the reference control inputs for the current controller of the converters, then sends them back to the plant via Modbus TCP/IP. The sampling time of the OPAL-RT simulator is $250\mu s$ and the action time of the Raspberry Pi controller is 1ms.
6.6.2.1 CPL Tolerance and Voltage Stability: In this section, to analyze the impact of the proposed EV charging method on the dynamic stability of the voltage control system, it is assumed that the voltage controllers have similar proportional and integral gains in Case 1 (i.e., the MG with the proposed EV charging method) and Case 2 (i.e., the MG with conventional EV charging method). In addition, the system parameters are exactly similar to the DC MGs that are compared in Fig. 74 to Fig. 78 for eigenvalue analysis in which \( \kappa_{pv} = 2.5 \), \( \kappa_{iv} = 20 \) and the PV has 10kW power generation. Also, there is a 1ms time delay between the real-time simulator (i.e., OPAL-RT) and the MG control system (i.e., the Raspberry Pi controller). In this experiment, the CPL value gradually increases in both cases to see which one of the case study systems becomes unstable sooner. Knowing the fact that the CPLs reduce the marginal stability of the DC MGs, the MG control strategy that provides higher CPL tolerance indicates a higher stability margin. As seen in Fig. 86 the DC bus voltage becomes unstable in the DC MG with the conventional EV charging method for CPLs larger than 65kW while the DC MG remains stable in the proposed EV charging method. This result also verifies the small-signal stability of the DC MGs provided in Section 6.5 showing the eigenvalues of the closed-loop system move to the unstable region for CPLs larger than 66kW.

6.6.2.1 Transient Voltage Stability: This section evaluates the transient voltage oscillations in the MG DC bus during sudden load changes. As discussed in the small-signal stability analysis of the DC MGs, the voltage controller can operate with larger gains in the DC MG with the proposed EV charging method due to its higher stability margin. In this respect, the gains of the voltage controller in Case 1 (i.e., the DC MG with proposed EV charging) are defined as \( \kappa_{pv} = 3.7 \) and \( \kappa_{iv} = 80 \). On the other hand, the gains of the
voltage controller in Case 2 (i.e., the DC MG with conventional EV charging) are defined as $K_p = 1.5$ and $K_i = 20$ to avoid instability in large CPLs. Fig. 87 shows the transient response of the case study systems during sudden load changes (please also see the definition of $E_{Vi}$, $CBESS_i$, $BESS_{EVi}$, and $SC_{EVi}$ in Fig. 4 and 5). In both case study systems, it is assumed that the CBESS is responsible for MG voltage regulation and EV chargers are in constant current charging mode to charge the EV’s BESS with its nominal current (i.e., 80A). Also, the nominal voltage is 200V and the nominal load power is 100kW. In addition to this constant current, in the proposed EV charging method (see Fig. 72) the EV charger coordinates with the CBESS to supply the transient current/power during the sudden load changes.
changes. As seen in Fig. 87(b), the DC MG that utilizes the proposed EV charging method (i.e., Case 1) experiences significantly fewer transient voltage deviations during the sudden load changes compared to the DC MG with the conventional EV charging technique. In addition, it is clear that the CBESS experiences smoother current variations in Case 1 (the proposed EV charging method) because a large portion of the transient power/current variations are supplied by EV (see Fig. 87(c) and (d)).

Fig. 87(e) and (f) illustrate that using the proposed data-driven adaptive filtering technique, the transient/instantaneous current fluctuations are only absorbed by the internal SC of the EV. As a result, the charge current profile of the internal BESS of the EV remains constant which is similar to the conventional method for EV charging. Therefore, the proposed control structure and adaptive filtering technique can effectively utilize the internal SC of modern EVs with HESS technologies to supply the transient power/current oscillations without impacting the standard charging profile of the internal BESS of the EVs validating the power smoothing results in Table 16. Table 17 also provides the quantified comparison between the proposed EV charging and the conventional method. As seen, the amplitude of the transient voltage deviations is decreased in Case 1 (i.e., the

<table>
<thead>
<tr>
<th>Case</th>
<th>Amplitude (p.u)</th>
<th>Settling Time (Error &lt;0.01 p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.011 p.u</td>
<td>0.41s</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.084 p.u</td>
<td>0.93s</td>
</tr>
</tbody>
</table>

1 Load steps up around 0.06 p.u. (see the load profile in Fig. 19 (a)).
2 Nominal voltage is 200V and nominal load is 100kW.
The simulation results showed the superiority of the proposed MG control structure and EV charging method over the conventional technique in terms of reducing the CBESS power variations (i.e., fewer CBESS degradation) and higher transient voltage quality (i.e., the better response of the MG voltage control system). In addition, as it was shown in Section V, the key advantage of the proposed technique is that it does not impact the charging profile of the EVs’ BESSs. This means that a building-level DC MG can take advantage of the proposed EV charging method without posing a cost to the EV owners by degrading the BESS of their EVs. However, the implementation of this technology may
still have some practical challenges that need to be addressed. The main challenge is that in some cases, the owners of the building-level DC MG and EVs are different which may cause a conflict of interest. To address this issue, the DC MG owner can consider some incentives or discounts for EVs that are charged with the proposed EV charging method because of sharing their SC capacity with the DC MG. To determine the optimal amount of these incentives further studies are still needed. Therefore, a future research direction of this work can be the investigation of optimal incentives for the EVs that share their SC capacity with the DC MG using the proposed approach.

In addition, in this work, a conservative approach is used to adjust the bandwidth of the CBESS power smoothing filter with respect to the EV internal power filtering system. For instance, the corner frequency of the CBESS power smoothing filter is defined as 10 times larger than the estimated corner frequency of the EV’s power filtering system. On the one hand, this conservative strategy is beneficial to simply guarantee that the high-frequency current variations of the RESs are only assigned to the EV’s SC so that the EV’s BESS is not degraded. On the other hand, a large portion (e.g., 30% to 50%) of the SC capacity of the EV may remain unused in this technique. So, further studies are suggested to find out the optimal value for the bandwidth of the CBESS power smoothing filter. Besides, if the EV companies, provides the specifications of the EV power management system, in a way that this information is easily accessible for the EV charger or the MG controller, it can significantly facilitate the implementation of this work and enhance the efficiency of the proposed EV charging method.
6.8 Conclusion

This chapter proposes a method for utilizing the internal SC of EVs with battery-SC HESS technologies to absorb the instantaneous power variations in an islanded building-scale DC MG. The primary goal of this method is to increase the lifetime of the MG’s CBESS and improve the performance of the MG voltage control system. Wherefore, an adaptive FB current allocation system is designed which assigns the high-frequency current variations to the internal SC of the EV and the low-frequency current variations to the CBESS without impacting the charge current of the EV’s BESS. So, the output current/power of the MG’s CBESS is smoothed while the charging profile of the EV’s BESS is not affected. In other words, using the proposed EV charging method, the lifetime of the MG’s CBESS can be improved without degrading the internal BESS of the EV. In addition, a small-signal stability analysis is performed to assess the impact of the proposed EV charging method on the voltage stability of an islanded building-scale DC MGs. The stability analysis indicates that the stability margin of the DC MG increases during the charging process of the EV with the proposed method enabling the PI voltage controller to operate with higher gains. Hence, the MG voltage controller can provide faster responses to load variations, thereby reducing the transient voltage deviations during sudden load changes. Then, the performance of the proposed approach is validated using MATLAB/Simulink as well as a HIL testbed that employs a real-time OPAL-RT simulator, and a Raspberry Pi microprocessor. The simulation results show that the CBESS has 86% fewer power variations using the proposed approach. Besides, the HIL testing results shows that the transient voltage quality of the system is improved by reducing the amplitude of the voltage deviations and shortening the settling time of the DC bus voltage variations in a specific load change scenario.
Chapter 7: Conclusions and Future works

7.1 Conclusions

This dissertation focuses on proposing and validating control and power management strategies for battery-supercapacitor and battery energy storage systems in DC nanogrids. These strategies aim to improve the stability, efficiency, and lifetime of the energy storage systems while also enhancing the performance of the dc nanogrids as a whole.

In Chapter 2: Adaptive Control and Management of Clustered DC Nano-grids, an adaptive multi-agent control strategy is proposed to provide effective voltage regulation and power sharing in an MNG system. The proposed approach utilizes a hierarchical control system, with top-level discrete-event supervisory controllers and low-level controllers responsible for power sharing and voltage regulation. An adaptive model predictive controller is deployed to regulate the voltage of the NGs' local DC bus, while a switching consensus control algorithm regulates the voltage of the MG common DC bus and offers accurate power sharing among the NGs. Overall, the proposed adaptive multi-agent control strategy provides effective cooperation of the clustered NGs while maintaining scalability and flexibility.

In Chapter 3: A Distributed Rule-based Power Management Strategy in a Photovoltaic/Hybrid Energy Storage System based on an Active Compensation Filtering Technique, a distributed rule-based supervisory control and power management technique is presented for a PV/HESS system. The approach utilizes intelligent agents that can react to the environment by changing their dynamical behavior and/or operational mode. The proposed hybrid modeling framework facilitates the design of a hybrid adaptive filter for
the HESS agent that can manage the current oscillations after switching instances. The distributed supervisory control approach provides efficient and reliable operation of the PV/HESS system by preventing the SCs and BESSs from SOC violation. Additionally, the proposed distributed power management technique reduces the computational complexity of the supervisory control system compared to its equivalent centralized method.

In Chapter 4: A Model Predictive Control Strategy for Performance Improvement of Hybrid Energy Storage Systems in DC Nano-grids, an MPC-based SC SoC restoration technique is proposed that works in tandem with an LTI filter to perform the current allocation between the BESS and SC. The proposed approach maintains the SoC of SC in a predefined range, ensuring the continuous operation of the SC and filter, and improves the transient response and voltage quality of the system by enabling the MG voltage controller to work with higher gain values. The performance of the proposed FB-MPC method is then validated by simulating a case study DC MG.

In Chapter 5: Effective Utilization of Grid-forming Cloud Hybrid Energy Storage Systems in Islanded Clustered DC Nano-grids for Improving Transient Voltage Quality and Battery Lifetime, a CHESS technology is proposed along with a modified control scheme for DC NGs to improve the voltage quality and battery lifetime in an islanded DC MNG system. The proposed CHESS technology can provide fewer power variations for all the community and local BESSs by sending all the high-frequency power variations to the community SC of the CHESS unit. Additionally, the CHESS technology requires less SC size compared to its equivalent distributed HESS technology, showing higher efficiency. The advantages of the proposed CHESS technology over the conventional
CBESS method are discussed by simulating and comparing two case study MNG systems in MATLAB/Simulink.

In Chapter 6: A Method for Charging Electric Vehicles with Battery-supercapacitor Hybrid Energy Storage Systems to Improve Voltage Quality and Battery Lifetime in Islanded Building-level DC Microgrids, an adaptive FB current allocation system is designed to utilize the internal SC of EVs with battery-SC HESS technologies to absorb the instantaneous power variations in an islanded building-scale DC MG. The proposed method assigns the high-frequency current variations to the internal SC of the EV and the low-frequency current variations to the CBESS without impacting the charge current of the EV's BESS. The primary goal of the method is to increase the lifetime of the MG's CBESS and improve the performance of the MG voltage control system. The effectiveness of proposed approach is also validated using theoretical and experimental testing.

### 7.2 Future works

In future works, the following topics can be studied:

- A future work for proposed adaptive battery SoC balancing strategy in Chapter 2: Adaptive Control and Management of Clustered DC Nano-grids could include implementing the in a real-world MG system and conducting a comprehensive performance evaluation in various scenarios. Additionally, investigating the impact of renewable energy sources and the integration of other distributed energy resources on the proposed approach's effectiveness could be an interesting research direction. Furthermore, exploring the applicability of the proposed technique in other types of
microgrids, such as AC MGs or hybrid AC/DC MGs, could be a fruitful area for future research.

- A possible future research direction for Chapter 3: A Distributed Rule-based Power Management Strategy in a Photovoltaic/Hybrid Energy Storage System based on an Active Compensation Filtering Technique could be to explore the potential of incorporating machine learning and optimization techniques to improve the system's performance and reduce the reliance on rule-based control strategies. This could involve developing more sophisticated control algorithms that can adapt to changing conditions and optimize the system's performance in real-time.

- The proposed FB-MPC control strategy In Chapter 4: A Model Predictive Control Strategy for Performance Improvement of Hybrid Energy Storage Systems in DC Nano-grids can be also applied in HESS which are used DC microgrids with more complex topology and multiple grid-forming DERs. However, changing the line impedance, MG topology, and the number of grid-forming HESS units can affect the dynamic stability of a system. Therefore, future research for the proposed control strategy can focus on developing a detailed dynamic model of the system and applying further stability analysis to investigate the impact of these parameters on the dynamic stability of a DC MG with multiple DERs.

- The proposed FB-MPC technique in can address the instability effect of the CPLs and improve the transient voltage stability of the DC MG. A future research direction is to compare the performance of the proposed FB-MPC
technique with existing active stabilizers in terms of stability improvement and cost-efficiency for different MG applications.

• The proposed CHESS technology in Chapter 5: Effective Utilization of Grid-forming Cloud Hybrid Energy Storage Systems in Islanded Clustered DC Nano-grids for Improving Transient Voltage Quality and Battery Lifetime can deliver the same power smoothing performance as its distributed HESS counterpart, but with fewer converters and a smaller required SC size if the same filter bandwidth is designed for current allocation systems. As a result, the proposed CHESS architecture can be a more cost-effective solution for clustered MG applications. Therefore, conducting a precise cost analysis of the various technologies for real microgrid conditions could further substantiate the benefits of the proposed CHESS technology in practical applications.

• One of the primary challenges in implementing the proposed EV charging method discussed in Chapter 6: A Method for Charging Electric Vehicles with Battery-supercapacitor Hybrid Energy Storage Systems to Improve Voltage Quality and Battery Lifetime in Islanded Building-level DC Microgrids for real world applications is the potential conflict of interest arising from different owners of building-level DC microgrid (MG) and electric vehicles (EVs). However, to mitigate this challenge, the owner of the DC MG could provide incentives or discounts for EVs charged with the proposed EV charging method in exchange for sharing their storage capacity with the DC MG. More research is required to determine the
optimal amount of these incentives. As such, a potential future research direction for this study is to explore the ideal incentives for EVs that share their storage capacity with the DC MG through the proposed approach.

- The approach in Chapter 6: A Method for Charging Electric Vehicles with Battery-supercapacitor Hybrid Energy Storage Systems to Improve Voltage Quality and Battery Lifetime in Islanded Building-level DC Microgrids that is used to adjust the bandwidth of the CBESS power smoothing filter in relation to the EV's power filtering system is very conservative. This conservative strategy is beneficial to guarantee that the high-frequency current variations of the RESs are only assigned to the EV's SC, but it may lead to a large portion of the EV's SC capacity remaining unused. Further research is suggested to find the optimal value for the bandwidth of the CBESS power smoothing filter. If EV companies provide specifications for their power management system, it would significantly facilitate the implementation of this work and enhance the efficiency of the proposed EV charging method.
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