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Optimal Relay Location in a Microgrid Using Optimization Techniques

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Abstract

This thesis proposes an optimal relay placement approach for microgrids. The algorithm separately calculates the System Average Interruption Frequency Index (SAIFI) of a microgrid in both grid-connected and islanded microgrid modes. The objective is to find the optimal relay locations such that the microgrid overall SAIFI is minimized. The power electronics interfaces associated with distributed energy resources may be classified as grid following or grid forming. As opposed to grid-following distributed energy resources (DERs) such as typical solar inverters, grid-forming inverters can control the microgrid voltage and frequency at the point of their interconnection. Therefore, these DERs can facilitate the formation of sub-islands in the microgrid when the protective relays isolate a portion of the microgrid. The exchange market algorithm (EMA) is used as the optimizing function. The effectiveness of the proposed optimal relay placement approach is verified using an 18-bus microgrid and IEEE 123-bus test system.

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Introduction

Optimal relay placement in microgrids and distribution systems has gained much attention to improving power system resilience. There are many techniques available in the literature that utilize different optimization tools to optimally place relays in distribution systems and microgrids 0. These techniques can be categorized based upon their objective function definition, system type, and optimization technique utilized. In terms of the optimization objectives, the majority of the techniques focus on minimizing the protection system capital cost, customer power interruption duration or frequency, or both. The protection system capital cost relates to the total number of available relays. The customer power interruption duration or frequency are quantified using the System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI). The system type refers to the test systems under study which include distribution systems with and without distributed energy resources (DERs) and microgrids.

The optimal relay placement problem has been addressed using various optimization techniques including genetic algorithm 0-[3], tabu search [4], ant colony system algorithm [5], immune algorithm [6], binary programming [7], mixed-integer linear programming [8], particle swarm optimization (PSO) and a Monte Carlo simulation [9]. Optimal relay placement in radial distribution systems without DERs has been investigated in [6]-[11]. In [6], fault indicators are optimally placed in the distribution system using the immune algorithm. The objective is based on the reliability index of each service zone to solve the expected energy not served due to fault contingency. In [7], protective relays are optimally placed using binary programming with the objective of minimizing interruption of service. In [8], mixed-integer linear programming (MILP) is used to determine the optimal locations for sectionalizer placement in a distribution system. In

[9], PSO and Monte Carlo simulations are used to optimally place reclosers and autosectionalizers in a distribution system. However, these are verified using a radial distribution system in which DERs are not present. DERs can adversely impact the coordination of protective devices by inducing a reverse power flow condition [12]-[13]. In [14], risk analysis is used to optimize the placement of relays in systems with large DER penetration. The protection system risk is defined as the probability of a particular fault multiplied by the total affected load. In [15], fault indicators are optimally placed in a DER penetrated distribution system using the genetic algorithm. The objective is to minimize the average outage times of customers and outage costs. This reference proposes a formula to calculate the fault probability for each section using the fault probabilities of individual components such as conductors, DERs, and switches.

Optimal relay placement in microgrids has been addressed in [16]-[20]. In [17], a differential zone protection scheme for microgrids is proposed. The proposed scheme utilizes the genetic algorithm to find the optimal quantity and location of differential relays with the objective of minimizing the total cost of the relays and customer power outages. The proposed scheme relies heavily upon differential schemes which are communication assisted and are not common practice in electric power utilities. The common protection practice in distribution systems is built upon overcurrent relays, reclosers, and sectionalizers. Reference [18] uses PSO to optimally place overcurrent relays in a microgrid. An optimization problem is defined to coordinate overcurrent relays. However, the proposed method in [18] does not take the possibility of reverse power flow into consideration. Moreover, the objective of the relay placement approach proposed in [19] is to find the relay locations that satisfy the coordination of available overcurrent relays. This objective is useful when planning out a new distribution network or expanding an already existing one. However, for the already existing portion of the network, moving around relays that have already been placed may be costly or impractical. In [19], a multi-objective PSO approach considering binary decision variables is proposed which seeks to minimize SAIFI, SAIDI. However, the proposed method does not consider both islanded and grid-connected modes of the microgrid. Moreover, the possibility of load shedding is disregarded by assuming that all of the loads in the system are uncontrollable. The impact of microgrid operating mode on the optimal location of protective relays is considered in [20]. The optimization problem in [20] is formulated to minimize SAIFI, SAIDI, and energy not supplied. PSO and Monte Carlo simulation are used to solve the optimization problem. However, the optimization problem formulation and test results only consider microgrid islanded mode.

The literature review highlights the significance of finding optimal relay locations in highly DER penetrated distribution systems and microgrids. However, there is a need for designing a comprehensive tool that

- addresses the optimal relay locations in a microgrid considering both islanded and grid-connected modes,
- performs load shedding in created sub-islands after the protection system operates,
- accounts for the type of DERs (grid-forming versus grid-following).

DER classification is of particular importance because of the distinct ability of grid-forming DERs for facilitating the stable operating distribution system islands [21].

In this thesis, these challenges are addressed by designing an optimization tool for finding the optimal relay locations in a microgrid system considering different operating modes, DER types, and the possibility of load shedding. The proposed approach considers both grid-connected and islanded operating modes and finds the optimal locations of relays such that the overall SAIFI of the microgrid in both modes is minimized. The proposed optimization problem is solved using

Exchange Market Algorithm (EMA) which is a population-based, meta-heuristic optimization algorithm [22]-[28]. The effectiveness of the proposed optimal relay placement approach is verified using an 18-bus microgrid and IEEE 123-bus test system. The algorithm is also compared against the Matlab PSO function and a brute force algorithm.

Background

Microgrid Protection

Microgrids can operate in both grid-connected and islanded modes. Depending on the operating mode, microgrid buses may experience different fault current levels. Therefore, it is of value to design a microgrid protection system that can effectively protect the microgrid in both grid-connected and islanded modes. Due to the presence of DERs and potential reverse power flow in microgrids, the traditional overcurrent relays used in distribution systems cannot be employed. According to [29], conventional microgrid protection schemes utilize nondirectional overcurrent relays, communication assisted differential protection or adaptive protection. In this thesis, it is assumed that microgrid is adopting nondirectional overcurrent relays.

An Introduction to EMA

In this thesis, the relay placement algorithm is optimized using EMA. EMA is inspired by the stock market in which stockholders may adopt different decisions according to rules and their own experience and policies **Error! Reference source not found.**. Stockholders seek to increase their own benefits by dividing stocks while undertaking less loss. In EMA, the optimization is performed in two modes corresponding to balanced and fluctuating condition of the market. In the balanced condition of market, unlike fluctuating mode, stockholders can obtain the highest possible profit by predicting the current situation without considering the risk in their transactions. In a stock market, the risk of swinging degrees may be either very beneficial or very harmful for the stockholders **Error! Reference source not found.**. The diverse nature of prevailing situations in the market results in the market complexity and different behaviors of stockholders **Error! Reference source not found.**. A successful stockholder follows performance of other successful stockholders, uses past events to improve current performance, learns from the mistakes to modify the process, avoids investing in sectors that do not comply with stockholder's policy, performs the maximum purchase in favorable conditions, avoids participation in unfavorable conditions, and gives the highest priority to maintaining capital in all market conditions. In EMA, each answer of the problem resembles a stockholder, while its stocks are considered as the parameters related to the optimization problem. At the end of each exchange, the algorithm ranks stockholders in terms of the total value of their shares in the market **Error! Reference source not found.**.

EMA in Balanced Mode

In this mode, various stockholders compete with each other to obtain the maximum benefit without taking any risk. In the balanced mode, members of stock market according to their fitness function are classified into three categories:

- Top-rank stockholders form around 10% to 30% of total population members. These stockholders do not change their stocks in order to maintain their rank in the market. These stockholders represent the best answers of the problem.
- Medium-rank stockholders from around 20% to 50% of total population members. These stockholders seek to achieve a global optimum by comparing their stocks with stocks of the first category. Each stockholder selects the value of his/her shares based on the values of stocks of the first category members using

$$pop_j^{group(2)} = r \times pop_{1,i}^{group(1)} + (1-r) \times pop_{2,i}^{group(1)}, \quad i = 1,2,3,\cdots n_i \quad and \quad j = 1,2,3,\cdots n_j \tag{1}$$

where $pop_{1,i}^{group(1)}$ and $pop_{2,i}^{group(1)}$ are two randomly selected stocks from the top-rank stockholders. $pop_j^{group(2)}$ is the stock value of the intended member of the second category. n_i and n_j are the number of members in the first and second category, respectively. r is a random number between zero and one.

- Low-rank stakeholders change their share values using the stocks of first category by taking more risk and a broader search domain compared to the second category as

$$S_k = 2\times r_1 \times \left(pop_{1,i}^{group(1)} - pop_k^{group(3)} \right) + 2\times r_2 \times \left(pop_{2,i}^{group(1)} - pop_k^{group(3)} \right), \qquad (2)$$

$$pop_k^{group(3),new} = pop_k^{group(3)} + 0.8\times S_k , \qquad (3)$$

where $pop_{1,i}^{group(1)}$ and $pop_{2,i}^{group(1)}$ are the selected stocks from the top-rank stockholders. $pop_k^{group(3)}$ is the stock value of the intended member of the third category. r_1 and r_2 are random numbers between zero and one.

EMA in Oscillation Mode

When the stock market conditions fluctuate, the stockholders exchange their stocks by intelligently taking risks to achieve a higher rank in the market. In this case, similar to the balanced state, members of stock market are divided into 3 categories:

- Top-rank stockholders (10% to 30% of total members) seek to maintain their rank among the other stockholders and do not change their stocks.

- Medium-rank stockholders (20% to 50% of total members) seek to improve their rank by changing their stocks. As their rank in the market improves, they are associated with less risk. After modifying the stocks, the total value of stakeholder shares must remain constant according to

$$\Delta n_{t1} = n_{t1} - \delta + \left(2\times r\times \mu \times \eta_1 \right), \qquad (4)$$

$$\mu = \frac{t_{pop}}{n_{pop}}, \tag{5}$$

$$n_{t1} = \sum_{y=1}^{n} s_{ty} \quad y = 1, 2, 3, \cdots, n, \tag{6}$$

$$\eta_1 = n_{t1} \times g_1, \tag{7}$$

$$g_1^k = g_{1,\max} - \frac{g_{1,\max} - g_{1,\min}}{iter_{\max}} \times k, \tag{8}$$

where Δn_{t1} represents the total changes in the stocks of a member from the second category. This amount of change is deducted from a number of shares of the intended member in a probabilistic manner and is then added to a number of its shares such that the total stock remains constant. n_{t1} is the sum of the intended member's shares before the changes. δ, μ, η_1, and r represent market characteristic, the rank coefficient of the intended member, risk level for the members of the medium-rank category, and a random number between zero and one, respectively. In (5), t_{pop} and n_{pop} indicate the rank of the member and the total number of market members, respectively. g_1^k and k are the risk level of the intended member from the medium-rank category and the value of the algorithm's iteration counter. In the medium-rank category, a portion of Δn_{t1} is randomly added to one of the stocks of a stakeholder in the second category. This process continues until Δn_{t1} is completely added to all stocks of the corresponding stockholder. In this procedure, the total value of stocks for each shareholder must remain constant. Market information, δ, plays an important role to increase the convergence speed of algorithm to the final answer.

- Low-rank stockholders seek to achieve higher ratings by changing their stock values in a broader search domain. Stock changes in this category are based on

$$\Delta n_{t3} = 4 \times r_s \times \mu \times \eta_2, \tag{9}$$

$$r_S = 0.5 - rand\,, \tag{10}$$

$$\eta_2 = n_{t1} \times g_2\,, \tag{11}$$

where Δn_{t2} is the total changes in the shares of the low-rank stockholders. η_2 and g_2 are the risk level of the intended member and the risk taken, respectively. r_s is a random number in the [−0.5, 0.5] range. *rand* denotes a uniformly distributed random number. In the oscillation mode, the low-rank category members are not required to maintain their total value of stocks at a constant value. In the above equations, g_2 is between zero and one and describes the amount of risk taken in changing stocks.

RELAY PLACEMENT ALGORITHM FOR MICROGRIDS

The objective of the proposed relay placement algorithm is to find the optimal locations for a fixed number of available relays such that the microgrid's overall SAIFI is minimized. The proposed optimal relay placement algorithm considers both grid-connected and islanded microgrid modes. The algorithm separately calculates the SAIFI of the microgrid in each operating mode. Then, two weighting factors corresponding to different operating modes are used to calculate the overall SAIFI of the microgrid. As opposed to grid-following DERs, grid-forming DERs can control the microgrid voltage and frequency at the point of their interconnection. Therefore, these DERs can facilitate the formation of sub-islands in the microgrid when the protective relays isolate a portion of the microgrid. If there is at least one grid-forming DER available in a sub-island, that sub-island may be able to continue supplying its local load depending upon load demand and load shedding capability.

The proposed relay placement algorithm utilizes a matrix representation to model the microgrid. The connectivity matrix (CM) describes the connection between two buses in the microgrid, with a one for connected and zero otherwise. The protection matrix (PM) denotes the locations of relays. If there is a relay located on a line from bus *i* to *j*, then the element at row *i* and column *j* of PM matrix is equal to one. It is assumed that microgrid has a limited number of relays available. Based on the number of relays and microgrid topology, a limited number of PM candidates are created which will be later used in the optimization process. In the microgrid system, all relays are assumed to be nondirectional. The load matrix (LM) defines the location of loads inside microgrid. If there is a load connected to bus *i*, then the element at row *i* and column *i* of LM matrix is equal to the power rating of that load, otherwise zero. The generation matrix (GM) defines the locations of DERs within the microgrid. If there is a DER connected to bus *i*, then the element at row *i* and column *i* of GM matrix is equal to the power rating of that DER, otherwise zero. In the grid-connected mode, the point of common coupling (PCC) bus will have a nonzero value in GM. This value is assumed to be very high due to the support from the bulk electric system. In the islanded mode of operation, the PCC will have a zero value in GM. The fault probability matrix defines the probability of fault occurrence on each of the microgrid lines or cables.

The proposed algorithm for finding the optimized location of protective relays is as follows

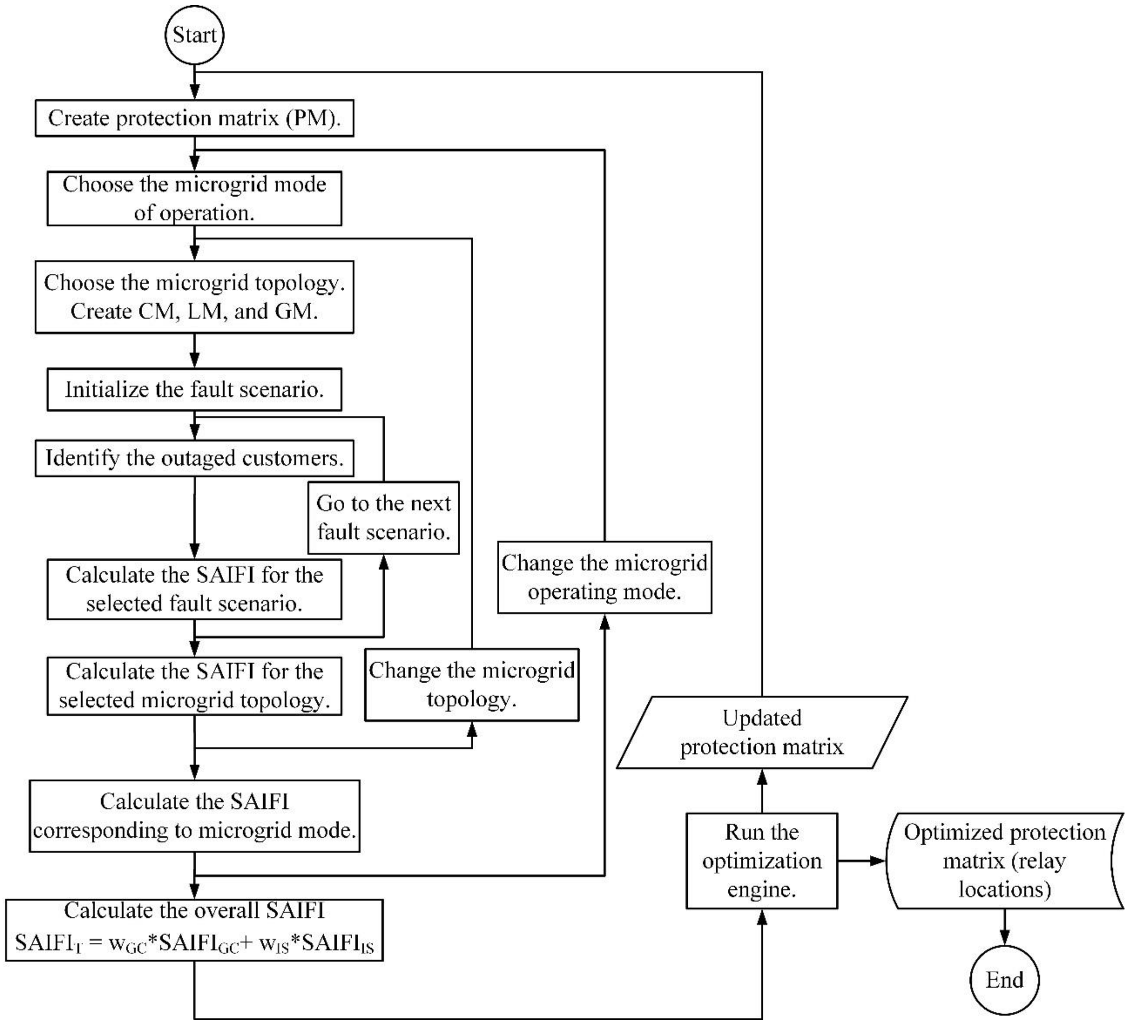

Figure 1 Optimal relay placement algorithm flowchart

Step 1. Initialize PM.

Step 2. Choose the microgrid mode of operation, i.e., grid-connected or islanded mode.

Step 3. Choose the microgrid topology based on the status of the tie lines. Create CM, LM, and GM accordingly.

Step 4. Apply a fault at every single line or cable section one at a time (this is an interruption event).

Step 5. For each fault scenario (interruption event), calculate the SAIFI:

a. Go to PM to find what relays are located on the faulted line:

i. If there is a relay at each terminal, the algorithm stops searching for protection elements.

ii. If there is not a relay on at least one terminal of faulted line, the algorithm will look for backup protection elements until all the backup elements are identified.

b. Identify the available sub-islands after the protection relays operate:

i. If there is at least one grid-forming DERs inside that sub-island: Define the island load matrix (LM_i) by adopting the elements of LM that correspond to the available buses in the island. Define the island generation matrix (GM_i) by adopting the elements of GM that correspond to the available buses in the island. Identify the power deficit in the sub-island.

ii. If there are no grid-forming DERs inside the sub-island, loads will experience power outage.

c. Identify number of customers that face power outage.

Step 6. Return to Step 3 if all fault scenarios have not yet been considered. Calculate the total SAIFI for all interruption events as

$$SAIFI_{Ti} = \sum_{i=1}^{N} \lambda_i N_{load,i} \Big/ N_{load,T} \,, \qquad (12)$$

where $SAIFI_{Ti}$ is the microgrid SAIFI in i^{th} topology; N is the total number of fault scenarios; λ_i is the probability of fault on line *i;* $N_{load,i}$ is the number of interrupted customers for the interruption event under study; and $N_{load,T}$ is the total number of customers.

Step 7. Go to Step 2 until all microgrid possible topologies are covered.

Step 8. Calculate the overall SAIFI for the specific microgrid operating mode as

$$SAIFI_m = \sum_{i=1}^{N_T} w_{Ti} SAIFI_{Ti} \,, \qquad (13)$$

where N_T shows the total number of possible topologies; w_{Ti} denotes the weighting factor for i^{th} topology; $SAIFI_m$ is the microgrid SAIFI in a specific operating mode (i.e., $SAIFI_{GC}$ and $SAIFI_{IS}$ denoting the SAIFI in grid-connected and islanded modes, respectively).

Step 9. Return to Step 2 until both microgrid connection modes are considered.

Step 10. Calculate the overall SAIFI for the microgrid as

$$SAIFI_T = w_{GC}SAIFI_{GC} + w_{IS}SAIFI_{IS}\,, \qquad (14)$$

where w_{GC} and w_{IS} are the weighting factors that are chosen by the microgrid operator based on the probability of microgrid operation during a year in islanded or grid-connected mode. $SAIFI_T$ is the objective function of the optimization algorithm.

Step 11. EMA generates a new PM. EMA continues this process until the PM with the minimum $SAIFI_T$ is found.

Results

The effectiveness of the proposed optimal relay placement algorithm is verified using two sample microgrid test systems, namely 18-bus and 123-bus microgrids which are shown in **Error! Reference source not found.** and Fig. 7, respectively. In both cases, grid-connected and islanded weighting factors are equal to 0.8 and 0.2, respectively.

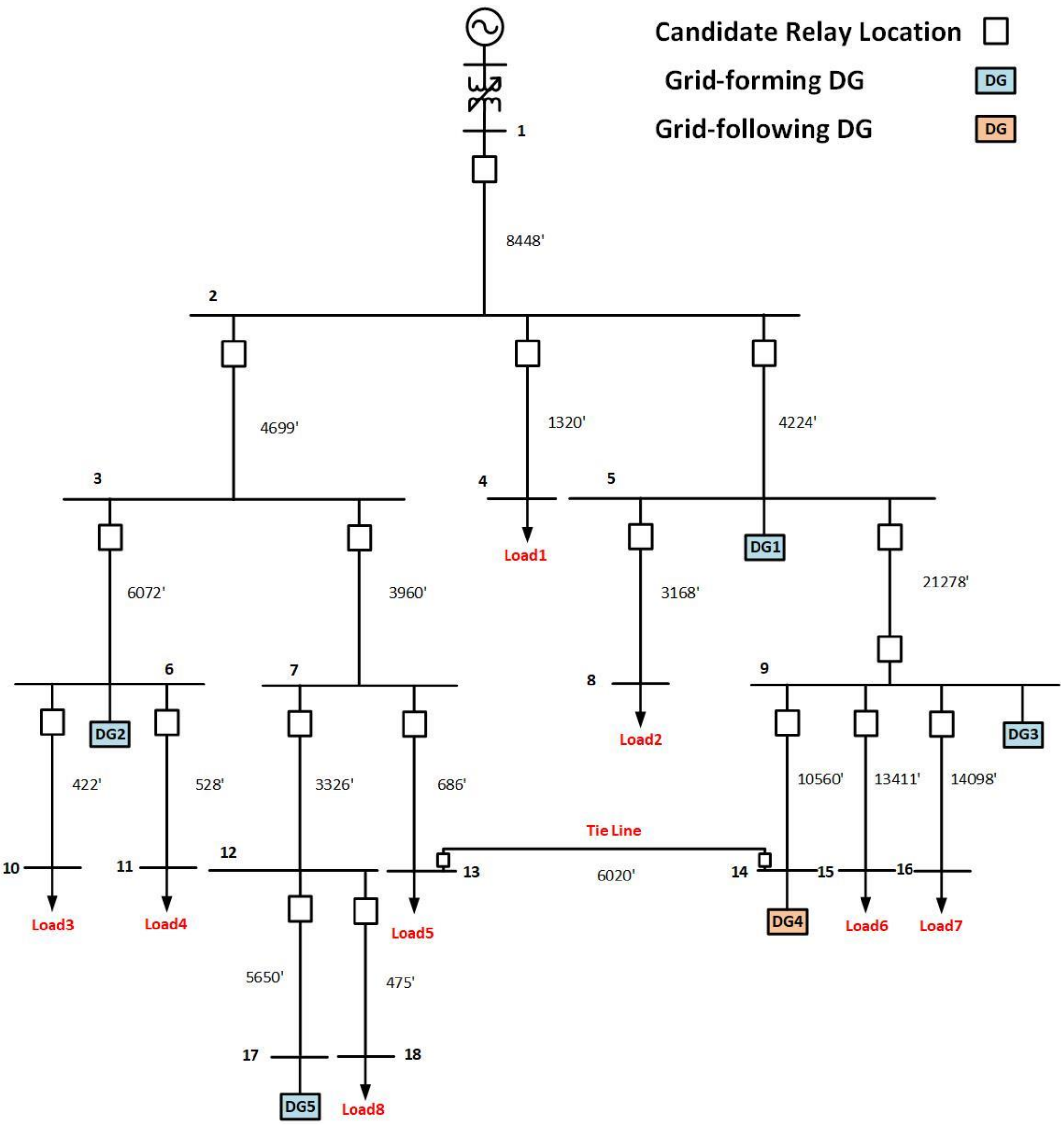

Figure 2: 18 Bus Microgrid with DGs

18-bus Microgrid System Simulation Results

The 18-bus distribution system in 0 is slightly modified and converted to a microgrid by adding five DERs. The single line diagram of the 18-bus microgrid test system is shown in **Error! Reference source not found.**. The microgrid load and DER ratings are provided in Tables 1 and 2, respectively.

TABLE 1

18-BUS MICROGRID LOAD RATINGS

Load#	1	2	3	4	5	6	7	8
kVA	50	50	50	50	150	50	50	50

TABLE 2

18-BUS MICROGRID DER RATINGS

DG#	1	2	3	4	5
kVA	50	50	50	50	50

It is assumed that DG4 is a grid-following DER, while the others are grid-forming. This microgrid system has 17 lines interconnecting microgrid buses. For SAIFI calculations, the probability of faults on the lines corresponds to the line lengths shown in **Error! Reference source not found.**. The longer a line is, the higher fault probability is for that line. The longest line is assumed to have a fault probability of 1 while the other line probabilities are scaled down based on their lengths. It should be noted that the fault probability on the lines also depends on the geographic conditions of the lines. For example, the fault probability is higher in heavily vegetated areas. Herein, we assume that all lines are in areas with similar geographic conditions. A total of 7 relays are available for installation. The optimal relay locations are identified using the proposed optimization approach for two different circuit topologies corresponding to the status of the tie line. When the tie line is open, the weighting factor in (13) is 0.75. When the tie line is closed and lines 9-14 is de-energized, the weighting factor in (13) is 0.25. The optimal relay placement algorithm identifies the relay locations on lines 1-2, 3-6, 5-9, 7-12, 9-14, 9-15, and 9-16. The minimum reported SAIFI is 1.27. The relay locations skew to bus 9 because the lines from 9 to 14, 15, and 16 are the longest in the whole system. These lines have the greatest probability of faulting.

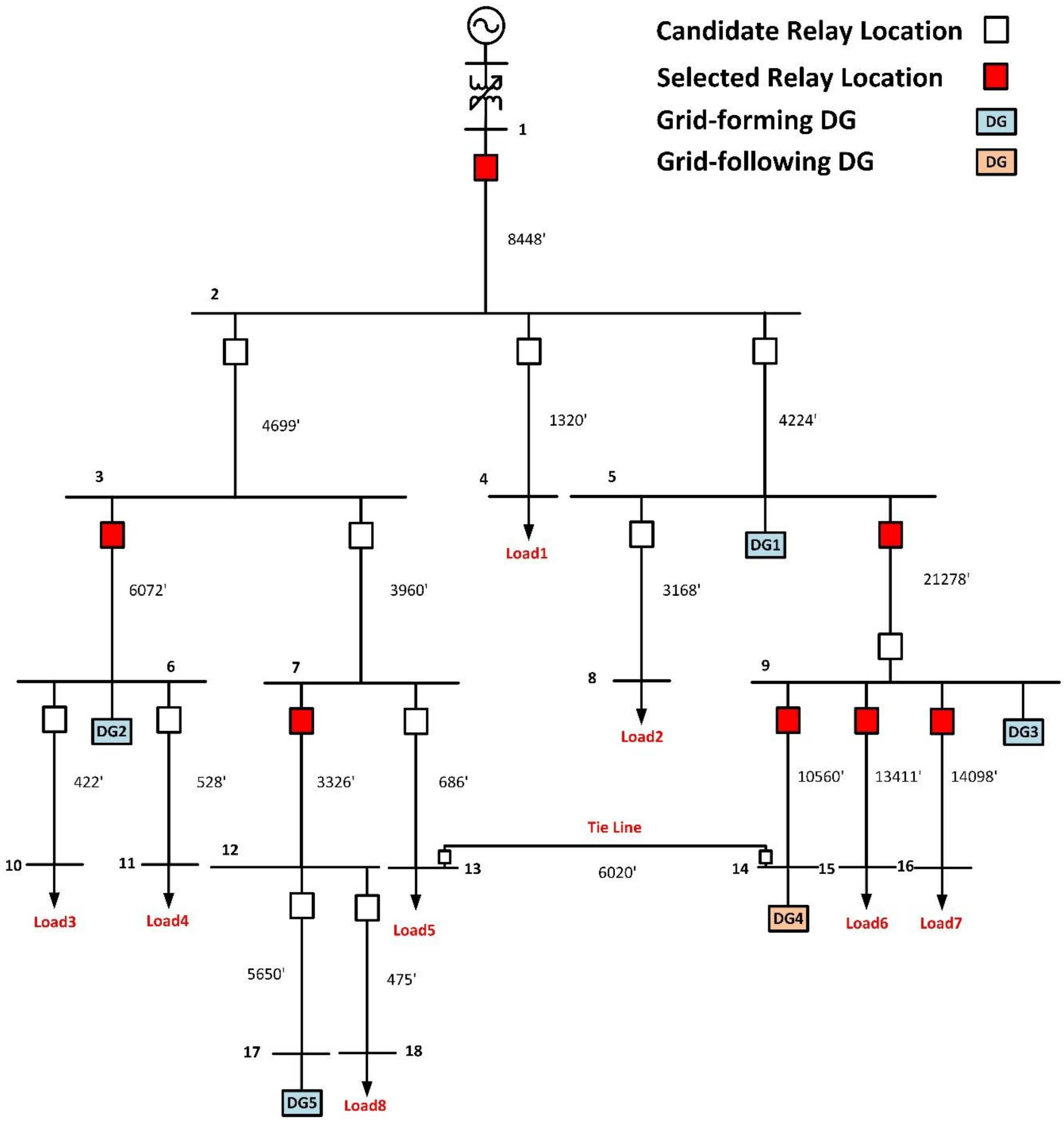

Figure 3: 18 Bus System Results

Alternate Cases

The algorithm works to find the optimal placement with any set of initial conditions. For these cases, a different number of protective relays will be available.

3 Relay Case

The optimal relay placement algorithm identifies the relay locations on lines 1-2, 5-9, 9-14. The minimum reported SAIFI is 2.51.

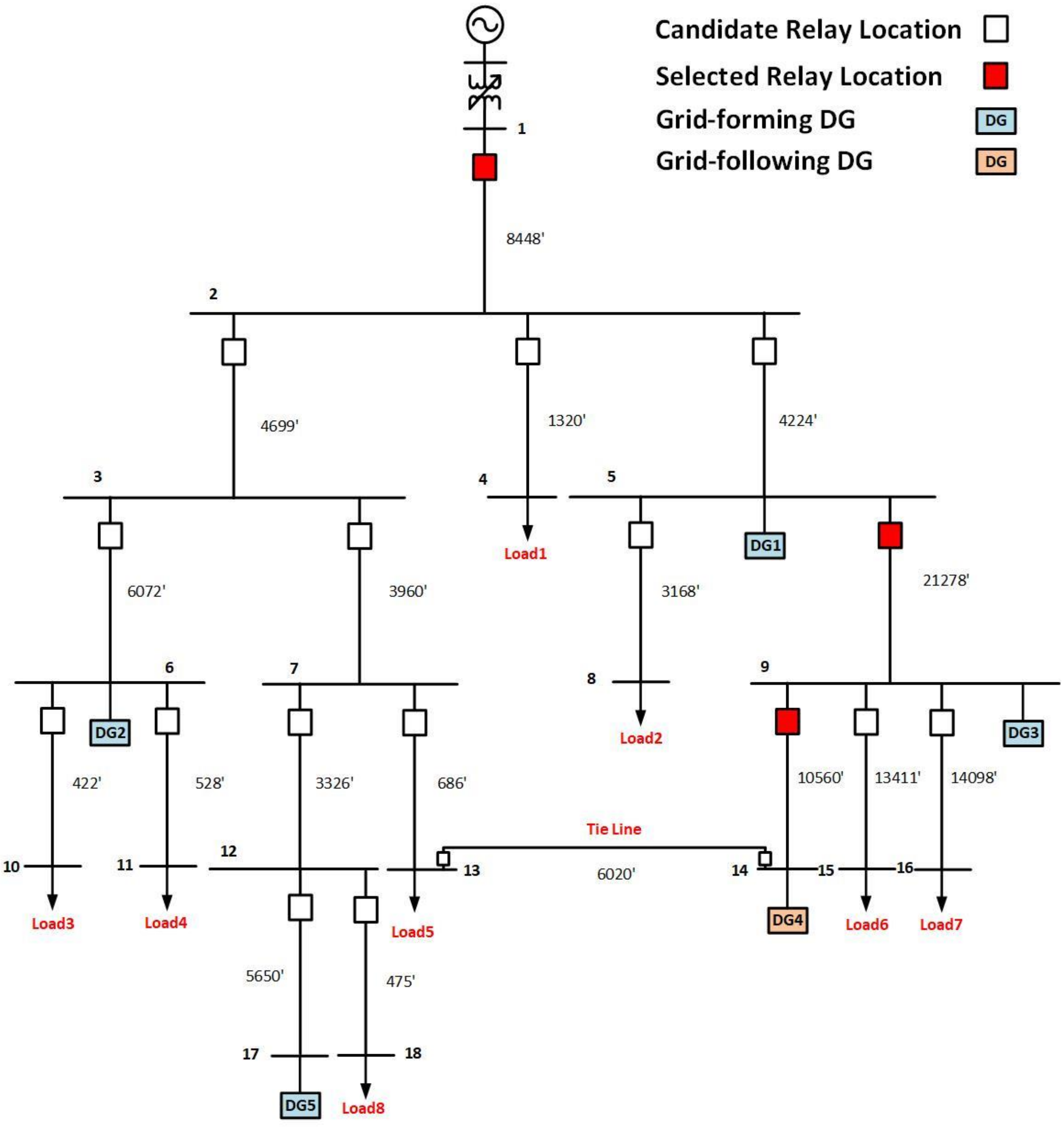

Figure 4: 18 Bus System 3 Relays

5 Relay Case

The optimal relay placement algorithm identifies the relay locations on lines 1-2, 5-9, 9-14, 9-15, and 9-16. The minimum reported SAIFI is 1.44.

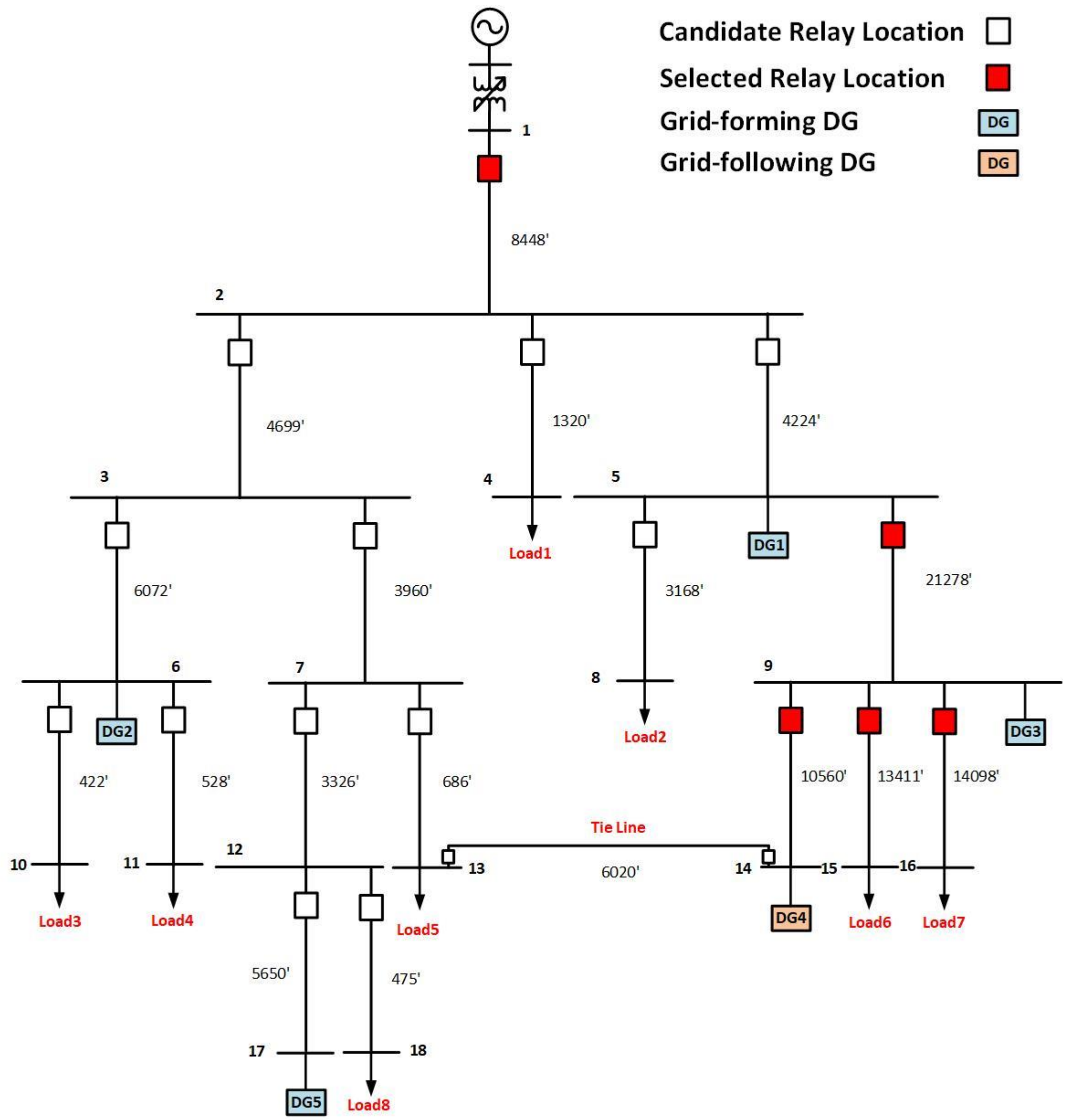

Figure 5: 18 Bus System 5 Relays

9 Relay Case

The optimal relay placement algorithm identifies the relay locations on lines 1-2, 5-9, 9-14. The minimum reported SAIFI is 1.10.

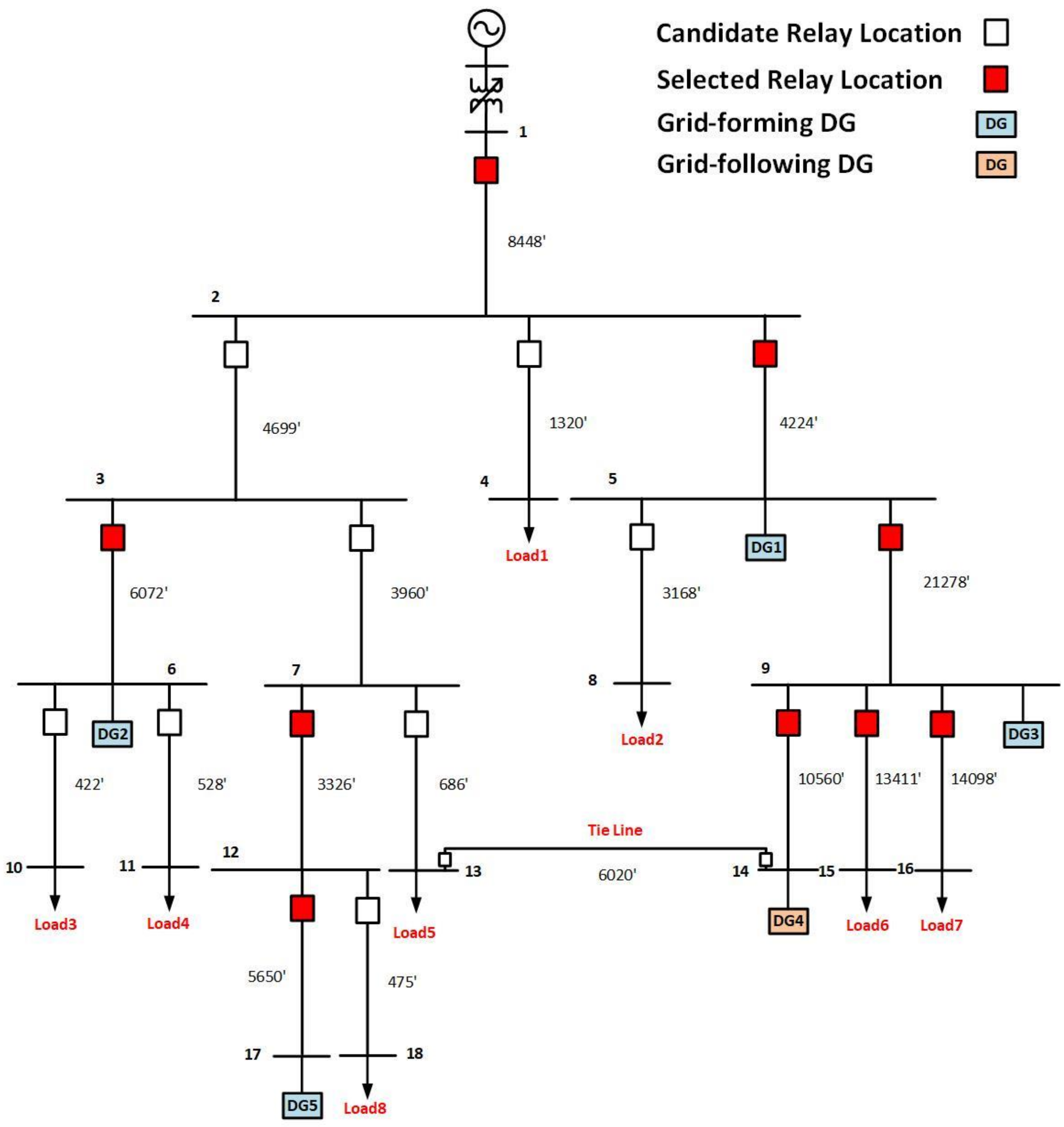

Figure 6: 18 Bus System 9 Relays

TABLE 3

IMPACT OF NUMBER OF RELAYS ON THE OPTIMIZED SAIFI OF MICROGRID FOR 18 BUS SYSTEM

Number of Relays	**SAIFI**
9	1.10
7	1.27
5	1.44
3	2.51

123-bus Microgrid System Simulation Results

The IEEE 123-bus distribution system [30] is modified and converted to a microgrid by adding nine DERs. The single line diagram of the 123-bus microgrid test system is shown in Fig. 7. The microgrid load values are provided in [30]. The microgrid has 9 DERs and the locations are highlighted in red in **Error! Reference source not found.**. Microgrid DER ratings are summarized in Table 4. This microgrid system has 114 lines interconnecting microgrid buses. The probability of faults on the lines corresponds to the line lengths shown in **Error! Reference source not found.**. The longest line is assumed to have a fault probability of 0.25 while the other line probabilities are scaled down proportionally based on their lengths.

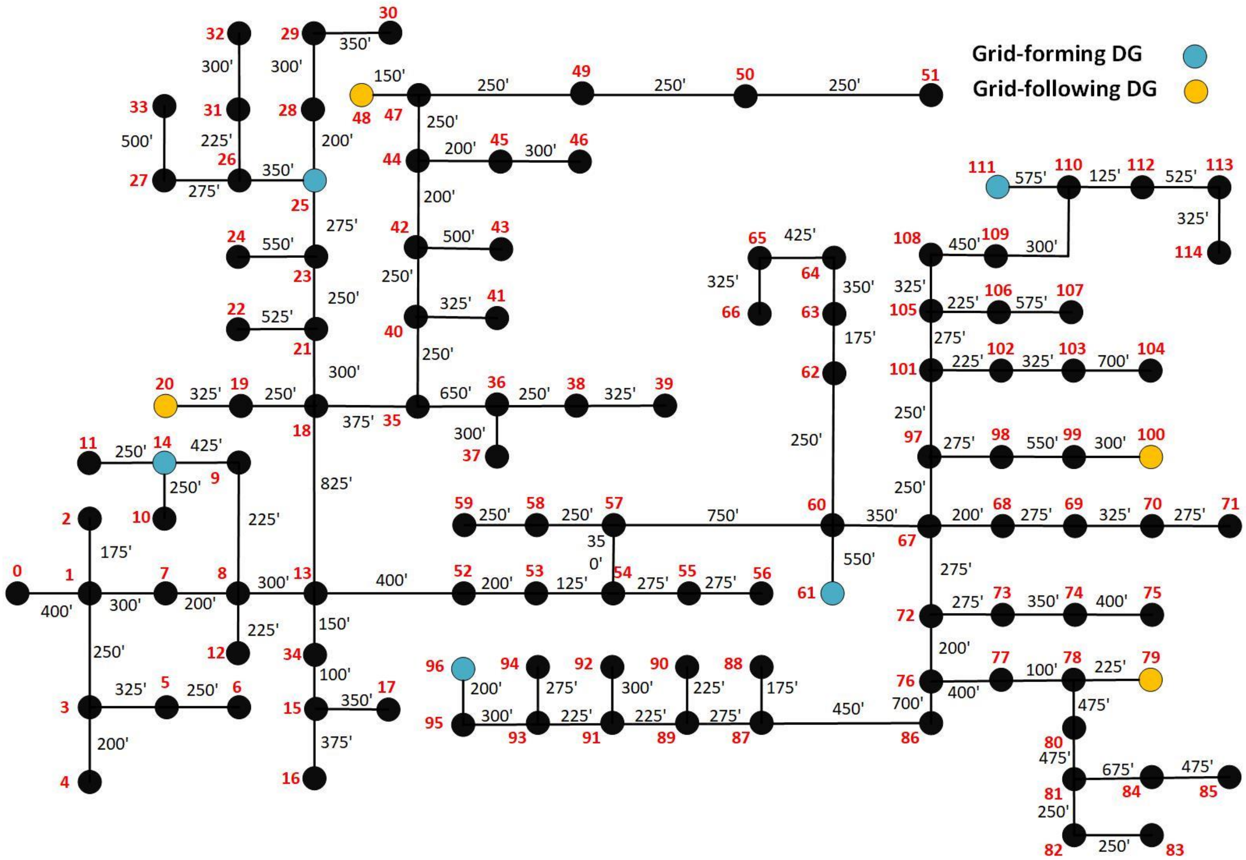

Figure 7: IEEE 123 Bus System

TABLE 4

123-BUS MICROGRID DER RATINGS

Bus #	14	20	25	48	61	79	96	100	111
kVA	500	700	500	1000	500	500	1000	500	500

123-bus Case 1: Variable Relays

In this case study, the impact of the number of relays the minimum achievable SAIFI is investigated. It is assumed that 3-phase DERs connected to Bus 14, 25, 61, 96, and 111 are operating in grid-forming mode while the others operate in grid-following mode. The calculated optimized SAIFI values using the proposed relay placement algorithm for the different number of relays are summarized in Table 5. As the number of relays increases, the microgrid achieves a smaller SAIFI if the relays are located at the optimized locations determined by the proposed algorithm. The optimal relay locations for the IEEE 123 bus system with 20, 16, 12, 8, and 4 relays are shown in Fig 8, 9, 10, 11, and 12.

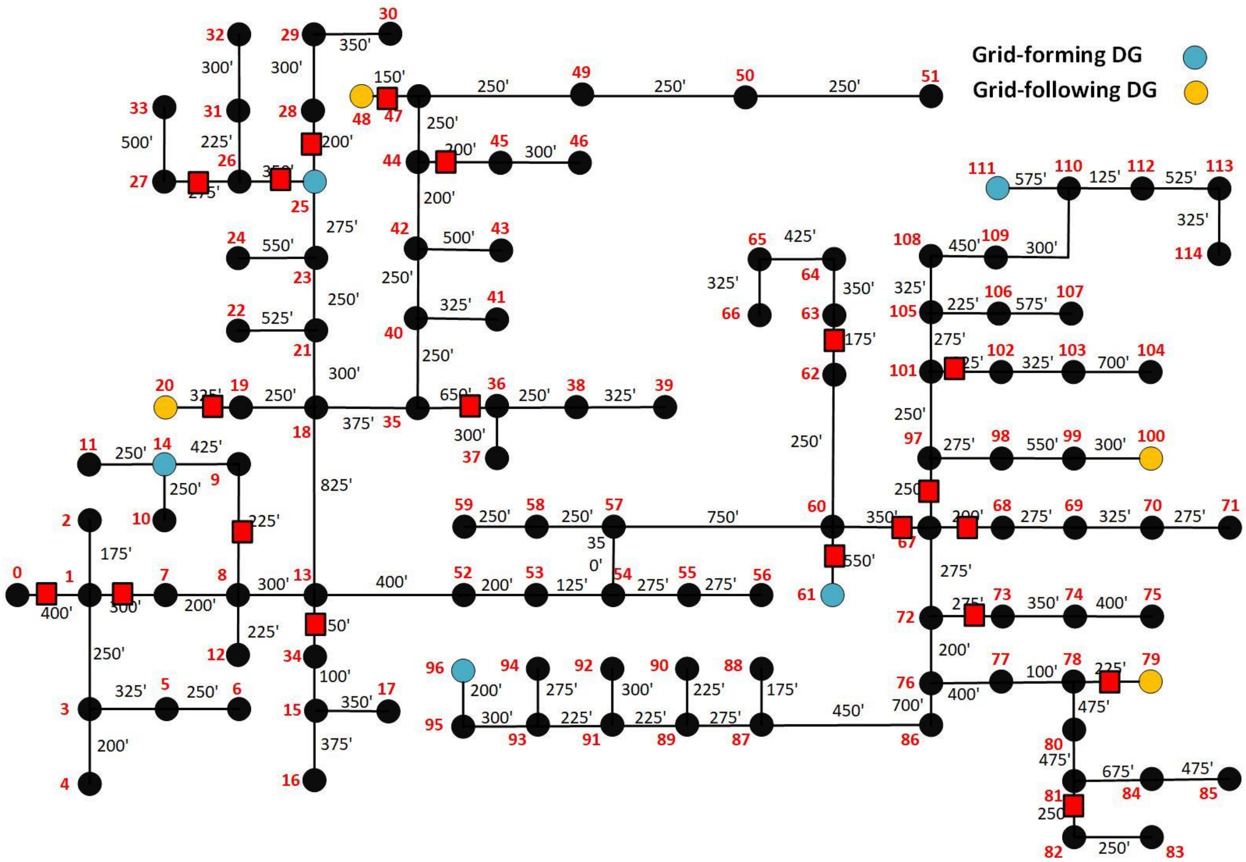

Figure 8: 123 Bus System with 20 Relays

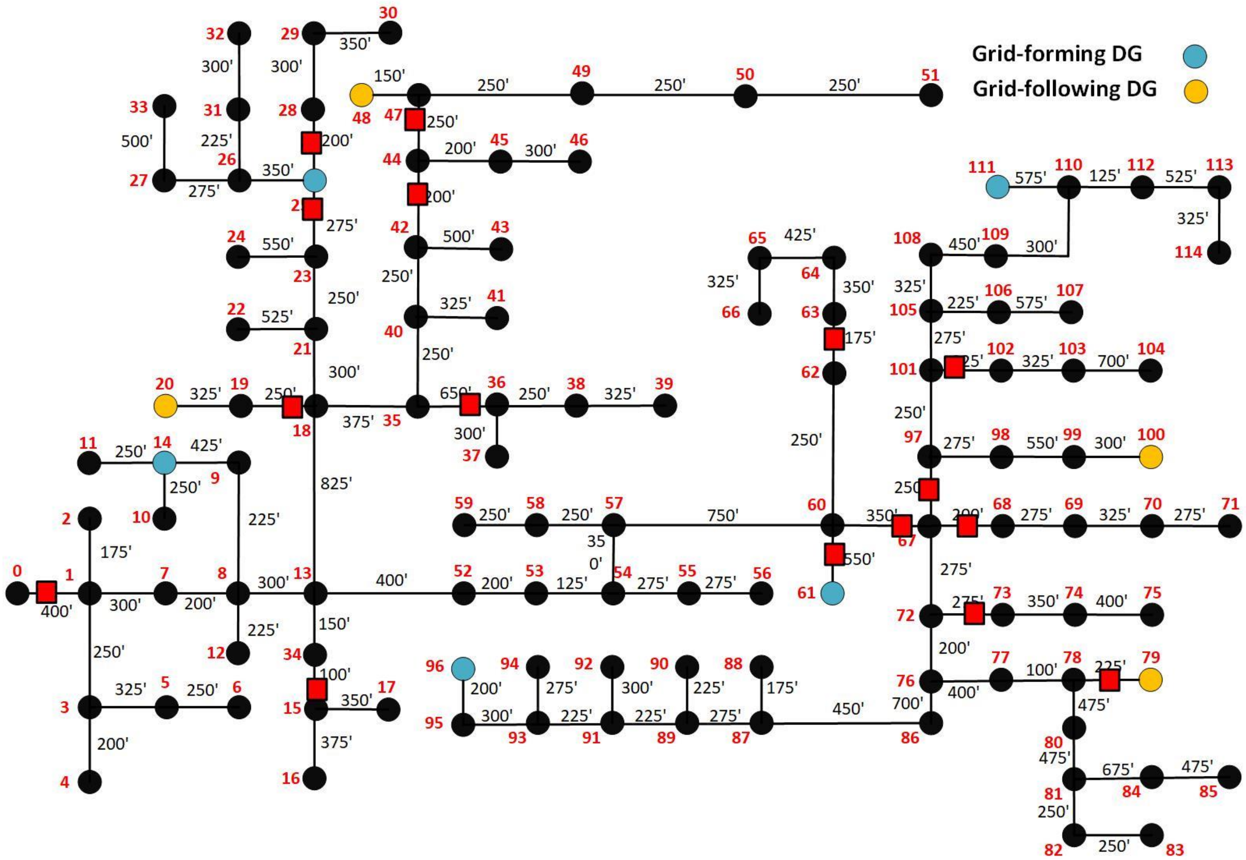

Figure 9: 123 Bus System with 16 Relays

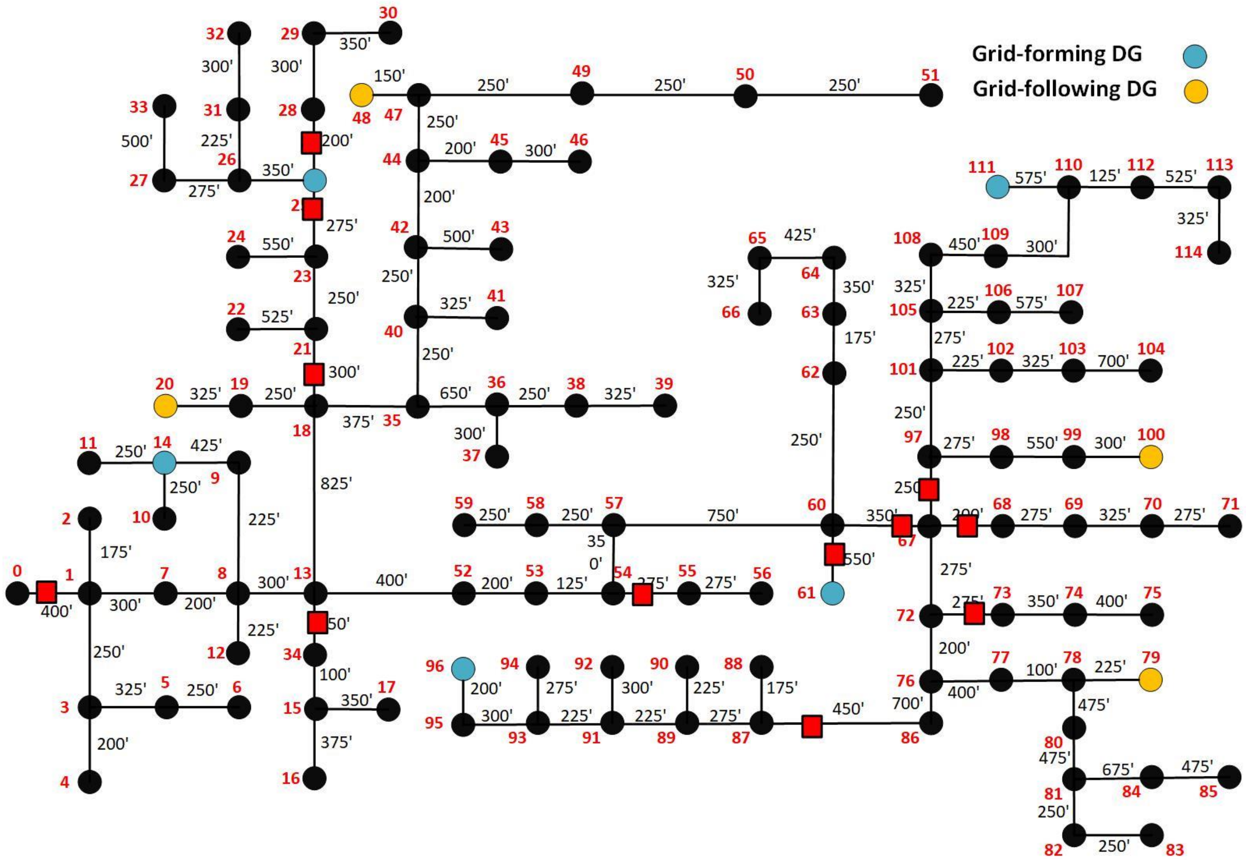

Figure 60: 123 Bus System with 12 Relays

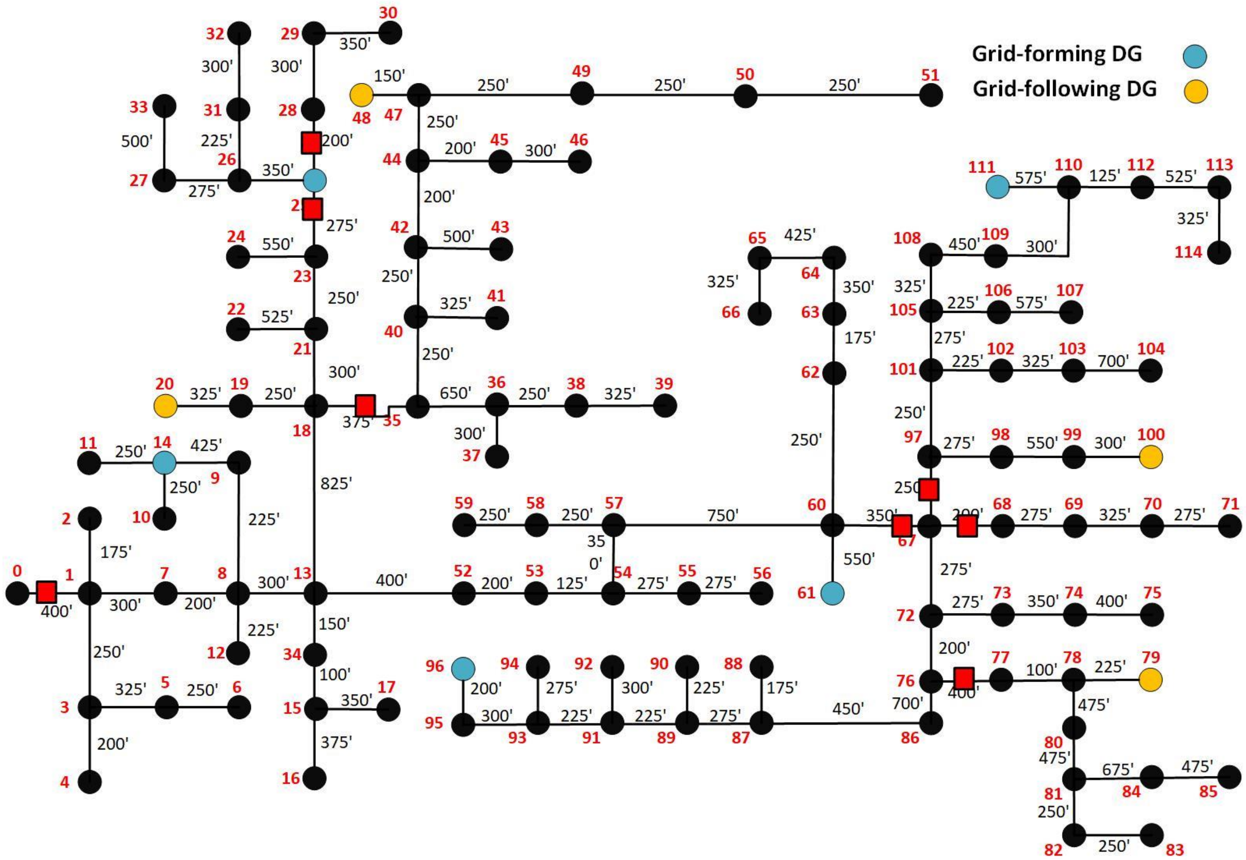

Figure 11: 123 Bus System with 8 Relays

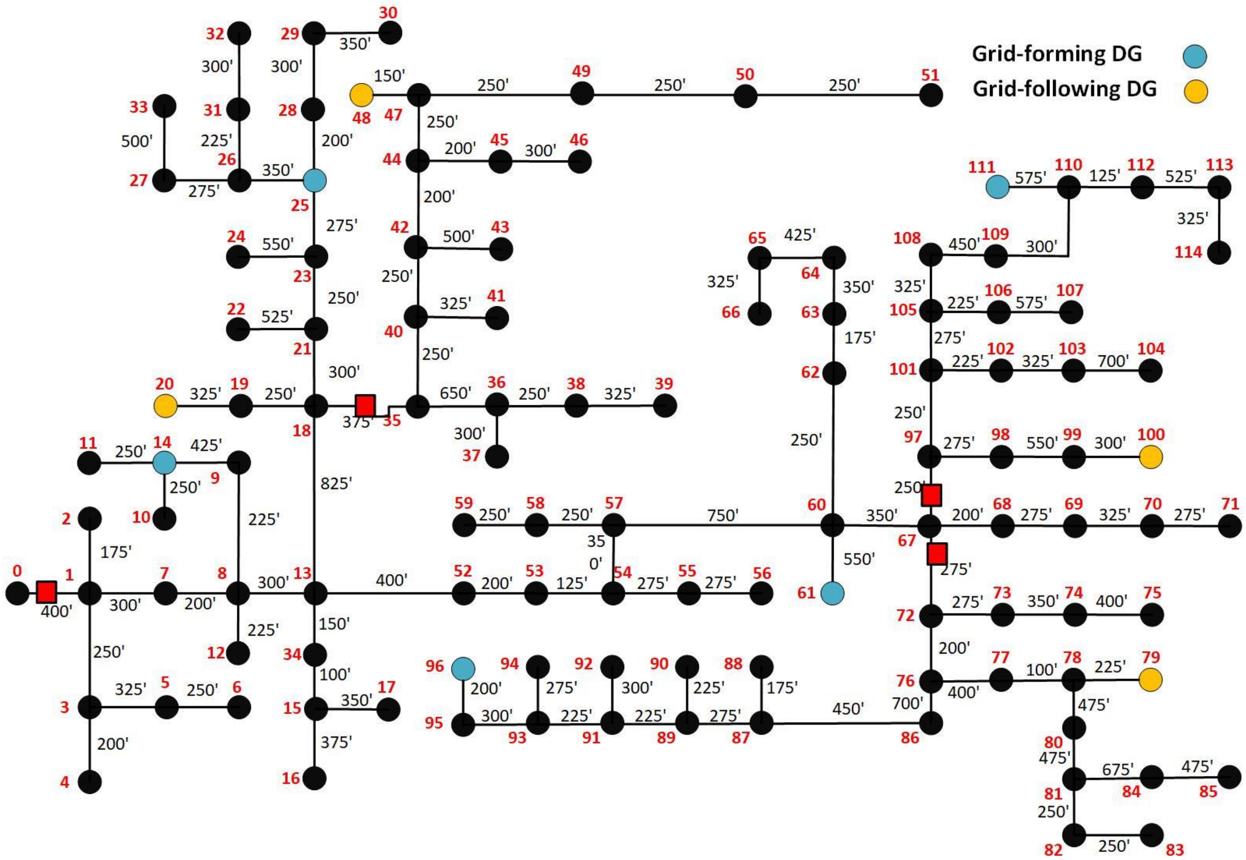

Figure 12: 123 Bus System with 4 Relays

TABLE 5

IMPACT OF NUMBER OF RELAYS ON THE OPTIMIZED SAIFI OF MICROGRID

Number of Relays	**SAIFI**
20	1.42
16	1.55
12	1.75
8	2.12
4	2.48

123-bus Case 2: Variable DERs

In this case study, it is assumed that 20 relays are available for installation. The impact of the number of grid-forming DERs on the optimal SAIFI is investigated. To this end, the number of grid-forming DERs is swept from 0 (all grid-following) to 9 (all grid-forming). The optimal SAIFI values computed using the proposed relay placement algorithm for the different numbers of grid-forming inverters are summarized in Table 6. When most of the DERs are of the grid-forming type, the microgrid can achieve a smaller SAIFI. The figures showing which DER's are grid forming and which are grid following for table V can be found in the appendices.

TABLE 6

IMPACT OF GRID-FORMING DERS ON THE OPTIMIZED SAIFI OF MICROGRID

NUMBER OF GRID-FORMING DERS	0	1	2	3	4	5	6	7	8
SAIFI	2.93	2.22	2.19	2.00	1.74	1.35	1.22	0.98	0.81

Comparing the Results of EMA to PSO

Particle Swarm Algorithm (PSO) is a different optimization algorithm and is provided in the global optimization toolbox in Matlab. In this case study, the results from the EMA algorithm will be compared to the results of the PSO algorithm. The smaller 18 bus system will be used with 7 available relays. The optimal relay placement algorithm using PSO identifies the relay locations on lines 1-2, 2-3, 2-4, 5-9, 9-15, 9-16, and 12-18. The minimum reported SAIFI is 1.54. The relay locations for the PSO optimization can be seen in Fig. 13 and the comparison to EMA can be seen in Table 7. The EMA algorithm provides a superior SAIFI and relay placement as well as running much quicker than PSO.

TABLE 7

EMA AND PSO COMPARISON

	EMA	**PSO**
SAIFI	1.27	1.54
Algorithm Running Time	15 seconds	125 seconds

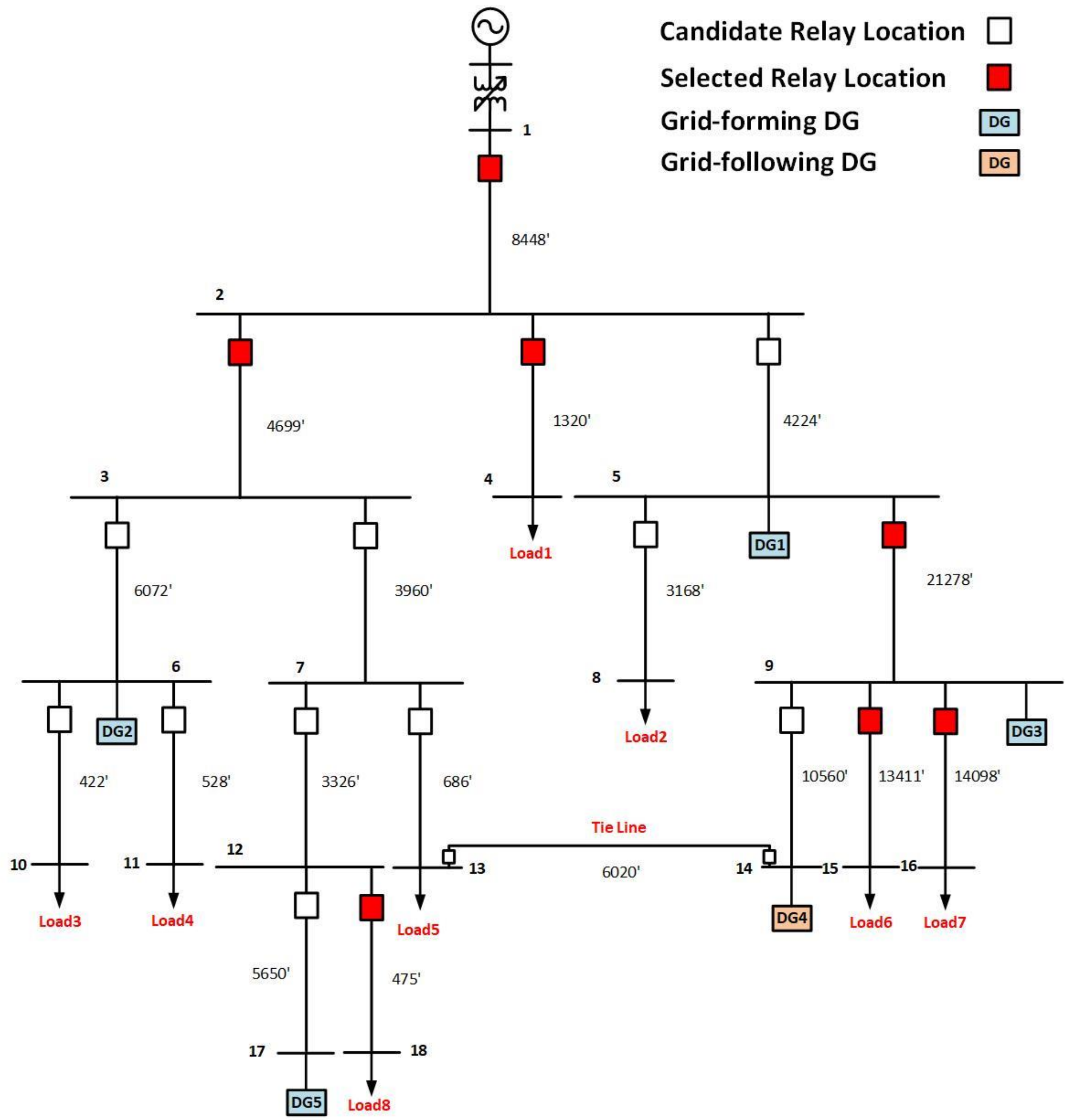

Figure 13: 18 Bus System with PSO Optimization

Comparing the Results of EMA to a Brute Force Algorithm

The optimization problem, as it has been set up in this thesis, is discrete and therefore can be directly compared to a brute force algorithm if the problem is sufficiently small. In this case study, the results from the EMA algorithm will be compared to the results of a brute force algorithm. The smaller 18 bus system will be used with 7 available relays. The optimal relay placement algorithm using brute force identifies the relay locations on lines 2-3, 3-4, 3-7, 5-9, 9-14, 9-15, 9-16, and 12-17. The minimum reported SAIFI is 1.17. This gives us an optimality gap of 0.1. The locations can be seen on Fig. 14. The brute force found more optimized relay locations than the EMA but there are two considerations. Firstly, the brute force took an immense amount of time and secondly, the brute force algorithm was not required to put a relay at 1-2 like the EMA was. Table 8 shows a comparison of the EMA, PSO and brute force. The brute force solution will work better for extremely small-scale problems but in unusable past 4 or 5 relays.

TABLE 8

EMA, PSO, AND BRUTE FORCE COMPARISON

	EMA	**PSO**	**Brute Force**
SAIFI	1.27	1.54	1.17
Algorithm Running Time	15 seconds	125 seconds	37066 seconds (Over 10 hours)

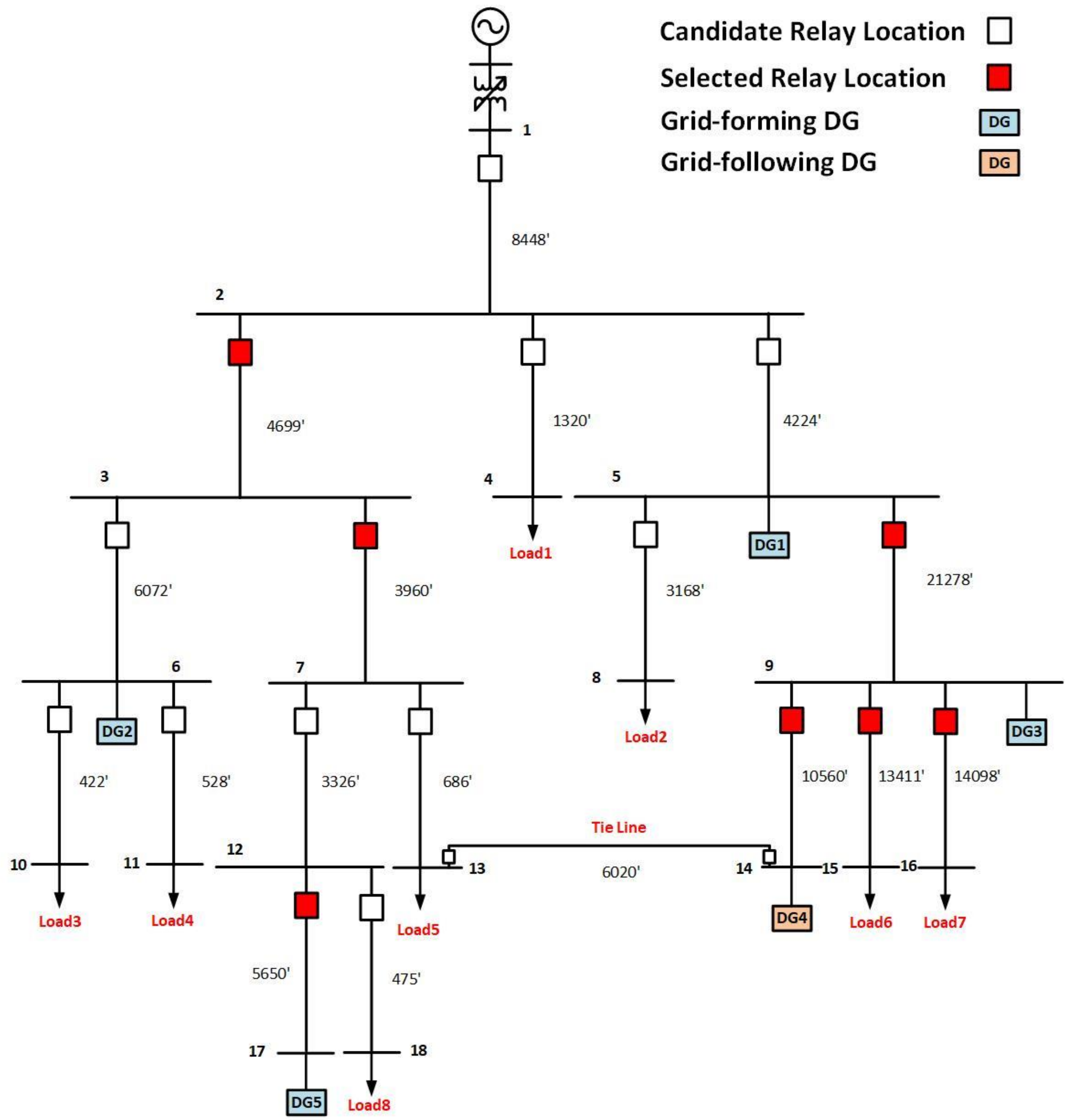

Figure 14: 18 Bus System with Brute Force Optimization

Conclusion

In this thesis, an optimal relay placement approach for microgrids was proposed. The objective of the relay placement algorithm was to find the optimal locations for a fixed number of available relays such that the microgrid overall SAIFI was minimized. The proposed approach considered both grid-connected and islanded microgrid modes. It was assumed that microgrids could form sub-islands through the grid-forming DERs. The EMA was applied to the system to determine an optimal relay placement. The effectiveness of the proposed optimal relay placement approach was verified using an 18-bus microgrid and IEEE 123-bus test system. The simulation results validated the effectiveness of the proposed approach in minimizing the microgrid SAIFI. The EMA algorithm optimization was superior to the PSO in minimizing the SAIFI and the EMA algorithm is much faster than a brute force solution.

Future work could include implementing a cost of outage function and either optimizing by cost or both SAIFI and cost. More future work could include load shedding calculations. The project, in its current state, does not do any load shedding calculations. When the generation provided in an island cannot meet the required load, all loads are outraged. More future work can be more sophisticated fault probability parameters. Currently, the project only considers line length in calculating its fault probability. Also, the thesis does not consider the effects of any possible reconfigurations, such as opening and closing the tie line after fault scenarios. Lastly, other optimization algorithms can be tested within the frame-work of the system to see if there are other advantages or disadvantages over EMA.

Appendix

IEEE 123 Bus Diagrams for Variable DER's

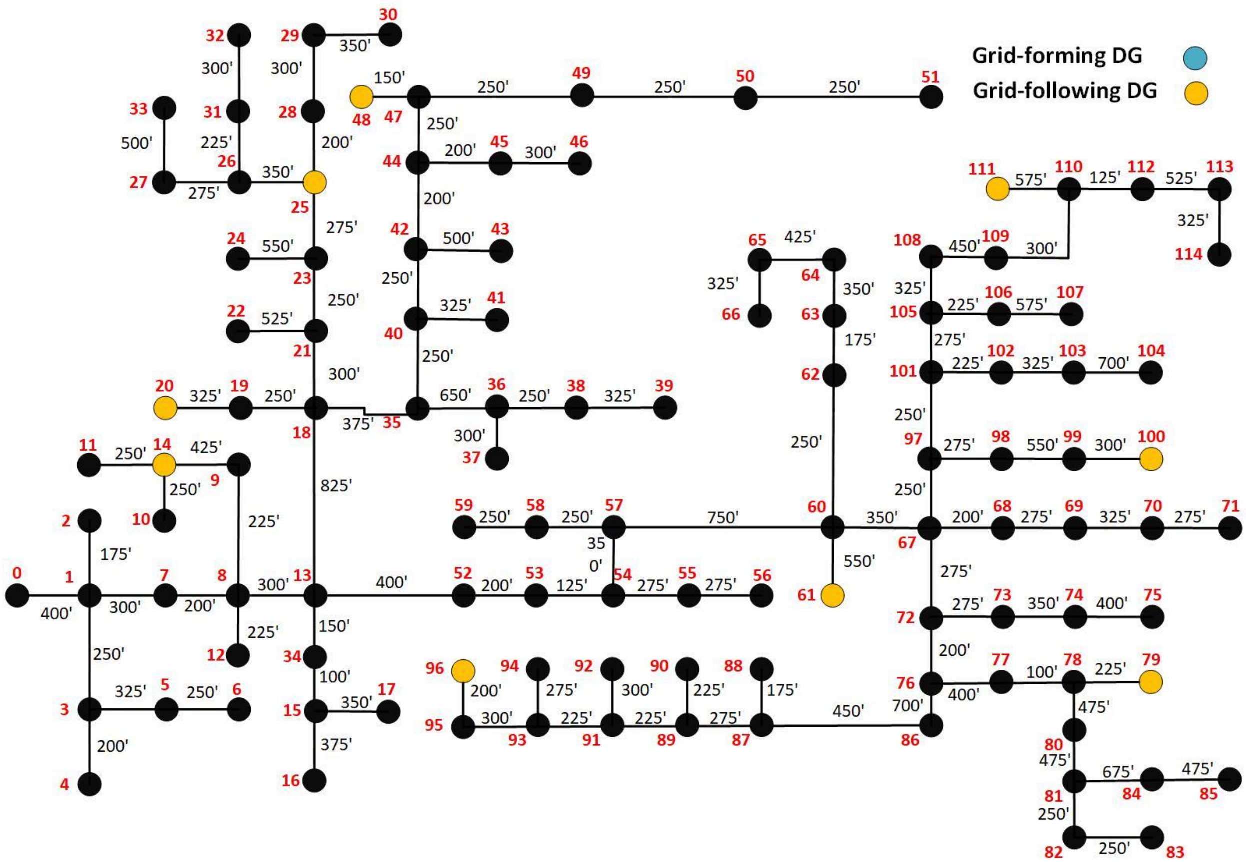

Figure 15: 123 Bus System with 0 Grid Forming DER's

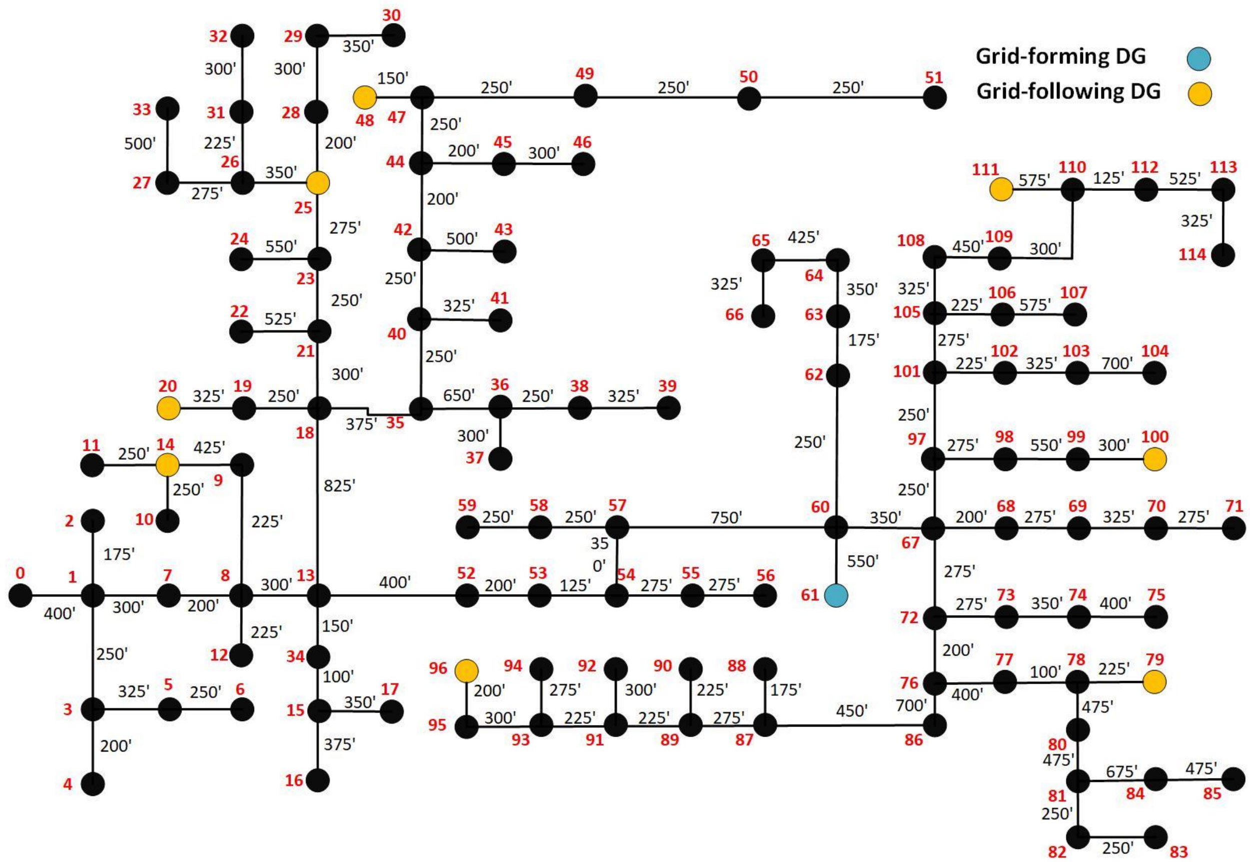

Figure 16: 123 Bus System with 1 Grid Forming DER

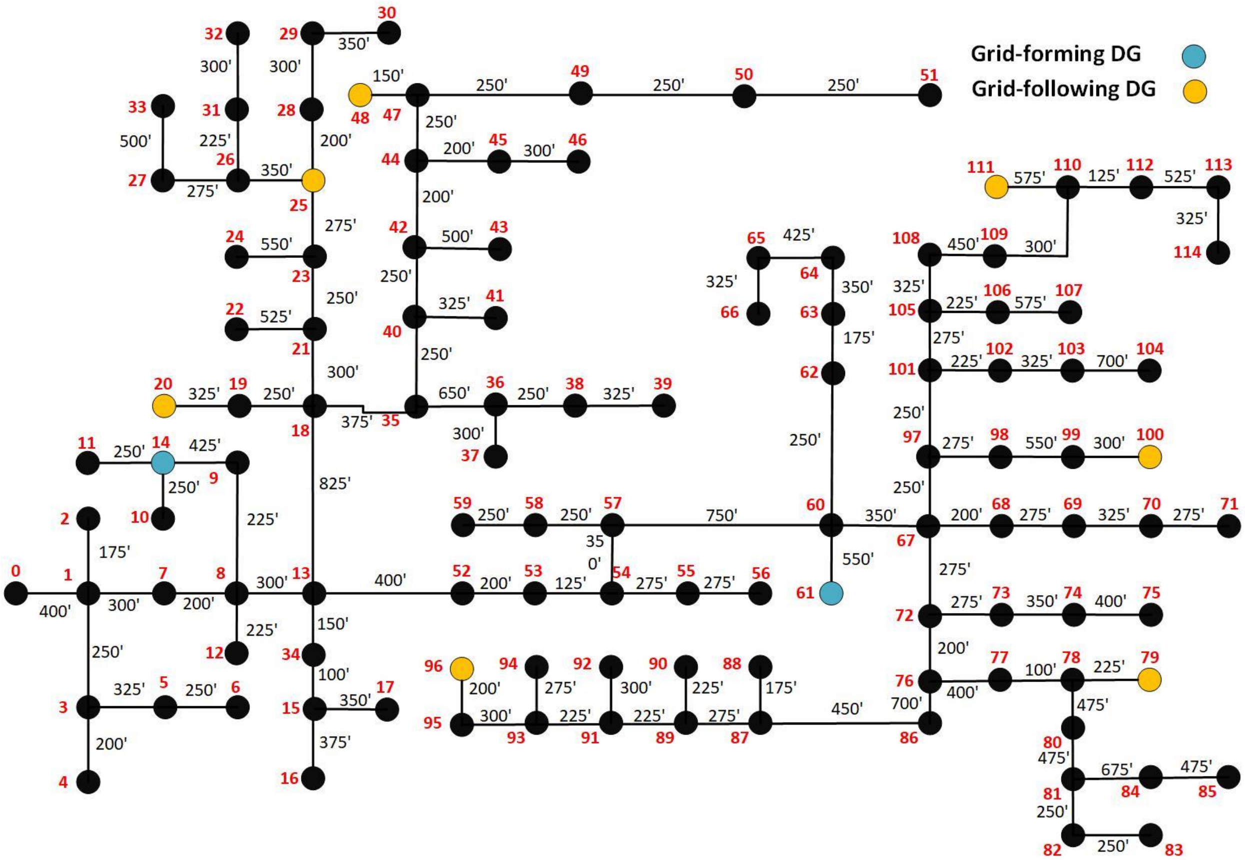

Figure 17: 123 Bus System with 2 Grid Forming DER's

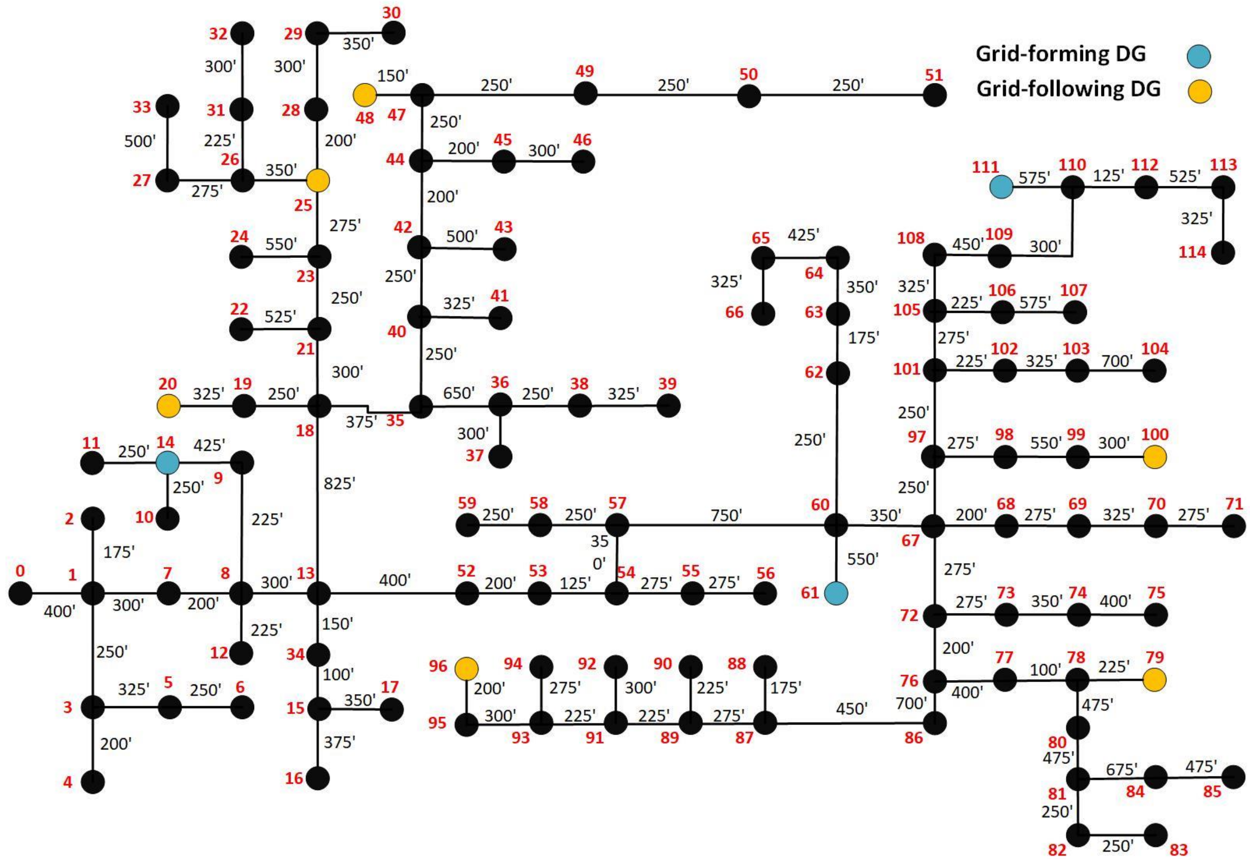

Figure 18: 123 Bus System with 3 Grid Forming DER's

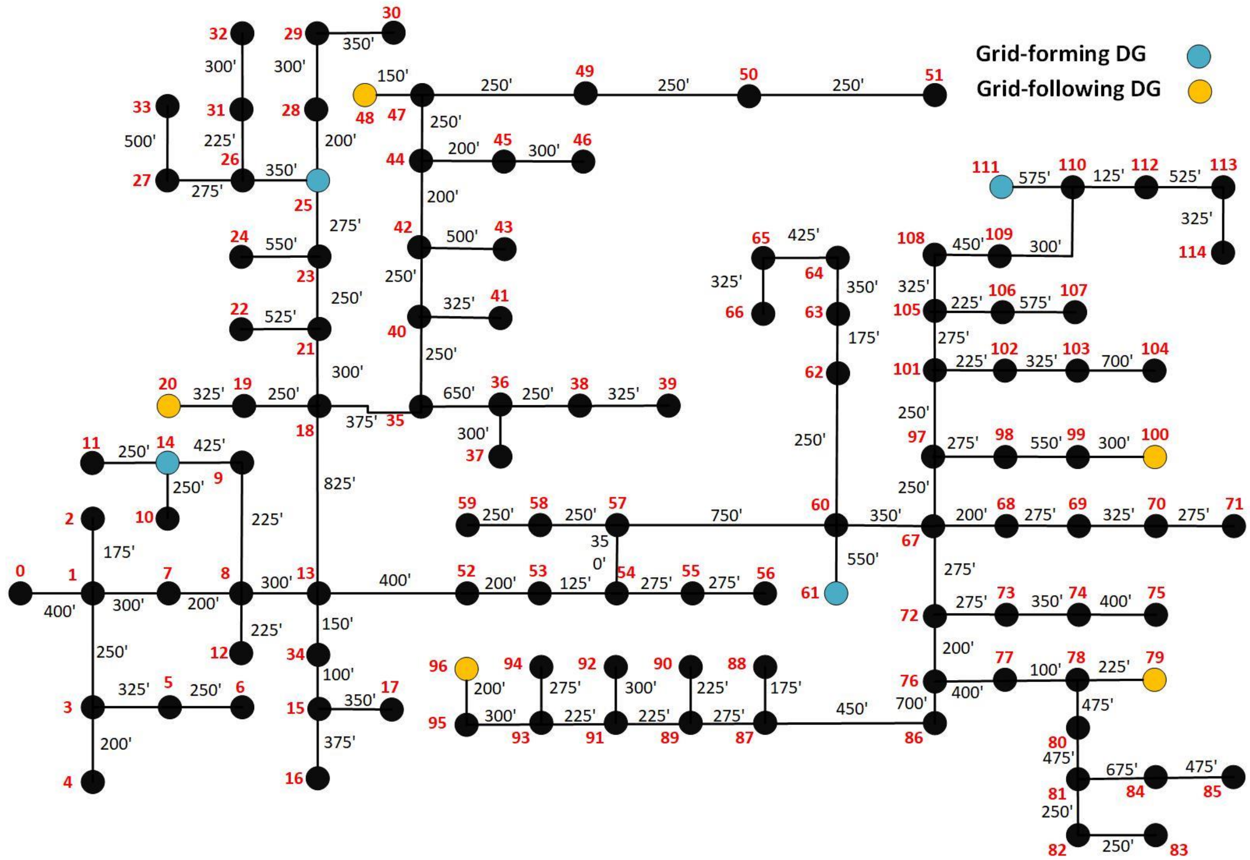

Figure 19: 123 Bus System with 4 Grid Forming DER's

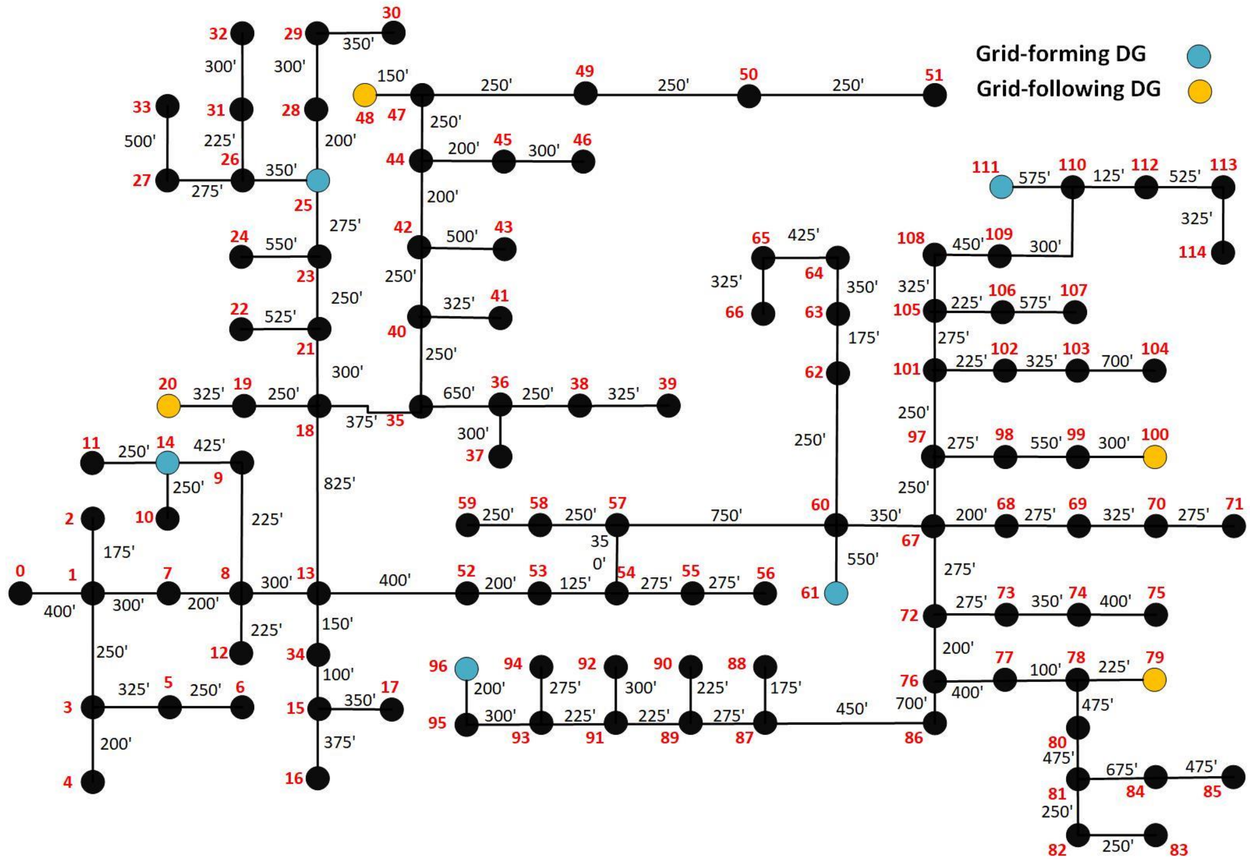

Figure 20: 123 Bus System with 5 Grid Forming DER's

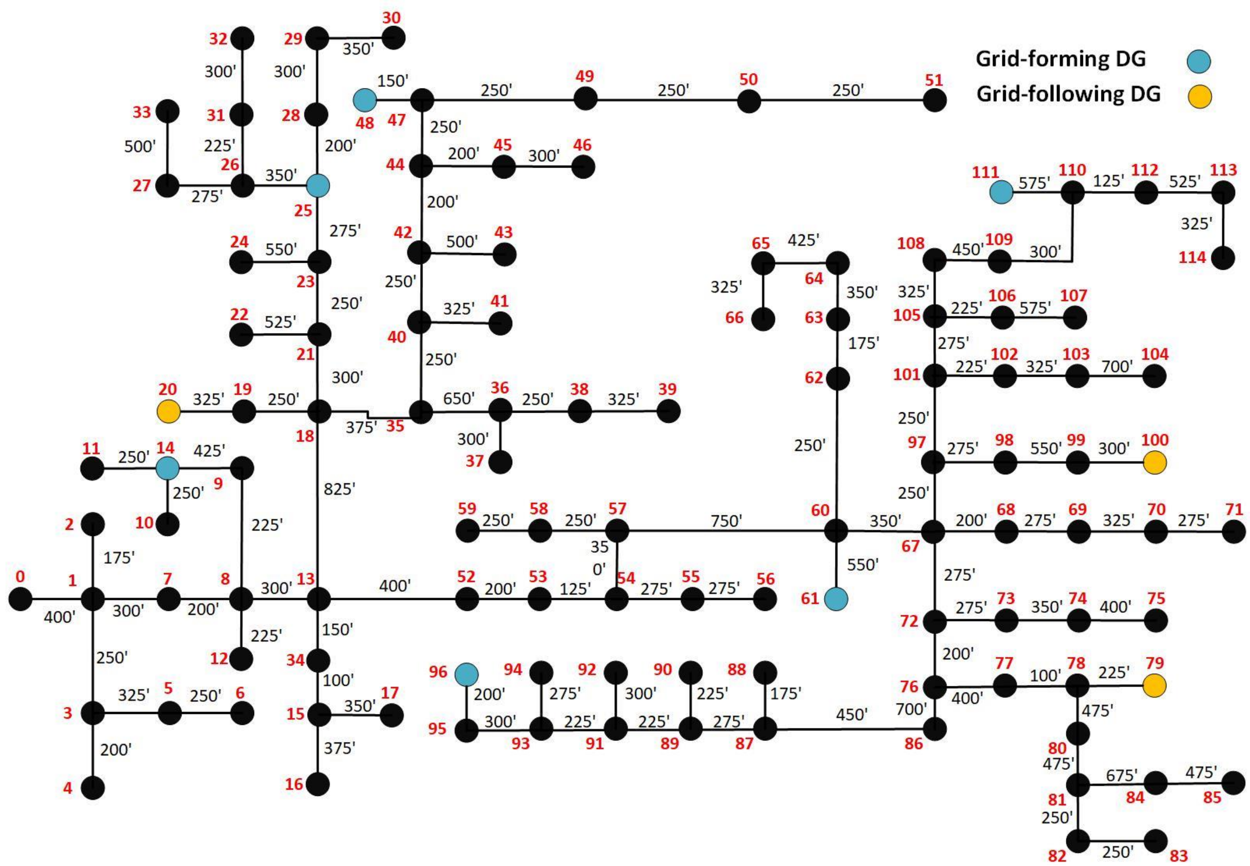

Figure 21: 123 Bus System with 6 Grid Forming DER's

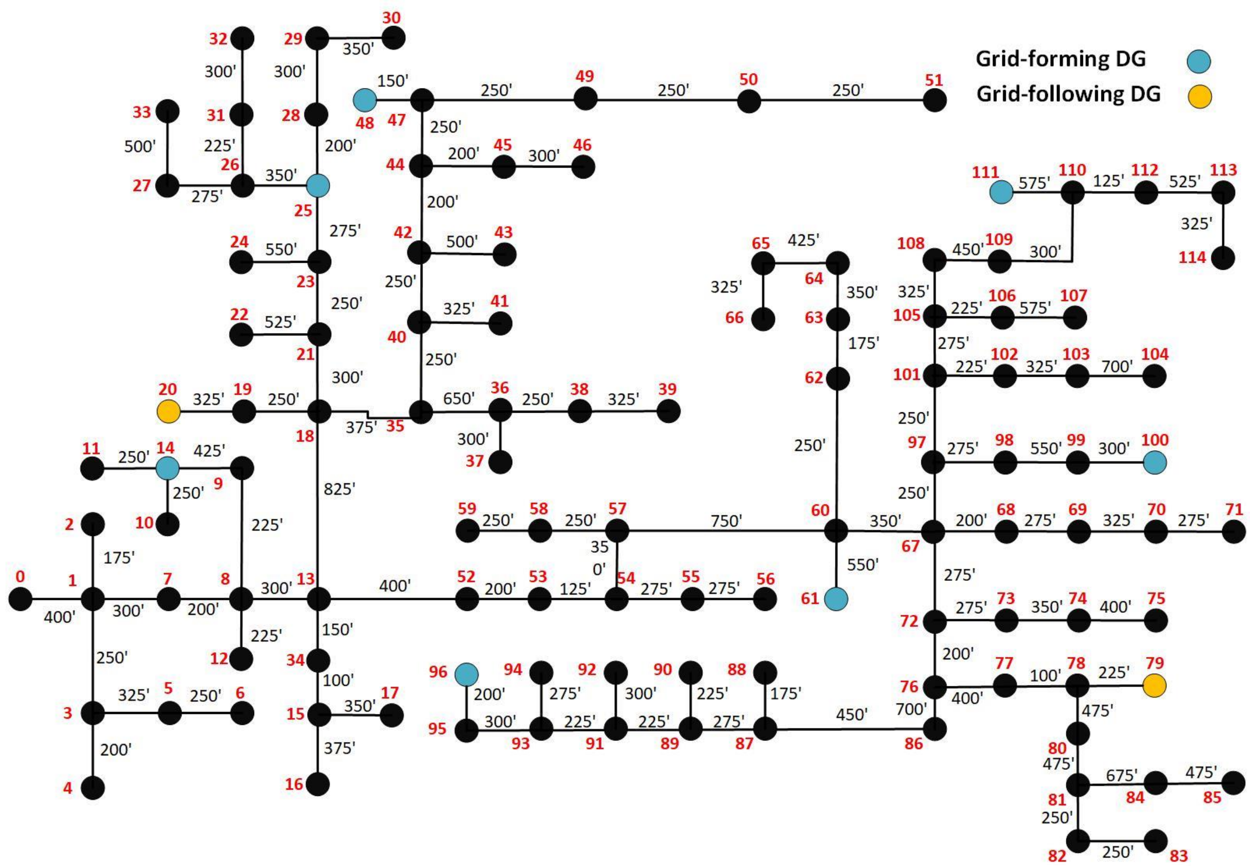

Figure 22: 123 Bus System with 7 Grid Forming DER's

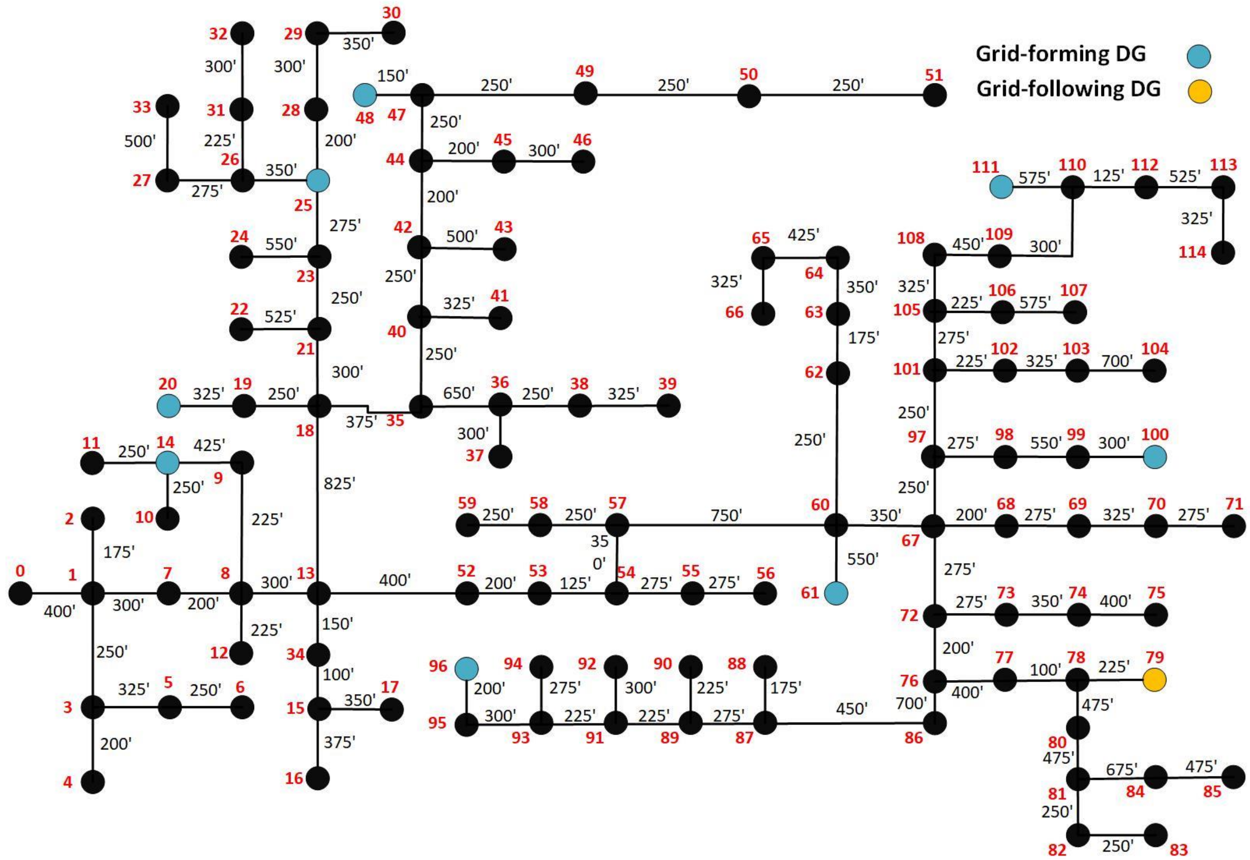

Figure 23: 123 Bus System with 8 Grid Forming DER's

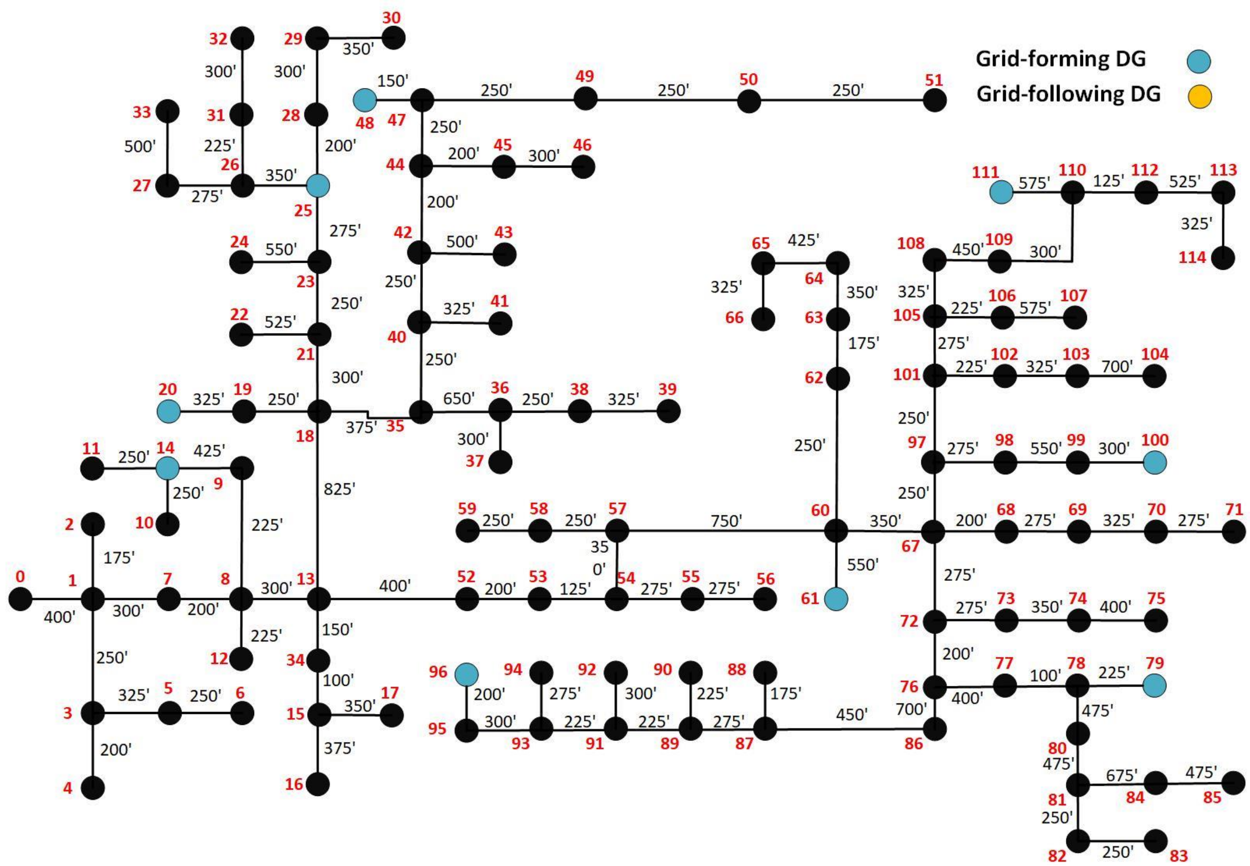

Figure 24: 123 Bus System with 9 Grid Forming DER's

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