Optimizing Distribution System Power Loss Using Behind-the-Meter Type 3 Generators

by

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M.Sc., Azad Universiy, Iran, 2013

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ABSTRACT

Power utilities are expected to meet increasing power demands considering environmental concerns and financial restrictions and power loss minimization is an attractive solution. Operating current and power losses in distribution systems are higher than in transmission systems, so finding feasible methods to reduce power loss in distribution systems is important. Among the existing power loss reduction methods in distribution systems, distributed generation (DG) integration is the most effective. Generating power using renewable energy DG sources will also help environmental concerns. The increasing cost of fossil fuels and technological developments have made renewable energy sources financially viable.

This report considers power loss reduction in distribution systems by integrating behind-the-meter type 3 DG sources. The IEEE 33 bus distribution system is considered as an example. Power loss is estimated by applying the forward/backward sweep (FBS) method, and power loss reduction is optimized using particle swarm optimization (PSO). The power factor, and DG location and size are used as optimization parameters to reduce power loss. The PSS SINCAL software is used to evaluate the proposed solution. Results presented show that for the same amount of DG penetration in a distribution system, behind-the-meter type 3 DG sources reduce the power loss more than front-of-the-meter DG sources. Thus, utilities can not only benefit from saving investment costs but also higher efficiency in their distribution systems. DG sources are typically renewable, so environmental concerns are also mitigated.

Contents

List of Tables

List of Figures

List of Abbreviations

FBS	Forward/Backward Sweep
DG	Distributed Generation
R/X	Resistance/Reactance
PV	Photo-Voltaic
BES	Battery Energy Storage
NR	Newton-Raphson
GS	Gauss-Seidel
PSO	Particle Swarm Optimization
EA	Efficient Analytical

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Chapter 1

Introduction

Electricity demand is continuously on the rise due to population growth and technological developments. Power utilities are expected to meet this increasing demand. This demand could be met by constructing new power plants or by expanding existing power systems. However, these approaches require significant financial investment and can create environmental concerns. Moreover, many existing systems cannot be expanded because they are located in densely populated areas. As a result, alternative methods to support extra demand with minimal additional investment are preferred by utilities [1].

Worldwide transmission and distribution power loss in 2014 was 8.12% of the total generated power of 2.72 terawatts (TW) [2], [3]. This loss is more than twice the global electricity demand increase in 2018 [3]. Further, because of higher operation currents, power loss in distribution systems is approximately twice that of transmission systems, as shown in Figure 1.1 [4]. Minimizing power loss in distribution systems increases the loading capacity of the lines and minimizes the heating effect in power system cables. Thus, utilities can meet increasing power demands without investing in new generation or transmission infrastructure by reducing power losses especially in distribution system [5].

1.1 Existing Loss Reduction Methods

The most common approaches adopted by power utilities to minimize power loss are briefly described below.

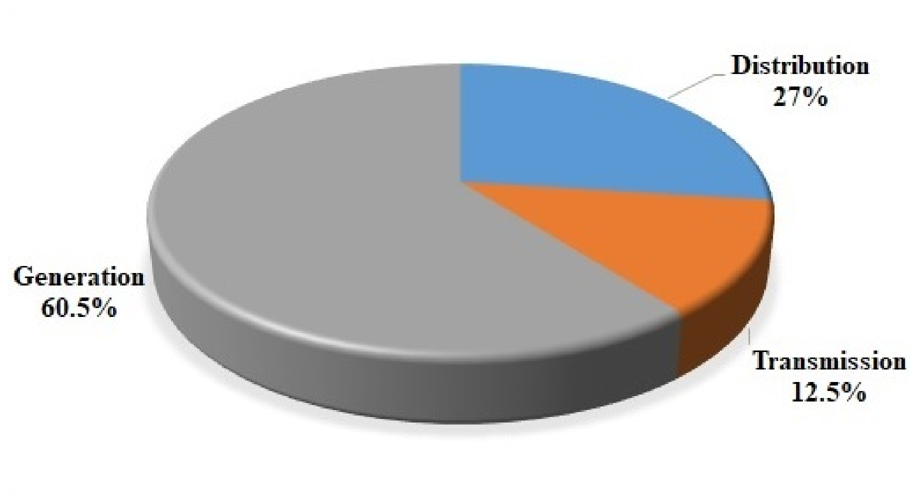

Figure 1.1: Power loss in a power system.

1.1.1 Capacitor Placement

Power loss in distribution systems has been reduced by adding shunt capacitors [6], [7], [8]. In this method, shunt capacitors are added to the power system to supply reactive power and improve power factor. As a portion of the active power loss depends on reactive current, the addition of capacitors can reduce the reactive current supplied by the power system thereby reducing active power loss. Consequently, the efficiency of the power system is improved [9]. Cable size and the number of capacitors required are major limitations of this method. Moreover, power loss resulting from the in-phase current component is not affected by the capacitors [1].

1.1.2 Network Reconfiguration

Network reconfiguration is another approach to reducing power loss in distribution systems. This is achieved by changing the network topology via switches [10]. Tie and sectional switches are employed which are normally open and closed, respectively. Network reconfiguration improves system reliability and power quality by improving the voltage profile. Furthermore, it affects operational costs by reducing power loss and restoring power under fault conditions. It also allows utilities to plan system outages for maintenance. The challenge with this method is to ensure that the topology after network reconfiguration continues to energize all feeder sections while maintaining the initial radial structure. In addition, overload conditions and voltage drop limits for feeders and transformers must be adhered to [10], [11]. Moreover, continuously changing switch positions makes protection coordination a challenge as it is not easy for dispatchers to follow the reconfigured system. Reconfiguration also increases the risk of temporary power outages [1]. These challenges limit the use of network reconfiguration.

1.1.3 Distributed Generation Integration

Distributed generation (DG) is achieved with electric power sources that are connected directly to a distribution system [12]. Recent technological developments enable small commercial and residential units to generate and feed power to distribution systems. These can be renewable or non-renewable. This has led to increased DG integration in distribution systems. Rising concerns about increased greenhouse gas emissions and the high cost of fossil fuels have made renewable energy based DG sources popular. DG improves distribution system operation by reducing loss and improving the voltage profile [13], [14]. DG sources are classified based on their ability to produce real and reactive power as shown in Table 1.1.

Table 1.1: DG Types Based on the Power Factor

Type	Power Factor	Example
1	1	Photovoltaic (PV)
2	0	VAR compensator
3	Variable	Synchronous machines and hybrid PV with battery energy storage (PV+BES)

The power generated by photovoltaic (PV) devices depends on the time and weather conditions and hence, they are considered to be intermittent and non-dispatchable sources. Thus, they must be improved to be popular in the power supply market. Integrating with battery energy storage (BES) enables PV devices to act as type 3 source similar to conventional generators by producing power at any desired power factor. In this study, hybrid PV sources with battery energy storage (PV+BES) sources capable of producing both active and reactive power are considered because of their suitability and growing popularity [15]. They can be integrated into a distribution system to reduce power loss and improve the voltage profile [13], [14].

DG sources can be divided into two main categories based on their size and location in the power system as shown in Figure 1.2 [16]. The first category are sources installed in front of the utility meter and administered by the utility. They are usually used to supply large residential communities or a group of commercial buildings. They can be up to 30 MW which is considered to be the maximum DG size [16]. Most of the related research focuses on the integration of this type of DG source to reduce power loss in distribution systems. The second category are sources located behind the utility meter on the owner side. Thus, meters measure the power generated by these sources. The size of behind-the-meter sources is limited by utility companies to prevent bidirectional power flow in radial distribution systems. Thus, sources up to 10 kVA for residential and 500 kVA for commercial buildings are allowed to be installed behind-the-meter [16]. However, these sizes are ideal for use in residential and commercial buildings, and utility companies encourage customers to use behind-the-meter sources. In some cases, customers are given subsidies to install these sources and they can sell the surplus power generated to the utility [17].

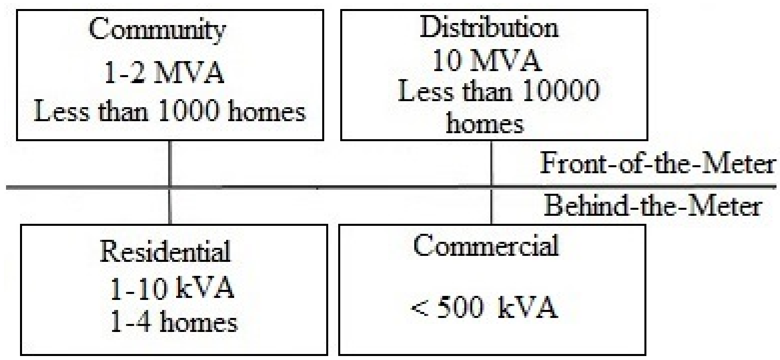

Figure 1.2: DG categories based on size and location.

While DG integration reduces power loss, the optimum location of a DG source for maximum power loss reduction is affected by the DG type [18], [19]. For example, the appropriate installation areas in the IEEE 33 bus system for front-of-the-meter DG sources are indicated in Figure 1.3 [20]. Zone A is the optimum area for DG sources of type 1 while DG sources of type 2 provide the most efficient results in zone B. DG sources with a variable power factor (type 3) are best integrated in zone C. Finally, zone D is not suitable for any type of DG source [20]. The optimal DG location is also affected by the optimization objective function as shown in Table 1.2. In this table, the optimization methods are given with their objective functions. The optimal bus locations for DG sources and the number of integrated DG sources are also shown.

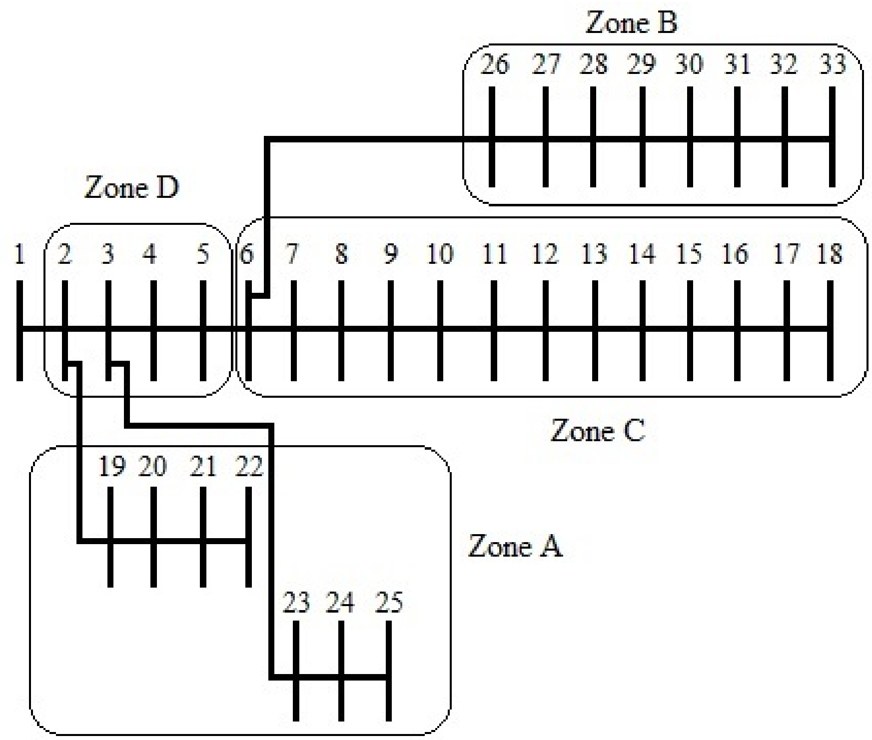

Figure 1.3: IEEE 33 bus radial distribution system zones for DG integration.

1.2 Report Outline

The focus of this report is on maximizing power loss reduction in distribution systems considering behind-the-meter PV-BES (type 3) DG sources in commercial buildings. The IEEE 33 bus radial distribution network is used for evaluation purposes. The remainder of this report is organized as follows. In Chapter 2, the forward/backward sweep (FBS) method is used to estimate power loss with and without DG sources. The commercial PSS SINCAL power analysis software is used to verify the results obtained. In Chapter 3, power loss is optimized by applying particle swarm optimization (PSO). The PSO algorithm is used for the IEEE 33 bus radial distribution system with and without restrictions on the DG size. Various scenarios of integrating DG sources into the distribution system are considered to evaluate the impact of these sources on power loss. The results obtained are validated using the PSS SINCAL software. Finally, Chapter 4 provides some concluding remarks and directions for future work.

Table 1.2: Optimal DG Locations in the IEEE 33 Bus Radial Distribution System

Optimization Method	Objective Function	Optimal DG Bus Location	Number of Front-of-the-meter DG Sources
Fuzzy Logic [21]	Power Loss	6	1
Whale Algorithm [22]	Power Loss	30	1
Genetic Algorithm+ [23] Inteligent Water Drops	Power Loss+ Voltage Stability	11,16,32	3
Genetic Algorithm [24]	Power Loss	6	1
Cat Swarm Optimization [25]	Power Loss	13,30	2
Particle Swarm Optimization [26]	Power Loss	6,30	2
Power Loss [20]	EA+OPF	13,30	2

Chapter 2

Power Loss Calculation in the Presence of DG Sources

In order to minimize power loss, it is essential to have accurate power loss calculations. Power loss in a power system operating at steady state is calculated using bus voltages and branch currents [27]. Bus voltages and branch currents are obtained by performing load flow analysis. Load flow analysis solves nonlinear algebraic power equations subject to the following conditions.

- The power system is in steady state.
- The power system topology is fixed.
- The load power demand at each bus is fixed.
- The generated power at P-|V| buses is fixed.

The final solutions are obtained when the power equations converge to definite values [28], [29].

By design, transmission systems have almost perfectly balanced three phase loads and a lower R/X ratio in the power lines compared to distribution systems, where R and X are the resistance and reactance, respectively. Moreover, bus voltage magnitudes in a transmission system are significantly larger compared to the currents carried by the conductors. Finally, they are typically designed in a mesh architecture. On the contrary, distribution systems have a large number of unbalanced three phase loads. Furthermore, the low inductance and high resistance of the system components leads to a high R/X ratio. Moreover, the distribution systems have comparable current and voltage magnitudes and they are mostly radial in architecture [30]. As a result of these differences, different load flow algorithms have to be used with transmission and distribution systems. Newton-Raphson (NR) and Gauss-Seidel (GS) based load flow methods are widely used to analyze transmission systems while the forward/backward sweep (FBS) method is more suitable for distribution systems [31], [32].

2.1 Forward/Backward Sweep Load Flow

Lower construction costs and higher reliability make radial distribution systems more popular than ring topology systems. The forward/backward sweep (FBS) load flow method is widely employed with radial distribution systems due to the short computation time, low memory requirements, and fast convergence [33]. This method has two iterative steps named the backward and forward sweeps. Consider a section of a distribution system shown in Figure 2.1. First, the power flow through the branches is calculated in the back-

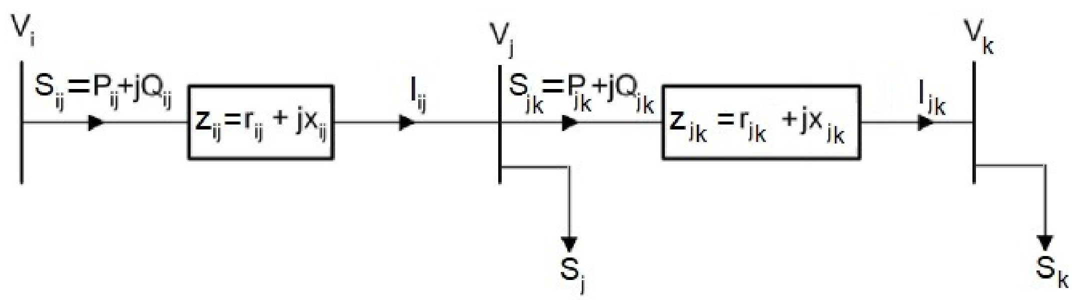

Figure 2.1: A two branch section of a radial distribution system.

ward sweep. This calculation starts from the end bus and moves towards the slack bus. It is assumed that initially all bus voltages and branch losses are 1 and 0 (pu), respectively. The backward sweep calculates the injected apparent power and current in the branches using [34]

$$S_{ij} = S_j + S_{jk} + Loss_{ij}, \tag{2.1}$$

and

$$I_{ij} = (S_{ij}/V_j)^*, \tag{2.2}$$

where S_{ij} is the injected apparent power into branch ij, j is the end bus in branch ij, S_j is the delivered apparent power to the load connected at bus j, S_{jk} is the apparent power of branch jk, and $Loss_{ij}$ is the loss in branch ij, which is set to zero in the first iteration.

Second, in the forward sweep, the bus voltage magnitudes and angles are calculated using

$$V_j = V_i - (Z_{ij} I_{ij}). \tag{2.3}$$

Calculation starts from the slack bus and proceeds to the end bus. The values obtained in the previous backward sweep are used in the forward sweep.

Power flow in the branches is computed using the initial voltage values. The forward sweep updates the bus voltage magnitudes and angles using the power flow data. Then the power loss of the branches is obtained as

$$Loss_{ij} = (V_i - V_j) I_{ij}^*, \tag{2.4}$$

where V_i is the voltage at the sending bus i and V_j is the voltage at the receiving bus j. The algorithm stops when the error is less than a specified value (ϵ) [35]. The error at the end of each iteration ($\Delta(V_i)^n$) is defined as the voltage difference between two consecutive iterations

$$\Delta(V_i)^n = |(V_i)^n| - |(V_i)^{(n-1)}| \tag{2.5}$$

where n is the current iteration. Figure 2.2 shows the flowchart of the forward/backward sweep algorithm.

2.2 Validation of the Forward/Backward Sweep Algorithm

Figure 2.3 shows the IEEE 33 bus radial distribution system which is used to validate the implementation of the FBS algorithm. The IEEE 33 bus system supplies 3.72 MW and 2.3 MVAr to the connected loads [36]. The FBS algorithm is used to calculate the real power loss in this system. The active and reactive loads connected to the buses and resistance and reactance of the branches are given in Appendix A. Table 2.1 gives the power loss result obtained from the FBS algorithm implemented in MATLAB. This result is verified by comparing it with power loss results in [36], [37]. Based on these results, it is concluded that the algorithm has been implemented successfully.

Table 2.1: Forward/Backward Sweep Algorithm Results

Load Flow Method	Real Power Loss (kW)
FBS reported in literature [36]	211.0
Implemented forward/backward sweep	210.8

2.2.1 Validation with PSS SINCAL

The load flow results obtained using MATLAB are validated by the PSS SINCAL software, a SIEMENS product for load flow calculation in distribution systems [38]. The IEEE 33 bus system modeled in PSS SINCAL is shown in Figure 2.4. Loads at each bus in the network as well as the bus voltages in per unit are indicated in the figure. Table 2.2 gives the active and reactive power loss in the IEEE 33 bus system. These results from PSS SINCAL validate the FBS results.

Table 2.2: Forward/Backward Load Flow Results without a DG Source

Load Flow Method	Total Active Power Loss (kW)	Total Reactive Power Loss (kVAr)
Forward/Backward Sweep	210.8	143.0
PSS SINCAL	211	143

2.3 DG Modeling in the Forward/Backward Sweep Load Flow Algorithm

The original FBS load flow equation must be modified if DG sources are employed. This modification is done by modeling DG sources as P-|V| or PQ buses in the distribution system. A DG source based on synchronous generator technology is able to keep its terminal voltage constant by controlling generated reactive power and is modeled as a P-|V| bus. In contrast, a DG source based on asynchronous generator technology like a photovoltaic panel or fuelcell needs power electronic inverter technology to connect to the grid and so they are modeled as PQ bus. In this report, photovoltaic based DG sources are considered. Hence, they are modeled as PQ buses [39], [40]. A PQ type DG source is represented as a negative load as shown in Figure 2.5. The net active and reactive power at a DG source connected to the bus are given by

$$P_{j,new} = P_j - P_{DG}, \tag{2.6}$$

and

$$Q_{j,new} = Q_j - Q_{DG}, \tag{2.7}$$

where P_j and Q_j are the active and reactive power of the load at bus j, and P_{DG} and Q_{DG} are the active and reactive power generated by the DG source integrated at bus j. Load flow analysis is done using the new values of P and Q at the DG integrated buses.

2.3.1 Algorithm Implementation and Validation of Results

In order to validate the proposed method, a 4 MVA front-of-the-meter, type 3 DG source is integrated at bus 6 as in [41]. The FBS load flow algorithm is used to calculate the power loss after DG integration. The results obtained and those in [41] are given in Table 2.3. The size and power factor of the DG source is selected as in [41] in order to compare the power loss values. From Table 2.3, it is evident that the result obtained using the FBS algorithm match those in [41]. In addition, the PSS SINCAL model of the DG integrated distribution system shown in Figure 2.6 is used to verify the results. In this model, the IEEE 33 bus distribution system is integrated with a DG source at bus 6 and the same size and power factor as in [41]. Based on the results obtained, adding a DG source to the distribution system results in significant power loss reduction.

Table 2.3: Forward/Backward Sweep Load Flow Results

Load Flow Method	DG Bus 6		Power Loss (kW)
	Size (kW)	pf	
FBS Algorithm with DG	2528	0.82	67.8
EA Method [41]	2528	0.82	67.8
PSS SINCAL	2528	0.82	68

2.4 Power Loss Estimation with Behind-the-Meter DG Sources

The power loss with a behind-the-meter DG source depends on parameters such as the size, power factor and location. In order to obtain the optimal power loss, an optimization algorithm needs to be used to identify the optimal combination of size, power factor and location. As there has been little research on behind-the-meter DG sources, the results obtained should be verified using the PSS SINCAL software.

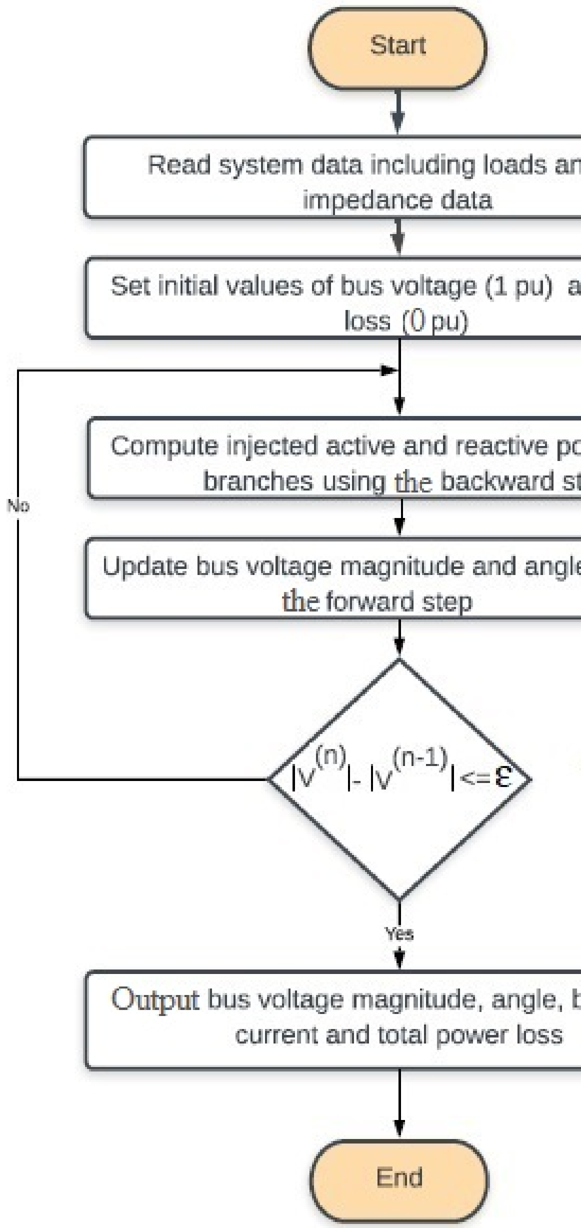

Figure 2.2: The forward/backward sweep load flow algorithm.

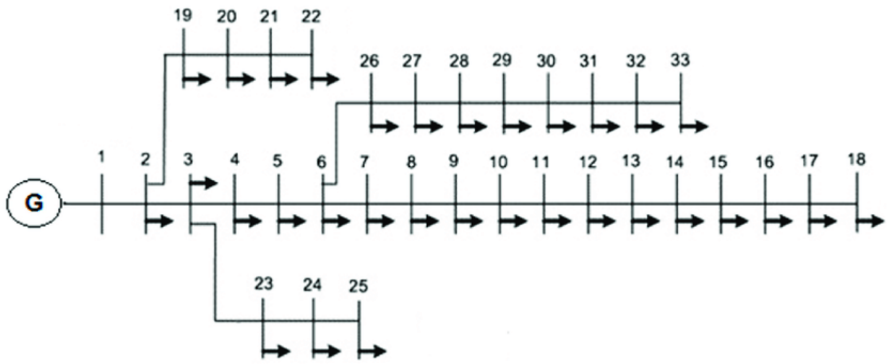

Figure 2.3: IEEE 33 bus radial distribution system schematic diagram.

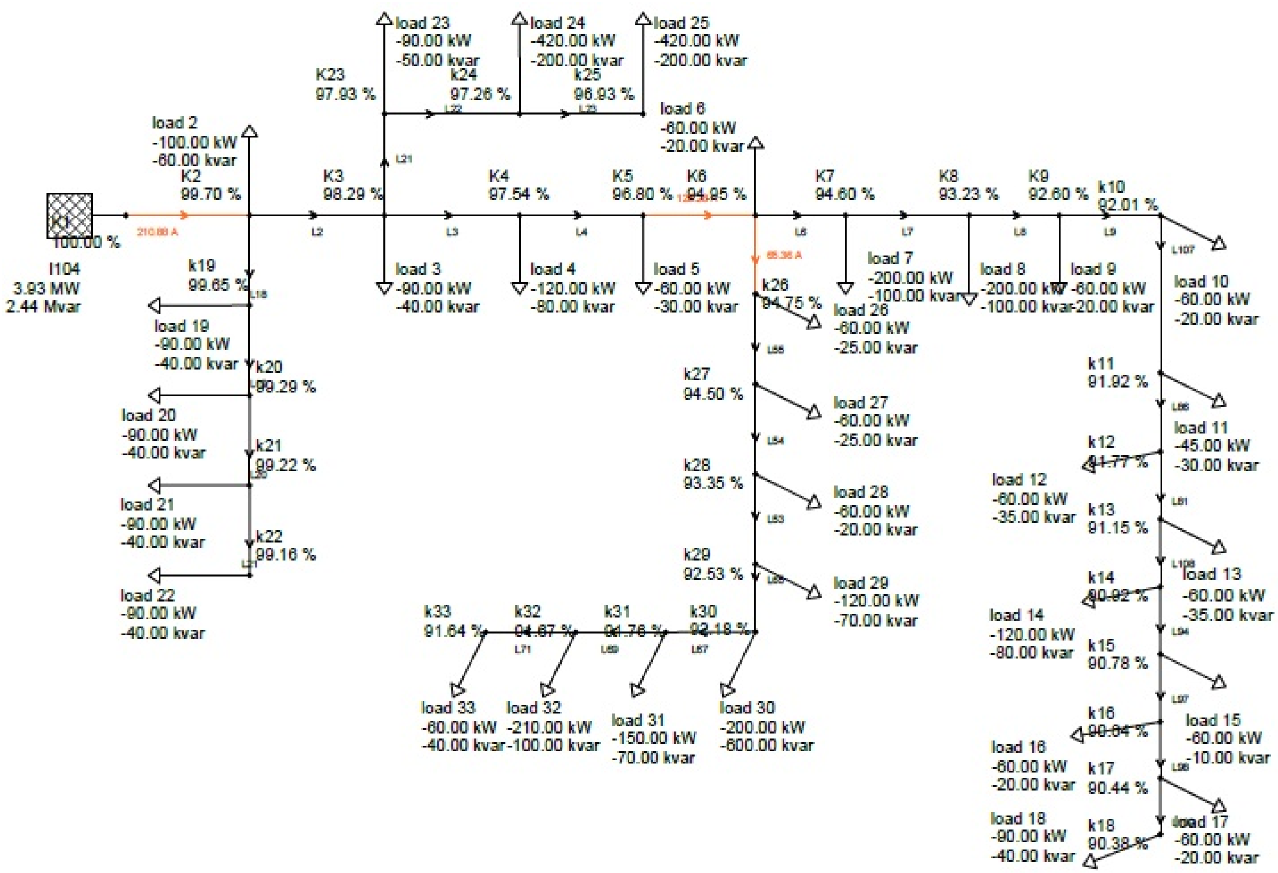

Figure 2.4: PSS SINCAL model of the IEEE 33 bus radial distribution system.

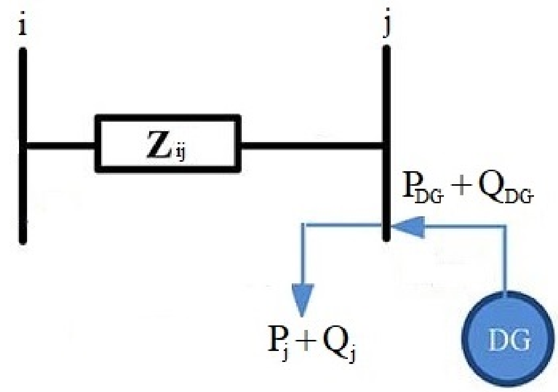

Figure 2.5: A DG source modeled as a PQ bus.

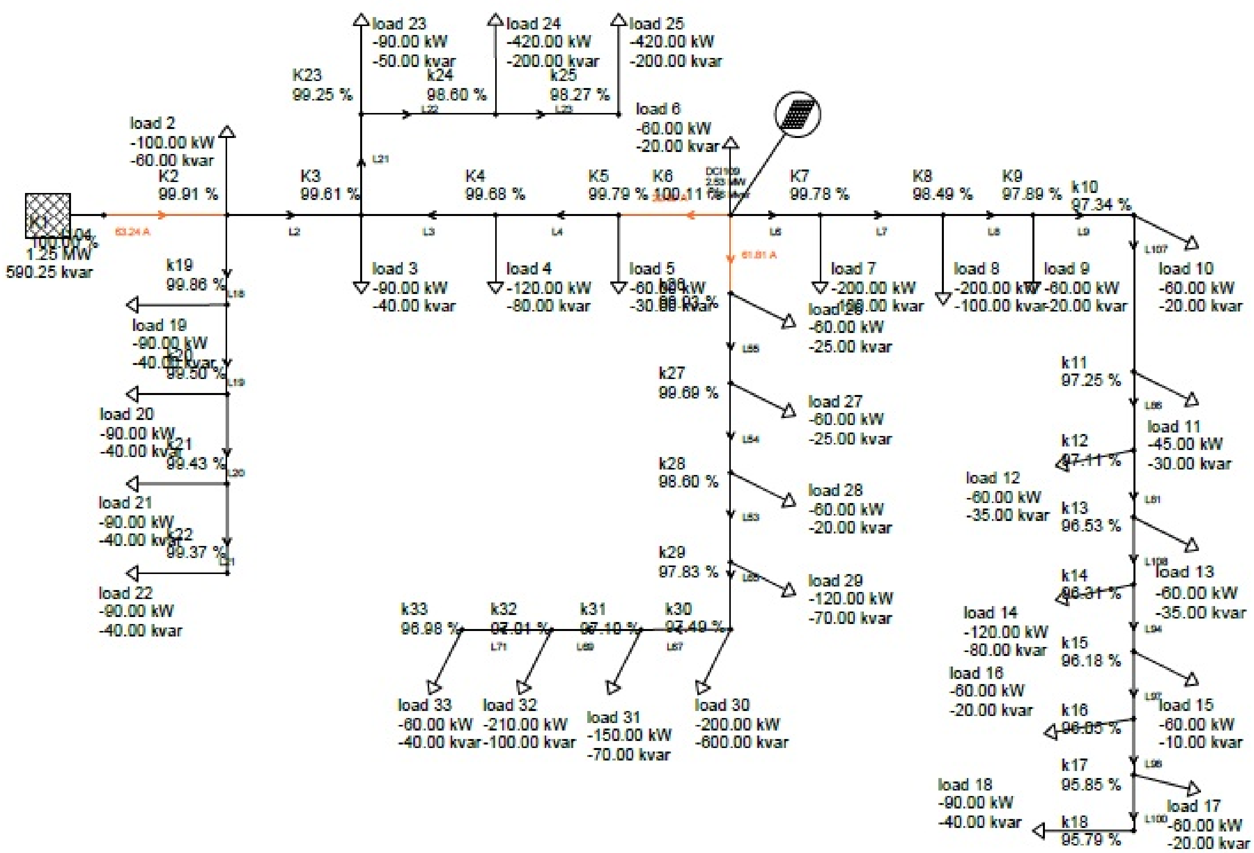

Figure 2.6: PSS SINCAL model of the IEEE 33 bus radial distribution system with an integrated DG source.

Chapter 3

Power Loss Optimization

Power loss reduction using behind-the-meter DG integration can be optimized using variables such as the size, power factor, and the number and location of the DG sources [42], [43]. In this work, particle swarm optimization (PSO) is used. PSO is an evolutionary optimization algorithm introduced by Kennedy and Eberhart in 1995 [44]. This algorithm mimics the way a flock of birds looks for roosting places or a school of fish looks for food sources. It has been shown to be more efficient than other random statistical approaches [44], and is preferred in engineering optimization problems due to its simple realization and fast convergence [45].

3.1 PSO Algorithm for DG Integration in a IEEE 33 Bus Distribution System

The IEEE 33 bus distribution system is used as the test system for power loss minimization. Optimization is carried out using the power factor, size, and location of the DG sources as variables. The active and reactive power of the system form the equality constraints while the boundary conditions of the variables give the inequality constraints. The problem is then defined as

$$\min(P_{Loss}), \tag{3.1}$$

subject to

$$\sum_{j=1}^{K} P_{DGj} - \sum_{i=1}^{N} P_{Di} - \sum_{n=1}^{B} P_{Ln} = 0, \tag{3.2}$$

$$\sum_{j=1}^{K} Q_{DGj} - \sum_{i=1}^{N} Q_{Di} - \sum_{n=1}^{B} Q_{Ln} = 0, \tag{3.3}$$

$$S_{DG_{\min}} \leq S_{DGj} \leq S_{DG_{\max}}, \tag{3.4}$$

$$pf_{DG_{\min}} \leq pf_{DGj} \leq pf_{DG_{\max}}, \tag{3.5}$$

$$Loc_{DG_{\min}} \leq Loc_{DGj} \leq Loc_{DG_{\max}}, \tag{3.6}$$

where K is the number of DG sources, N is the number of buses, B is the number of branches, P_{DGj} is the real power generated by DG source j, P_{Di} is the real demand power at bus i, P_{Ln} is the injected real power in branch n, Q_{DGj} is the generated reactive power by DG source j, Q_{Di} is the reactive power demand at bus i, Q_{Ln} is the injected reactive power in branch n, S_{DGj} is the apparent power of DG source j with minimum value 0, pf_{DGj} is the power factor of DG source j which can be between 0 and 1, and Loc_{DGj} is the bus location of DG source j that can be between 2 and 33.

Figure 3.1 shows the PSO algorithm used to optimize the objective function. The solution obtained is verified using the Efficient Analytical (EA) method results in [41] and the PSS SINCAL results. Table 3.1 gives the power loss of the test system with two type 3 DG sources. The power loss results obtained with PSO and EA are compared with the power loss of the initial system without a DG source. The DG locations with PSO are at buses 13 and 30 as in [41].

Table 3.1: IEEE 33 Bus System Optimization Results

	DG Bus 13		DG Bus 30		
Optimization Method	Size (kW)	pf	Size (kW)	pf	Power Loss (kW)
Initial System					211.0
PSO	845.7	0.90	1137.2	0.73	28.5
EA [41]	846.0	0.90	1163.0	0.73	28.5

3.2 Impact of the Number of DG Sources on Power Loss

In this section, the power loss reduction is examined for different numbers of DG sources. Table 3.2 gives the power loss resulting from integrating two to six DG sources. The location, generated active power and power factor (pf) of the DG sources are also given in the table. This shows that the power loss reduction increases with the number of integrated DG sources. Simulations were conducted in PSS SINCAL with different numbers of 500

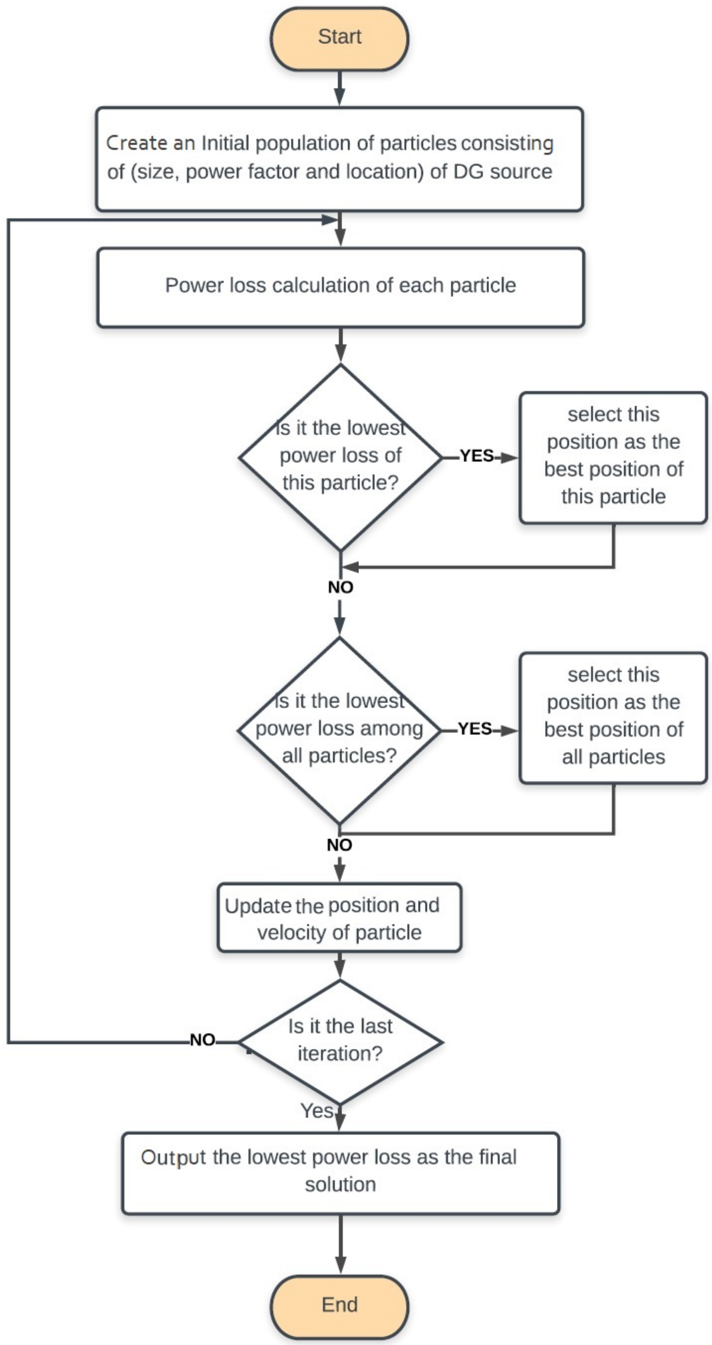

Figure 3.1: Flowchart of the PSO algorithm implementation.

kVA sources integrated in the system at the same locations as with PSO. Figure 3.2 shows one such case with four DG sources added in buses 8, 15, 30 and 32. Table 3.3 gives the power loss results obtained by using PSO and PSS SINCAL for 0, 2, 3, and 4 DG sources. The power loss obtained with PSS SINCAL shows good agreement with the PSO results. Next, 100 kVA DG sources are integrated to see how smaller size DG sources affect power loss reduction. The results in Figure 3.3 show that the loss reduction still depends on the number of integrated DGs. It could be claimed that, regardless of DG source size, power loss reduction increases as the number of integrated sources is increased.

Table 3.2: Power Loss with Different Numbers of 500 kVA DG Source

DG Locations	DG 1		DG 2		DG 3		DG 4		DG 5		DG 6		Power Loss (kW)
	(kW)	pf	(kW)	pf	(kW)	pf	(kW)	pf	(kW)	pf	(kW)	pf	
15, 32	436.0	0.87	382.0	0.76									86.3
31, 15, 30	385.0	0.77	442.0	0.88	373.4	0.74							52.6
32, 15, 8, 30	379.6	0.75	446.5	0.89	432.9	0.86	361.0	0.72					31.8
30, 6, 32, 8, 15	341.0	0.68	423.1	0.84	375.2	0.75	439.2	0.87	450.8	0.9			21.5
27, 8, 32, 25, 15, 30	417.0	0.83	440.0	0.88	370.0	0.74	447.0	0.89	451.0	0.9	330.0	0.66	9.2

Table 3.3: Power Loss Results with PSS SINCAL

Number of Integrated DG Sources	DG Source Locations	Power Loss (kW)	
		PSO	PSS SINCAL
0	-	211.0	211
2	15, 32	86.3	86
3	31, 15, 30	52.6	52
4	32, 15, 8, 30	31.8	31

Figures 3.3 and 3.4 show that the increase in power loss reduction is minimal beyond six 500 kVA and sixteen 100 kVA sources. It was shown in [41] that integrating four 4 MVA DG sources into the IEEE 33 bus distribution system provides the maximum power loss reduction. Hence, it could be concluded that the optimal number of behind-the-meter DG sources for maximum power loss reduction varies with size.

Table 3.4 gives the power loss results obtained from integrating various numbers of DG sources. The number of integrated sources, DG size, and total power generated by DG sources are also presented in the table. These results show that the power loss reduction is increased by integrating several smaller sized DG sources rather than one large DG source. Thus, the same amount of power loss is obtained with less DG penetration power if several

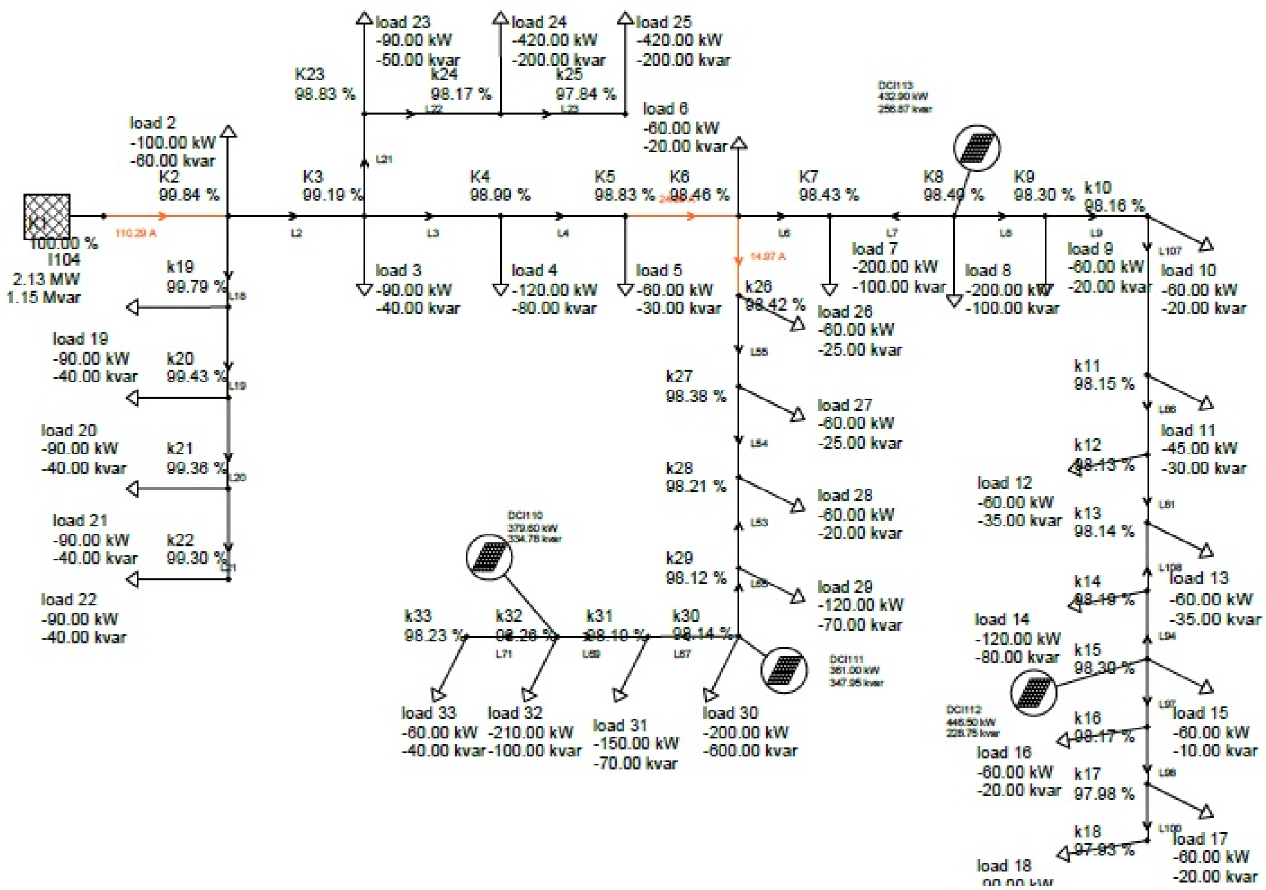

Figure 3.2: PSS SINCAL model of the IEEE 33 bus radial distribution system with four integrated DG sources.

behind-the-meter DG sources are used instead of one front-of-the-meter DG source. This is a major benefit of using behind-the-meter DG sources rather than front-of-the-meter DG sources.

3.3 Fixed DG Penetration

In this section, the power loss reduction is examined for fixed DG source penetration. The generated power of the DG sources is defined as DG penetration [46]. To demonstrate the effectiveness of behind-the-meter type 3 DG sources, full penetration (4 MVA) of the IEEE 33 bus distribution system is considered for the following four scenarios.

1- One 4 MVA DG

2- Two 2 MVA DG Sources

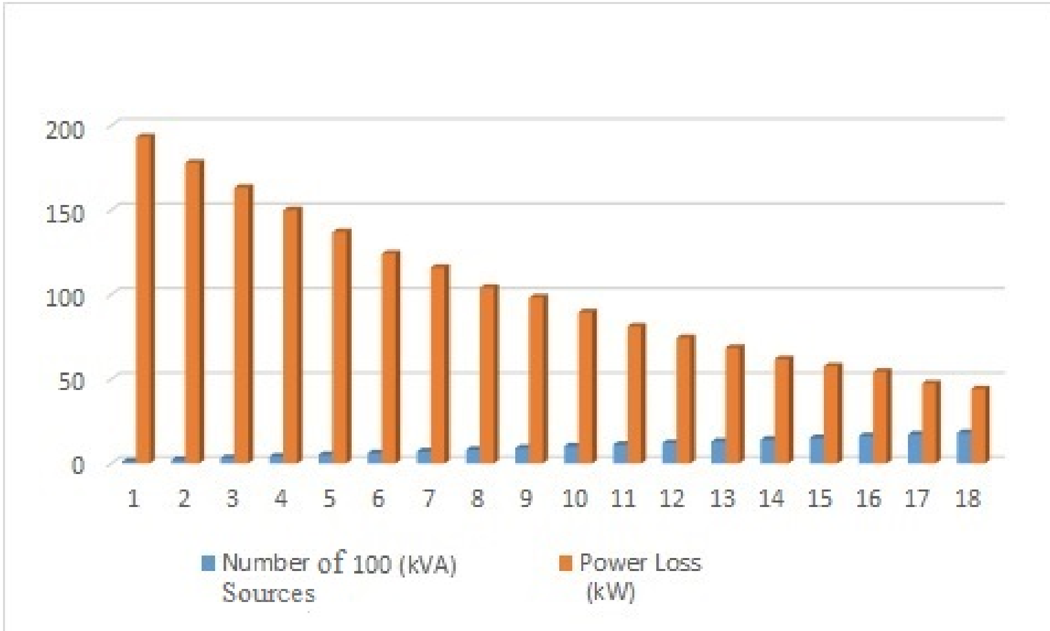

Figure 3.3: IEEE 33 bus distribution system power loss with various numbers of 100 kVA DG sources.

Table 3.4: Impact of Integrated DG Size on Power Loss Reduction

Number of DG Sources	DG Source Power (kVA)	Total DG Source (kVA) Power	Power Loss (kW)
1	4000	4000	68.0
13	100	1300	67.9
18	100	1800	48.1

3- Four 1 MVA DG Sources

4- Eight 500 kVA DG Sources

Table 3.5 gives the power loss for the four scenarios obtained with the PSO algorithm on the IEEE 33 bus distribution system. The size and number of sources as well as their locations are also given in the table. This shows that for a fixed DG penetration, using a number of smaller sized DG sources provides greater loss reduction than fewer larger DG sources. In particular, integrating eight 500 kVA DG sources reduces the power loss by a factor of 23 over using one 4 MVA DG source.

Figure 3.4: IEEE 33 bus loss reduction with various numbers of 500 kVA DG sources.

Table 3.5: Power Loss with Four 4 MVA Scenarios

DG size (MVA)	Scenario	DG Source Locations	Power Loss (kW)
4	1	6	68.0
2	2	13, 30	28.5
1	3	6, 14, 24, 30	7.7
0.5	4	32, 16, 10, 7, 24, 29, 25, 30	3.2

3.4 Impact of DG Size on the Optimal DG Locations

In this section, the power loss reduction is examined for different size DG sources and the impact of DG size on the optimal locations is evaluated. Table 3.6 gives the PSO algorithm results for two integrated DG sources with different maximum sizes. For each maximum DG source power, the bus locations, active power, power factor, and total power loss are given. These results show that the optimal locations for behind-the-meter DGs depend on their size. This is significant because for 1 MVA and larger sized integrated DG sources, the optimal locations are independent of the size.

Optimizing the DG locations is important as it can affect the power loss reduction. Table 3.7 shows the power loss obtained using the PSO algorithm for two integrated DG sources with different maximum sizes. For each maximum size, three cases were considered to examine the power loss of the IEEE 33 bus distribution system. First, the source locations were fixed at buses 13 and 30 as in [41] which are the optimal locations with a 1 MVA

Figure 3.5: Power loss reduction with 4 MVA DG scenarios.

source. Hence, the PSO algorithm only determines the optimal sizes and power factors of the DG sources. Second, the PSO algorithm determines the optimal DG locations as well as the sizes and power factors. Third, the source locations were randomly selected at buses 8, 22. Therefore, the PSO algorithm determines the optimal power loss along with the optimal size and power factor of the DG sources. The results in Table 3.7 indicate that the optimal power loss is affected by fixing the DG locations. In addition, the results also show the impact of the PSO algorithm on power loss reduction. It is observed that there is a considerable difference between the power loss results for optimal and random DG source locations.

Table 3.6: Optimal DG Locations for Different Maximum DG Sizes

Mazimum DG Size (kVA)	Optimal DG Bus Locations	DG1 Size (kW)	DG1 pf	DG2 Size (kW)	DG2 pf	Power Loss (kW)
100	18, 17	86.8	0.86	86.7	0.86	177.7
300	32, 17	231.0	0.77	261.6	0.87	125.0
500	32, 15	382.5	0.76	436.6	0.87	86.3
800	31, 14	602.5	0.75	703.0	0.87	49.8
1000	13, 30	885.4	0.88	732.6	0.73	37.6
1500	13, 30	856.9	0.90	1094.0	0.73	28.6

Table 3.7: Power Loss with Fixed and Optimal DG Source Locations

Mazimum DG Size (kVA)	Optimal DG Bus Locations	Power Loss (kW)	Fixed DG Bus Location	Power Loss (kW)	Random DG Bus Location	Power Loss (kW)
100	17, 18	177.7	13, 30	180.0	8, 22	197.2
300	17, 32	125.0	13, 30	128.0	8, 22	172.9
500	15, 32	86.3	13, 30	88.8	8, 22	152.8
800	14, 31	49.8	13, 30	50.6	8, 22	127.8
1000	13, 30	37.6	13, 30	37.6	8, 22	114.4
1500	13, 30	28.6	13, 30	28.6	8, 22	91.1

Chapter 4

Conclusion and Future Work

In this work, it was shown that the power loss in a distribution system can be reduced by using behind-the-meter type 3 DG sources. Results obtained using the IEEE 33 bus distribution system showed that for the same amount of DG penetration, integration of more behind-the-meter type 3 DG sources increased the power loss reduction. As a result, distributed power generation using small sources makes the distribution system more efficient. This could be vital in situations that have restrictions on generated power. Meanwhile, the same power loss reduction can be achieved by injecting less power from small sized DG sources rather than large sized DG sources. Power loss was further reduced by using DG location as an optimization variable. Moreover, it was observed that the optimal locations depend on the size of the DG sources. Hence, there is a need to identify the optimal DG locations as size changes. Accordingly, the DG locations must be part of any DG integration optimization problem. The results obtained were validated using the commercial power analysis software PSS SINCAL. Thus, by encouraging behind-the-meter DG source integration, utilities not only avoid power generation costs but also gain from reduced power loss.

4.1 Future Work

In this work, type 3 DG buses were modeled as PQ buses. Future work can model type 3 DG sources as a P-$|V|$ bus and analyze the impact of DG integration on power loss reduction. Another direction would be to use reactive loss reduction in the objective problem. Finally, the impact of power loss reduction using behind-the-meter type 3 DG sources on power quality parameters such as voltage profile can be studied.

Appendix A

IEEE 33 Bus Distribution Data

The system data including bus connected loads and branch resistance and inductance are presented in Table A.1. The send and receive buses of every branch are also identified in the table.

Table A.1: IEEE 33 Bus System Data [37]

Send Bus	**Recieve Bus**	**R (Ω)**	**X (Ω)**	**P (kW)**	**Q (kVAr)**
1	2	0.0922	0.0470	100	60
2	3	0.4930	0.2511	90	40
3	4	0.3660	0.1864	120	80
4	5	0.3811	0.1941	60	30
5	6	0.8190	0.7070	60	20
6	7	0.1872	0.6188	200	100
7	8	1.7114	1.2351	200	100
8	9	1.03	0.74	60	20
9	10	1.044	0.74	60	20
10	11	0.1966	0.065	45	30
11	12	0.3744	0.1238	60	35
12	13	1.468	1.155	60	35
13	14	0.5416	0.7129	120	80
14	15	0.591	0.526	60	10
15	16	0.7463	0.5450	60	20
16	17	1.289	1.721	60	20

Continued on next page

Table A.1 – continued from previous page

Send Bus	**Recieve Bus**	**R (Ω)**	**X (Ω)**	**P (kW)**	**Q (kVAr)**
17	18	0.732	0.574	90	40
2	19	0.164	0.1565	90	40
19	20	1.5042	1.3554	90	40
20	21	0.4095	0.4784	90	40
21	22	0.7089	0.9373	90	40
3	23	0.4512	0.3083	90	50
23	24	0.898	0.7091	420	200
24	25	0.8960	0.7011	420	200
6	26	0.2030	0.1034	60	25
26	27	0.2842	0.1447	60	25
27	28	1.059	0.9337	60	20
28	29	0.8042	0.7006	120	70
29	30	0.5075	0.2585	200	600
30	31	0.9744	0.9630	150	70
31	32	0.3105	0.3619	210	100
32	33	0.3410	0.5302	60	40

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