Chapter 5

Reliability Assessment Considering Wind Energy with Conventional Generation

5.1 Introduction

In a power system, the unexpected load fluctuations must be handled efficiently. For continuous electrical power delivery to the loads, the EPDN manages these load fluctuations. Radial and Loop DSs are the two types of the system. Since it is simple, inexpensive, and mainly suited to sparsely dispersed loads, the radial system is chosen for research. Furthermore, integration of DER in DS is needed to handle the fast increase in load. The DERs, which include Conventional Generation (CG),WTG, minimize system voltage disturbance, power loss depreciation, operating cost reduction, and CO_2 emission reduction. As a result, lowering these parameters increases the reliability of the power supply. As a result, the research on DS's reliability and performance analysis while evaluating the best DER siting and size is critical. The DER integration in EPDN has a significant effect on the operation and planning strategy of power systems [130].

The system's stability and power quality improvement are achieved, but it is required to add Battery Energy Storage Device (BESD), economically. Thus, the multi-objective optimization problems, including DER location and size, CO_2 emission, total power loss, voltage deviation, demand-side management, charging-discharging of batteries, total harmonic distortion, and system reliability are established [144, 147, 154–156]. Improvement in network reliability has been observed when congestion management algorithms to identify the transmission line congestion are implemented [157]. DERs and BESDs are scheduled optimally to alleviate this transmission line congestion. A two-step optimization problem is provided for the congestion problem [158].

In [146], the authors propose an index for determining the best location for DERs in a distribution system. This index is used to address a variety of issues, such as reducing total electrical power loss, energy not provided, and voltage variation. Another goal, annual energy reduction loss, is seen when RESs-based DERs and network reconfiguration [159] are combined. Furthermore, two-stage stochastic programming has been suggested, and uncertainty consideration, including wind and solar power production, as well as load fluctuation, has been investigated [160]. Simultaneously, achieving an optimum BESD size and placement improves power system's reliability. Compound co-optimization strategy plan [161] has depicted to enhance network reliability and reduce network losses. The co-optimization approach also defines the reliability indices, which include EENS, Energy Index of Reliability (EIR), LOLE, and LOLP.

Further, the reliability assessment provides a better evaluation of any power system's performance. For assessing the power system reliability, several indices have been mentioned in the literature. The indices are categorized as Energy-Oriented and Customer-Oriented Indices, as already mentioned in Equations (1.18)–(1.19) and Equations (1.20)–(1.25c), respectively. The indices' values decrease if the aging of the sub-components is considered in reliability assessment [167]. Reliability is regarded as a primary requirement in the designing phase of DS. Thus, the optimal site and optimal size of three DERs for further reliability assessment has been considered. The conventional generation and WTGs are implemented as DGs in 33 bus and 118 bus DSs and observed an improvement in reliability. To fulfill the reliability assessment in EPDN, [155] has introduced a restoration strategy for the calculation of energy not supplied. The optimization of reliability indices are considered [146, 161], and the improvement in DS's reliability was observed.

The literature focuses on optimal allocation and size of DERs obtaining a better power system performance. All proposed optimization techniques are proven to be better when compared with other methods. The system's reliability assessment is discussed individually without analysing the impact of optimal DG integration. Thus, an optimization technique for optimal siting and sizing of DER for 33 bus DS is presented. Simultaneously, the parameters, as given in Table 2.7, which were not discussed in the literature, are also considered. The comparison with other previous techniques shows the competitiveness of the CF-PSO technique. The comparative analysis for the reduction in electrical power loss and voltage deviation is performed by integrating the 1CG, 1CG+1WTG, and 1CG+2WTG in 33 bus and 118 bus DSs. After that, the findings are compared to previously completed works. The reliability assessment is completed after achieving decreased power loss and better bus voltages. The performance analysis for adapted test systems is carried out first, followed by the system's reliability assessment with and without integration of DERs. As a result, the chapter concentrates mostly on the reliability assessment of test systems. It is expected that the suggested approach can be used in larger systems that are integrated with both conventional and renewable energy sources. For the accomplishment of the above task, a work flowchart is framed in Figure 5.1.

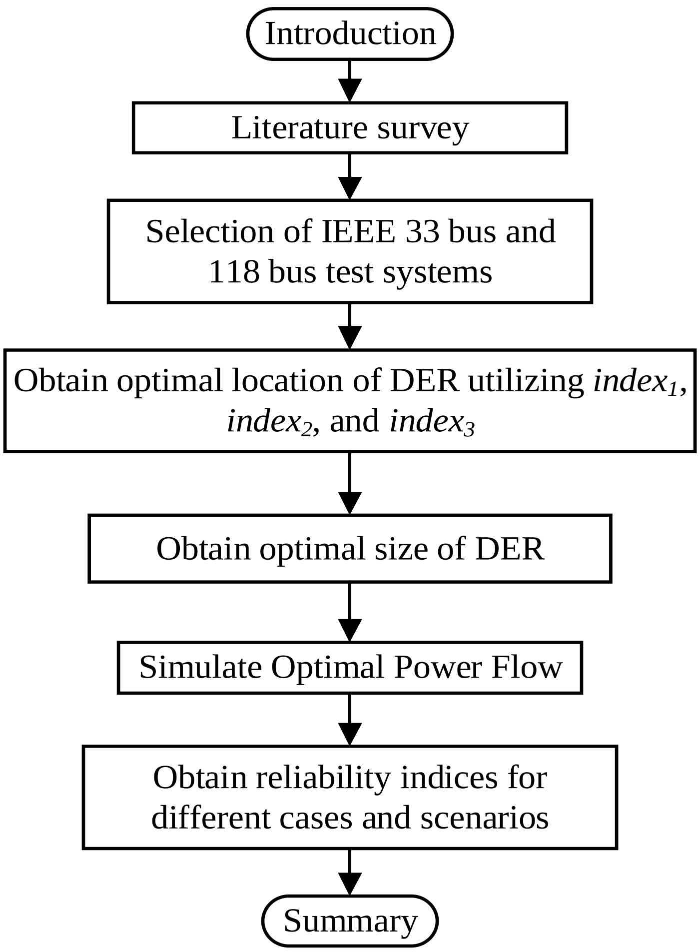

Figure 5.1: Flow chart of research work performed in this chapter.

5.2 Problem Formulation

The electrical power distribution network has considerable I^2R loss, which must be minimized. The Distribution Companies promote DERs' integration as the ancillary services for several electrical parameters, including power loss minimization. Therefore, bus voltage and system reliability are the most affecting factors for EPDN when losses are considered. It becomes necessary to improve these two factors by implementing DER into the system. DER siting is one of the favoured techniques used in the DS to improve the system's reliability and bus voltage profile, including power loss minimization. The DER allocation, DER size, DER pf, and DER type are required to be considered for the implementation of DERs in the distribution network. Simultaneously, it is required to study mathematical expressions, and modellings of related parameters and DERs integrated into the system. An overview of the parameters considered for the loss minimization and mathematical modeling is discussed in this chapter and briefly discussed the impact on DS.

5.2.1 Parameters adapted

(i) DER location and DER rating: The work on optimal power flow is performed by the utilities for electrical power system operation and control. Optimal flow of power does the determination of bus voltages, flow of active power, and reactive power. The optimal siting of DERs is required for power loss minimization during power flow results. The location of DER is preferably near the load points. The performance of the power network is affected by an inappropriate location of DER. So, it necessitates obtaining the relevant siting and rating of DER without altering the system configuration. The IEEE 1547 standards for integration and operation of DER into Electrical Power Distribution Networks are presented in [231].
(ii) Power loss: The techniques used for power loss minimisation during Optimal Power Flow create the constructive means of acquiring a desirable system voltage profile. Further, the loss minimisation techniques improve the convergence of the equations to avoid any ill condition in the system. The occurrence of active power loss is greater than reactive power loss in DS. Hence, Distribution Companies should reduce these losses through DER integration. The integration of DER is one technique for power loss minimization, as discussed.
(iii) Node or Bus Voltage: It is expected to maintain bus voltages nearly 1pu with an angle of 0^0. The power loss occurring in EPDN during optimal flow of electrical power creates a

voltage drop at each bus of the system. So, the DER integration technique is implemented for the improvement of bus voltage profile.

(iv) Power Factor: The DERs, including conventional generation, WTG, Gas Turbine, and Micro-Turbine, are considered to operate at non-unity pfs. The three DERs operating at 1, 0.90, 0.85, and 0.82 pfs are considered in this chapter.

(vi) Type of Loads: The three types of loads as (a) Commercial, (b) Industrial, and (c) Residential are considered. The reliability worth of DS is got affected according to the type of load connected to each bus.

(vii) Type of DER: The three numbers of DERs are implemented. These three DERs are categorized in conventional DER and WTG technologies.

(viii) Reliability: Reliability assessment of a Distribution System is a deciding factor to analyse the system's performance. The reliability indices, including CAIDI, SAIDI, SAIFI, ECOST, and EENS have been considered for the system's reliability. These indices are further being computed to obtain the other indices, as described in Chapter 1.

5.2.2 Optimal location

The two indexes for finding the optimal locations are utilised for 33 bus test system. The $index_1$ is implemented only for placing the 1CG, and $index_2$ is for placing more than one DERs in the EPDN, as formulated in Chapter 4. It is examined while performing Electrical Power Loss Minimization (EPLM) problem that, according to $index_1$, minimum power loss is obtained for single DER (1CG) integration. However, $index_2$ provides minimum power loss for multiple DERs (1CG, 1CG+1WTG, and 1CG+2WTG). Furthermore, a $index_3$ has been introduced in this chapter for 118 bus test system. These three indicators are described by Equations (5.1)–(5.3), respectively. As it is observed from the equation of $index_1$ a large index value depicts the weakest node of the system because the complex power injected at bus i is large. It implies that 1CG can be placed on this particular bus. On the other hand, $index_2$ shows the voltage stability, which concludes that this index's reduced values give the weakest bus of the distribution system. Therefore, DERs can be placed on these buses. For a quick reference, $index_1$ and $index_2$ are defined in Equations (5.1) and (5.2), respectively.

$$(index_1)_i = |A_i| \times |S_{in_{eff_i}}| \tag{5.1}$$

$S_{in_{eff_i}}$ is the effective injection of complex power, which is the sum of injected powers from other buses connected to ith bus.

$$(index_2)_{a+1} = |V_a|^4 - 4(P_{in,b}X_l - Q_{in,b}R_l)^2 - 4(P_{in,b}R_l - Q_{in,b}X_l)|V_a|^2 \geq 0 \tag{5.2}$$

Where *j* is branch number, V_i is sending bus voltage, P_{i+1} and Q_{i+1} are the active power and reactive power at the receiving end bus, respectively. R_j and X_j are the resistance and reactance between sending and receiving end bus, respectively.

The buses in conventional IEEE bus systems are classified into two categories: directly linked buses and loaded buses, which helps to comprehend the concept of $index_3$ given in this chapter. A directly linked bus is connected directly to any bus "i" in the system, and it must not pass through any other bus, i.e., no other bus must come between it and bus "i". The number of directly linked buses for bus "i" will be the same as the lines connected to it, based on this definition. The set "C_i" is defined as the set of directly linked buses to bus "i" and bus "i" itself for the purpose of simplicity and mathematical clarity. The line length for the bus is zero, resulting in line loss. The load-carrying buses are those that are fully loaded. A zero load may be considered for a bus with no load in order to get broader definitions and mathematical expressions. The $index_3$ of each bus in the system is computed, and buses are placed in decreasing order according to their index. The buses with the highest index will then be selected as potential sites depending on the required number of DERs to be installed. The index values with corresponding bus numbers for 118 bus system are illustrated in Table 5.1.

$$(index_3 =)LC_i = \sum_{j \in C_i} P_{D_j} \tag{5.3}$$

Where

- LC_i is termed as Load Concentration $index_3$, which is the sum of loads connected to each member bus of set C_i. If there is not load connected to any bus, its power demand at j^{th} bus (P_{D_j}) will be taken as zero.

The values obtained for $index_1$, $index_2$, and $index_3$ are mentioned in Tables C.1, C.2 and C.3, respectively in Appendix C.

Table 5.1: Values of indexes with corresponding bus number for the two test systems

$index_1$	Bus No.	$index_2$	Bus No.	$index_3$	Bus No.
1.349×10^{-3}	6	41.52×10^{-3}	30	1.9203	115
0.928×10^{-3}	29	16.44×10^{-3}	13	1.3944	74
0.871×10^{-3}	30	16.43×10^{-3}	24	1.3864	52
0.866×10^{-3}	5	7.36×10^{-3}	31	1.2509	82
0.856×10^{-3}	28	6.49×10^{-3}	20	1.2350	43

5.2.3 Power balance

The active power and reactive power balance expressions are shown in Equations (5.4) and (5.5).

$$P_{net_i} = P_{dg_i} - P_{dem_i} - V_i \sum_{j=1}^{N_{bus}} V_j Y_{i,j} cos(\delta_i - \delta_j - \theta_i + \theta_j) \quad (5.4)$$

$$Q_{net_i} = Q_{dg_i} - Q_{dem_i} - V_i \sum_{j=1}^{N_{bus}} V_j Y_{i,j} sin(\delta_i - \delta_j - \theta_i + \theta_j) \quad (5.5)$$

Where P_{net_i} = 0 and Q_{net_i} = 0 are the net active power and reactive power at i-bus, respectively. P_{dg_i} and Q_{dg_i} represent DER's active power and reactive power at i-bus, respectively. Active and reactive load demands are mentioned by P_{dem_i} and Q_{dem_i}, respectively. V_j is the bus voltage at j-bus, $Y_{i,j}$ is the branch admittance between i, j-buses, δ_i and δ_j represent the phase angles of i-bus and j-bus voltages, respectively. (θ_i - θ_j) are the impedance angle of branch connected between i and j-buses.

5.2.4 Objective function

In this chapter, the objective function is considered as active power loss minimization in the DS. The reliability indices are then evaluated by fixing the optimal site and size of the DERs. The Objective Function of the problem is given in Equation (5.6).

A. Active Power Loss

The minimization of active power loss occurred in DS is the Objective Function considered. The primary aim of optimal power flow technique is to minimize the system active power loss, which is given as Equation (5.6).

$$\min AP_{loss} = \sum_{i=1}^{N_{bus}} \sum_{j=1}^{N_{bus}} C_{1_{ij}} (P_{real_i} P_{real_j} + Q_{real_i} Q_{real_j}) + C_{2_{ij}} (Q_{real_i} P_{real_j} - P_{real_i} Q_{real_j}) \quad (5.6)$$

Where $P_{real_i}, P_{real_j}, Q_{real_i}, Q_{real_j}$ are the active power and reactive power at i and j-buses, respectively. N_{bus} = number of buses or nodes, $C_{1_{ij}}$ and $C_{2_{ij}}$ are defined as follows.

$$C_{1_{ij}} = \frac{R_{ij}}{V_i V_j} cos(\delta_i - \delta_j) \quad (5.7a)$$

$$C_{2_{ij}} = \frac{R_{ij}}{V_i V_j} sin(\delta_i - \delta_j) \quad (5.7b)$$

Where V_i, δ_i and V_j, δ_j are the voltages and corresponding angles at i^{th} and j^{th} buses, respectively, R_{ij} = resistance of a branch between i and j-buses.

B. Reactive Power Loss

The availability of reactive power ensure the active power transmission from source to load. Voltage stability margin or bus voltages are also dependent on this reactive power support. The reactive power loss is obtained at different pf of DER using Equation (5.8).

$$RP_{loss} = \sum_{i=1}^{N_{bus}} Q_{gen_i} - \sum_{i=1}^{N_{bus}} Q_{dem_i} \quad (5.8)$$

Where Q_{gen_i} and Q_{dem_i} are the reactive power generation and demand at i^{th} bus (including the slack bus), respectively. Q_{dem_i} = reactive power demand at i^{th} bus.

5.2.5 Constraints

The Objective Function minimization is a primary task to obtain the optimal results. The minimization is subjected to design the constraints. So that the requirements of the EPDN must be satisfied with DER operation. Thus, the constraints are discussed in the following subsection [232, 233].

A. Equality constraints

These constraints follow the Kirchhoff's current rule as the algebraic sum of powers in and powers out should be equal in an EPDN [233, 234]. Two of these constraints are described as follows.

$$\sum_{i=1}^{N_{bus}} AP_{gen_i} = \sum_{i=1}^{N_{bus}} AP_{dem_i} + AP_{loss} \tag{5.9}$$

Where AP_{gen_i} = active power generated by the generation units at i^{th} bus, AP_{dem_i} = active power demand at i^{th} bus.

$$\sum_{i=1}^{N_{bus}} RP_{gen_i} = \sum_{i=1}^{N_{bus}} RP_{dem_i} + RP_{loss} \tag{5.10}$$

Where RP_{gen_i} = reactive power generated by the generation units at i^{th} bus, RP_{dem_i} = reactive power demand at i^{th} bus.

B. Inequality constraints

These constraints are associated to the limits applied to the system parameters for the operation of DS. Some of these constraints are described as follows.

(1) Power flow

To maintain the line capacity within limits, these constraints ensure the apparent power to be within limits at the ends of a line [232, 233].

$$AP_{a_{ij}} \leq AP_{a_{ij}}^{max} \tag{5.11}$$

Where $AP_{a_{ij}}^{max}$ = the highest permissible apparent powers (AP_a) for lines i to j, $AP_{a_{ij}}$ = the actual AP_a transmitted from i to j.

(2) DER capacity

These limits ensure the non reversal of power flow. The power from the substation is provided to the DS must be greater than the DER power. Also, the DER has the minimum and maximum power generation boundaries [235].

$$\sum_{i=1}^{n_{DG}} AP_{DG_i} \leq \sum_{i=1}^{n_{bus}} AP_{dem_i} + AP_{loss} \tag{5.12}$$

$$\sum_{i=1}^{n_{DG}} RP_{DG_i} \leq \sum_{i=1}^{n_{bus}} RP_{dem_i} + RP_{loss} \tag{5.13}$$

$$AP_{DG_p}^{min} \leq AP_{DG_p} \leq AP_{DG_p}^{max} \tag{5.14}$$

$$RP_{DG_p}^{min} \leq RP_{DG_p} \leq RP_{DG_p}^{max} \tag{5.15}$$

Where p = 1, 2,......, n_{DG}, $AP_{DG_p}^{min}$ (set to zero) and $AP_{DG_p}^{max}$ (from Equation 5.12) are the lower and upper active power outputs of DER unit p, respectively. $RP_{DG_p}^{min}$ (set to zero) and $RP_{DG_p}^{max}$ (from Equation 5.13) are the lower and upper RP outputs of DER unit p, respectively. n_{DG} = number of DERs present in the distribution network.

(3) Bus voltage

The voltages at buses present in the DS must be limited within minimum and maximum limits [236, 237].

$$|V_{i_{min}}| \leq |V_i| \leq |V_{i_{max}}| \tag{5.16}$$

Where $|V_{i_{min}}|$ and $|V_{i_{max}}|$ = the lower and upper boundaries of the bus voltage $|V_i|$ which are set to 95% and 105%, respectively.

(4) Branch current

It refers as thermal capacity of the DS lines. The current in the distribution lines must be within limits and should not exceed the maximum current limit [146], which is given in Equation 5.17.

$$I_i \leq I_i^{max} \tag{5.17}$$

Where the maximum branch current (I_{max}) for 33 bus and 118 bus distribution system are set to 215 A and 1500 A, respectively.

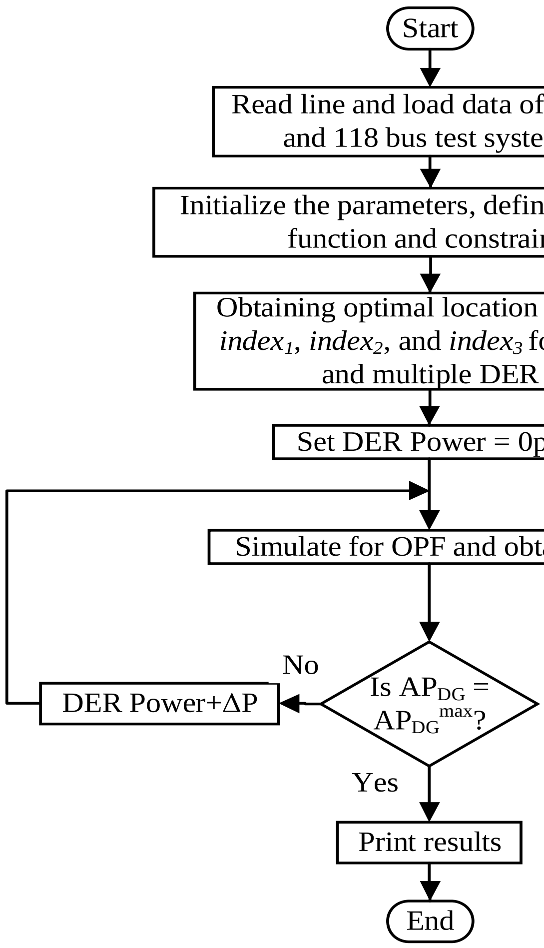

Figure 5.2: Algorithm implemented.

5.3 Results and Discussion

In this section, the DER siting, DER size, and DS reliability are obtained. The two test systems, as illustrated in Figure A.1 and Figure A.2 have been considered for the study [130, 238]. The branch and load data for the 33 bus system have been adopted from [174]. It contains 33 buses and 32-branches with a total of 3.715 MW and 2.3 MVar active power and reactive power loads, respectively. This DS operates at 12.66kV, 100 MVA base values. The active power loss and reactive power loss for without DER are obtained as 0.211009 MW and 0.143056 MVar, respectively. The branch and load data for the 118 bus system have been adopted from [239]. It contains 118 buses and 117 branches with a total of 22.71 MW and 17.04 MVar active power and reactive power loads, respectively. This DS operates at 11 kV, 100 MVA base values. The active power loss and reactive power loss for without DER cases are obtained as 1.29787 MW and 0.97865 MVar, respectively. The test systems are integrated with wind energy with conventional generation to assess the system's reliability.[1]

The following steps are followed to obtain the results:

Step 1: Optimal DER siting and size of 1CG, 1CG+1WTG, and 1CG+2WTG are evaluated using PSO for loss minimization and improved voltage profile.

Step 2: Active power loss, reactive power loss, and voltages at each bus are obtained for unity pf, 0.9 pf, 0.85 pf, and 0.82 pf to analyse the results obtained in Step 1.

Step 3: Reliability indices are estimated for 1CG, 1CG+1WTG, and 1CG+2WTG for two different DER reliability data, including λ_p and RT.

Step 4: The best result obtained in Step 3 is utilised for reliability indices estimation for different pfs, DER size, and load type at reliability data mentioned in Tables 1.1 and 1.2.

5.3.1 Distributed Energy Resources siting and sizing

The two indexes are implemented to obtain the DERs' locations. It is observed from the study that $index_1$ provides the location suitable for 1CG. This index examines the effective apparent power injection to the buses. The value of LoadFactor of k^{th} line depends whether the k^{th} is in path of i^{th} bus to the source node or not. The multiplication of LoadFactor and injected apparent power provides the active power loss and reactive power loss of k^{th} line due to i^{th} bus AP_a injection. Thus, the maximum value of $index_1$ at i^{th} bus indicates the candidate node to allocate 1CG. On the other hand, $index_2$ provides the hierarchy of weak buses in the distribution system; thus, the $index_2$ maximum values indicate the candidate nodes to allocate multiple DERs in 33 bus test system. The buses with topmost LC_i have been considered for single DER and multiple DER placement in IEEE 118 bus test system. The index values for respective buses are provided in Table 5.1.

The optimal siting for multiple DERs are found by implementing the $index_2$ in 33 bus radial DS. It shows the sensitivity of the bus towards voltage collapse. For the stable operation of the system, it should be larger than or exactly equals zero. This index's minimum value depicts more sensitive to voltage collapse; thus, referred to the weak bus. The optimal siting and sizing of 1CG, 1CG+1WTG, and 1CG+2WTG at different pfs are obtained and reproduced in Table 5.2. The optimal siting of single and multiple DERs are considered by implementing

[1]Sachin Kumar, R.K. Saket, Dharmendra Kumar, P. SanjeeviKumar, Frede Blaabjerg, "Layout optimization algorithms and reliability assessment of wind farm for microgrid integration: a comprehensive review", IET Renewable Power Generation, pp. 1-22 (2021) doi: https://doi.org/10.1049/rpg2.12060

the LC_i in 118 bus DS. The DERs are accommodated according to the locations obtained from the indexes described above. The DER size and minimum active power loss are then evaluated, implementing CF-PSO as described.

Table 5.2: Location and size of DER(s) obtained for different pfs

System	pf	1CG	1CG+1WTG	1CG+2WTG
33 bus	**Location (bus no.) →**	6	13, 30	13, 24, 30
	@UPF (MW)	2.558	0.844, 1.148	0.798, 1.098, 1.048
	@0.9pf (MVA)	2.842	0.937, 1.275	0.886, 1.220, 1.164
	@0.85pf (MVA)	3.009	0.992, 1.350	0.938, 1.291, 1.235
	@0.82pf (MVA)	3.119	1.029, 1.400	0.973, 1.339, 1.278
118 bus	**Location (bus no.) →**	74	74, 115	74, 115, 52
	@UPF (MW)	2.962	2.962, 2.860	2.962, 2.860, 2.861
	@0.9pf (MVA)	3.291	3.291, 3.177	3.291, 3.177, 3.178
	@0.85pf (MVA)	3.484	3.484, 3.364	3.484, 3.364, 3.365
	@0.82pf (MVA)	3.612	3.612, 3.487	3.612, 3.487, 3.489

5.3.2 Active Power Loss, Reactive Power Loss, and Bus Voltage Profile

The accommodation of DER at an optimal location with optimal size reflects in voltage profile improvement and minimization of active power loss and reactive power loss. Most of the researches have concentrated on active power loss minimization because of the dominance of I^2R losses in the DS. In contrast, the reactive power loss minimization for overall voltage improvement of the 32 buses of the DS has also been observed. The estimation of active power loss, reactive power loss, and voltage profile is considered before analysing the system's reliability. This is performed to analyse the system's reliability with the optimal DER size, DER location, minimum power loss, and better voltage profile.

The output results obtained for the active power loss are compared with the previous researches[2] and tabulated in Table 5.3. It shows that the active power loss is too comparable or better than the previously published works for 1CG, 1CG+1WTG, and 1CG+2WTG at different

[2] These researches have considered conventional generations only

Table 5.3: Active power loss obtained

Test System	pf	No DG(MW)	1CG(MW)	1CG+1WTG(MW)	1CG+2WTG(MW)
33 bus (**This Thesis**)	Unity	0.211009	0.111036	0.087179	0.072793
	0.90	”	0.071381	0.0367	0.019678
	0.85	”	0.068212	0.032077	0.015543
	0.82	”	0.067914	0.031196	0.014069
33 bus [152]	Unity	0.211	0.11107	0.087172	0.072787
	0.90	”	Not reported (NR)	NR	NR
	0.85	”	0.068170	0.03119	0.01552
	0.82	”	0.067870	0.03041	0.01514
118 bus (**This Thesis**)	Unity	1.29787	1.01655	0.80525	0.66730
	0.90	”	0.92501	0.60964	0.39034
	0.85	”	0.91975	0.59162	0.36083
	0.82	”	0.91991	0.58742	0.352
118 bus [149, 159, 177]	Unity	1.2963	1.01524	0.80373	0.711
	0.90	”	0.92294	0.60460	0.3052 (5CGs)
	0.85	”	NR	NR	NR
	0.82	”	NR	NR	0.132787 (7CGs)
	0.80	”	0.91995	0.58567	NR

pfs. Further, the voltage profile with 1CG and multiple DERs at unity, 0.9, 0.85 and 0.82 are drawn in Figure 5.3. The improvement in bus voltages is observed when multiple DERs are placed at a Unity Power Factor (UPF). This voltage profile is further improved at 0.9, 0.85, and 0.82 pfs. It is because of increment in RP support at system buses. In the 33 bus test system, it is interesting to know about the two peaks during the system operated with 1CG. These voltage peaks are at bus numbers 7 and 26, and these buses are straight away linked to bus number 6, which is the optimal siting of 1CG. Also, the size of the 1CG is greater than the sum of the size of 1CG+1WTG and slightly lesser than the sum of the size of 1CG+2WTG, as obtained in Table 5.3. In the 118 bus test system, it is observed that the voltage profile is almost similar for buses 1 to 65 with 1CG and 1CG+1WTG. It is because of DER locations, which affects the voltages of buses 66-118. In contrast, the voltage profile is improved at all the buses with 1CG+2WTG. It is because of the placement of the third DG, which affects the voltages on buses 2-65. A comparison between present work and best available method is made for minimum active power loss. Simultaneously, Table 5.4 shows that the minimum bus voltage is improved, and RP is minimized with the implementation of multiple DERs at different pfs as mentioned.

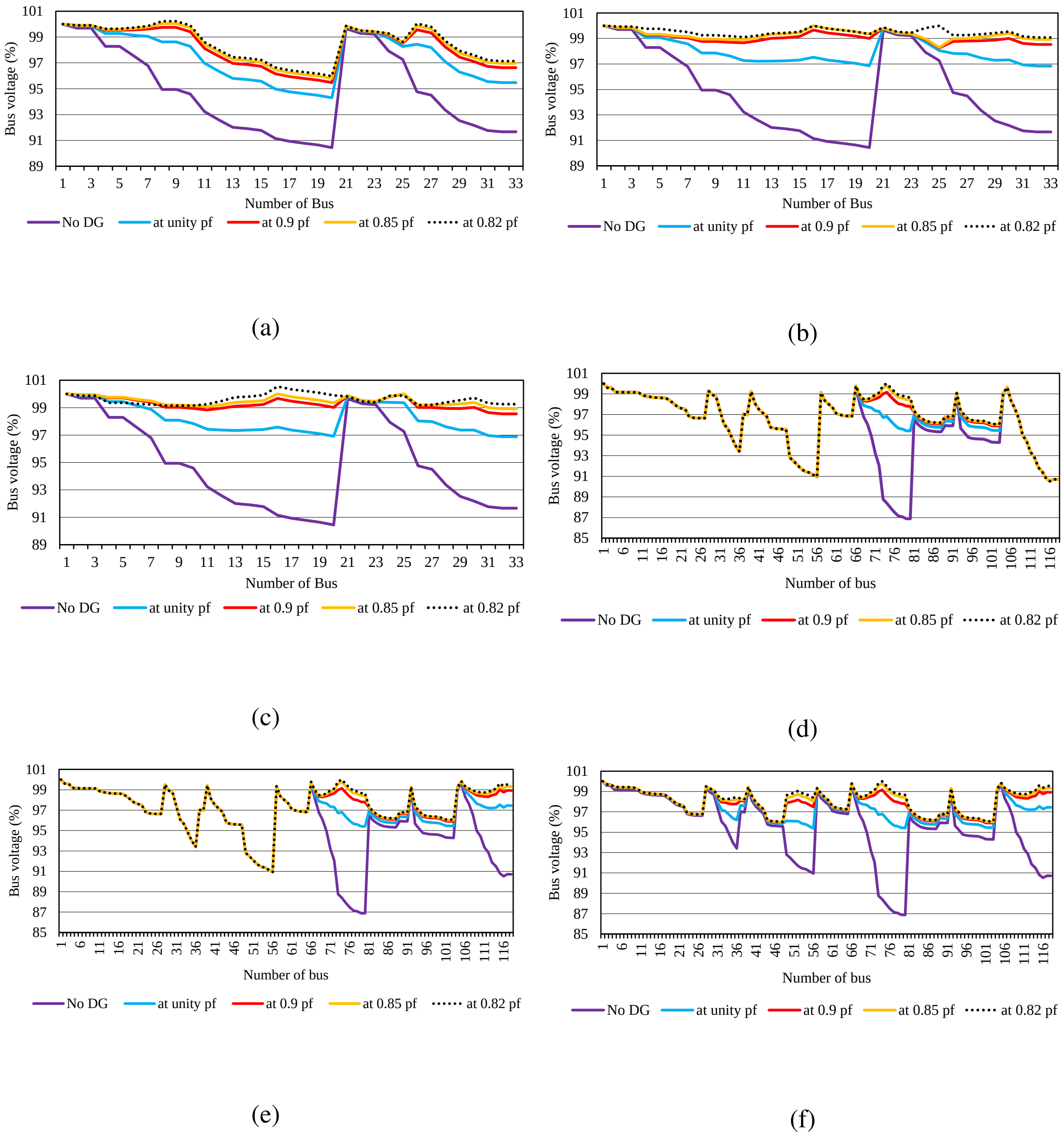

Figure 5.3: Voltage profile at UPF, 0.9 pf, 0.85 pf, and 0.82 pf for (a) 33 bus with 1CG, (b) 33 bus with 1CG+1WTG, (c) 33 bus with 1CG+2WTG, (d) 118 bus with 1CG, (e) 118 bus with 1CG+1WTG, and (f) 118 bus with 1CG+2WTG.

5.3.3 Reliability Assessment

The chapter considers a small as well as a large test system to analyze the robustness of the proposed method.[3] The indices are assessed for divergent DER reliability data by fixing the

[3]Sachin Kumar, Kumari Sarita, R.K. Saket, Dharmendra Kumar Dheer, "Reliability assessment of optimally DG integrated distribution system based on power loss minimization", EPCS, T&F (2020) (Revision#1 Submitted)

Table 5.4: Minimum voltage and reactive loss obtained

System	pf	Minimum voltage(%)				reactive power loss (MVar)			
		No DG	1DG	2DG	3DG	No DG	1DG	2DG	3DG
33 bus	Unity	90.4	94.3	96.8	96.9	0.143056	0.081698	0.059766	0.050673
	0.90	”	95.5	98.3	98.5	”	0.056866	0.025559	0.015121
	0.85	”	95.8	98.3	98.9	”	0.055015	0.022566	0.012272
	0.82	”	96.0	98.1	98.3	”	0.054931	0.022203	0.011260
118 bus	Unity	86.9	90.5	90.94	95.4	0.97865	0.77612	0.65957	0.50888
	0.90	”	”	”	95.9	”	0.70958	0.53877	0.30227
	0.85	”	”	”	96.0	”	0.70365	0.52521	0.27610
	0.82	”	”	”	96.1	”	0.70272	0.52124	0.26685

site and size of DERs. Further, the reliability improvement of the distribution network has been observed by integrating 1CG and multiple DERs in the test systems. Several reliability indices, including EENS, SAIDI, SAIFI, and ASAI, are obtained for system's reliability improvement. The other indices, including AENS, CAIDI, and ASUI, can be obtained using the indices mentioned in Chapter 2. The indices of the network reliability are dependent function of λ_p and RT, as illustrated in Equation (5.18) [146, 161].

$$\text{Reliability Indices} = f(\lambda_p, RT) \tag{5.18}$$

The indices' values obtained show the improvement in the system's reliability. The indices are calculated for two different reliability data of DERs. It is observed that the indices are dependent on two reliability data, namely, λ_p and RT of the system's elements. This chapter has considered different reliability data for DER only. The best reliability improvement is observed for 0.1 of λ_p and 6 hours of RT. A detailed description of the DER reliability data effect on indices is given as per the following cases.

Case 1: 0.3 f/yr and 12 hr

Case 2: 0.2 f/yr and 12 hr, as provided in Table 1.1

Case 3: 0.1 f/yr and 12 hr

Case 4: 0.1 f/yr and 18 hr

Case 5: 0.1 f/yr and 6 hr

Cases 1, 2, and 3 are considered by fixing the RT and varying λ_p. The appropriate case from the

Table 5.5: Reliability indices calculated in the literature for different distribution systems

Test System	Index	Value	No. of DER	Ref.	Remarks
33 bus	EENS	57.733	0	[146]	UPF DER
	”	53.941	1		
85 bus	”	70.172	0		
	”	65.399	1		UPF DER
MCMG	EENS	40.9	0	[161]	Microgrid is in islanding mode
14 bus	SAIDI	0.714, 0.222	No DER	[182]	Two values considering reward-penalty scheme or not
	EENS	8.694, 5.047	”		
33 bus	SAIDI	1.6287, 1.4802, 1.3257	3	[183]	First value is obtained considering 3 DERs without restructuring and other two values for two optimal structures of the distribution system
	SAIFI	0.2714, 0.2467, 0.2209	”		
	EENS	5.2968, 4.8795, 4.9412	”		
52 bus	SAIDI	5.013, 5.319, 3.791	3		
	SAIFI	0.824, 0.886, 0.632	”		
	EENS	26.719, 27.965, 23.177	”		
69 bus	SAIDI	1.776, 1.0279, 0.9684	3		
	SAIFI	0.1851, 0.1712, 0.1613	”		
	EENS	4.8623, 4.1928, 3.8498	”		
RBTS	EENS	9.841, 7.344, 5.920, 4.496	0, 1, 2, 4	[184]	Four values are obtained for 0, 1, 2, 4 DERs
IEEE RTS	”	1197.57, 932.97, 778.74, 600.35	0, 1, 2, 4		
33 bus	EENS	59.834, 24.755, 21.906	**1, 2, 3**	**This Thesis**	**The Reliability indices are calculated for Case 5 considering optimal CGs' locations and ratings**
	AENS	0.0184, 0.0076, 0.0068			
	SAIDI	17.773, 6.888, 6.45			
	SAIFI	2.054, 0.8874, 0.8411			
	ASAI	0.99797, 0.99921, 0.99926			
118 bus	EENS	141.323, 113.769, 65.382			
	AENS	0.0121, 0.0097, 0.0056			
	SAIDI	6.3184, 5.6027, 3.6971			
	SAIFI	2.3653, 2.1014, 1.3667			
	ASAI	0.99928, 0.99936, 0.99958			

MCMG = multi-carrier microgrid, RBTS = Roy Billinton Test System first three cases is then considered in Cases 4 and 5 for variable RT to extract the best case from the above five cases. The values of DG reliability data (λ and RT) are being utilized to obtain the reliability indices for the system's reliability improvement. Equations (1.11) and (1.12) take these DG reliability data for further calculations. Also, the following key assumptions are considered to assess the reliability of the EPDN.

- Circuit breakers, distribution lines, and potential transformers are available throughout with 100% reliability
- The λ_p and RT of DER, Buses, feeders, and substations are given in Tables 1.1 and 1.2
- Load distribution and classification for 33 bus and 118 bus DSs have been adapted from Appendix B Tables B.2 and B.4, respectively.

The authors in [226] have examined the failure rate of 0.0096 failure per year for 110 kV line. The high voltage lines are having low failure rate of approximately 0.02 failure per year, as mentioned in the [227]. The potential transformer has low failure rate of (1/29.29 =) 0.03 failure per year, as the time to first failure is given as 29.29 years in the [228]. Also, [7] has assumed the transformer to be 100% reliable.

The reliability indices have been obtained for 33 bus and 118 bus test systems considering optimal siting and sizing of three conventional DERs. In contrast, methods, including reward penalty scheme and restructuring of the distribution system, have been implemented in the literature to obtain several test systems' reliability indices, as mentioned in the Table 5.5. It is also observed that the calculated indices values are coherent to the values provided in the literature.

A. Effect on Load-Oriented Indices

The EENS and AENS are obtained for 33 bus and 118 bus DSs considering all the cases, as shown in Tables 5.6 and 5.7. The reliability indices calculated for the systems are described graphically in Figures 5.4–5.7, respectively. It is important to note that the EENS and AENS decrease with DERs' integration and these are also decreased with decreasing values of λ_p and RT. As an increasing number of DERs integrated into the EPDN, the supplied energy is improved in the DS, and thus, the indices related to the energy not supplied are reduced. This reduction is more while integrating the DERs with lesser λ_p and RT values. The reducing EENS and AENS are desirable, and thus, the DS reliability of the system improves.

Table 5.6: EENS (MWh per year) evaluated for different DER reliability data

System	# DER	Case 1	Case 2	Case 3	Case 4	Case 5
33 bus	No DER	82.763	82.763	82.763	82.763	82.763
	1CG	65.999	65.333	61.067	62.3	59.834
	1CG+1WTG	27.965	26.681	25.397	26.039	24.755
	1CG+2WTG	24.666	23.562	22.458	23.01	21.906
118 bus	No DER	168.12	168.12	168.12	168.12	168.12
	1CG	147.141	144.814	142.487	143.65	141.323
	1CG+1WTG	123.985	119.899	115.812	117.855	113.769
	1CG+2WTG	80.611	74.52	68.428	71.474	65.382

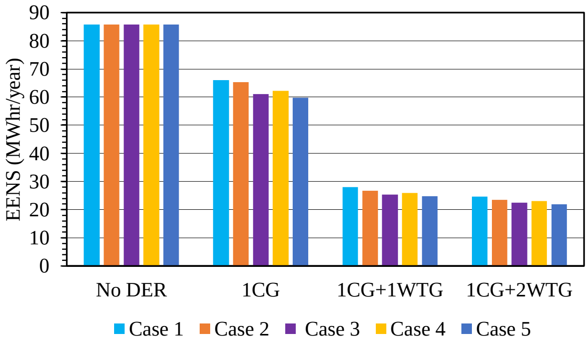

Figure 5.4: EENS for 33 bus system.

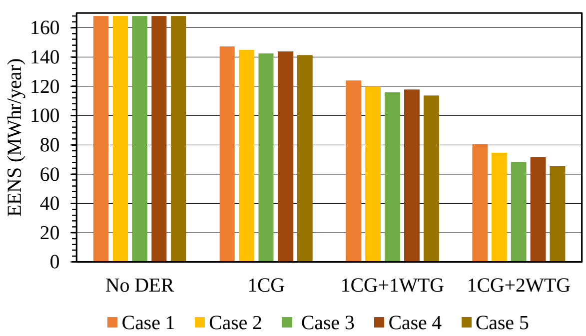

Figure 5.5: EENS for 118 bus system.

Table 5.7: AENS (MWh per customer per year) evaluated for different DER reliability data

System	# DER	Case 1	Case 2	Case 3	Case 4	Case 5
33 bus	No DER	0.0255	0.0255	0.0255	0.0255	0.0255
	1CG	0.0203	0.0196	0.0188	0.0192	0.0184
	1CG+1WTG	0.0086	0.0082	0.0078	0.008	0.0076
	1CG+2WTG	0.0076	0.0073	0.0069	0.0071	0.0068
118 bus	No DER	0.0144	0.0144	0.0144	0.0144	0.0144
	1CG	0.0126	0.0124	0.0122	0.0123	0.0121
	1CG+1WTG	0.0106	0.0102	0.0099	0.0101	0.0097
	1CG+2WTG	0.0069	0.0064	0.0058	0.0061	0.0056

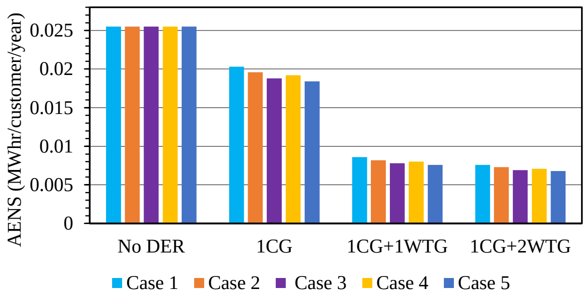

Figure 5.6: AENS for 33 bus system.

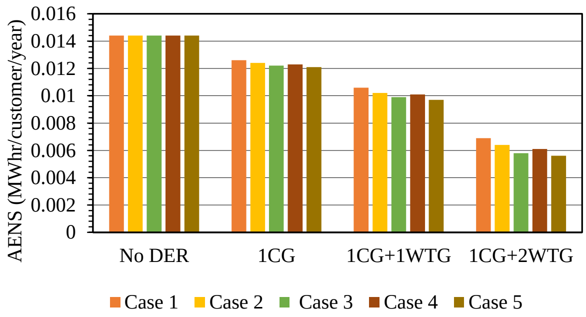

Figure 5.7: AENS for 118 bus system.

B. Effect on Customer Oriented Indices

The EENS and AENS are obtained for 33 bus and 118 bus DSs considering all the cases, as shown in Tables 5.8 and 5.9. The reliability indices calculated for the systems are described graphically in Figures 5.8–5.11, respectively. The key point to be noted here that the SAIDI and SAIFI decrease with the increasing number of DERs; SAIDI is also decreased with decreasing values of λ_p and RT. It is worthy to note that the SAIFI is not affected by the RT of the DER. It is because this index is independent of RT, as mentioned in Equation (1.23). The interruption duration and the number of interruptions in the system are reduced as the number of DERs incorporated into the DS increased. Thus, the SAIDI and SAIFI are reduced. CAIDI is determined using the ratio of SAIDI and SAIFI, as mentioned in Equation (1.24). The reduction in indices' value is more while integrating the DERs with lesser λ_p and RT values. Reducing SAIDI and SAIFI are desirable for the system's reliability enhancement.

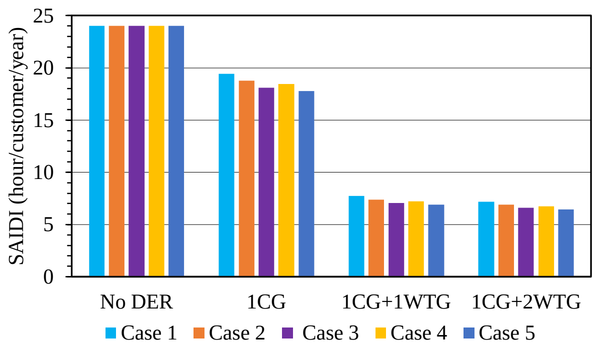

Figure 5.8: SAIDI for 33 bus system.

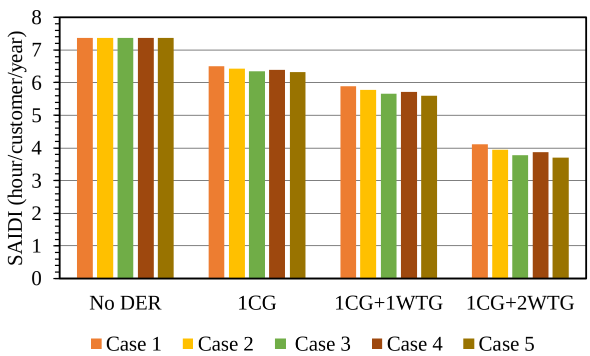

Figure 5.9: SAIDI for 118 bus system.

The ASAI is determined for all cases considering single and multiple DERs, as illustrated in Table 5.10, which is represented in Figure 5.12 and 5.13. The electrical power service availability for all loads increases with the integration of multiple DERs. This index is fur-

Table 5.8: SAIDI (hour per customer per year) evaluated for different DER reliability data

System	# DER	Case 1	Case 2	Case 3	Case 4	Case 5
33 bus	No DER	24.012	24.012	24.012	24.012	24.012
	1CG	19.424	18.764	18.103	18.433	17.773
	1CG+1WTG	7.721	7.388	7.055	7.221	6.888
	1CG+2WTG	7.1828	6.889	6.596	6.743	6.45
118 bus	No DER	7.367	7.367	7.367	7.367	7.367
	1CG	6.4979	6.4261	6.3543	6.3902	6.3184
	1CG+1WTG	5.8847	5.7719	5.6591	5.7155	5.6027
	1CG+2WTG	4.1074	3.9433	3.7792	3.8612	3.6971

Table 5.9: SAIFI (failure per customer per year) evaluated for different DER reliability data

System	# DER	Case 1	Case 2	Case 3	Case 4	Case 5
33 bus	No DER	3.1794	3.1794	3.1794	3.1794	3.1794
	1CG	2.1642	2.1091	2.054	2.054	2.054
	1CG+1WTG	0.9429	0.9152	0.8874	0.8874	0.8874
	1CG+2WTG	0.8899	0.8655	0.8411	0.8411	0.8411
118 bus	No DER	2.7614	2.7614	2.7614	2.7614	2.7614
	1CG	2.3773	2.3713	2.3653	2.3653	2.3653
	1CG+1WTG	2.1202	2.1108	2.1014	2.1014	2.1014
	1CG+2WTG	1.3941	1.3804	1.3667	1.3667	1.3667

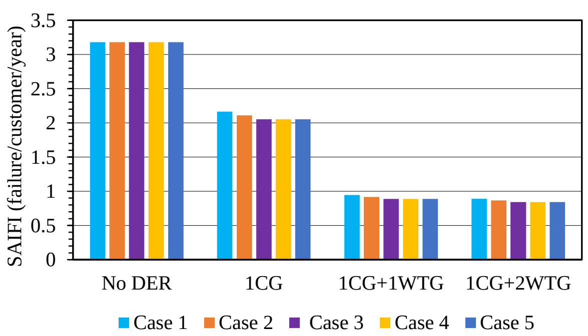

Figure 5.10: SAIFI for 33 bus system.

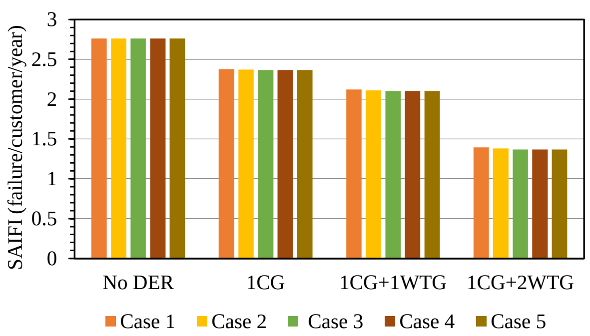

Figure 5.11: SAIFI for 118 bus system.

ther increased when DERs are having a lower λ_p, and RT values as ASAI increases lead to the decrement in ASUI, as mentioned in Equations (1.25a) and (1.25c), which is desirable for the system's reliability improvement.

Table 5.10: ASAI (pu) evaluated for different DER reliability data

System	# DER	Case 1	Case 2	Case 3	Case 4	Case 5
33 bus	No DER	0.99726	0.99726	0.99726	0.99726	0.99726
	1CG	0.99778	0.99786	0.99793	0.99790	0.99797
	1CG+1WTG	0.99912	0.99916	0.99919	0.99918	0.99921
	1CG+2WTG	0.99918	0.99921	0.99925	0.99923	0.99926
118 bus	No DER	0.99916	0.99916	0.99916	0.99916	0.99916
	1CG	0.99926	0.99927	0.99927	0.99927	0.99928
	1CG+1WTG	0.99933	0.99934	0.99935	0.99935	0.99936
	1CG+2WTG	0.99953	0.99955	0.99957	0.99956	0.99958

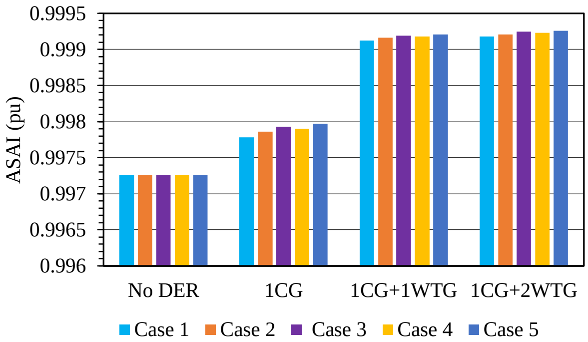

Figure 5.12: ASAI for 33 bus system.

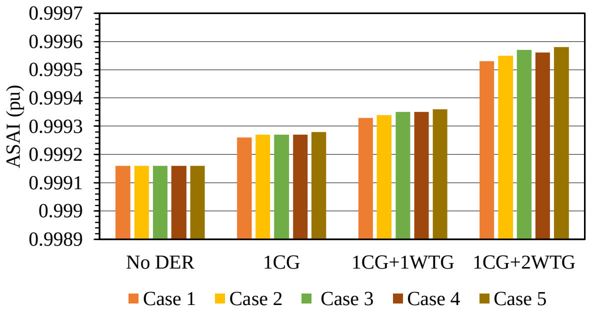

Figure 5.13: ASAI for 118 bus system.

C. Effect of pf, DER Penetration and Load Type on Reliability Indices

It is noticed while doing the results' compilation that the effect of pf and DER penetration is not present in the system's reliability indices. This is because of the non-dependency of reliability indices on pf and DER penetration, as illustrated in Equations (1.20)-(1.25c). However, the effect of load type is seen on ECOST and IEAR, termed as reliability worth of the system. These indices are obtained for optimal DER reliability data of 0.1 failure per year and 6 hours of repair time. The values of these indices are tabulated in Table 5.11, which are found using the data tabulated in Table B.5 of the Appendix B. As the increasing number of DERs is integrated into the DS, the interruption duration and interruption cost are reduced. It is because of the different customer damage functions for commercial, industrial, and residential loads. The other index IEAR can be obtained using the ratio of ECOST and EENS, as mentioned in Equation (3.14). The system should obtain a reduced value of ECOST of the test systems to make the system reliable in terms of cost-saving.

Table 5.11: Reliability worth considering case 5

System	Load type	Reliability worth	without DER	with 1CG	with 1CG+1WTG	with 1CG+2WTG
33 bus	Commercial	ECOST	865452	679577.6	281180.4	247361.7
	Industrial		586482.4	424253	175339.3	155176.5
	Residential		160502	120106.2	47837.98	41955.47
118 bus	Commercial		1393985	1173464	944588	548048
	Industrial		1189800	1000438	805808	462656
	Residential		175620	148257	119060	71056

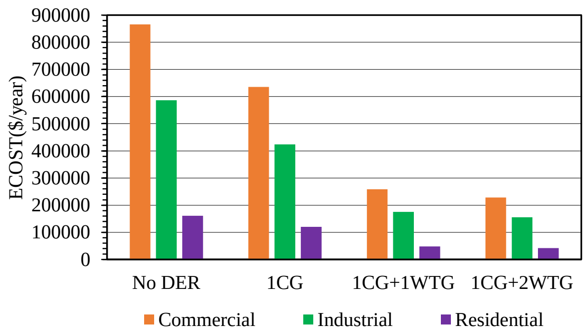

Figure 5.14: ECOST for 33 bus system.

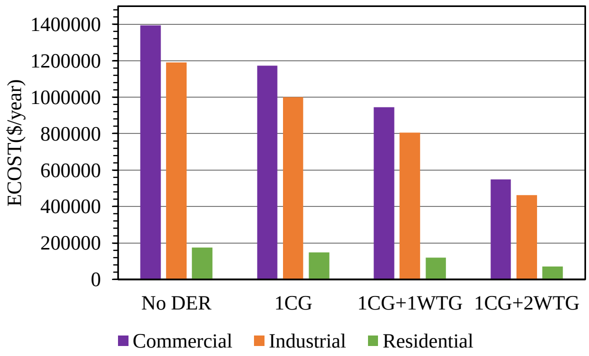

Figure 5.15: ECOST for 118 bus system.

5.4 Summary

The chapter proposes a reliability improvement method by integrating Conventional Generations optimally to the adapted test systems 33 buses and 118 buses. For the integration of DER/s at optimal locations, three indexes were proposed. $index_1$ was for locating one DER, and $index_2$ and $index_3$ were implemented for locating two and three DERs. Then, an optimization technique was proposed to obtain the optimal ratings of the DERs. The power loss minimization and improved bus voltage profile were obtained, which were coherent to the results mentioned in [149, 152, 159, 177].

Further, the chapter performs the reliability assessment of electrical distribution systems. The reliability data related to the DSs and DER were considered, as mentioned in the Appendix B. As the active power loss and reactive power loss were reduced, the energy-oriented reliability indicators, namely, EENS and AENS, were minimized, which improves the system's reliability. Simultaneously, the effect of failure rate and repair time of DER were observed on the customer and energy-related reliability indices. SAIFI and SAIDI were decreased with the integration DERs. It was due to the decrease in interruption duration and the occurrence of interruptions for the system when a number of DERs increases. As the values of failure and repair data of DER increase, the SAIDI decreases but SAIFI decreases only with λ_p because SAIFI is independent of RT. The ASAI, which defines the service availability of power system for all loads, was increased too with a DER integration. This index improves the system's reliability with lower values of λ_p and RT. Finally, the following values were calculated for the excellent reliability of the two DSs.

For 33 bus system:
EENS: 21.906 MWh per year
AENS: 0.0068 MWh per customer per year
SAIDI: 6.45 hour per customer per year
SAIFI: 0.8411 failure per customer per year
ASAI: 0.99926 per unit
ECOST: 41955.47 $ per year
For 118 bus system:
EENS: 65.382 MWh per year
AENS: 0.0056 MWh per customer per year
SAIDI: 3.6971 hour per customer per year
SAIFI: 1.3667 failure per customer per year
ASAI: 0.99958 per unit
ECOST: 71056 $ per year
The next chapter covers the overall results, advantages of the planned effort, and future research opportunities towards the conclusion of the thesis.