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Exploration and mitigation of power quality problems in radial distribution system by placing distributed generation through voltage stability index

Introduction. *Distributed generation has played an important role in many aspects of sustainability, such as improving voltage profiles and reducing power losses, in the distribution network.* ***Problem.*** *Frequent variation of loads causes many complications while placing and sizing of distributed generation in the radial distribution network, via quality of supply, and stability of the system.* ***Goal*** *of the paper is to investigate and mitigate the power quality issues towards stabilizing the system during distributed generations placed in the system under various loading conditions.* ***Methodology.*** *The line voltage stability index analyses and enhances the performance of the radial distribution network by effective sizing and location of distributed generation towards the objective function.* ***Practical value.*** *A standard test system IEEE-69 bus radial distribution network is used to understand through MATLAB environment.* References 38, table 4, figures 11.

Key words: **voltage stability index, distribution system, voltage sag, power quality, distributed generation.**

Вступ. *Розподілена генерація відіграла важливу роль у багатьох аспектах стійкості, таких як покращення профілів напруги та зниження втрат електроенергії у розподільній мережі.* ***Проблема***. *Часті коливання навантаження викликають безліч складнощів при розміщенні та визначенні розміру розподіленої генерації в радіальній розподільній мережі через якість постачання та стабільність системи.* ***Мета*** *статті полягає в тому, щоб дослідити та пом'якшити проблеми з якістю електроенергії для стабілізації системи під час розподіленої генерації, розміщеної у системі за різних умов навантаження.* ***Методологія.*** *Індекс стабільності лінійної напруги аналізує та підвищує продуктивність радіальної розподільної мережі за рахунок ефективного визначення розміру та розташування розподіленої генерації щодо цільової функції.* ***Практична цінність***. *Для розуміння використовується стандартна тестова система радіальної розподільної мережі IEEE-69 за допомогою середовища MATLAB.* Бібл. 38, табл. 4, рис. 11.

Ключові слова: **індекс стабільності напруги, розподільна система, провали напруги, якість електроенергії, розподілена генерація.**

Introduction. Regardless of enhancement value in the active power and the developments of transmission and distribution system, ongoing development of touchy loads and utilizing them in modern and medical clinic places, the quality issue of power is significant. Power quality issues like voltage sag are because by some reasons like shortcomings, abrupt burden increment, and an enormous increase in the consumption of electrical appliances. Voltage droop in modern delicate burdens emerges because of short out in various pieces of the organization. Voltage dip under basic worth in these heaps causes malfunctioning of electrical hardware and efficient misfortunes, accordingly, an answer for this issue ought to be found.

Distributed generation (DG) additionally increments the age limit and to ease public worries about contamination, conveyed age plants have been presented in circulation organizations. By expanding the short-out limit, the establishment of DG assets can forestall voltage hang in touchy burdens. The extent of voltage list after issue exceptionally relies upon the way between the issue area and delicate loads just as short out limits such that the DG and reconfiguration of the network can be implemented. Changing the geography of the organization won't improve the circumstance; in addition, other organization imperatives might restrict the execution of every single arrangement. Besides, to acquire the benefit of the DG assets, a few boundaries, like the finest area, no. and limit of the DGs are required. Another issue is while fusing them for a huge scope for example glitches of assurance circuits, recurrence deviation, voltage profile rising, and dependability issues; in this manner, every one of referenced strategies is powerful however numerous limitations are being used every one of them independently [1-5].

DG assets designation is likewise a muddled improvement issue for which various techniques were utilized to tackle before. Viral and Khatod completed an exhaustive audit of various strategies, for example, scientific, meta-heuristic, man-made reasoning, and hereditary calculations crossover draws near. In scientists applied the affectability examination for DG assets distribution; besides, reconfiguration and DG assets portion cooperatively diminish misfortune at three diverse burdens [6-9]. DG assets assignment for further developing power quality lists is another point that is introduced by a couple of analysts of late. Hamedi and Gandomkar thought about the power quality due to DG assets. Though utilizing DG assets for further developing voltage lists is worthwhile, it isn't sufficient in substantial burdens or extreme deficiencies; in addition, as referenced previously, fusing DG assets for a huge scope would prompt genuine results. In this manner, it is strongly prescribed to apply different strategies, for example, reconfiguration alongside utilizing DG assets [10-24].

As previously stated, to improve voltage sag induced by failures, reconfiguration and DG resource placement have been explored separately. The fundamental idea of this work is to use both reconfiguration and DG resource placement at the same time to improve voltage sag while still achieving the main goal of reconfiguration (loss reduction) [25-30]. The ideal DG resource capacity and network design can be accomplished by inserting the DG resource in one of the distribution network buses and a trade-off between power quality indices and system power loss. The BPSO algorithm is used for optimization because of its simplicity and great efficiency in reconfiguration situations. The proposed method is highly effective at reducing voltage sag, as evidenced by the results [31-35].

Problem formulation. In the operation and control of Radial Distribution Network (RDN), minimization of real power loss is one of the major goals. This can be achieved mainly by improving the voltage profile across the network, and consequently, the loss can reduce by having reduced current flow through each branch/element. In addition, an improved voltage profile can result in enhanced voltage stability.

Objective function. The primary objective is to consider loss minimization in the feeder by having maximum PV penetration at appropriate locations. The real power loss of a branch in a distribution system is given by:

$$\min f(P_{loss}) = \sum_{mn} r_{(mn)} I_{(mn)}^2 , \quad (1)$$

where P_{loss} is the total real power loss in the feeder distribution; mn is the branch index; $P(n)$, $Q(n)$, $|V(n)|$ are the real, reactive power loads and voltage magnitude of the n^{th} bus.

The following bus voltage, branch current, DG active, and reactive power compensation constraints are considered in solving the proposed objective function:

$$|V_i|_{\min} \le |V_i| \le |V_i|_{\max} \quad i = 1,2,...,nb , \quad (2)$$

$$|I_i| \le |I_i|_{\max} \quad i = 1,2,...,nl , \quad (3)$$

$$Q_{cb}(T) \le Q_{load}(T) . \quad (4)$$

Enhancement of power quality. There are many quality issues that arise at the end user because of load variations. The major focus is to minimize the voltage sag and voltage swell. The system voltage profile must be increased to voltage sag limits 0.9 to 1.

Mathematical model. The huge R/X ratio in RDNs leads traditional load flow algorithms to fail to converge. A single-line diagram of a balanced RDN can be used to depict the network. So, at the distribution operating voltage, line shunt capacitances are highly malleable and may thus be ignored [5, 36]. The i-node apparent power is calculated for i^{th} node is given by

$$S_i = V_i (LI)_i^* = P_i + jQ_i . \quad (5)$$

Branch current calculations:

$$I_{brj} = \sum_{i=1}^{n} |LI_i| \cos\theta_i + j\sum_{i=1}^{n} |LI_i| \sin\theta_i = \mathrm{Re}(I_{brj}) + \mathrm{Im}(I_{brj}) . (6)$$

Receiving end voltage calculations are [37, 38]:

$$V_r = V_s - I_{br} Z_{br} ; \quad (7)$$

$$V_r \angle\theta_r = V_s \angle\theta_s - I_{br} \angle\theta_r Z_{br} \angle\theta_r . \quad (8)$$

Equations (6)-(8) are used to compute branch currents as well as the bus voltages. The active and reactive power at each bus is estimated from the above I_{br} and V_{br}.

Line voltage stability index. Voltage instability is the result of the power system's inability to handle the additional demand brought on by the growing load. However, studies of this kind don't typically produce stability or sensitivity data. So, dynamic simulations can only be used to study certain types of voltage collapse, like sudden or transient voltage collapse, and to make sure that protection and control are working together.

Voltage stability requirements were created based on a paradigm for power transmission on a single line. By reducing a linked system to a single-line network, the overall stability of the system is evaluated. Using the same idea, a stability requirement is constructed and applied to every network line. The line voltage stability index (LVSI) is given by (9)

$$LVSI = \frac{4XQ_r}{[V_s \sin(\theta - \delta)]^2} \le 1 . \quad (9)$$

In an interconnected network that connects two bus bars, the stability criteria known as LVSI are utilized to determine the stability index for each line. Line stability indices can be used to predict voltage collapse with accuracy. As long as the stability index is less than 1, the system is stable. However, if it exceeds 1, the system as a whole loses stability, leading to voltage collapse.

Distributed generation. Depending on the different powers available, the DG is classified into four types [3].

Type 1: This form of DG can only supply active electricity, such as photovoltaic (PV), microturbines, and fuel cells, and is connected to the main grid via converters/inverters.

Type 2: Only reactive power may be delivered via DG. Gas turbines and capacitor banks are examples of synchronous compensators, which perform at zero power factors.

Type 3: DG can supply real power while also using reactive power. This category mostly includes induction generators used in wind farms. However, like synchronous generators, doubly-fed induction generators devices can utilize or create reactive power.

Type 4: Both active and reactive electricity can be delivered via DG. This category includes synchronous machine-based DG units (cogeneration, gas turbine, and so on).

Static mathematical model of DG. The real and reactive power at the i^{th} bus is modeled as below [4]:

$$P_i = P_{DG_i} - P_{D_i} ; \quad (10)$$

$$Q_i = Q_{DG_i} - Q_{D_i} = \alpha_i \times P_{DG_i} - Q_{D_i} ; \quad (11)$$

$$\alpha_i = \tan(\cos^{-1} PF_{DG});$$

where P_{DG} is the real power at DG; Q_{DG} is the reactive power at DG; P_D is the real power demand; Q_D is the reactive power demand; PF_{DG} is the power factor.

The power factor is determined by the kind of DG and the DG unit's working state:

Type 1 – $PF_{DGi} = 1$;
Type 2 – PFDGi = 0;
Type 3 – $0 < PF_{DGi} < 1$ and sign = –1;
Type 4 – $0 < PF_{DGi} < 1$ and sign = +1.

DG in load flow analysis. DG as load bus. PQ buses made up of DGs can be treated as passive loads or negative loads. The quantity of DG produced reduces the total burden.

DG units as PV bus. The modeling of DGs managed like PV buses are more difficult than that of PQ buses. The compensating approach from [7] is used to modulate the voltage of PV nodes.

Impacts of DG installation. The system with DG is shown in Fig. 1, where Z_3 is the impedance between PCC and DG resources, while Z_4 is the DG resources' transient reactance. As the capacity of DG resources grows, branch-power flow decreases, voltage drops decrease, and V_p approaches 1 p.u. as a typical value. As a result, the voltage of the sensitive load increases by 1. Furthermore, the placement of DG resources has an impact on Z_3, and raising Z_3 sensitive load voltage might increase Z_3.

The magnitude of the sag is calculated as:

$$V_{sag} = 1 - \left[\frac{Z_4}{Z_3 + Z_4} \cdot (1 - V_{PCC}) \right] ; \quad (12)$$

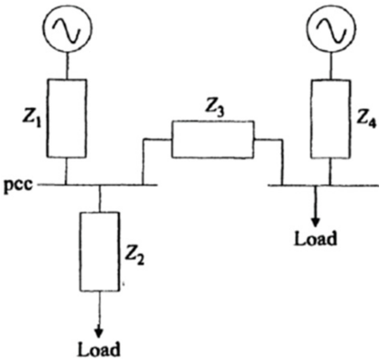

Fig. 1. A simple system representing the load

Computational aspects to reach the objective.

Step-I: Read the system data and set all node voltages and branch currents to 1.0 p. u. (per unit) at the beginning.

Step-II: Calculate the branch currents.

Step-III: Update the bus voltages with branch currents as in step II.

Step-IV: Calculate the power and power losses at each bus.

Step-V: Identify the candidate bus using LVSI analysis.

Step-VI: Estimate the voltage sag and swell by comparing the voltage values from the results.

Step-VII: Select and calculate the size of DG, and place it randomly at each bus to minimize the losses.

Step VIII: Again, repeat Step IV, if it is in constraints then go to the next step else go to Step II.

Step IX: Stop.

Proposed algorithm. The schematic representation of the proposed algorithm flow toward the theme as shown in Fig. 2.

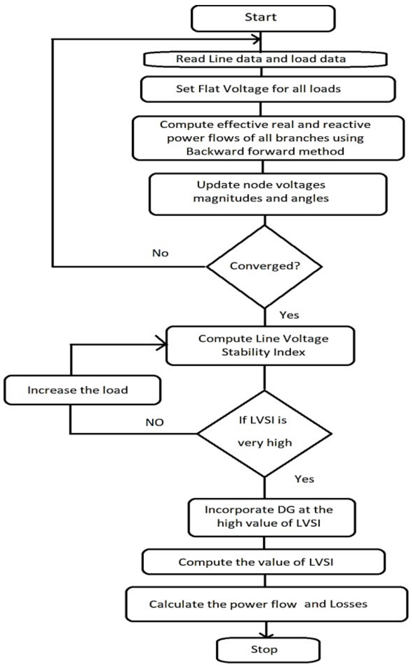

Fig. 2. Flowchart of the proposed algorithm

Test system and simulation results. To comprehend the suggested algorithm, a simulation of the IEEE-69 radial distribution system is taken into account. There are 48 load buses and 68 lines in this system. Table 1 lists the load buses that were taken into account when analyzing the IEEE-69 bus system. As bus number one is regarded as the generator bus in the radial distribution network, only 48 of the 69 buses are load buses, and the rest are not connected to any loads.

Table 1
Considered load buses for analysis in IEEE-69 bus system

S. No.	Bus No.	S. No.	Bus No.	S. No.	Bus No.	S. No.	Bus No.
1	6	13	20	25	37	37	53
2	7	14	21	26	39	38	54
3	8	15	22	27	40	39	55
4	9	16	24	28	41	40	59
5	10	17	26	29	43	41	61
6	11	18	27	30	45	42	62
7	12	19	28	31	46	43	64
8	13	20	29	32	48	44	65
9	14	21	33	33	49	45	66
10	16	22	34	34	50	46	67
11	17	23	35	35	51	47	68
12	18	24	36	36	52	48	69

Comparative analysis of distribution load flows for 69 bus system. In Table 2 describe and analyzed the 69-bus system during composite load models and figures out its behaviour with critical buses and voltage profile. In fact, in many cases, it is noticed that the system reaches sag conditions.

Table 2
Comparative analysis of 69-bus system

Type of load	P, kW	Q, kVAR	P losses, kW	Q losses, kVAR	V_{min}, p.u.	Bus numbers
DLF	3033.43	2275.07	123.94	56.386	0.93155	6, 7, 57, 58, 59, 60, 61, 66
Constant P Model	3825.02	2635.20	317.19	143.49	0.87549	6, 7, 57, 58, 59, 60, 61, 66
Constant I Model	3567.15	2469.34	245.93	112.97	0.89139	6, 7, 57, 58, 59, 61, 66
Constant Z Model	3337.11	2319.30	192.44	89.98	0.90492	6, 7, 57, 58, 66

The voltage sag condition without DG for the load variation is shown in Fig. 3 for conditions ranging from 50 % system loading to 150 % system loading. The voltage on each individual bus drops as the load rises. Without adding DG to the system, the lowest voltage for 50 %, 100 %, and 150 % system loading conditions is at bus numbers 63 and 27. For 50 %, 100 %, and 150 % system loads, bus numbers 28 and 36 have maximum voltages of 1, 0.99, 0.999, and 0.999, respectively.

The active power flow and the reactive power flow in the system without DG are shown in Fig. 4, 5 for the load variation from a 50 % system loading state to a 150 % system loading condition. Figures 6, 7 display the active power and reactive power loss in the system.

Table 3 shows the voltage profile for different loading scenarios without DG in the system. The voltage sag observed through the index value is presented in Table 3. The high value of the index at a particular bus is considered to have voltage sag at that bus. Compared to all the load buses available in the system, bus no. 6 is the most complex load bus with the maximum sag.

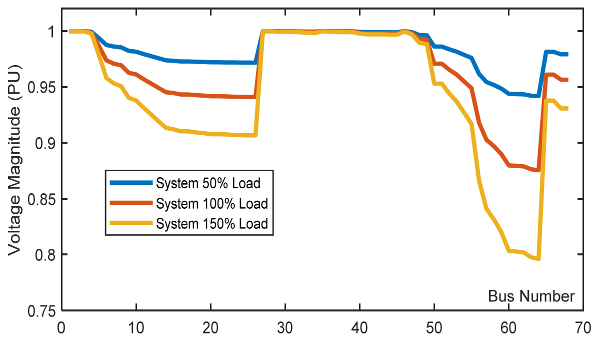

Fig. 3. Voltage sag condition without DG in IEEE-69 bus system

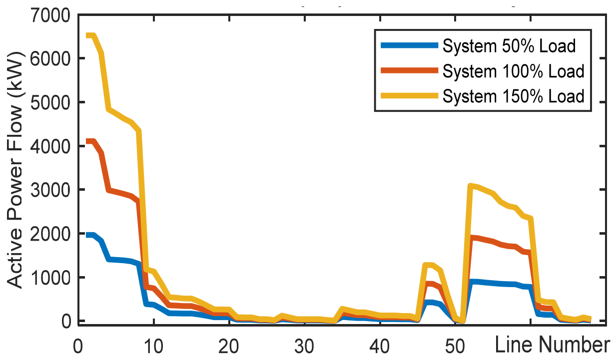

Fig. 4 Active power flow without DG in IEEE-69 bus system

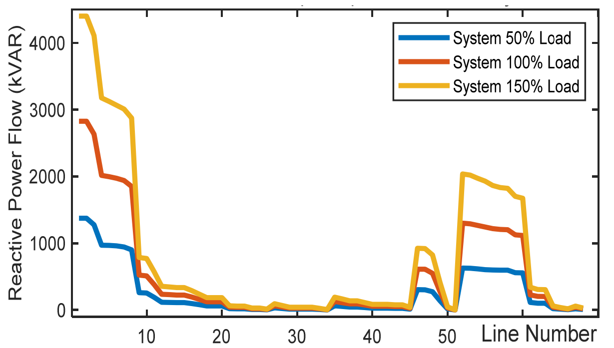

Fig. 5. Reactive power flow without DG in IEEE-69 bus system

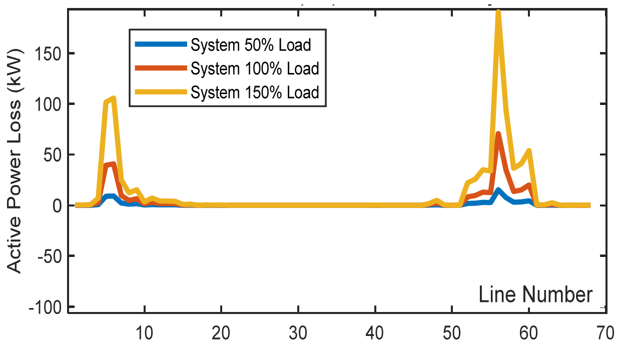

Fig. 6. Active power loss without DG in IEEE-69 bus system

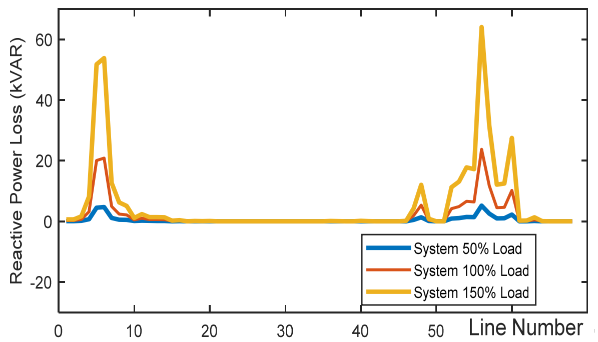

Fig. 7. Reactive power loss without DG in IEEE-69 bus system

Table 3
Identification of voltage sag through line voltage stability index

Bus. no.	Index value		
	50 % system loading	100 % system loading	150 % system loading
6	0.0289	0.0598	0.0936
7	0.0301	0.0623	0.0976
8	0.0072	0.015	0.0237
9	0.0037	0.0077	0.0122
10	0.024	0.049	0.0752
11	0.0054	0.011	0.017
12	0.0153	0.0313	0.0483
13	0.0138	0.0283	0.0437
14	0.0137	0.0281	0.0435
16	0.0025	0.0052	0.0081
17	0.0042	0.0086	0.0133
18	0	0.0001	0.0001
20	0.0015	0.0031	0.0048
21	0.0024	0.005	0.0078
22	0	0.0001	0.0001
24	0.0008	0.0016	0.0025
26	0.0004	0.0007	0.0011
27	0.0001	0.0002	0.0003
28	0	0	0
29	0.0001	0.0003	0.0004
33	0.0013	0.0026	0.0039
34	0.0017	0.0034	0.0051
35	0.0003	0.0007	0.001
36	0	0.0001	0.0001
37	0.0003	0.0007	0.001
39	0.0001	0.0002	0.0003
40	0	0	0
41	0.0014	0.0028	0.0042
43	0.0001	0.0002	0.0002
45	0.0002	0.0004	0.0006
46	0	0	0
48	0.0024	0.0049	0.0074
49	0.0075	0.0151	0.0226
50	0.0011	0.0021	0.0032
51	0.0001	0.0002	0.0004
52	0	0.0001	0.0002
53	0.0091	0.0191	0.0305
54	0.0106	0.0222	0.0355
55	0.0146	0.0306	0.0489
59	0.0211	0.0449	0.0731
61	0.0244	0.052	0.0847
62	0.001	0.0021	0.0034
64	0.0063	0.0135	0.0222
65	0.0019	0.0041	0.0067
66	0.0003	0.0006	0.001
67	0	0	0
68	0.0017	0.0034	0.0053
69	0	0	0

The DG is located at bus number 35, and it has the same power loss as other DGs of similar capacity when placed in other buses. Its size is 0.035 MW. As the load increases, the voltage at each bus drops. Since DG was incorporated into the system, the voltage sag at each individual load bus has improved. For three system loading scenarios, the maximum voltage is at bus nos. 28, and 36, respectively.

Figures 8, 9 depict the active power flow and reactive power flow in the system with DG for the load fluctuation from 50 % system loading condition to 150 % system loading condition. Figures 10, 11 show the system's reduced active and reactive power with DG in place.

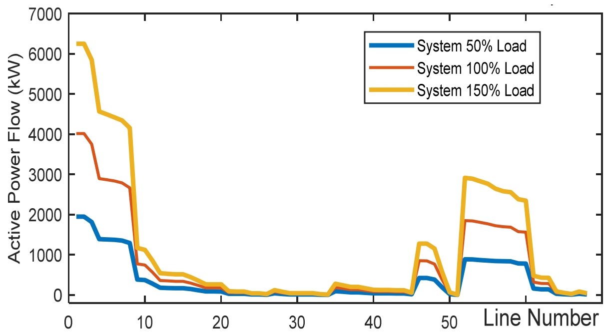

Fig. 8. Active power flow with DG in IEEE-69 bus system

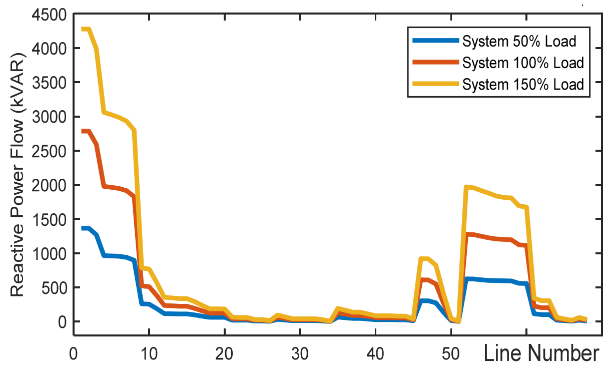

Fig. 9. Reactive power flow with DG in IEEE-69 bus system

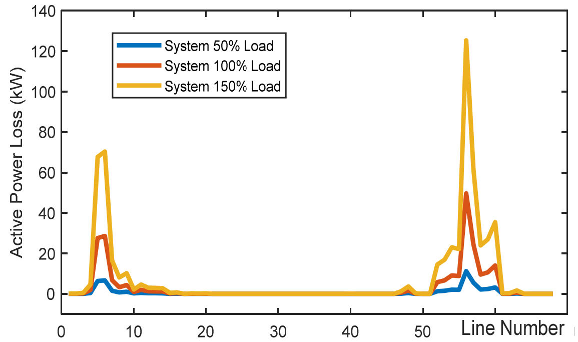

Fig. 10. Active power loss with DG in IEEE-69 bus system

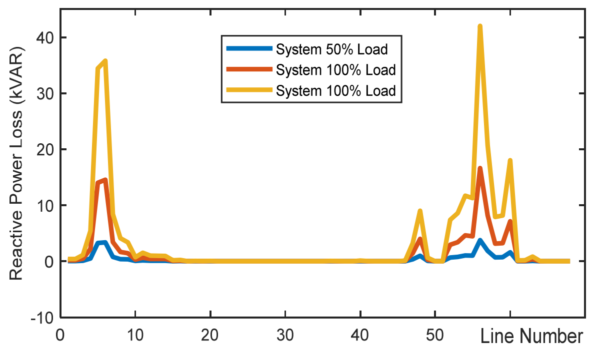

Fig. 11. Reactive power loss with DG in IEEE-69 bus system

Table 4 presents the improvement of voltage sag incorporating DG in the system. The minimum voltage is at bus no. 26 and 27 and is 0.9855, 0.9705, 0.9553 for 50 %, 100 %, and 150 % system loading condition respectively. The maximum voltage is at the bus no. 36 for 50 %, 100 %, and 150 % system loading condition respectively. The voltage sag with DG in the system has been enhanced compared without DG in the system. The change in the voltage in the system can also be observed.

Table 4
Improvement of voltage sag incorporating DG in the system

Bus. no.	Index value		
	50% system loading	100% system loading	150% system loading
6	0.0215	0.0439	0.0677
7	0.0224	0.0457	0.0705
8	0.0053	0.011	0.017
9	0.0027	0.0056	0.0087
10	0.0173	0.0352	0.0536
11	0.0039	0.0079	0.0121
12	0.0109	0.0221	0.0338
13	0.0103	0.021	0.0322
14	0.0102	0.0209	0.032
16	0.0019	0.0039	0.0059
17	0.0031	0.0064	0.0098
18	0	0.0001	0.0001
20	0.0011	0.0023	0.0036
21	0.0018	0.0037	0.0057
22	0	0.0001	0.0001
24	0.0006	0.0012	0.0019
26	0.0003	0.0005	0.0008
27	0.0001	0.0002	0.0002
28	0	0	0
29	0.0001	0.0002	0.0003
33	0.001	0.0019	0.0029
34	0.0013	0.0026	0.0039
35	0.0002	0.0005	0.0007
36	0	0	0.0001
37	0.0003	0.0005	0.0008
39	0.0001	0.0001	0.0002
40	0	0	0
41	0.0011	0.0021	0.0032
43	0.0001	0.0001	0.0002
45	0.0001	0.0003	0.0004
46	0	0	0
48	0.0018	0.0037	0.0056
49	0.0057	0.0114	0.0171
50	0.0008	0.0016	0.0024
51	0.0001	0.0002	0.0003
52	0	0.0001	0.0001
53	0.0068	0.014	0.0219
54	0.0079	0.0163	0.0255
55	0.0109	0.0225	0.0352
59	0.0157	0.0328	0.0518
61	0.0182	0.038	0.06
62	0.0007	0.0015	0.0024
64	0.0047	0.0098	0.0156
65	0.0014	0.003	0.0047
66	0.0002	0.0005	0.0007
67	0	0	0
68	0.0006	0.0013	0.002
69	0	0	0

Discussions.

1. The IEEE-69 bus system performance is analyzed during composite and different loading conditions.
2. The location and sizing of DG is estimated to mitigate the power quality issues.
3. LVSI indices provide the system stability with and without DG at each location.
4. Enhancement of RDS performance by appropriate DG placement with the LVSI method.

Conclusions.

The effectiveness of the IEEE-69 bus radial distribution system is examined under various loading scenarios. This leads to system instability, which lowers voltage and improves power losses, both of which have an effect on the supply's quality. The right size and placement of typical DG solutions to reduce quality problems and improve the voltage profile in the system. The stability analysis at each load bus provides unambiguous estimations of the precise position of the DG to prevent outages and quality problems. In this, the system is examined and its performance is improved based on LVSI indices, without the use of any meta-heuristic techniques.

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

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