New Reliability Indices for Microgrids and Provisional Microgrids in Smart Distribution Systems

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Received 25 November 2021; Accepted 12 August 2022;
Publication 03 January 2023

Abstract

The construction of provisional microgrids paired with microgrids was recently introduced taking into consideration, the less critical zones of the distribution system. Similar to the microgrids, the provisional microgrids have distributed generators and a master controller. But these provisional microgrids cannot switch to islanded mode as a single entity as in the case of microgrids. Instead, they move to islanded mode along with the coupled microgrid, thus meeting the economic and reliability requirements of the less sensitive zones of the distribution system. This work first proposes few new device-based reliability indices for the sustained faults that cater to the new requirements arising due to the presence of distributed generators all over the system, embedded in clusters of microgrids and provisional microgrids. Secondly, considering the occurrences of temporary faults in similar systems, another new load-based reliability index is proposed. Later, for the chosen example distribution system with 69-buses, the existing reliability indices, and the proposed new indices are calculated. At last, the influence of these

Distributed Generation & Alternative Energy Journal, Vol. 38_2, 435–466.
doi: 10.13052/dgaej2156-3306.3824

indices on generation expansion planning problems like placement and sizing of the distributed generators, construction of clusters of microgrids and provisional microgrids, and economic decisions on scheduling of maintenance is discussed in detail.

Keywords: Distributed generation, microgrid reliability assessment, provisional microgrid security, renewable energy resources, smart distribution system.

1 Introduction

Up-gradation of smart distribution systems defined in [1] to include Microgrids (MGs) and to increase the percentage of penetration of distributed generation has become a widespread area of research in recent times. Reference [2] discusses in detail, the benefits and the various disadvantages involved with the construction of microgrids, and proposes the new concept of building Provisional Microgrids. Reference [3] defines a Provisional Microgrid (PMG) as “a group of interconnected loads and renewable distributed generators (DGs) with clearly defined electrical boundaries that acts as a single entity with respect to the grid but requires additional generation from electrically connected microgrids to enable it to operate in island modes.” MGs are characterized by excess distributed generation capacity to meet the peak load and to ensure maximum reliability of the distribution zone during the islanded mode of operation. This encourages the installation of dispatchable generators because of the uncertainties that arise from the installation of renewable energy DGs and distributed energy storage devices. Under-utilization of the capital intensive DGs of the MGs during the grid-connected mode is a very common issue when it comes to economic planning as energy purchase from the upstream grid is cheaper most of the time. Moreover, finding space for the installation of DGs in urban areas at times becomes an issue when the constructions of MGs are considered. The concept of PMG has been proposed for less sensitive zones of the distribution system to inherit maximum benefits that are generally offered by MGs and to overcome the various disadvantages of the MGs stated above. The PMGs have a lesser percentage of penetration of distributed renewable energy generators and thus it purchases energy from an electrically connected MG or curtails some of its least critical load during the islanded mode. For the grid-connected mode of operation, PMG purchases energy from MG or the main grid apart from utilizing its generation based on the requirement. PMGs guarantee 100%

utilization of the renewable energy DGs installed within its boundary. PMGs do not encourage the installation of dispatchable generators like MGs and compromise on their reliability to some extent. A PMG is always controlled by a connected MG during islanding conditions. The MG which is connected to PMG benefits by selling its extra generation to the PMG whereas, the PMG benefits due to the improvement of its reliability on the purchase of energy from the nearby MG [2]. When the economic feasibility is checked, PMG becomes a cheaper solution offering a faster return on investment. Another important feature of PMGs is that PMGs are suitable only when the Customer Average Interruption Duration Index (CAIDI) is low, unlike the MGs [3]. This research adds up to the existing work in the literature by constructing MGs and PMGs in a large radial distribution system, suggesting new reliability indices, evaluating the values of various reliability indices and providing optimal construction plans for generation expansion planning.

2 Literature Review

Reference [4] constructs a cluster of MGs based on the concept of Reverse Current Flow (RCF), considering all the involved uncertainties of the chosen radial distribution system. In the RCF concept, the normal flow of branch current was studied for a given year for all the possible load-generation combinations. Whenever the flow of branch current reverses in a particular branch, the branch number is noted down. On solving the power flow problem, the sign reversal of the real part of the branch current denotes this reversal. Those branches with the highest number of reversals and their neighboring branches become the candidate for breaking up the large radial distribution system into several MGs. From this set of candidate branches, a maximum number of MGs are formed, taking into consideration the minimum number of nodes per MG and the voltage limits of the nodes. The concept of Modified Reverse Current Flow (MRCF) explained in [5] was found to be even more accurate as it considered both real and imaginary parts of the branch currents to give equal importance to the requirement of active power and reactive power arising from the system. Also, [5] took into account, the first and the fourth quadrant operations of the P–Q curve of the DGs, representing both the inductive and the capacitive power factor operations.

When it comes to the literature survey of various types of sizing of the DGs, [6] points out the existing Downstream Sizing (DS), and defines the Up-Down Sizing (UDS) and Sensitivity Sizing (SS). DS sizes the DGs based on requirement down-the-stream, UDS sizes the DGs to supply partially on both the sides, whereas SS sizes the DGs based on the active power loss sensitivity calculations made. Later, the RCF strategy has been used in [6] to split the distribution system into several MGs based on the defined types of sizing methods.

Customer-based reliability indices like System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), CAIDI, Customer Average Interruption Frequency Index (CAIFI), etc. and load-based indices like Average System Interruption Frequency Index (ASIFI) and Average System Interruption Duration Index (ASIDI) have been well defined by the IEEE Standards Association in [7] for the sustained faults occurring in a distribution system. Momentary Average Interruption Frequency Index (MAIFI) and few other indices have also been defined in [7] for the momentary faults of the system. Apart from the definition of these standard indices, it has been a common practice in the literature to define various new reliability indices whenever special cases arose, as in [8, 9], and [10]. Wind Generation Interrupted Energy Benefit (WGIEB), Equivalent Capacity Rate (ECR), etc. are some special indices defined for the integration of wind farms in distribution systems as in [8]. The authors in [9] describe the new index Expected VAR Not Supplied (EVNS) due to power shortages to give special attention to the shortage of reactive power in a system. Similarly, the authors in [10] propose a list of indices considering the various characteristics of MGs.

Based on the above survey of the literature, the following points are now listed out as the research gap found along with the scope for the study:

- Construction of MGs along with a PMG by splitting a chosen large distribution system has not been tried so far, using RCF or MRCF. The current work will concentrate on such a construction.
- When it comes to the construction of PMGs that is electrically coupled to an MG, consideration of the various sizing methods available in the literature is expected to take the research, a step ahead. This point adds scope to the current study.
- For the newly restructured system that includes both MGs and PMG, there is a scope for defining some new indices that will help the utility do better planning. This study will propose few new indices for the current upgraded distribution system.

For an improved dispatch strategy of the DGs, [11] considers Energy Index of Reliability (EIR) along with minimization of losses, cost and nodal voltage deviation. [12] evaluates the reliability of MGs using the well-known indices Expected Energy Not Served (EENS), EIR, Loss of Load Expectation (LOLE) and Loss of Load Probability (LOLP). To implement a reliability-centered maintenance in MGs, [13] calculates SAIDI, SAIFI, and EENS. [5] and [14] use LOLP to calculate the reliability of a modern distribution system including DGs. This work will calculate SAIDI, SAIFI, ASIDI, ASIFI, MAIFI, and LOLP following the procedure found in the literature, for a chosen radial distribution system.

The main contributions of this research work are listed below:

- Defining three new device-based reliability indices for the sustained faults and the momentary faults occurring in the cluster of microgrids
- Defining a new load-based reliability index for the temporary faults of the radial distribution system.
- Construction of a cluster of MGs and a PMG, using the MRCF splitting strategy.
- Calculating the values of the existing and the newly defined indices to bring out the benefits of the new indices.
- Deciding on the type of sizing of the distributed generators, using the calculated indices at the stage of generation expansion planning of microgrids. A sensitivity analysis is also performed in addition, to aid the budgetary decisions.

The rest of the paper is structured as follows. The mathematical expression for the newly proposed reliability indices will be given in Section 3. Section 4 gives the details of all the considered test systems and calculates the values of the reliability indices. Section 5 reports the inferences obtained using the indices and lists out the various benefits of the reliability calculation made. Then the relevant conclusions will be at last given in Section 6.

3 Reliability Indices for the Cluster of MGs and PMGs

3.1 Existing Reliability Indices

The customer-based reliability indices like SAIDI and SAIFI, and the load-based indices like ASIDI and ASIFI for the sustained faults are defined in [7]. The reliability index MAIFI for the momentary faults occurring in the system is also defined in [7]. The formula for LOLP is,

$$\mathrm{LOLP} = \sum_{q=1}^{n} \sum_{\mathrm{p}=1}^{m} \mathrm{SFPH_{pq}} \times \mathrm{TOR_{pq}} \times \frac{\mathrm{LOL_{pq}}}{\mathrm{TL_{pq}}} \tag{1}$$

where *SFPH* is the expected count of sustained failures per hour, *TOR* is the time of repair in hours, *LOL* is the expected loss of load in kVA, *TL* is the expected total kVA required, *m* is the number of components in the system that might undergo a failure, and *n* is the number of discrete count of percentages of active power output of the DGs installed.

The Total Repair Time Per Year (TRPY) is the total time taken to clear the sustained faults added to the total time taken for maintenance outage activities in a given year. It is expressed as below:

$$\mathrm{TRPY} = \sum_{q=1}^{n}\sum_{\mathrm{p}=1}^{m} \mathrm{MO}_{\mathrm{pq}} \times \mathrm{TOM}_{\mathrm{pq}} \times \mathrm{SFPY}_{\mathrm{pq}} \times \mathrm{TOR}_{\mathrm{pq}} \tag{2}$$

where *MO* is the planned count of maintenance outages per year, *TOM* is the time required for maintenance in hours, and *SFPY* is the expected count of sustained failures for the chosen year.

3.2 Newly Proposed Device-based Reliability Indices

Whenever a distribution system is upgraded to include distributed generation, the count of devices increases by a considerable number. The system will include extra protective devices like circuit breakers, reclosers, sectionalizers, etc. so that the MGs can work in isolation at good reliability, disconnected from the main grid. Here arises the need to introduce the new device-based reliability indices for both the sustained and the momentary fault conditions. The device-based indices are,

3.2.1 DAIFI: Device Average Interruption Frequency Index

The Device Average Interruption Frequency Index (DAIFI) indicates how often an average device encounters a sustained interruption over a specified period of time. Equation (3) gives the mathematical expression:

$$\mathrm{DAIFI} = \frac{\sum \text{Total count of the device interruptions}}{\text{Total count of the devices installed}} \tag{3}$$

If D_i denotes the total number of device interruptions for a given period, and D_t represent the total count of devices of the distribution system including the substation, the substation transformer, the substation breaker and the substation sectionalizer; DAIFI is given by,

$$\mathrm{DAIFI} = \frac{\sum \mathrm{D_i}}{\mathrm{D_t}} \tag{4}$$

3.2.2 DAIDI: Device Average Interruption Duration Index

The Device Average Interruption Duration Index (DAIDI) indicates the total duration of interruption for an average device for a predefined span of time. DAIDI is normally measured in terms of minutes or hours per year. Equations (5) and (6) give the mathematical expression below:

$$\mathrm{DAIDI} = \frac{\sum \text{Device minutes or hours of interruption}}{\text{Total count of the devices installed}} \tag{5}$$

$$\mathrm{DAIDI} = \frac{\sum \mathrm{D_{it}}}{\mathrm{D_t}} \tag{6}$$

where D_{it} denote the total minutes of device interruptions for a given period of time due to sustained faults or due to the maintenance scheduled.

3.2.3 DMAIFI: Device Momentary Average Interruption Frequency Index

The Device Momentary Average Interruption Frequency Index (DMAIFI) indicates how often an average device encounters a temporary interruption over a specified period of time. Equation (7) gives the mathematical expression:

$$\mathrm{DMAIFI} = \frac{\sum \text{Total count of the device momentary interruptions}}{\text{Total count of the devices installed}} \tag{7}$$

When D_{mi} denote the total number of momentary device interruptions for a given period, DMAIFI is given by Equation (8).

$$\mathrm{DMAIFI} = \frac{\sum \mathrm{D_{mi}}}{\mathrm{D_t}} \tag{8}$$

3.3 Newly Proposed Load-based Reliability Index

When a distribution system is sparsely populated and has highly concentrated loads (industrial/commercial loads) connected, a new index based on the load instead of the customers or the devices, is required to measure the system performance. The index is,

3.3.1 AMIFI: Average Momentary Interruption Frequency Index

The Average Momentary Interruption Frequency Index (AMIFI) indicates how often a kVA load encounters a temporary interruption over a particular time span. In case, the load distribution in the radial system becomes uniform, AMIFI would match the value of MAIFI. Equations (9) and (10) give the formula for AMIFI:

$$\mathrm{AMIFI} = \frac{\sum \text{Total count of kVA load interruptions}}{\text{Total kVA load served}} \tag{9}$$

$$\mathrm{AMIFI} = \frac{\sum \mathrm{DMD_{mi}}}{\mathrm{DMD_t}} \tag{10}$$

where DMD_{mi} denote the total kVA demand interruptions of temporary nature for a specific period of time and DMD_t represent the total kVA demand that is supplied.

4 Distribution System Reliability Studies

4.1 Input Test System Details

The most popular 69-bus radial distribution system [15] having DGs installed as in Table 1 is chosen to act as the input system. Four different percentages of penetration of the DGs and placement of the DGs are considered here. For the case of sparse allocation (SA), the placement of the DGs is sparse and the number of nodes in which the DGs are connected is less than 30% of the total number of nodes in the system [5]. The placement of the DGs is such that many numbers of DGs are available in the highly concentrated load zone of the system. The DGs are capable of meeting a maximum of 65% of the total load requirement. For the cases of DS, UDS, and SS, the placement of the

Table 1 Placement of the DGs

Case Number	Type of the DG	Bus Number of Installation of the DG	Maximum Active Power Output in kW
1	Solar PV	20, 23, 32, 37, 41, 56	58, 58, 116, 58, 58, 58
	Wind	16, 25, 46, 49, 52, 64	116, 58, 174, 174, 232, 58
	Biomass	9, 48, 51, 54	116, 290, 406, 464
2	Solar PV	9, 18, 27, 36, 45, 54, 63	225, 57, 13, 436, 0, 55, 24
	Wind	6, 15, 24, 33, 42, 51, 60	152, 99, 39, 37, 51, 243, 47
	Biomass	3, 12, 21, 30, 39, 48, 57, 66	73, 151, 112, 0, 362, 1263, 53, 79
3	Solar PV	9, 18, 27, 36, 45, 54, 63	159, 108, 25, 71, 22, 257, 44
	Wind	6, 15, 24, 33, 42, 51, 60	39, 48, 25, 36, 28, 1148, 47
	Biomass	3, 12, 21, 30, 39, 48, 57, 66	23, 301, 108, 23, 692, 90, 50, 76
4	Solar PV	9, 18, 27, 36, 45, 54, 63	88, 175, 183, 0, 146, 378, 1
	Wind	6, 15, 24, 33, 42, 51, 60	38, 168, 181, 3, 99, 366, 0
	Biomass	3, 12, 21, 30, 39, 48, 57, 66	0, 130, 180, 1, 8, 309, 131, 2

DGs is such that nearly one-third of the total number of nodes has an installed DG [6]. The percentage of penetration of the DGs at 0.82 power factor (pf) leading for DS equals 94%, for UDS equals 90% and for SS equals 68%. The total load demand of the system is 3802.19 kW and 2694.6 kVAR, and the DGs are capable of meeting both the real power and the reactive power requirements of the system. It has already been proved in [5] and [6] that these percentages of penetration give a minimum energy loss at 0.82 pf leading to the sizes of the DGs shown in Table 1. Reference [16] discusses the impact of the reverse power flow that happens due to the installation of DGs. As the capacities of the DGs increase beyond a certain level, the cluster of MGs tends to become an exporter of electricity. At this condition, the substation must be restructured to receive the energy from downstream and the voltage levels in the MGs rise above the permitted limits. In this research, such conditions involving the redesign of the substation are avoided and the penetration level of generation is maintained at a much lower level.

The 69-bus distribution system is split into several MGs using the process of MRCF as shown in Figure 1 for SA. In the MRCF method, the load flow problem is solved to get the flow of current in the branches. The direction of flow of real power and reactive power is obtained on studying the sign reversals of the real part and the imaginary part of the branch

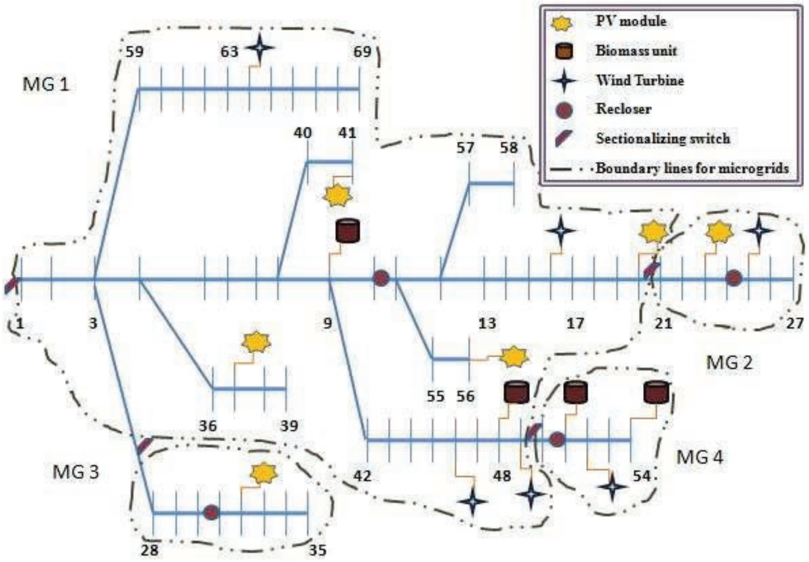

Figure 1 SA-Optimal construction of MGs for 65% penetration of the DGs.

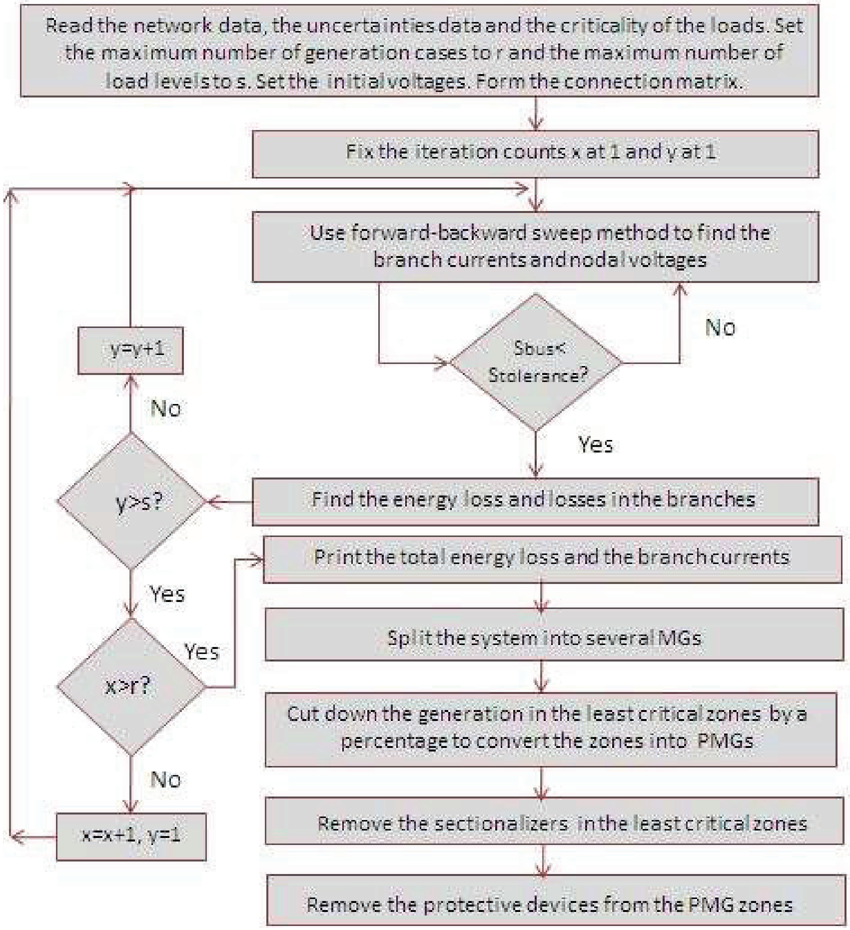

Figure 2 Flow chart to define the MGs and PMGs.

currents for various load-generation combinations. The branches in which the current flow direction reverses from upstream-to-downstream or vice-versa frequently becomes the candidate branches for splitting the system. Then splitting is performed to get a maximum number of MGs at minimum energy loss condition as in [5] based on the maximum number of branches per MG, adequacy in generation, and strength of trend reversal. This process is shown in a sequence in Figure 2.

Using the same MRCF method, the splitting operation is performed for the other cases too. For DS, the candidate branches to mark the boundaries of

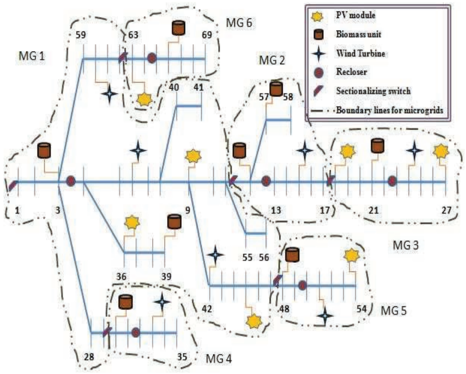

Figure 3 DS-Optimal construction of MGs for 94% penetration of the DGs.

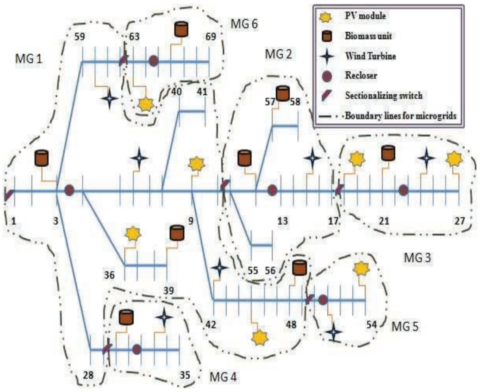

Figure 4 UDS-Optimal construction of MGs for 90% penetration of the DGs.

MGs are 8, 11, 14, 17, 20, 29, 32, 35, 41, 44, 47, 59, 62, and 65. The minimum number of nodes per MG equals four. Figure 3 shows the optimal split for DS for a minimum energy loss and a maximum number of splits.

For UDS, the candidate branches are 10, 11, 12, 16, 17, 18, 28, 29, 30, 49, 50, 61, 62, and 63; and Figure 4 shows the details of the split performed similarly to that in [6]. Finally, for SS the candidate branches are 8, 9, 49, and 50. Figure 5 shows the cluster of MGs formed similar to [6].

4.2 The Construction of PMGs

This research attempts to restructure the already available system generation expansion plans shown in Figures 1, 3, 4, and 5 with a cluster of MGs to

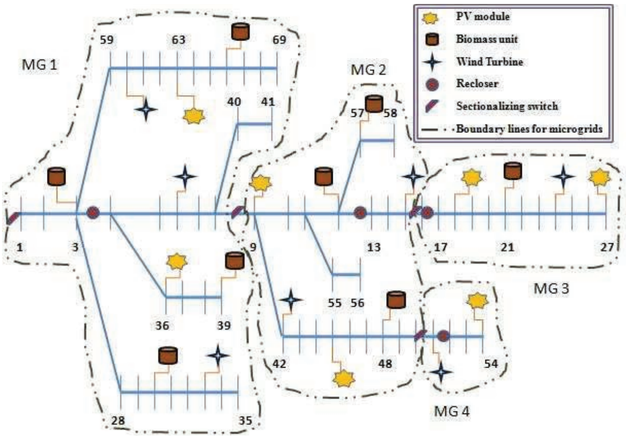

Figure 5 SS-Optimal construction of MGs for 68% penetration of the DGs.

include a PMG, based on the criticality data. As a first step, the list of least critical loads or a map of least critical zones of the distribution system is obtained. Then the renewable energy generation in the marked least critical area is cut down by a considerable percentage such that the generation capacity does not meet the peak load during isolated operation as mentioned in Figure 2. In case the generation in PMG is not sufficient, it will buy energy from the main grid or from the connected MG. The PMG cannot go to isolation mode without the coupled MG and hence the sectionalizer linked to it is removed. As the connected MG provides protection to the PMG, the protective devices are excluded from the PMG zone. This set of operations tends to convert an MG into a PMG and ensure economic savings. The reliability of the PMG will be reduced considerably as it embeds only the least critical loads.

It is now assumed that the bus numbers 16 to 27 of the distribution system support the least critical loads. For SA, the MG 2 that includes the least critical nodes is converted into a PMG by following the flow chart in Figure 2. A wind generator, a recloser and the sectionalizer connecting MG 1 and the PMG has been removed. Therefore, the construction of the PMG is as shown in Figure 6. Following the same procedure, a PMG is constructed for DS by removing a DG install that was planned for the node 21 along with the protective device and the sectionalizer. This modifies the plan in Figure 3 and the boundary of the PMG is marked as in Figure 7. Then on the removal of the DGs in the nodes 18 and 27 along with the recloser and the sectionalizer, a PMG can be defined for the case of UDS as found in Figure 8.

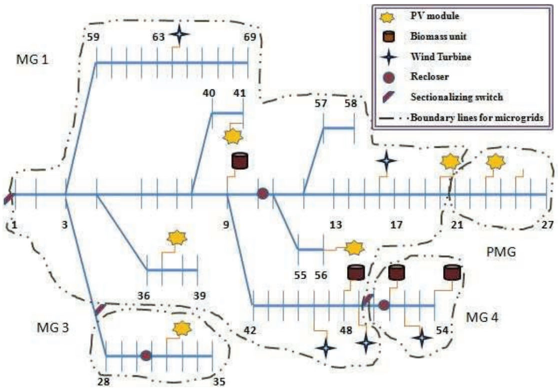

Figure 6 SA-Optimal construction of PMG for 65% penetration of the DGs.

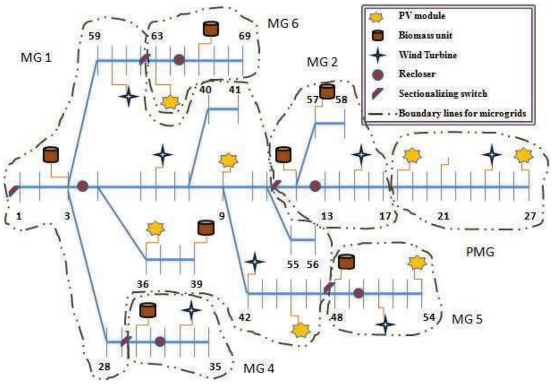

Figure 7 DS-Optimal construction of PMG for 94% penetration of the DGs.

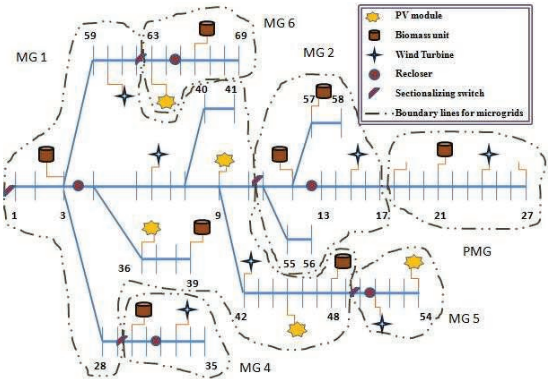

Figure 8 UDS-Optimal construction of PMG for 90% penetration of the DGs.

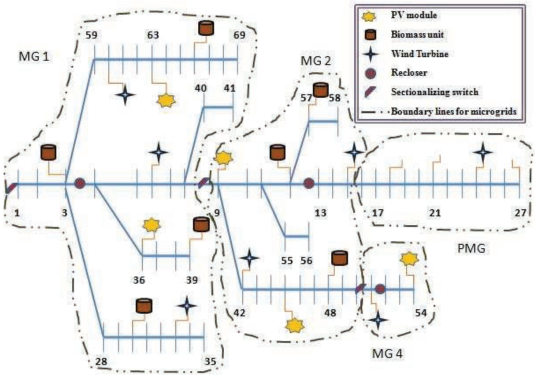

Figure 9 SS-Optimal construction of PMG for 68% penetration of the DGs.

At last, Figure 9 gives the plan for the construction of a PMG for the case of SS on making changes to the plan in Figure 5. The DGs in nodes 18, 21, and 27, the recloser and the sectionalizer has been removed. The percentage of penetration of the DGs gets reduced slightly for all the four cases with a PMG. It is assumed that the MG that is coupled to the PMG generates more than what is required, to meet its critical loads for both grid-connected and islanded modes of operation. Therefore, the PMG can always purchase energy from the coupled MG or the utility even if it lacks generation capacity.

4.3 Reliability Evaluation for Sustained Faults

To model the load, [17] is referred. To denote the yearly load pattern, ten discrete load levels along with their probabilities of occurrence are used.

The following assumptions are made for the reliability evaluation:

- The load is at an average level of 61% while the percentages of penetration of the DGs for various cases are at optimal values.
- The DGs operate at a leading pf giving a maximum real power output. Reactive power is also supplied by the DGs.
- At sustained fault conditions, one-third of the customers or kVA load in the particular MG boundary gets affected on an average when the recloser operates, if the MG is not connected to any PMG.
- When a sustained fault occurs in a PMG or the coupled MG connected to it, the total number of customers is obtained on adding the customers in the PMG to the customers in the MG. Similarly, the value of the total load is obtained. One-third of the total customers or the total load gets affected on an average.

References [18] and [19] give the details for the protective devices, the transformer, and the substation. Using these details and by using the data available in the Appendix, the reliability calculation is made for the systems drawn in Figures 1, 3 to 9.

Reference [20] uses the failure rate, the repair time, and the isolation time of various components of the chosen distribution system to find the SAIDI, Expected Energy Not Served, cost of interruption, etc. Reference [21] gives the failure statistics of all the required components in the system and calculates SAIFI, SAIDI, CAIDI, etc. Chapter 7 of the book [22] explains in detail, various reliability indices and calculates the reliability of the system. The chapter then discusses the impact of lateral distributor protection, the effect of disconnects, the impact of protection failures, and the effect of transferring loads. SAIDI, SAIFI, CAIDI, and ASAI have been calculated for the overall power system including generation, transmission, and the distribution segments using the failure details of the various components in [23]. All these references give clarity on the procedure to be followed for the calculation of the reliability of any given system.

The sustained faults that occur in the substation components (transformer, breaker, and sectionalizer) are taken into account for the reliability calculation. The permanent faults of the reclosers in the MGs and the PMG, the sectionalizers connecting various MGs, the feeder and the faults related to the DGs are considered for calculation of the indices.

Figures 10, 11, and 12 give the values for various reliability indices and repair time details for the construction plan of MGs found in Figures 1, 3, 4,

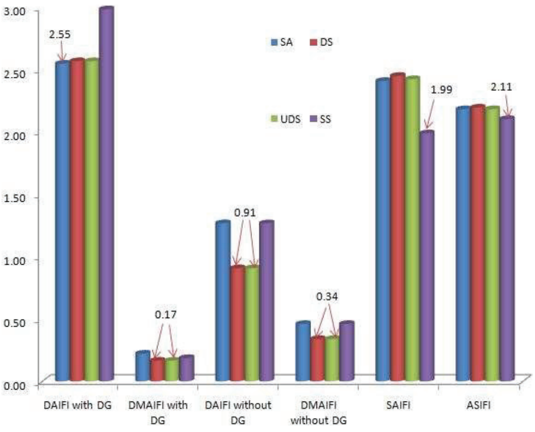

Figure 10 Fault frequency-based indices for the cluster of MGs.

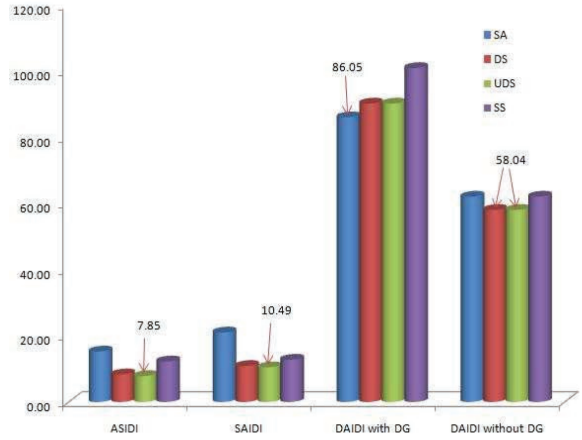

Figure 11 Interruption duration-based indices for the cluster of MGs.

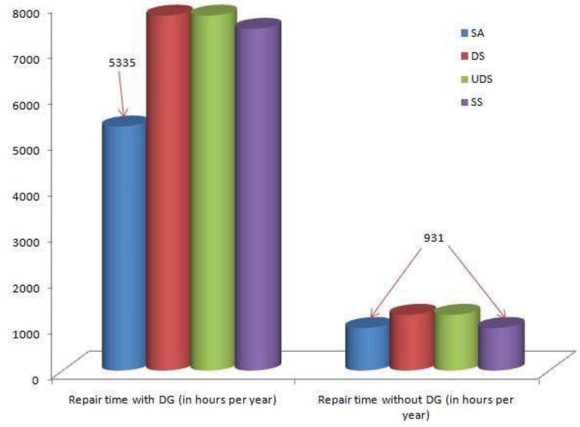

Figure 12 Repair time for the cluster of MGs.

and 5. The values for DAIFI with DG and DAIDI with DG are halved for all the cases. The minimum values of the indices for various cases are displayed in all the graphs.

The case with a lesser repair time becomes a cost-efficient design and gives reduced expenses on installation and salary for the maintenance personnel. The lesser the newly suggested device-based indices are, the lesser is the cost of installation and the time duration of maintenance.

Figures 13, 14, and 15 display the values of various parameters of the reliability calculation and the repair time in hours for the construction of a

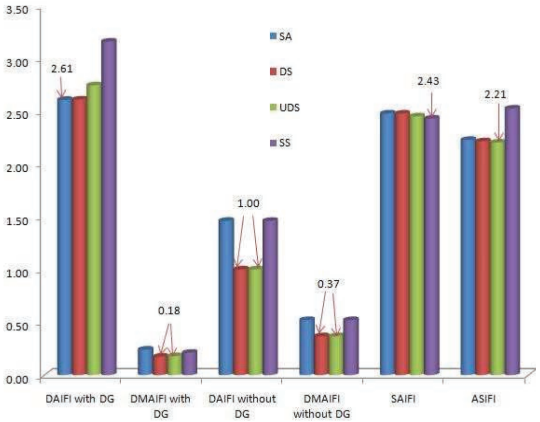

Figure 13 Fault frequency-based indices for the system with a PMG.

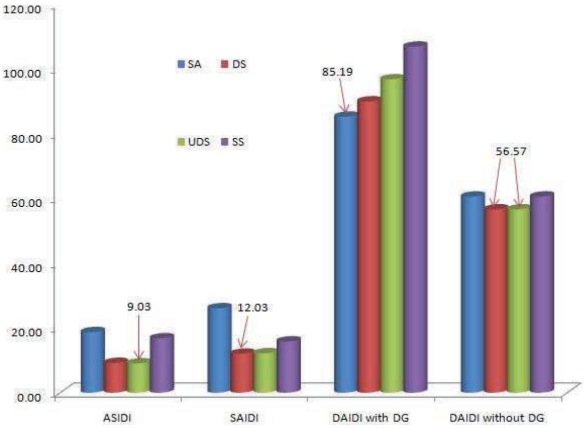

Figure 14 Interruption duration-based indices for the system with a PMG.

PMG shown in Figures 6, 7, 8, and 9. The values for DAIFI with DG and DAIDI with DG are halved for all the cases, as in the case of only MGs. The LOLP values are given in Table 2.

4.4 Reliability Evaluation for Temporary Faults

The mechanism of momentary interruption, the procedure for calculation of various momentary indices is described in [24] and [25] discusses the importance of the index, MAIFI in detail.

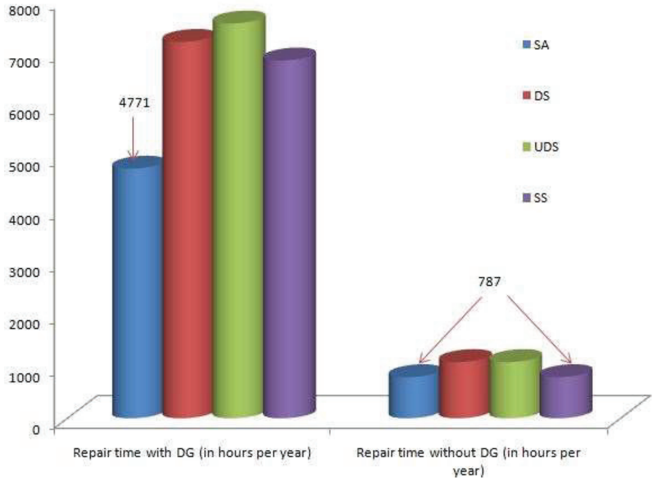

Figure 15 Repair time for the system with a PMG.

Table 2 Loss of load probability

	SA	DS	UDS	SS
Only MGs	0.0017	0.0010	0.0009	0.0014
MGs and PMG	0.0021	0.0010	0.0010	0.0019

The following assumptions are made for the calculation of the momentary indices:

- The temporary operations of the protective devices are independent of the response of the device for a sustained fault condition.
- A third of the total number of customers or total kVA load of an MG get interrupted due to the operation of the reclosers and the substation breakers, when no PMG is electrically connected to the MG.
- A third of the total number of consumers/total kVA demand of an MG added to a third of the customers/total kVA demand of the connected PMG get affected due to the temporary operation of the reclosers and the substation breakers.
- The number of times the reclosers and the substation breaker operates in case of temporary faults is assumed for calculation of MAIFI and AMIFI.

Figure 16 documents the temporary index values for the cases with and without a PMG for SS.

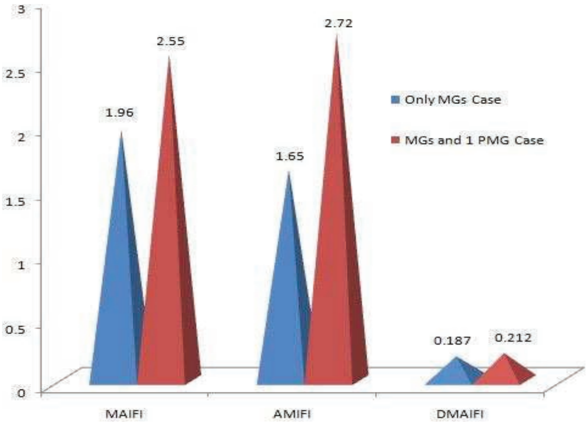

Figure 16 Reliability indices for temporary faults for SS.

5 Result Analysis

On recalling the contributions stated in Section 2 above, at this stage it may be concluded that the new reliability indices have been defined in Section 3, referring to [7]. Later, using the MRCF procedure in the literature, few test systems have been built to include either a cluster of MGs or a set of MGs along with a PMG as seen in the Figures 1, 3 to 9 to satisfy the next stated contribution of the research work. Then the reliability of all the test systems were found and plotted as shown in Figures 10 to 16. LOLP values may be found in Table 2. Now, to address the final contribution and to decide on the type of sizing and budgetary decisions, the below discussions are made:

5.1 Discussions on the Case of Only MGs During Sustained Faults

Inferences made from Table 2 and Figures 10, 11, and 12 for the cluster of MGs are listed below:

- Case A-Lack of budget/space for installation/renewable energy resources: The cases of DS, UDS, and SS have a higher installation and maintenance cost due to a greater percentage of penetration of the DGs, compared to SA, as denoted by the DAIFI with DG, and DAIDI with DG (shown in Figures 10 and 11). Also, the cases of DS, UDS, and SS display a longer duration for repair with the availability of the DGs, as shown in Figure 12. These results indicate that SA with lesser number of devices is the best plan to be chosen.

SA gives low-reliability values for old customer-based indices, load-based indices, and the LOLP, whereas the same case gives good values for new device-based indices.

- Case B-Enough budget/space for installation/renewable energy resources: SAIFI and ASIFI indicate that SS is better (Figure 10). Whereas, SAIDI and ASIDI prove that the case of UDS is better (Figure 11). The non-homogeneous distribution of the load in the chosen distribution system creates the necessity to calculate both the customer-based indices and the load-based indices. When importance needs to be given to the interruption faced by a consumer, SAIFI and SAIDI becomes the decision-maker. When importance is needed for the interruption faced by a kVA load, ASIFI and ASIDI give the final choices. Here, both UDS and SS can give highly reliable construction plans for the MGs, irrespective of the importance given for the interruption of consumers or the load.

  The case of DS, UDS, and SS show poor values for the newly defined device-based indices and high-reliability values for the older customer-based indices, load-based indices, and the LOLP.
- Inferences from Table 2: When there is high importance for reliability compared to budgetary constraints, LOLP values in Table 2 show that the case of UDS is a better design.
- Reliability characteristics for device-based indices: DS and UDS show almost similar reliability characteristics for device-based indices with and without considering DGs. SA and SS show similar reliability characteristics when DGs are not considered (Figures 10 and 11).

Thus, Table 3 gives the summary of the final choices on deciding the construction plans.

5.2 Discussions on the Case of a PMG During Sustained Faults

Inferences made from Table 2 and Figures 13, 14, and 15 for the cluster of MGs along with a PMG are listed below:

- Case A-Lack of budget/space for installation/renewable energy resources: The cases of DS, UDS, and SS are not cost-efficient compared to SA. DAIFI with DG and DAIDI with DG values given in Figures 13 and 14 prove this. DS, UDS, and SS exhibit a longer TRPY with the availability of the DGs (Figure 15). Therefore, SA is the best plan to be chosen, just like the case of only MGs in Section 5.1.

Table 3 Decision on choosing a construction plan for "Only MGs" case

Case	Best Plan	Existing/ Proposed Indices*	Values Obtained for the Reliability Indices
Lack of space for installation/ budget/renewable energy resources	SA	Existing indices	High and not recommended
		Proposed indices	Low and recommended
Enough space for installation/ budget/renewable energy resources	UDS/SS	Existing indices	Low and recommended
		Proposed indices	High and not recommended

*Existing indices – SAIFI, SAIDI, ASIFI, ASIDI; Proposed indices – DAIDI, DAIFI.

Older indices prove that SA has low reliability. But it gives improved values for the newly suggested indices.

- Case B-Enough budget/space for installation/renewable energy resources: SAIFI indicates that SS is a good option, whereas ASIFI and ASIDI indicate that UDS is better (Figures 13 and 14). SAIDI proves that the case of the DS is better (Figure 14). When there is an increased importance for the interruption faced by a consumer, SAIFI, and SAIDI end up picking the plans of SS and DS for the construction of MGs and a PMG. When importance is required for the interruption faced by a kVA load, ASIFI and ASIDI ends up with DS as the final choice.

  The construction plans of DS/UDS/SS display very high reliability as shown by the older reliability indices. But the values of the newly defined indices for these cases are poor.
- Inferences from Table 2: When a highly reliable plan is demanded, the values of LOLP recommend either DS or UDS.
- Reliability characteristics for device-based indices: When the DGs are ignored, DS and UDS show almost similar reliability characteristics for the device-based indices, and SA and SS show similar reliability characteristics (Figures 13 and 14).

Thus, Table 4 gives the summary on the final decision on choosing the best construction plans.

5.3 Comparison Between the Case of Only MGs and the Case of a PMG

The results discussed so far show that the case with only MGs and the case with one PMG give some final decisions on fixing the construction plan, in

Table 4 Decision on choosing a construction plan for "MGs and PMG" case

Case	Best Plan	Existing/ Proposed Indices*	Values Obtained for the Reliability Indices
Lack of space for installation/ budget/renewable energy resources	SA	Existing indices	High and not recommended
		Proposed indices	Low and recommended
Enough space for installation/ budget/renewable energy resources	DS/UDS/SS	Existing indices	Low and recommended
		Proposed indices	High and not recommended

*Existing indices – SAIFI, SAIDI, ASIFI, ASIDI; Proposed indices – DAIDI, DAIFI.

common, whereas certain decisions vary because of the modification made in the plan to construct the PMG. On converting a portion of the system to a PMG, the following parameters differ between the two cases:

- TRPY indicates that there are lesser number of components installed in the case of a PMG and thus results in lesser installation and maintenance costs compared to the case of only MGs (Figures 12 and 15).
- Increased value of LOLP, SAIFI, SAIDI, ASIFI and ASIDI for the case of one PMG gives reduced reliability for the considered radial distribution system. This reduction is restricted only to the PMG and the coupled MG, when the cluster of MGs operates in isolation from the grid.
- Figure 16 shows the comparative graphs for the temporary indices MAIFI, AMIFI, and DMAIFI for the cases with and without a PMG. All the three indices are much higher for the case with a PMG as a failure in the PMG needs to be taken care of by the attached MG. A failure in the PMG causes disturbance in the electrically coupled MG along with the PMG. Similarly, a failure in the attached MG causes a disturbance in the PMG along with the MG.

5.4 Sensitivity Analysis

A sensitivity analysis is carried out at this point to decide on the budget allotment for the DGs and the protective devices. Modified UDS1 (MUDS1) is a construction plan where the PMG includes only those generators that are characterized by lower repair and maintenance time, and reduced frequency of faults. Modified UDS2 (MUDS2) is a modified version of MUDS1 that

Table 5 MUDS1 Vs UDS for "MGs and PMG" case

Case	TRPY with DG	DAIFI with DG	DAIDI with DG
MUDS1	6773	5.06	173.66
UDS	7545	5.5	193.46

Table 6 MUDS1 Vs MUDS2 for "MGs and PMG" case

Case	DMAIFI with DG
MUDS1	0.18
MUDS2	0.176

includes extra protective devices in the coupled MG. The benefits of these two plans are discussed underneath:

- Case A-MUDS1: When the planning stage gives higher importance to the reduction in frequency of interruptions and TRPY without compromising on the generation mix ratio, MUDS1 may be tried. Here, two DGs in the buses 21 and 24 are removed instead of the DGs in the buses 18 and 27 shown in Figure 8. Table 5 shows that MUDS1 results in lesser values for certain parameters. This reduction occurs because the repair and maintenance time, and the frequency of faults for 2 solar PV units in the PMG is much lesser for MUDS1 than that required for 1 biomass unit and 1 wind turbine generator, installed in the PMG for UDS. MUDS1 offers better savings when it comes to repair and maintenance cost.
- Case B-MUDS2: When the planning stage stresses more on improving the reliability, an extra recloser is added to the MG coupled to the PMG in the MUDS1 plan and this becomes the MUDS2 plan. Now, a decrease in DMAIFI with DG for MUDS2 is noticed as shown in Table 6. This indicates an improvement in the reliability of the MUDS2 system with added cost for the recloser. It may now be concluded that DMAIFI decides the count of protective devices to be placed in the system.

5.5 Managerial Insights

Based on this research, the below recommendations are given for the decision-makers to upgrade the functioning of modern distribution systems:

- The newly defined indices, DAIFI, DAIDI and DMAIFI may be used to employ and allot manpower for repair and maintenance of the system i.e., to plan for recruitment, the salary of personnel and scheduled maintenance, and to attend repairs 24X7, instantly. This is directly linked to the budgetary constraints in the stage of expansion planning.

- The newly defined load-based index, AMIFI may be used in the expansion planning stage to place the protective devices appropriately in the system.
- During the construction of PMGs, a high preference might be given for a lesser repair and maintenance time along with a lesser count of failures per year, without compromising on the required DG mix ratio or for improved reliability. Either MUDS1 plan or MUDS2 plan may be chosen based on the requirement.
- A pico-grid is an off-grid low voltage system suitable for isolated remote areas that are not connected to the main grid as discussed in [29] and [30]. For such isolated systems, the indices discussed here can be calculated to find the reliability.
- In case the distribution system is upgraded in future to include electric vehicles and DC loads, the corresponding real power and reactive power can be added to the power flow studies. Later, a similar splitting methodology followed by reliability calculation can also be performed.

6 Conclusion

This study has constructed a cluster of MGs and a PMG, on considering a radial distribution system with a least critical zone. The construction of PMG reduces the reliability of the least critical zone and gives considerable savings on the installation and maintenance cost. The work then defined few new reliability indices namely, DAIFI, DAIDI, DMAIFI, and AMIFI for the sustained and the momentary faults occurring in the system, to meet the requirements arising from an increased percentage of penetration of the distributed generation. The evaluation of the new indices aids in choosing the best generation expansion plan when a set of plans are available. The new indices are calculated when increased importance is required for the average frequency and average duration of faults on the installed components. The older indices give extra importance for the average frequency and average duration of faults on the load or the consumers. The new indices resulted in choosing the case of SA with a lesser count of the DGs working at 65% penetration of the DGs, in the case of economical constraints or space allotment constraints or lack of renewable resource input. A compromise on the total reliability is inevitable in this condition. When reliability cannot be compromised and if there is enough budget, space for installation, and renewable energy resources, the older indices are used to decide on the expansion plan. When importance is required for the customer-based indices or load-based indices, the SS or the UDS plan is selected for the case of only MGs, whereas the customer-based indices result in the selection of SS or DS plan, and the load-based indices picked up the UDS plan, for the case of PMG.

The value of the temporary indices MAIFI, DMAIFI, and AMIFI were calculated to show a reduction made in the overall reliability for the least critical zone. The evaluation of TRPY, DAIDI, and DAIFI concludes that the construction of a PMG becomes highly beneficial when the PMG includes DGs with lesser repair and maintenance time, and lesser count of failures per year, without compromising on the generation mix ratio. Later, on finding DMAIFI, it was proved that when reliability improvement becomes important, addition of protective devices helps. Finally, a few recommendations were suggested for the decision-makers on the usage of these indices.

Appendix

[18, 26] and [27] give the values of repair time per year (RTPY), SFPY, MO, and TOM for the DGs for reliability calculation. Table A.1 shows these values. The bus numbers (BN) have been mapped to 61% of the kVA load connected (LC) to them and to the total number of customers connected (CC) as seen in Table A.2 [5]. Table A.3 gives the details of the branches of the system like branch length (BL), mean time to repair (MTTR), scheduled maintenance time (SMT), SFPY, and momentary faults per year (MFPY), on referring to [18, 27] and [28].

Table A.1 Details of the renewable energy DGs

Type of the DG	RTPY	SFPY	MO	TOM (In Hours)
Solar PV	33	3.329	1	1
Wind generator	419	11.914	1	1
Biomass generator	419	11.914	1	1

Table A.2 Customer and load details

BN	LC	CC	BN	LC	CC	BN	LC	CC
1	0	0	24	21	11	47	0	0
2	0	0	25	0	0	48	75	28

(*Continued*)

Table A.2 Continued

BN	LC	CC	BN	LC	CC	BN	LC	CC
3	0	0	26	10	5	49	0	0
4	0	0	27	10	5	50	932	1
5	0	0	28	20	9	51	24	11
6	2	1	29	20	10	52	0	0
7	31	13	30	0	0	53	170	95
8	56	23	31	0	0	54	44	12
9	23	11	32	0	0	55	14	7
10	21	9	33	10	4	56	14	7
11	109	45	34	15	9	57	21	10
12	109	42	35	4	2	58	21	10
13	6	3	36	0	0	59	19	9
14	6	3	37	59	26	60	19	8
15	0	0	38	288	125	61	0	0
16	33	17	39	288	120	62	18	8
17	42	10	40	30	13	63	18	7
18	42	13	41	3	1	64	1	1
19	0	0	42	3	1	65	0	0
20	1	1	43	20	10	66	5	2
21	85	35	44	18	8	67	0	0
22	4	2	45	0	0	68	29	13
23	0	0	46	0	0	69	29	12

Table A.3 Branch details for reliability calculation

BN	BL (In Miles)	MTTR	SMT (In Minutes)	SFPY	MFPY
1, 7, 8, 14, 16, 21, 22, 23, 28, 30, 31, 32, 44, 45, 47, 52, 57, 58, 66, 67, 68	3	0.4515	6	0.1506	60
5, 11, 12, 13, 18, 19, 20, 24, 26, 39, 49, 51, 56, 63, 64, 65	2	0.3010	6	0.1004	45
2, 3, 4, 6, 9, 10, 15, 17, 25, 27, 29, 33, 34, 35, 36, 37, 38, 40, 41, 42, 43, 46, 48, 50, 53, 54, 55, 59, 60, 61, 62	1	0.1505	6	0.0502	30

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