Optimal feeder reconfiguration in distributed generation environment under time-varying loading condition

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Abstract

The development and planning of optimal network reconfiguration strategies for electrical networks is greatly improved with proper application of graph theory techniques. This paper investigates the application of Kruskal's maximal spanning tree algorithm in finding the optimal radial networks for different loading scenarios from an interconnected meshed electrical network integrated with distributed generation (DG). The work is done with an objective to assess the prowess of Kruskal's algorithm to compute, obtain or derive an optimal radial network (optimal maximal spanning tree) that gives improved voltage stability and highest loss minimization from among all the possible radial networks obtainable from the DG-integrated mesh network for different time-varying loading scenarios. The proposed technique has been demonstrated on a multiple test systems considering time-varying load levels to investigate the performance and effectiveness of the suggested method. For interconnected electrical networks with the presence of distributed generation, it was found that application of Kruskal's algorithm quickly computes optimal radial configurations that gives the least amount of power losses and better voltage stability even under varying load conditions.

Article Highlights

- Investigated network reconfiguration strategies for electrical networks with the presence of Distributed Generation for time-varying loading conditions.
- Investigated the application of graph theory techniques in electrical networks for developing and planning reconfiguration strategies.
- Applied Kruskal's maximal spanning tree algorithm to obtain the optimal radial electrical networks for different loading scenarios from DG-integrated meshed electrical network.

Keywords Network reconfiguration · Distributed generation · Graph theory · Kruskal's maximal spanning tree algorithm

1 Introduction

In the delivery and supply of electricity, the distribution stage is the final stage following the generation and transmission stages. The electrical distribution network delivers the electrical power to the consumers via its distribution

feeders. Certain problems faced in lengthy distribution feeders include fall in voltage levels [1], power factor distortion, power loss, etc. In order to mitigate these problems, the authors in [2–4] implemented measures such as embodiment of additional hardware like tap-changing transformers, shunt capacitors, FACTS devices etc. Apart

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from these approaches, another important approach is by reconfiguring the network via network reconfiguration by operating the series and sectional switches [5, 6]. By means of network reconfiguration, the power lines can be restructured in such a way that an optimal radial network may be obtained thereby providing a path for optimal power to flow in the network. The authors in [7, 8] discussed that appropriate reconfiguration arrangement can contribute towards reduction in power loss in the network. In [9] the authors have used reconfiguration studies for microgrid applications, and in [10] the authors have worked on developing reconfiguration strategies for ship-board power systems considering local and global reconfiguration. The advantage of network reconfiguration technique over other methods is that just by operating the sectional and tie line switches network reconfiguration can help obtain an optimal stable network with minimized losses, with no requirement for additional equipment or supports. In [11], the authors found that application of graph theory techniques such as Edmond's Maximal Spanning Tree Algorithm can help obtain optimal radial network configurations from an originally meshed network. It may be worth noted that in practice, radial structured networks are generally used in rural and sub-urban areas due to several advantages it offers such as lower short circuit current and less complex relay coordination. Also, sometimes during situations such as during fault or planned maintenance condition, a mesh network may be required to be reconfigured into a radial network thereby keeping the supply uninterrupted when the maintenance is being carried out. Some of the advantages of network reconfiguration were further discussed by the authors in [12] such as trimming of peak demands leading to curtailment of overburdening of network components and enhancing the system stability.

A substantial amount of time has been invested by contemporary researchers in studying the influence of network reconfiguration in achieving loss reduction [13] and voltage stability improvement [14]. It can be seen from the works presented in [15–18] that most of the strategies are focused on reducing the feeder active power losses and enhancement of voltage stability for constant loading condition. This particular aspect of considering only constant loading condition becomes a limitation since in a practical scenario the power demands in a distribution network varies with time. The demand for electricity depends on the consumers, and the requirements of power by the consumers vary throughout the day; thus in actual practice, the demand seldom remains constant instead it varies continuously with time. This varying loading scenario follows a pattern, and thus by relying on past historical data, a predictive varying load model can be generated in the form of daily load curves.

By using the information from the daily load curves, network reconfiguration plans can be formulated for the different varying load scenarios. The authors in [12, 19] considered time-varying load demand in the study and by employing network reconfiguration techniques were able to obtain the best network with minimum system power loss and higher voltage stability.

Now, the demand for electricity is always on the rise, but the same cannot be said for the improvement in the transmission infrastructure. Thus, with increasing demand, the power transmission and distribution lines operate under a heavy burden and sometimes even under over loaded conditions, resulting in high transmission losses and low voltage stability. One ingenious solution to this problem is to connect certain capacity power plants or distributed generation (DG) sources directly or nearby to the load centres, thereby minimizing the burden on the transmission and distribution networks, which ultimately contributes to reduction in transmission losses and improvement in the voltage stability [20].

Apart from the potential benefits that come with the integration of distributed generation (DG) to an electrical network, another aspect of DG integration is its impact on the topology of the power system. In a traditional power system architecture or a centralized power system topology, the distribution or transfer of power is unidirectional [21] i.e., electricity is transferred from the centralized generating stations to the loads through the transmission and distribution lines, but in a power system network where small-scale DGs are connected directly to the distribution side any excess power generated by the DG can be fed back to the main grid via the feeders thereby making the flow of power in the feeder bidirectional [22]. This simple characteristic of an electrical network with and without DGs contributes to huge changes in the planning and implementation of network reconfiguration strategies of respective power system networks. Proper integration of DG offers technical benefits including power loss minimization and improvement in voltage stability, and also environmental as well as economic benefits [23–25]. The incorporation of DGs to supply the demand during peak load periods renders benefits in both technical as well as economical areas. DGs can also supply reactive power for improving the voltage profile to meet real power demands [26]. The technical benefits of incorporating distributed generation include voltage stability improvement, power loss minimization, distribution capacity release, improved system reliability and voltage support [27, 28]. The integration of renewable energy-based DGs also has a small likelihood of causing some disturbance in the system stability owing to its intermittent nature which is affected by natural conditions, which ultimately will have some impact on the electrical energy losses in distribution lines, voltage

profile, Var Control and set of pollutants produced by the grid, etc. [29–31].

Now, with the presence of distributed generation in the grid, the issue of distribution feeder planning and reconfiguration becomes more complex. As discussed earlier, due to the bidirectional nature of power flow in electrical networks with DG, the reconfiguration process and strategies for an electrical network with and without DG become slightly different. It can be observed from the literature that by means of network reconfiguration an optimal radial reconfigured network with minimized line losses and improved voltage stability can be obtained. However, there still exists some issues (with regards to computation) when carrying out network reconfiguration techniques. The larger the system, the more complex it becomes to find the optimal radial configuration via manual network reconfiguration process, since if a network has 'n' number of switches, then there exists 2^n possible switching combinations with some set of switching configurations resulting in radial network topologies. Thus, for large systems, any manual attempts to find the optimal radial network by tracking all the possible configurations becomes a tedious task involving an impractically long duration of time. The proper application of graph theory techniques in the field of network reconfiguration has been found helpful in resolving these issues.

In this paper, the application of graph theory-based Kruskal's maximal spanning algorithm in electrical networks for developing reconfiguration and planning strategies is further investigated for a network with time-varying load model and in the presence of DG. The work is done with an objective to assess the ability of Kruskal's maximal spanning algorithm to compute an optimal radial network (an optimal maximum spanning tree) that gives the best voltage stability and highest loss minimization from among all the possible radial configurations that can be obtained from the original DG-integrated connected mesh network for different time-varying loading scenarios. A computation is carried out on a modified IEEE 30 bus network in MATLAB to assess the performance of the suggested method.

2 Theory

2.1 Reconfiguration strategy

Consider a 4-node power distribution network consisting of one power supply bus, three load buses, and four feeders, as shown in Fig. 1. Let the reactance (in p.u.) of the feeders be X_1 , X_2 , X_3 and X_4 , respectively, and the voltage (in p.u.) of the nodes be $V_1 \angle \delta_1$, $V_2 \angle \delta_2$, $V_3 \angle \delta_3$, and $V_4 \angle \delta_4$,

Fig. 1 A 4-node mesh network

respectively. From the available data, the load-carrying capabilities of the feeders 1 to 4 can be calculated as,

$$P_1 = \left| \left(\frac{V_1 V_2}{X_1} \right) \sin (\delta_1 - \delta_2) \right| \quad (1)$$

$$P_2 = \left| \left(\frac{V_1 V_3}{X_2} \right) \sin (\delta_1 - \delta_3) \right| \quad (2)$$

$$P_3 = \left| \left(\frac{V_3 V_4}{X_3} \right) \sin (\delta_3 - \delta_4) \right| \quad (3)$$

$$P_4 = \left| \left(\frac{V_2 V_4}{X_4} \right) \sin (\delta_2 - \delta_4) \right| \quad (4)$$

Now, if we consider that the load carrying capabilities of the feeders are in the order $P_1 > P_2 > P_3 > P_4$, then reconfiguring the network by eliminating the feeder with least load-carrying capability (i.e. feeder 4), a radial network can be obtained from the originally mesh network. The feeder can be eliminated or disconnected by opening the sectionalizing switch as shown in Fig. 2. The newly obtained radial network consists of only the feeders with high load carrying capability.

The cost matrix (weight matrix) can also be obtained from the load-carrying capability of feeders. For a system with n number of nodes, the size of the cost matrix (weight matrix) will be $n \times n$. If 'c' represents the cost matrix, then its elements will be represented as c_{ij} , where c_{ij} represents the load-carrying capability (in p.u.) of the feeder connected between node i and node j. For the system shown in Fig. 1, the cost matrix will be a 4×4 matrix. The elements of the cost matrix can be calculated as, $c_{11} = c_{22} = c_{33} = c_{44} = c_{14} = c_{41} = c_{23} = c_{32} = 0$, since these are either single nodes or there are no direct connection between these nodes. As for the connected nodes,

Fig. 2 A 4-node reconfigured radial network

the nonzero cost matrix elements are, $c_{12} = c_{21} = P_1$, $c_{13} = c_{31} = P_2$, $c_{34} = c_{43} = P_3$, and $c_{24} = c_{42} = P_4$. The values of the cost matrix elements can be calculated using the Newton–Raphson load flow analysis. For the reconfigured radial network shown in Fig. 2, since feeder 4 is now disconnected with help from sectionalizing switch, node 4 will receive the supply from feeder 3 only, and the new cost matrix element for $c_{24} = c_{42} = P_4 = 0$.

In Kruskal's algorithm, a radial network is extracted from a mesh network by disconnecting the feeder with lowest load-carrying capability from among all the feeders in a step-by-step manner. This results in a radial network where all the nodes are connected only by the feeders with higher load-carrying capacity. It is observed that for the reconfigured radial network obtained through Kruskal's algorithm, the active and reactive power losses in each feeder are also minimized. By minimizing the overall power loss of the system, the voltage stability of the system is also further improved.

For a 4-node network, the number of possible network configurations would be 2^4 . For a mesh network with ' n ' number of feeders, there will be 2^n possible switch configurations. The number of possible feeder configurations increases with the increase in the number of feeders in the network, which also makes the process of finding an optimal radial network from an originally mesh network more complex. In large networks, trying to find an optimal radial network by testing every possible network configuration is a very tedious, time consuming and labor intensive process, and if a time-varying loading condition is considered, the task becomes even more difficult. In such circumstances, the Kruskal's algorithm helps to obtain an optimal radial network in less time and makes the process easier.

Certain important criteria should be maintained during the reconfiguration process, three such important criteria are:

Fig. 3 Single line system

- i. All nodes should be in service.
- ii. The maximum power transfer capability of a feeder should not be violated during each operation.
- iii. The sectionalizing switches of the feeders with lower load-carrying capability should be opened first compared to the other lines.

The final radial network obtained using Kruskal's maximal spanning tree normally contains the feeders with higher load-carrying capability, while the feeders with lower load-carrying capability are disconnected.

2.2 Voltage stability indicator (L-index) evaluation

For the voltage stability analysis, single feeder equivalent method of distribution network which comprises of multiple feeders [32] has been employed. The single line system is shown in Fig. 3. P = injected real power, Q = injected reactive power, R = line resistance, X = line reactance, P_L = real load, Q_L = reactive load, V = voltage.

The real power equations from Fig. 3 may be derived as

$$P = r(P^2 + Q^2)/V^2 + P_L \quad (5)$$

$$\text{or, } P - P_L/r = (P^2 + Q^2)/V^2 \quad (6)$$

and the reactive power equations from Fig. 3 may be derived as

$$Q = x(P^2 + Q^2)/V^2 + Q_L \quad (7)$$

$$\text{or, } Q - Q_L/x = (P^2 + Q^2)/V^2 \quad (8)$$

From (6) and (8), the terms $(P^2 + Q^2)/V^2$ can be eliminated, and by rearranging the equations we acquire

$$x(P - P_L) = r(Q - Q_L) \quad (9)$$

Considering sending end voltage as reference voltage (thus, $V = 1$), and on rearranging Eq. (9), and eliminating Q from Eq. (5), a quadratic equation in terms of P is acquired.

$$(r^2 + x^2)P^2 - (2x^2P_L - 2rxQ_L + r)P + (x^2P_L^2 + r^2Q_L^2 - 2rxP_LQ_L + rP_L) = 0 \quad (10)$$

From Eq. (10) the real power P can be derived as,

$$P = \frac{2x^2P_L - 2rxQ_L + r}{2(r^2 + x^2)} \pm \frac{[(2x^2P_L - 2rxQ_L + r^2) - 4(r^2 + x^2) * (x^2P_L^2 + r^2Q_L^2 - 2rxP_LQ_L + rP_L)]^{1/2}}{2(r^2 + x^2)} \quad (11)$$

|||^{thy}, taking into consideration the symmetry between the real power and the reactive power in power systems, the reactive power Q can be derived as,

$$Q = \frac{2x^2Q_L - 2rxP_L + x}{2(r^2 + x^2)} \pm \frac{[(2x^2P_L - 2rxQ_L + r^2) - 4(r^2 + x^2) * (x^2P_L^2 + r^2Q_L^2 - 2rxP_LQ_L + rP_L)]^{1/2}}{2(r^2 + x^2)} \quad (12)$$

Now, for P and Q of Eqs. (11) and (12) to have real roots, the determinant of the quadratic equations should be $b^2 - 4ac > 0$.

Hence,

$$(2x^2P_L - 2rxQ_L + r)^2 - 4(r^2 + x^2)(x^2P_L^2 + r^2Q_L^2 - 2rxP_LQ_L + rP_L) > 0 \quad (13)$$

$$\text{or, } [(2x^2P_L - 2rxQ_L + r) * (2x^2P_L - 2rxQ_L + r)] - 4[r^2(x^2P_L^2 + r^2Q_L^2 - 2rxP_LQ_L + rP_L) + x^2(x^2P_L^2 + r^2Q_L^2 - 2rxP_LQ_L + rP_L)] > 0 \quad (14)$$

Which on simplification, reduces to,

$$4[(xP_L - rQ_L)^2 + xQ_L + rP_L] < 1 \quad (15)$$

Based on the network loading, if the calculated value of the LHS of Eq. (15) goes beyond the critical limit i.e., 1, then the power becomes imaginary and it results in voltage collapse. The LHS of Eq. (15) is also termed as the voltage stability index and is represented by the term L_{index} .

Thus for a stable system, $L_{\text{index}} < 1$.

Now, considering Eq. (5) with sending ending voltage as reference voltage (thus, $V=1$), the equation becomes

$$P = r(P^2 + Q^2) + P_L \quad (16)$$

$$\text{or, } P - P_L = r(P^2 + Q^2) \quad (17)$$

But we know that, Generation(P)–Demand (P_L) = Losses (P_{loss}).

Thus Eq. (17) becomes,

$$P_{\text{loss}} = r(P^2 + Q^2) \quad (18)$$

$$\text{or, } r = P_{\text{loss}} / [(P_L + P_{\text{loss}})^2 + (Q_L + Q_{\text{loss}})^2] \quad (19)$$

|||^{thy}, by considering Eq. (7), we get

$$x = Q_{\text{loss}} / [(P_L + P_{\text{loss}})^2 + (Q_L + Q_{\text{loss}})^2] \quad (20)$$

Now, for reduced network,

$$L_{\text{index}} = 4[(x_{\text{eq}}P_{\text{Leq}} - r_{\text{eq}}Q_{\text{Leq}})^2 + x_{\text{eq}}Q_{\text{Leq}} + r_{\text{eq}}P_{\text{Leq}}] \quad (21)$$

Where L_{index} = voltage stability index, r_{eq} = equivalent resistance for single line, x_{eq} = equivalent reactance for single

line, P_{Leq} = total real loads in the distribution network, Q_{Leq} = total reactive loads in the distribution network.

And from Eqs. (19) and (20), we get,

$$r_{\text{eq}} = (\sum P_{\text{loss}}) / [(P_{\text{Leq}} + \sum P_{\text{loss}})^2 + (Q_{\text{Leq}} + \sum Q_{\text{loss}})^2] \quad (22)$$

$$x_{\text{eq}} = (\sum Q_{\text{loss}}) / [(P_{\text{Leq}} + \sum P_{\text{loss}})^2 + (Q_{\text{Leq}} + \sum Q_{\text{loss}})^2] \quad (23)$$

where P_{loss} and Q_{loss} are the active and reactive power losses of the system.

The voltage stability index i.e. L_{index} value varies between 0 and 1, with values nearer to 0 designating a more stable system.

2.3 Kruskal's maximal spanning tree and its application in the present study

A graph is a set of nodes connected with edges. And, a connected graph whose edges have weights assigned to it forms a network. Figure 4(a) shows an arbitrary network G with three nodes A , B and C and three edges AB , AC and BC with weights 1, 2 and 3, respectively.

A connected sub-graph extracted from the graph G , which contains no cycles or loops in it, forms a spanning tree (T) of G . Figure 4(b), (c) and (d) is possible spanning tree of Fig. 4(a). The spanning tree with the most weight forms the maximum weight spanning tree. Kruskal's algorithm [33] helps compute a maximal spanning tree from a given network by initially sorting the edges in order of decreasing weight then systematically constructing a maximal spanning tree by prioritizing the edges with more weights in each step of forming the spanning tree.

2.3.1 Kruskal's maximal spanning tree algorithm

Consider, a graph G represented by,

$$G = \{((u, v), e_{u,v}) : u, v \text{ are nodes, } e_{u,v} \rightarrow \text{weight of the edge } (u, v)\} \quad (24)$$

Then, the target spanning tree T may be represented as,

$$T = \{((u, v), e_{u,v}) : u, v \text{ are nodes, } e_{u,v} \text{ is the weight of the edge } (u, v)\} \quad (25)$$

And edge, $E = \{(u, v), e_{u,v}\}$.

To obtain a maximum spanning tree from a given network G , a simplified procedure based on Kruskal's [34–36] may be summarized as:

Fig. 4 A Network and its Spanning Trees

- i. Arrange the edges of G in decreasing order of weight via sorting. And let T be the set of edges constituting the maximum spanning tree. Initially, $T = \Phi$.
- ii. Add the first edge to T .
- iii. Continue adding the remaining edges to T one edge at a time always checking that it does not form a loop in T . Exit and report G to be disconnected when no further edges can be added.
- iv. If the obtained tree (T) has $n - 1$ edges (n = number of nodes in G) stop and output T . Otherwise go to step 3.

The flow chart of the Kruskal's Maximal Spanning Tree Algorithm has been shown in Fig. 5.

3 Results and discussions

Here, for different varying loading scenarios, Kruskal's maximal spanning tree algorithm was applied to find an optimal radial network (optimal spanning tree) from among the many possible spanning trees present in a meshed electrical network integrated with distributed generation. The proposed algorithm was tested on a modified IEEE 30 node test system integrated with distributed generation, with each feeder of the test system containing series sectionalizing switches numbered from S1 to S41. All simulations were carried out in MATLAB and MATLAB-based Power System Analysis Toolbox (PSAT). A representation of the 30-node test system is shown in Fig. 6, and the test system input data for feeder and load have been shown in Appendix Tables 12 and 13, respectively, and are also obtainable from [37]. The DG unit is modelled as a wind turbine with doubly fed induction generator (DFIG) as per [38] and its output is considered to be constant. The parameters of the DG are also given in Appendix Table 15. Initially, a load flow analysis was carried out on the original mesh network, and from the information obtained, the node with the least voltage magnitude value (in per unit value) was chosen as the location for DG installation. In the case of 30-node test system, the bus (node) with the least value of voltage magnitude was found to be bus 30. The DG was thus installed at the chosen node under the constraint that the capacity of the installed DG does not exceed the base load of that particular node. Thus, for the modified 30 node system case since the base load at bus 30 is 10.6 MW, the capacity of the DG is thus fixed at a constant output of 10.6 MW for all cases. Similar procedure was done for the cases for 3-node test system [37] and a 14-node test system [39].

Fig. 5 Flowchart of Kruskal's maximal spanning tree algorithm

Consumers play an important part in shaping the load demand in electrical distribution systems. Depending on several factors the demand for power may rise or fall at any given time. By collecting and accumulating information over a period of time on power consumption in an area, the load demand in that area can be predicted following the pattern of consumption. One of the most popular method of observing and planning for the variable loading condition is through the information obtained via daily load curves. Since the load demands in a distribution system vary with time, it is reasonable to predict that in accordance with the time-varying load demands the optimal radial network which yields the optimal voltage stability will also vary. Thus, there potentially exists different optimal radial configurations corresponding to the different loading scenarios. Therefore, formulating network reconfiguration strategies and plans considering different varying loading scenarios can help power system operators better understand and well equipped to handle network reconfiguration tasks whenever required to do so.

In this study, we have considered a time-varying model based on data as given in Appendix Table 14. Figure 9 characterizes a typical daily load curve (with values in p.u.) for a 24-h time interval based on the time-varying demand furnished in appendix Table 14. By applying Kruskal's Maximal Spanning Tree algorithm, we have tried to obtain an optimally reconfigured radial network which yields lower losses and better voltage stability index value corresponding to the different loading conditions.

Initially we have considered a small network and carried out a detailed computation on a 3-node test system taken from Example 6.7 of [35], including a comparison study between all manually obtainable possible radial configurations and the radial configuration obtained via application of the Kruskal's algorithm, followed by Kruskal's computation of optimal radial networks for varying load scenario. The results of the computation carried out have been presented in Tables 1 and 2, respectively. It may be seen from Table 1 that the radial network computed by the Kruskal's algorithm corresponds to the best possible radial network obtained via manual operation of the switches.

Fig. 6 Modified IEEE 30-node test system considered for the study

Table 1 Comparison of the radial networks obtained via manual switching and via application of Kruskal algorithm for a 3-node test system with and without DG integration

DG status*	Configuration No.	Switches that should be opened in order to obtain a radial configuration	P-loss (MW)	Q-loss (MVar)	L-index (p.u.)	Time taken (seconds)
0	Manual switching 1	S3	19.4744	40.9814	0.2829	Not applicable
	Manual switching 2	S2	52.39644	104.7929	0.6137	-do-
	Manual switching 3	S1	35.16448	92.712	0.5226	-do-
	Kruskal's configuration	S3	19.4744	40.9814	0.2829	1.253
1	Manual switching 1	S3	6.595451	39.64932	0.1974	Not applicable
	Manual switching 2	S2	19.91884	68.27353	0.3786	-do-
	Manual switching 3	S1	10.01335	55.2271	0.2783	-do-
	Kruskal's configuration	S3	6.595451	39.64932	0.1974	1.241

*Where, 0 = network without DG, and 1 = network with DG

Similarly, computation was also carried out for the modified 30-node test system. For the 30-node test system, at base loading condition, the proposed technique recommends that sectionalizing switches S3, S6, S8, S12, S20, S23, S26, S28, S31, S32, S38, S40 should be open to successfully reconfigure the original network into the optimal radial network. When load flow calculation was done on the resulting radial network, we obtained a total active and reactive power losses of 25.0578 MW and 74.4049 MVar, respectively, and a voltage stability index value of 0.5516. Unlike a small network where all its radial networks can be manually mapped,

for large networks it is complex and lengthy to obtain all possible radial networks via manual operation. Thus, to validate the optimality of the radial network obtained via the proposed algorithm at base loading condition, its performance is compared with that of the performance of ten manually configured radial reconfigured networks (also at base loading condition). The ten manually reconfigured radial networks as the name implies are radial networks obtained by manually operating the switches without relying on graph theory techniques, and are just a small number of the many potential radial networks that can be obtained

Table 2 Performance of the radial networks obtained via application of Kruskal algorithm for a 3-node test system with and without DG integration for varying loading

Algorithm used	Loading (p.u.)	DG status*	Recommended switches be opened in order to obtain a radial configuration	Ploss (MW)	Qloss (Mvar)	L-index	Time(s)
Kruskal's	1	0	S3	19.4744	40.9814	0.2829	1.253
		1	S3	6.595451	39.6493	0.1974	1.241
	0.9	0	S3	15.41466	32.46648	0.2521	1.120
		1	S3	5.029018	35.77598	0.1911	1.308
	0.8	0	S3	11.9147	25.11583	0.2219	1.2332
		1	S3	3.808867	32.75537	0.1903	1.2662
	0.7	0	S3	8.932613	18.84478	0.1924	1.257
		1	S3	2.921155	30.551	0.1972	1.286
	0.6	0	S3	6.432	13.57994	0.1634	1.3096
		1	S3	2.353216	29.12948	0.2153	1.2503
	0.59	0	S3	6.20724	13.10625	0.1605	1.213
		1	S3	2.313553	29.02918	0.2179	1.224

*Where, 0 = network without DG, and 1 = network with DG

from the original mesh network. The performance of the ten manually reconfigured radial networks (viz. configuration number 1 to 10) with regard to active power loss, reactive power loss and voltage stability are compared to those of the optimal radial network obtained via the application of Kruskal's algorithm at base loading scenario is shown in Table 3. It can be clearly seen from the results furnished in Table 3 that the radial network configured through the application of Kruskal's maximal spanning tree algorithm gives better performance. Figure 7 shows the optimal radial network for base loading scenario obtained via the application of the proposed technique.

Similar to the computation and comparison carried out for the base loading scenario for the 30-node test system, identical procedures were applied to obtain, test for and verify the optimality of the radial networks computed by the proposed technique for all the different loading

scenarios considered. Further, in order to reduce confusion, the computations were done considering descending order of loading scenario. Tables 4, 5, 6, 7 and 8 represent the simulation results showing the different manual switching configurations (resulting in radial networks) and the switching configuration obtained via the proposed technique and comparing its corresponding resulting values of L-index, P-loss, and Q-loss for the loading conditions at 90%, 80%, 70%, 60% and 59% of base load conditions, respectively. For each of the different loading scenarios considered, it is clearly visible from the results that the optimal network computed via Kruskal's algorithm results in the least amount of losses and most optimal voltage stability index value. For 90% base-load scenario the Kruskal's algorithm computed radial network as shown in Fig. 7, and Fig. 8 depicts the optimal radial networks obtained via application of Kruskal's maximal spanning tree algorithm

Table 3 Calculated values of L-index, P-loss, and Q-loss at base loading scenario

Configuration No.	Switch configurations	P-loss (MW)	Q-loss (MVar)	L-index (p.u.)	Time taken (seconds)
1	S1,S6,S9,S14,S19,S20,S25,S28,S31,S32,S38,S40	70.5523	247.1022	0.9898	Not applicable
2	S4,S5,S6,S10,S14,S19,S20,S25,S28,S31,S32,S38	118.1715	352.0388	0.9849	-do-
3	S1,S6,S8,S14,S19,S20,S25,S28,S31,S32,S38,S40	61.7466	216.2223	0.9665	-do-
4	S4,S6,S7,S10,S14,S19,S20,S25,S28,S35,S32,S38	51.2592	171.6666	0.9004	-do-
5	S4,S6,S7,S10,S14,S19,S20,S25,S28,S31,S32,S38	49.6069	149.9626	0.8576	-do-
6	S4,S6,S9,S10,S14,S19,S20,S25,S28,S31,S32,S38	34.4377	88.6472	0.6468	-do-
7	S4,S6,S9,S14,S19,S20,S25,S28,S31,S32,S38,S40	33.1613	86.8368	0.6353	-do-
8	S3,S6,S8,S14,S19,S20,S23,S28,S31,S32,S38,S40	25.7642	86.7269	0.6056	-do-
9	S3,S6,S8,S14,S19,S20,S25,S28,S31,S32,S38,S40	25.6961	79.5294	0.5759	-do-
10	S3,S6,S8,S14,S20,S23,S26,S28,S31,S32,S38,S40	25.1826	77.6612	0.5656	-do-
Kruskal's	S3,S6,S8,S12,S20,S23,S26,S28,S31,S32,S38,S40	25.0578	74.4049	0.5516	3.414651

Fig. 7 Optimal radial network obtained by applying Kruskal's algorithm for base loading condition and 90% base-load condition

Table 4 Calculated values of L-index, P-loss, and Q-loss at 90% of base load

Configuration No.	Switch configurations	P-loss (MW)	Q-loss (MVar)	L-index (p.u.)	Time taken (seconds)
1	S1,S6,S9,S14,S19,S20,S25,S28,S31,S32,S38,S40	48.8007	162.6696	0.9519	Not applicable
2	S4,S5,S6,S10,S14,S19,S20,S25,S28,S31,S32,S38	77.1868	216.0878	0.9896	-do-
3	S1,S6,S8,S14,S19,S20,S25,S28,S31,S32,S38,S40	42.9753	142.4505	0.8725	-do-
4	S4,S6,S7,S10,S14,S19,S20,S25,S28,S35,S32,S38	38.0375	112.4931	0.7836	-do-
5	S4,S6,S7,S10,S14,S19,S20,S25,S28,S31,S32,S38	37.7379	104.5323	0.7579	-do-
6	S4,S6,S9,S10,S14,S19,S20,S25,S28,S31,S32,S38	26.3644	58.6465	0.5356	-do-
7	S4,S6,S9,S14,S19,S20,S25,S28,S31,S32,S38,S40	25.4732	58.9518	0.5316	-do-
8	S3,S6,S8,S14,S19,S20,S23,S28,S31,S32,S38,S40	19.6799	58.1736	0.4937	-do-
9	S3,S6,S8,S14,S19,S20,S25,S28,S31,S32,S38,S40	19.7355	53.9213	0.4728	-do-
10	S3,S6,S8,S14,S20,S23,S26,S28,S31,S32,S38,S40	19.3623	52.7668	0.4644	-do-
Kruskal's	S3,S6,S8,S12,S20,S23,S26,S28,S31,S32,S37,S40	19.3111	50.4591	0.4531	3.699503

at different loading scenarios of 80%, 70%, 60%, and 59% of the base load, respectively. Additionally, from Tables 3, 4, 5, 6, 7 and 8 it may also be noticed that, as the loading level is reduced from 100 to 59% of base load there is a corresponding reduction in the L-index value. Thus, for the different loading scenarios considered here, the L-index value of 0.1501 p.u. at 59% of base load is the least value.

In order to further validate the optimality of the reconfigured radial network obtained via the proposed technique for a given DG-integrated mesh network for different time-varying loading conditions, the proposed approach is compared with a similar graph theoretic approach known as Edmond's algorithm from [11]. Since in [11], the work is primarily focused on obtaining

Table 5 Calculated values of L-index, P-loss, and Q-loss at 80% of base load

Configuration No.	Switch configurations	P-loss (MW)	Q-loss (MVar)	L-index (p.u.)	Time taken (seconds)
1	S1,S6,S9,S14,S19,S20,S25,S28,S31,S32,S38,S40	33.5666	103.4047	0.7940	Not applicable
2	S4,S5,S6,S10,S14,S19,S20,S25,S28,S31,S32,S38	53.0881	137.0095	0.9170	-do-
3	S1,S6,S8,S14,S19,S20,S25,S28,S31,S32,S38,S40	29.6122	89.7923	0.7321	-do-
4	S4,S6,S7,S10,S14,S19,S20,S25,S28,S35,S32,S38	28.0667	71.5817	0.6509	-do-
5	S4,S6,S7,S10,S14,S19,S20,S25,S28,S31,S32,S38	28.0354	67.49774	0.6323	-do-
6	S4,S6,S9,S10,S14,S19,S20,S25,S28,S31,S32,S38	19.6768	33.9852	0.4159	-do-
7	S4,S6,S9,S14,S19,S20,S25,S28,S31,S32,S38,S40	19.0307	35.6440	0.4187	-do-
8	S3,S6,S8,S14,S19,S20,S23,S28,S31,S32,S38,S40	14.7383	35.4605	0.3805	-do-
9	S3,S6,S8,S14,S19,S20,S25,S28,S31,S32,S38,S40	14.8343	32.9197	0.3667	-do-
10	S3,S6,S8,S14,S20,S23,S26,S28,S31,S32,S38,S40	14.6158	32.4997	0.3617	-do-
Kruskal's	S3,S6,S8,S12,S20,S24,S26,S28,S31,S32,S37,S40	14.6471	31.1463	0.3552	3.714237

Table 6 Calculated values of L-index, P-loss, and Q-loss at 70% of base load

Configuration No.	Switch configurations	P-loss (MW)	Q-loss (MVar)	L-index (p.u.)	Time taken (seconds)
1	S1,S6,S9,S14,S19,S20,S25,S28,S31,S32,S38,S40	22.4141	59.9081	0.6220	Not applicable
2	S4,S5,S6,S10,S14,S19,S20,S25,S28,S31,S32,S38	36.3355	82.3800	0.7866	-do-
3	S1,S6,S8,S14,S19,S20,S25,S28,S31,S32,S38,S40	19.7677	50.8835	0.5557	-do-
4	S4,S6,S7,S10,S14,S19,S20,S25,S28,S35,S32,S38	20.1505	39.9141	0.4983	-do-
5	S4,S6,S7,S10,S14,S19,S20,S25,S28,S31,S32,S38	20.1878	37.5699	0.4853	-do-
6	S4,S6,S9,S10,S14,S19,S20,S25,S28,S31,S32,S38	14.2110	13.9257	0.2945	-do-
7	S4,S6,S9,S14,S19,S20,S25,S28,S31,S32,S38,S40	13.7222	16.4632	0.3017	-do-
8	S3,S6,S8,S14,S19,S20,S23,S28,S31,S32,S38,S40	10.7467	17.3263	0.2692	-do-
9	S3,S6,S8,S14,S19,S20,S25,S28,S31,S32,S38,S40	10.8475	15.8539	0.2615	-do-
10	S3,S6,S8,S14,S20,S23,S26,S28,S31,S32,S38,S40	10.6613	15.5266	0.2570	-do-
Kruskal's	S3,S6,S8,S12,S20,S24,S26,S28,S31,S32,S37,S40	10.7011	14.5975	0.2526	3.429168

Table 7 Calculated values of L-index, P-loss, and Q-loss at 60% of base load

Configuration No.	Switch configurations	P-loss (MW)	Q-loss (MVar)	L-index (p.u.)	Time taken (seconds)
1	S1,S6,S9,S14,S19,S20,S25,S28,S31,S32,S38,S40	14.2212	27.8497	0.4202	Not applicable
2	S4,S5,S6,S10,S14,S19,S20,S25,S28,S31,S32,S38	24.1677	42.87753	0.6082	-do-
3	S1,S6,S8,S14,S19,S20,S25,S28,S31,S32,S38,S40	12.5227	22.1387	0.3615	-do-
4	S4,S6,S7,S10,S14,S19,S20,S25,S28,S35,S32,S38	13.9224	15.3297	0.3384	-do-
5	S4,S6,S7,S10,S14,S19,S20,S25,S28,S31,S32,S38	13.9643	13.8164	0.3304	-do-
6	S4,S6,S9,S10,S14,S19,S20,S25,S28,S31,S32,S38	9.8445	-2.0562	0.1853	-do-
7	S4,S6,S9,S14,S19,S20,S25,S28,S31,S32,S38,S40	9.4569	1.0533	0.1917	-do-
8	S3,S6,S8,S14,S19,S20,S23,S28,S31,S32,S38,S40	7.5801	3.0298	0.1678	-do-
9	S3,S6,S8,S14,S19,S20,S25,S28,S31,S32,S38,S40	7.6700	2.2432	0.1655	-do-
10	S3,S6,S8,S14,S20,S23,S26,S28,S31,S32,S38,S40	7.5457	2.1409	0.1628	-do-
Kruskal's	S3,S6,S8,S12,S20,S24,S26,S28,S31,S32,S37,S40	7.5355	1.2317	0.1574	3.458026

the optimal radial network for an electrical system for constant load and without DG integration, we are unable to properly compare the performance of the algorithms against each other. Thus, in order to properly compare the performance of the algorithms under

similar conditions, we have also studied Edmond's algorithm as well and applied it to find the optimal radial network configurations of the test system for different time-varying loading conditions. The performance analysis based on the comparison of the active and reactive

Table 8 Calculated values of L-index, P-loss, and Q-loss at 59% of base load

Configuration No.	Switch configurations	P-loss (MW)	Q-loss (MVar)	L-index (p.u.)	Time taken (seconds)
1	S1,S6,S9,S14,S19,S20,S25,S28,S31,S32,S38,S40	13.5379	25.1698	0.3995	Not applicable
2	S4,S5,S6,S10,S14,S19,S20,S25,S28,S31,S32,S38	23.1476	39.5725	0.5884	-do-
3	S1,S6,S8,S14,S19,S20,S25,S28,S31,S32,S38,S40	11.9188	19.7356	0.3423	-do-
4	S4,S6,S7,S10,S14,S19,S20,S25,S28,S35,S32,S38	13.3833	13.2125	0.3230	-do-
5	S4,S6,S7,S10,S14,S19,S20,S25,S28,S31,S32,S38	13.4240	11.7519	0.3155	-do-
6	S4,S6,S9,S10,S14,S19,S20,S25,S28,S31,S32,S38	9.4645	-3.4463	0.1760	-do-
7	S4,S6,S9,S14,S19,S20,S25,S28,S31,S32,S38,S40	9.0848	-0.2919	0.1818	-do-
8	S3,S6,S8,S14,S19,S20,S23,S28,S31,S32,S38,S40	7.3051	1.7908	0.1588	-do-
9	S3,S6,S8,S14,S19,S20,S25,S28,S31,S32,S38,S40	7.3936	1.0576	0.1569	-do-
10	S3,S6,S8,S14,S20,S23,S26,S28,S31,S32,S38,S40	7.2745	0.9728	0.1544	-do-
Kruskal's	S3,S6,S8,S12,S20,S24,S26,S28,S31,S32,S37,S40	7.2943	0.18182	0.1501	3.218805

Fig. 8 Optimal radial network obtained by applying Kruskal's algorithm for the cases with 80%, 70%, 60% and 59% of base-load condition

power loss and the voltage stability index of the respective optimal radial networks obtained via application of Kruskal's algorithm and Edmond's algorithm for different time-varying loading scenarios for the test system

are summarily tabulated and presented in Table 9. The impact DG integration has on the network such as minimization of the active and reactive power losses and the corresponding improvement in the voltage stability

index (L-index) can also be observed from Table 9. Furthermore, it can be observed from Table 9 that in the case of finding an optimal radial network for an electrical network without DG integration, similar to [11] the performance of Edmond's algorithm outshines the performance of Kruskal's algorithm for base-load and 90% loading conditions, but when the load is less or equal 80% of the nominal load, the Kruskal's algorithm is superior to the Edmond's algorithm. As for when DG integrated networks are considered, the performance of Kruskal's algorithm is much better than that of Edmond's algorithm in finding the optimal radial network for all the different varying loading scenarios considered. The results obtained clearly indicate that for a DG integrated network, the optimal radial networks computed via the application of Kruskal's maximal spanning tree algorithm have lower losses and better L-index values for all the different time-varying loading scenarios considered.

The application of Kruskal's algorithm to obtain optimal radial networks from DG integrated meshed networks under time-varying load was further experimented on a robust test systems considering a modified IEEE-14 node

test system. The results of the computations are furnished below in detail in tabular form in Table 10.

4 Conclusion

The process of finding the optimal spanning tree of a mesh-connected network through manual procedure involves a lot of labour and time and becomes increasing difficult for networks containing large amounts of nodes and edges. In an electrical network with distributed generation the process becomes more complicated due to the introduction of the phenomenon of bi-directional flow of power. However, unlike manual operation, the use of graph theory techniques makes it easier to compute tasks such as finding the optimal spanning tree quickly and accurately, and by making slight adjustments, the complexity in DG integrated networks is also greatly reduced. In this paper, the performance of Kruskal's maximal spanning tree algorithm in obtaining optimal radial networks from DG integrated mesh networks was investigated. The proposed technique has been demonstrated in detail on a

Table 9 Comparison of the results of the network with and without DG using Kruskal's and Edmond's Algorithms

DG status*	Algorithm used	Loading (p.u.)	Network configuration obtained after running the algorithm (switches open)	Ploss (MW)	Qloss (Mvar)	L-index	Time(s)
0	Kruskal's	1	S3,S6,S8,S12,S20,S23,S26,S29,S31,S32,S39,S40	29.0571	91.4282	0.6358	3.9426
1			S3,S6,S8,S12,S20,S23,S26,S28,S31,S32,S38,S40	25.0578	74.4049	0.5516	3.4146
0	Edmond's		S3,S6,S8,S12,S20,S24,S26,S29,S32,S35,S39,S40	28.9324	91.0193	0.6337	2.0084
1			S3,S6,S8,S12,S20,S24,S26,S28,S32,S35,S38,S40	25.4246	77.2677	0.5650	1.7273
0	Kruskal's	0.9	S3,S6,S8,S12,S20,S23,S26,S29,S31,S32,S39,S40	23.1419	67.0876	0.5543	3.5221
1			S3,S6,S8,S12,S20,S23,S26,S28,S31,S32,S37,S40	19.3111	50.4591	0.4531	3.6995
0	Edmond's		S3,S6,S8,S12,S20,S24,S26,S29,S31,S35,S39,S40	14.6951	32.0598	0.3607	1.9451
1			S3,S6,S8,S12,S20,S24,S26,S28,S32,S35,S38,S40	19.5942	52.7367	0.4659	1.7554
0	Kruskal's	0.8	S3,S6,S8,S12,S20,S24,S26,S28,S31,S32,S37,S40	17.3907	42.4304	0.4403	4.1016
1			S3,S6,S8,S12,S20,S24,S26,S28,S31,S32,S37,S40	14.6471	31.1463	0.3552	3.7142
0	Edmond's		S3,S6,S8,S12,S20,S24,S26,S28,S32,S36,S38,S40	22.5262	64.1162	0.5375	1.7988
1			S3,S6,S8,S12,S20,S24,S26,S28,S32,S36,S38,S40	22.5262	64.1162	0.5375	1.7988
0	Kruskal's	0.7	S3,S6,S8,S12,S20,S24,S26,S28,S31,S32,S39,S40	12.7263	23.1052	0.3274	3.8004
1			S3,S6,S8,S12,S20,S24,S26,S28,S31,S32,S37,S40	10.7011	14.5975	0.2526	3.4291
0	Edmond's		S3,S6,S8,S12,S20,S23,S26,S29,S31,S32,S39,S40	12.9484	24.2187	0.3366	2.3917
1			S3,S6,S8,S12,S20,S24,S26,S28,S32,S36,S39,S40	10.7426	15.1022	0.2561	2.6270
0	Kruskal's	0.6	S3,S6,S8,S12,S20,S24,S26,S28,S31,S32,S39,S40	9.0934	7.7613	0.2208	3.8352
1			S3,S6,S8,S12,S20,S24,S26,S28,S31,S32,S37,S40	7.5355	1.2317	0.1574	3.4580
0	Edmond's		S3,S6,S8,S12,S20,S23,S26,S29,S31,S32,S39,S40	9.2295	8.4923	0.2273	2.2605
1			S3,S6,S8,S12,S20,S24,S26,S28,S32,S36,S39,S40	7.5824	1.414	0.1592	2.2698
0	Kruskal's	0.59	S3,S6,S8,S12,S20,S24,S26,S28,S31,S32,S39,S40	8.773	6.4046	0.2107	2.6388
1			S3,S6,S8,S12,S20,S24,S26,S28,S31,S32,S37,S40	7.2943	0.18182	0.1501	3.2188
0	Edmond's		S3,S6,S8,S12,S20,S23,S26,S29,S31,S32,S39,S40	8.9018	7.1029	0.2169	2.3346
1			S3,S6,S8,S12,S20,S24,S26,S28,S32,S36,S39,S40	9.6822	0.72294	0.1965	4.0848

*Where, 0 = network without DG, and 1 = network with DG

Table 10 Comparison of the radial networks obtained via manual switching and via application of Kruskal algorithm for a 14-node test system with and without DG integration

Algorithm used	Loading (p.u.)	DG status*	Network configuration obtained after running the algorithm (switches open)	Ploss (MW)	Qloss (Mvar)	L-index	Time(s)
Kruskal's	1	0	S5,S6,S7,S9,S18,S19,S20	18.93	59.928	0.4801	1.667
		1	S5,S6,S7,S9,S17,S18,S19	15.587	43.543	0.3767	1.5895
	0.9	0	S5,S6,S7,S9,S18,S19,S20	14.806	42.870	0.4033	1.6001
		1	S5,S6,S7,S9,S17,S18,S19	12.147	29.407	0.3063	1.654
	0.8	0	S5,S6,S7,S9,S18,S19,S20	11.171	27.558	0.3190	1.573
		1	S5,S6,S7,S9,S17,S18,S19	9.29	17.99	0.2407	1.5842
	0.7	0	S5,S6,S7,S9,S18,S19,S20	8.187	15.343	0.2390	1.546
		1	S5,S6,S7,S9,S17,S18,S19	6.913	8.571	0.1774	1.549
	0.6	0	S5,S6,S7,S9,S18,S19,S20	5.734	5.367	0.1604	1.544
		1	S5,S6,S7,S9,S17,S18,S19	4.889	0.480	0.1130	1.556

modified 30 node meshed distribution system integrated with DG, and multiple computations carried out for different time-varying load levels. The optimality of the radial networks obtained through the application of Kruskal's maximal spanning tree algorithm for different loading levels was verified by comparing the power loss and L-index values with those obtained from (randomly selected) manually configured radial networks. The performance of the proposed technique was further compared with another similar graph theory technique known as Edmond's algorithm, and it was found that the proposed technique performed better for DG integrated networks. The results of the study suggest that the proper application of Kruskal's maximal spanning tree algorithm in distributed generation integrated electrical networks can help power system researchers and operators quickly identify and obtain the most optimal radial network that can be reconfigured from the meshed network.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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Appendix

See Fig 9 is modeled as per Table 14 and Tables 11, 12, 13, 14, 15 and 16.

Fig. 9 Percentage loading versus time plot corresponding to Table 14**Table 11** The 3-node test system line data [37]

Start node	End node	R (p.u.)	X (p.u.)	Sectionalizing switch
1	2	0.02	0.04	S1
1	3	0.01	0.03	S2
2	3	0.0125	0.025	S3

Table 12 IEEE 30 bus feeder data [37]

Start node	End node	R (p.u.)	X (p.u.)	Sectionalizing Switch	Start node	End node	R (p.u.)	X (p.u.)	Sectionalizing Switch	Start node	End node	R (p.u.)	X (p.u.)	Sectionalizing Switch
1	2	0.0192	0.0575	S1	4	12	0	0.2560	S15	21	22	0.0116	0.0236	S29
1	3	0.0452	0.1852	S2	12	13	0	0.1400	S16	15	23	0.1000	0.2020	S30
2	4	0.0570	0.1737	S3	12	14	0.1231	0.2559	S17	22	24	0.1150	0.1790	S31
3	4	0.0132	0.0379	S4	12	15	0.0662	0.1304	S18	23	24	0.1320	0.2700	S32
2	5	0.0472	0.1983	S5	12	16	0.0945	0.1987	S19	24	25	0.1885	0.3292	S33
2	6	0.0581	0.1763	S6	14	15	0.2210	0.1997	S20	25	26	0.2544	0.3800	S34
4	6	0.0119	0.0414	S7	16	17	0.0824	0.1923	S21	25	27	0.1093	0.2087	S35
5	7	0.0460	0.1160	S8	15	18	0.1073	0.2185	S22	28	27	0	0.3960	S36
6	7	0.0267	0.0820	S9	18	19	0.0639	0.1292	S23	27	29	0.2198	0.4153	S37
6	8	0.0120	0.0420	S10	19	20	0.0340	0.0680	S24	27	30	0.3202	0.6027	S38
6	9	0	0.2080	S11	10	20	0.0936	0.2090	S25	29	30	0.2399	0.4533	S39
6	10	0	0.5560	S12	10	17	0.0324	0.0845	S26	8	28	0.0636	0.2000	S40
9	11	0	0.2080	S13	10	21	0.0348	0.0749	S27	6	28	0.0169	0.0599	S41
9	10	0	0.1100	S14	10	22	0.0727	0.1499	S28					

Table 13 IEEE 30 bus busdata [37]

Bus no	Bus types*	Voltage		Load		Generator				
		Magnitude	Angle	MW	MVAR	MW	MVAR	Qmin	Qmax	Static MVAR
1	Slack bus	1.06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	PV	1.043	0.0	21.7	12.7	40.0	0.0	−40.0	50.0	0.0
3	PQ	1.000	0.0	2.4	1.2	0.0	0.0	0.0	0.0	0.0
4	PQ	1.060	0.0	7.6	1.6	0.0	0.0	0.0	0.0	0.0
5	PV	1.010	0.0	94.2	19.0	0.0	0.0	−40	40.0	0.0
6	PQ	1.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	PQ	1.000	0.0	22.8	10.9	0.0	0.0	0.0	0.0	0.0
8	PV	1.010	0.0	30.0	30.0	0.0	0.0	−10	40.0	0.0
9	PQ	1.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	PQ	1.000	0.0	5.8	2.0	0.0	0.0	0.0	0.0	0.0
11	PV	1.082	0.0	0.0	0.0	0.0	0.0	−6	24.0	19
12	PQ	1.000	0.0	11.2	7.5	0.0	0.0	0.0	0.0	0.0
13	PV	1.071	0.0	0.0	0.0	0.0	0.0	−6	24.0	0.0
14	PQ	1.000	0.0	6.2	1.6	0.0	0.0	0.0	0.0	0.0
15	PQ	1.000	0.0	8.2	2.5	0.0	0.0	0.0	0.0	0.0
16	PQ	1.000	0.0	3.5	1.8	0.0	0.0	0.0	0.0	0.0
17	PQ	1.000	0.0	9.0	5.8	0.0	0.0	0.0	0.0	0.0
18	PQ	1.000	0.0	3.2	0.9	0.0	0.0	0.0	0.0	0.0
19	PQ	1.000	0.0	9.5	3.4	0.0	0.0	0.0	0.0	0.0
20	PQ	1.000	0.0	2.2	0.7	0.0	0.0	0.0	0.0	0.0
21	PQ	1.000	0.0	17.5	11.2	0.0	0.0	0.0	0.0	0.0
22	PQ	1.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	PQ	1.000	0.0	3.2	1.6	0.0	0.0	0.0	0.0	0.0
24	PQ	1.000	0.0	8.7	6.7	0.0	0.0	0.0	0.0	0.0
25	PQ	1.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.3
26	PQ	1.000	0.0	3.5	2.3	0.0	0.0	0.0	0.0	0.0
27	PQ	1.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	PQ	1.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	PQ	1.000	0.0	2.4	0.9	0.0	0.0	0.0	0.0	0.0
30	PQ	1.000	0.0	10.6	1.9	0.0	0.0	0.0	0.0	0.0

*slack bus = ref bus, PV bus= gen bus, PQ bus= load bus

Table 14 Time-varying loading considered

Time (hours)	Load level (p.u.)	Time (hours)	Load level (p.u.)
0–2	0.59 (59% of base load)	12–14	0.9 (90% of base load)
3–4	0.6 (60% of base load)	15–17	0.8 (80% of base load)
5–6	0.7 (70% of base load)	18–20	0.7 (70% of base load)
7–8	0.9 (90% of base load)	21–22	0.6 (60% of base load)
9–11	1.0 (base load*)	23–24	0.59 (59% of base load)

*The total maximum load or full load of the system was considered as base-load

Table 15 Data of doubly-fed induction machine (DFIG) wind turbine [38]

Power rating S_n (MVA)	60.0	Magnetization reactance X_m (p.u.)	3.00	Number of poles p	4
Voltage rating V_n (kV)	0.48	Initial constant H_m (kWs/kVA)	3.00	Number of Blades n_b	3
Frequency rating f_n (Hz)	60.0	Pitch control gain K_p (p.u.)	10	Gear box ratio η_{GB}	1/89
Stator resistance R_s (p.u.)	0.01	Pitch control time constant T_p (s)	3	P_{max} (p.u.)	1.0
Stator reactance X_s (p.u.)	0.10	Voltage control gain K_v (p.u.)	5	P_{min} (p.u.)	−1.0
Rotor resistance R_r (p.u.)	0.01	Power control time constant T_e (s)	0.01	Q_{max} (p.u.)	1.2
Rotor reactance X_r (p.u.)	0.08	Rotor radius R (m)	75	Q_{min} (p.u.)	−0.7

Table 16 The 14-node test system line data [39]

Start node	End node	R (p.u.)	X (p.u.)	Sectionalizing switch
1	2	0.01938	0.05917	S1
1	5	0.05403	0.22304	S2
2	3	0.04699	0.19797	S3
2	4	0.05811	0.17632	S4
2	5	0.05695	0.17388	S5
3	4	0.06701	0.17103	S6
4	5	0.01335	0.04211	S7
4	7	0	0.20912	S8
4	9	0	0.55618	S9
5	6	0	0.25202	S10
6	11	0.09498	0.1989	S11
6	12	0.12291	0.25581	S12
6	13	0.06615	0.13027	S13
7	8	0	0.17615	S14
7	9	0	0.11001	S15
9	10	0.03181	0.0845	S16
9	14	0.12711	0.27038	S17
10	11	0.08205	0.19207	S18
12	13	0.22092	0.19988	S19
13	14	0.17093	0.34802	S20

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