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Voltage Stability Analysis of Radial Distribution System Considering Distribution Generation and Composite Load Modeling

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Abstract

This paper has investigated the impact of DG sources on radial distribution system considering composite load modeling by using Power Stability Index (PSI), Line Stability Index (LSI) and Voltage Stability Index (VSI). The optimization problem is formulated such that optimization of DG sources at multiple locations and tap-changer settings at substation simultaneously by considering various operational constraints. The optimization problem is formulated for multi-objectives such as minimization of active power losses and stability and has been solved by using traditional particle swarm optimization (PSO). In order to get global optima, the simulations have been repeated with Improved PSO (IPSO) and Time-Varying Acceleration Coefficient PSO (TVAC-PSO). The results have shown the superiority of TVAC-PSO for real-time power system optimization problems.

Keywords: Radial distribution system, load modeling, distribution generation, voltage stability, pso algorithms.

INTRODUCTION

The application of Distribution Generation (DG) (also called decentralized generation, dispersed generation, and embedded generation) for loss minimization as well as voltage regulation in RDS is presented based on various research articles. In general, DG can be defined as “The generation of electricity from facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system” [1]. In other words, these generating units are suitable to connect directly to the distribution network or on the customer site of the energy meter.

Recently, DG penetration defined as ‘the ratio of total demand of the network and total generation by DG units in the network’ and has been increasing significantly across the world. The potential benefits with the integration of DG units across the network are as follows: (i) reduced active power losses, (ii) improved voltage profile, (iii) increased overall energy efficiency, (iv) congestion relief across the network elements, (v) potential increase of service quality to the end-customers, (v) possibility to increase renewable energy sources such as solar, wind, hydro, biomass, ocean energy and geothermal etc. integration and correspondingly reduced environmental impacts with conventional energy sources. According to comprehensive literature survey presented in [2], integration of DG units is most suitable approach for loss reduction in RDS as compared to other techniques discussed earlier. As mentioned in [3], it is also observed that the non-technical reasons such as (i) increases awareness on global warming and need of sustainability development, (ii) national and international policies aiming to increase the share of renewable energy sources in order to reduce greenhouse gas emissions and alleviate global warming, (ii) competitive energy policies, (iii) diversification of energy sources, (iv) reduction of on-peak operating cost as well as transmission and distribution loss cost, (v) deferral of network upgradation and expansion etc., are causing to continue the growth of DG integration considerably across the world.

On the other side, it is also observed that the improper location and sizing of DG can adversely affect the network performance. In general, the power flow direction is ‘from generating plants to distribution centers’ whereas with DG units, the reverse power flow direction ‘from distribution centers to generating plants’ needs to moderate all the existing protection system settings/set-ups. In addition, due to counter flows across the network with DG units, the raise in feeder voltage should be regulated properly to meet the distribution voltage level requirements. Hence the DG integration should not require for much change in the existing infrastructure of the network and that’s where the type of DG technology becomes most interesting factor in recent years.

In addition, the type of DG units such as renewable and non-renewable can also differ with their either positive and/or negative impacts on the network [2]. Apart from various technical and non-technical reasons, reliability and allocation flexibility are some of the major concerns with renewable type DG units with their intermittent nature. The geographical and meteorological conditions are the major root cause uncertainty in power generation with renewable type DG and cannot be consider these units as dispatchable generation sources. Hence the ‘non-dispatchable’ nature of renewable type DG units is become another concern in power system planning and operational studies.

Thus the problem of DG planning in terms of location, type, number and technical as well as non-technical objectives has become one of the high attractive research areas in power system. In recent years, a considerable effort has been done by various researchers in this area. Some of them are reviewed comprehensively and presented here to formulate the proposed research methodology for the multi-objective non-linear complex problem of DG planning.

RELEVANT CONCEPTS

The objective of this paper is to consider different types of load modeling in different types of DG planning studies. In addition, the impact of DG on voltage stability is explored by considering different types of voltage stability assessment methods. Hence, this section is focused on literature specially related to voltage dependent load modeling, different types of DG modeling and some of mostly used voltage stability analysis methods.

Load Modeling

Generally, the active and reactive power demands are assumed as constant irrespective of its associated bus voltage magnitude in conventional load flow studies [4]. But the operational characteristics of different types of loads are differ and are highly dependent on voltage and frequency variations in the network. On the other side, the nature of load characteristics and corresponding effective loading can cause for different load flow solution and convergence ability [5]. In view of voltage variation w.r.t. time, the voltage dependent load modeling can be consider as follows [6, 7].

$$P_{Di(t)} = P_{Di(0)} \times V_{i(t)}^{\alpha} \text{ and } Q_{Di(t)} = Q_{Di(0)} \times V_{i(t)}^{\beta} \tag{1}$$

where $P_{Di(0)}$ and $Q_{Di(0)}$ are the nominal active and reactive power loads at bus-i respectively; $V_{i(t)}$, $P_{Di(t)}$ and $Q_{Di(0)}$ are the voltage, effective active and reactive loading at bus-i at time (t) respectively; α, β are the active and reactive load voltage exponents and are taken for different types of loads from [6, 7].

Distribution Generation

Based on active power controlling capability, these sources can be classified as dispatchable or non–dispatchable. Small hydro power plants and biomass–based gas turbines are the examples of dispatchable where the active power is controllable by adjusting their input fuel consumption where as solar and wind generation sources which are non–controllable are the examples for non–dispatchable since their output is dependent on meteorological conditions.

- Type–1**:** Photovoltaic, micro turbines and fuel cells which are incorporated to main grid with the help of converters/inverters are good examples of this model. In this model, the real power load at bus–i will be reduced by an amount equal to DG real power output with unity power factor and is given by:

$$P_{Di(dg)} = P_{Di(0)} - P_{Gi(dg)} \tag{2}$$

- Type–2**:** Synchronous compensators such as gas turbines and capacitors are the examples for this type of modeling. In this model, the reactive power load at bus–i will be reduced by an amount equal to DG reactive power output with zero power factor and is given by:

$$Q_{Di(dg)} = Q_{Di(0)} - Q_{Gi(dg)} \tag{3}$$

- Type–3**:** Synchronous generators or wind farm is the example for this type of modeling. The power factor lies between 0 and 1. In this model, the active power will be reduced by an amount equal to DG active power and reactive power will be either increment/decrement by an amount equal to DG reactive power load at bus–*i* and is given by:

$$\left|P_{Di(dg)} + jQ_{Di(dg)}\right| = \left|\left(P_{Di(0)} - P_{Gi(dg)}\right) + j\left(Q_{Di(0)} \pm Q_{Gi(dg)}\right)\right| \tag{4}$$

As per the above three models, the DGs will decrease either active or reactive or both and causes to decrease net loading effect on the feeder. The decreased load has to balance and usually it may happen at slack bus in load flow studies. By the redistribution of power flows with reduced load, the net voltage profile, transmission loss and security margin can improve significantly.

Voltage Stability Analysis

In this work, the following stability indices have been used and compared in case studies. In [8], Power Stability Index (PSI) is introduced as given by (5) and is used to address the impact Type – 1 DG on network stability.

$$PSI_j = \frac{4 r_{ij} P_{Dj(0)}}{\left\{\left|V_i\right| \cos\left(\theta_{ij} - \delta_{ij}\right)\right\}^2} \le 1.00 \tag{5}$$

The percentage of DG penetration for Type – 1 ($\%DG_{1,pen}$) is expressed between total real power injected by DGs to total real power demand on the system as follows:

$$\%DG_{1,pen} = \left(\sum_{k=1}^{N_{DG1}} P_{Gk(dg)} \Bigg/ \sum_{i=1}^{N_{bus}} P_{Di(0)}\right) \times 100 \tag{6}$$

In [9], the Line Stability Index (LSI) is introduced as given by (7) and is used to address the impact Type – 2 DG on network stability.

$$LSI_j = \frac{4 x_{ij} Q_{Dj(0)}}{\left\{\left|V_i\right| \sin\left(\theta_{ij} - \delta_{ij}\right)\right\}^2} \le 1.00 \tag{7}$$

The percentage of DG penetration for Type – 2 ($\%DG_{2,pen}$) is expressed between total reactive power injected by DGs to total reactive power demand on the system as follows:

$$\%DG_{2,pen} = \left(\sum_{k=1}^{N_{DG2}} Q_{Gk(dg)} \Bigg/ \sum_{i=1}^{N_{bus}} Q_{Di(0)}\right) \times 100 \tag{8}$$

Stability Index (SI) given in [10] is used to analyze the impact of Type – 3 DG on network performance.

$$VSI_j = \frac{4x_{ij}}{|V_i|^2}\left(\frac{P^2_{Di(0)}}{Q^2_{Di(0)}} + Q_{Di(0)}\right) \le 1.00 \qquad (9)$$

The percentage of DG penetration for Type – 3 ($\%DG_{3,pen}$) is expressed between total apparent power injected by DGs to total apparent power demand on the system as follows:

$$\%DG_{3,pen} = \left(\sum_{k=1}^{N_{DG3}} S_{Dk(dg)} \Big/ \sum_{i=1}^{N_{bus}} S_{Di(0)}\right) \times 100 \qquad (10)$$

where $P_{Di(0)}$, $Q_{Di(0)}$ and $S_{Di(0)}$ are the base case active, reactive and apparent power loads at bus-*i* respectively; $P_{Gk(dg)}$, $Q_{Gk(dg)}$ and $S_{Gk(dg)}$ are the active, reactive and apparent power generations by DGs at bus-*k* respectively; $P_{Di(dg)}$, $Q_{Di(dg)}$ and $S_{Di(dg)}$ are the active, reactive and apparent power loads at bus-*i* after DG integration respectively; r_{ij} , x_{ij} and θ_{ij} are the resistance, reactance and impedance angle of the branch between *i* and *j* respectively; V_i is the voltage magnitude at bus *i*; $\delta_{ij} = \left(\delta_i - \delta_j\right)$ is the load angle difference of buses *i* and *j*. N_{DG1} , N_{DG2} , N_{DG3} are the number of type -1, type-2, and type-3 DGs respectively;

For stable operation, the LSI and PSI should be less than 1 for all the lines. The LSI or PSI greater than 1 indicates the proximity of instability or voltage collapse. Under normal operating conditions, VSI value should be less than unity. If the value of SI is closer to zero, then the system will be more stable. If the value of SI is low, then the node is vulnerable to stability. The bus with low SI value is more sensitivity and needs some corrective actions like Volt/VAr controls/DG installation/Load shed etc.

PROBLEM FORMULATION

Minimization of active power loss as the primary objective, the problem is formulated. The total active power loss (P_{loss}) of the network is obtained by the adding all branch losses and given as follows:

$$\min(P_{loss}) = \min\left\{\sum_l \frac{r_{l,ij}\left(P^2_{Dj(0)} + Q^2_{Dj(0)}\right)}{V_j^2}\right\} \qquad \forall l = 1,2,...,N_{br} \qquad (7)$$

where is the resistance of branch *l* connected between buses *i* and *j* respectively.

Since the uncertainty of DG penetration can cause to either increase or decrease the feeder voltage significantly, it is required to regulate the feeder voltage within the acceptable range in the network. The proposed methodology is capable to regulate the feeder voltage suitably for any loading conditions by limiting the DG sizes irrespective of locations and type by satisfying the following objective function.

$$\min(AVDI) = \min\left(\frac{1}{n_{bus}}\sum_{n_{bus}} |V_s - V_i|\right) \qquad (8)$$

where V_s and V_i are the sub-station bus voltage and bus-i voltage respectively; I_{br} and R_{br} are the branch current and resistance respectively; *nb* and *br* are the number of buses and number of branches respectively, r_l is the branch resistance, P_l and Q_l are the active and reactive power flows in a branch *l*, V_s is sending end node voltage and N_{br} is the total number of branches/lines in the system.

The operational constraints such as voltage magnitude limits, the kVA flow of each branch, the tap-changing transformer's tap positions at the sub-station, kW, kVAr and kVA injections by Type-1, Type-2 and Type-3 DG units must be within specified limits as follows:

$$|V_{i,\min}| \le |V_i| \le |V_{i,\max}| \qquad \forall i = 1,2,...,N_{bus} \qquad (9)$$

$$S_l \le S_{l,\max} \qquad \forall l = 1,2,...,N_{br} \qquad (10)$$

$$a_i^{\min} \le a_i \le a_i^{\max} \qquad i = 1 \qquad (11)$$

$$kW_i^{\min} \le kW_i \le kW_i^{\max} \qquad \forall i = 1,2,...,N_{DG1} \qquad (12)$$

$$kVAr_i^{\min} \le kVAr_i \le kVAr_i^{\max} \qquad \forall i = 1,2,...,N_{DG2} \qquad (13)$$

$$kVA_i^{\min} \le kVA_i \le kVA_i^{\max} \qquad \forall i = 1,2,...,N_{DG3} \qquad (14)$$

SOLUTION METHODOLOGY

The particle swarm optimization algorithms and their applications in power system optimization studies are well addressed in the comprehensive literature survey in [11]. From the introduction, it has various improvements and advancements towards global optima by avoiding local optima. Among those modified PSO algorithms, Improved PSO (IPSO) [12] and Time Varying Acceleration Coefficient (TVAC-PSO) [13] are adopted to solve the multi-objective non-linear problem of DG optimal location and sizing. The generalized procedure is given in this section.

Step 1) Read system data and run base case load flow and find the voltage stability of the system and total real power losses.

Step 2) Rank the buses as per voltage stability index and identify most suitable locations for DG integration based on normalized voltage profile.

Step 3) Modify the loads as per different types of load modeling

Step 4) Define PSO variables as No. of particles (NP) = 50; No. of variables (Size) = 2 (bus voltages v and SVC reactive power q; Inertial weight (w) = 0.9; Specify velocity min and max range $V_{\min} = \begin{bmatrix} -v_{\min} * 0.5 \\ -q_{\min} * 0.5 \end{bmatrix}$ and $V_{\max} = \begin{bmatrix} v_{\max} * 0.5 \\ q_{\max} * 0.5 \end{bmatrix}$

Here the voltage magnitudes of all buses as [0.9 p.u to 1.1 p.u], [0 MW to + $P_{d,i}$] for Type-1 DG units, [0 MVAr to + $Q_{d,i}$] for Type-2 DG units and [0 MVA to + $S_{d,i}$] for Type-3 DG units.

Step 5) Find initial velocity using $V = V_{\min} + U\left(V_{\max} - V_{\min}\right)$ for NP times.

Step 6) Find initial solution $v^0 = v_{\min} + U\left(v_{\max} - v_{\min}\right)$ and $q^0 = q_{\min} + U\left(q_{\max} - q_{\min}\right)$

Step 7) Update all equations in section 3 with initial solution obtained at step 6.

Step 8) Repeat step (7) for NP times and at each time, finds P_{best} and G_{best} values of v and q which gives minimum losses.

Step 9) Set No. of iteration (IT) = 50 and $\alpha = 0.5$

Step 10) Compute $V_{\max} = \begin{bmatrix} \dfrac{v_{\min} - v_{\max}}{\alpha} \\ \dfrac{q_{\min} - q_{\max}}{\alpha} \end{bmatrix}$ and

Step 11) Update the velocity and variables. Repeat step (6) to step (10) for IT times and update at each iteration P_{best} and G_{best} . Stop after reaching the convergence criterion. Here we have taken IT as convergence criterion.

Step 12) Print the load flow solution with optimal ratings and determined new Voltage Stability Indices for all buses.

The modifications for different types of PSO algorithms will take place at step 11 and are well addressed in [14].

RESULTS AND DISCUSSIONS

The effectiveness of proposed algorithm for optimal location and sizing DG problem is analyzed by having simulation results on standard 12-bus radial distribution systems. The branch data and load data are taken from [15]. The test system has 435 kW real power load and 405 kVAr reactive loads at base case. By performing backward/forward sweep load flow method, the system subjected to 20.7117 kW real power loss and 8.0393 kVAr reactive power loss. The normalized voltage profile with 0.95 p.u as well as various stability indices i.e., PSI, VSI and SI are given for base in Figure 1. According to LSI and PSI, the most instable location is bus 9 in the system. Similarly ranking can be given for all other buses as per high values. But *Norm V(i)* is used to decide whether that location needs any DG installation or not. According to *Norm V(i)*, buses 9 to 12 are less than 1 p.u which indicates low voltage profile as well as DG locations. The various stability indices have been calculated for base case loading or nominal load and composite load and are illustrated in Figure 1.

The simulations are performed for single DG to multiple DGs for each type of DG technology. By the optimized DG penetration in to the network using PSO algorithm, the two objective functions i.e., loss and AVDI are given in Table. 1. In addition, the impact of DG on stability w.r.t. type of DG is also given. By observing the results, the DG penetration at optimal locations is resulted for low losses, improved voltage profile and improved stability. The similar observation can be made with the simulation results given in Table 2 and Table 3 for IPSO and TVAC-PSO respectively.

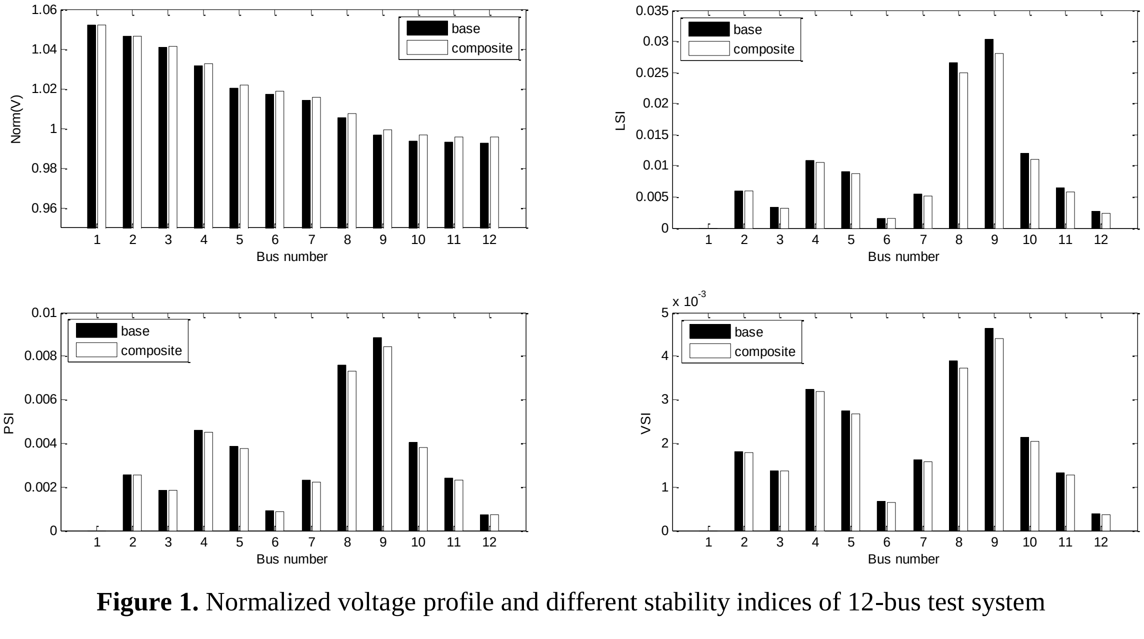

Figure 1. Normalized voltage profile and different stability indices of 12-bus test system

Table 1. Impact of different types of DG in 12-bus test system for nominal load

Location(s)	Type	Algorithm	Penetration (%)	Loss (kW)	AVDI (p.u)	Stability
9	1	TVAC-PSO	9.0235	15.9307	5.96E-04	0.0069
		IPSO	9.0120	15.9312	5.99E-04	0.0069
		PSO	9.1934	15.9436	5.31E-04	0.0069
	2	TVAC-PSO	9.7818	16.3322	4.82E-04	0.0246
		IPSO	9.6705	16.3380	4.98E-04	0.0245
		PSO	9.8190	16.3384	4.71E-04	0.0246
	3	TVAC-PSO	9.4701	13.5875	3.93E-04	0.0035
		IPSO	9.4931	13.6143	3.61E-04	0.0036
		PSO	9.3307	13.6510	4.00E-04	0.0035
9, 10	1	TVAC-PSO	12.0678	14.0695	4.16E-04	0.0069
		IPSO	12.1692	14.1560	3.12E-04	0.0069
		PSO	12.4599	14.0099	3.53E-04	0.0070
	2	TVAC-PSO	11.6388	14.8024	5.64E-04	0.0246
		IPSO	11.3669	14.8658	5.97E-04	0.0245
		PSO	11.3967	14.8949	3.82E-04	0.0249
	3	TVAC-PSO	16.4937	10.3176	2.89E-04	0.0036
		IPSO	16.8807	10.0884	1.98E-04	0.0036
		PSO	16.9967	10.0958	3.09E-04	0.0036
9, 10, 11	1	TVAC-PSO	18.6488	11.5993	3.32E-04	0.0069
		IPSO	17.0852	11.7527	3.08E-04	0.0069
		PSO	16.8761	12.3013	3.48E-04	0.0069
	2	TVAC-PSO	16.1955	13.6008	5.21E-04	0.0248
		IPSO	15.2816	13.7702	6.39E-04	0.0246
		PSO	16.5035	13.6221	3.51E-04	0.0251
	3	TVAC-PSO	23.9645	7.4135	1.55E-04	0.0036
		IPSO	24.1680	7.3371	1.71E-04	0.0036
		PSO	24.7046	7.1973	9.17E-05	0.0036
9, 10, 11, 12	1	TVAC-PSO	19.5298	10.6473	2.74E-04	0.0070
		IPSO	18.2683	11.0126	2.77E-04	0.0070
		PSO	18.0902	11.0405	2.75E-04	0.0070
	2	TVAC-PSO	17.8401	13.1997	6.06E-04	0.0247
		IPSO	17.9639	13.2556	4.13E-04	0.0250
		PSO	17.3811	13.3086	5.76E-04	0.0247
	3	TVAC-PSO	27.2041	6.3967	9.14E-05	0.0037
		IPSO	26.3030	6.7683	1.18E-04	0.0037
		PSO	25.5097	6.8547	9.02E-05	0.0036

Table 2. Impact of different types of DG in 12-bus test system for composite load

Location(s)	Type	Algorithm	Penetration (%)	Loss (kW)	AVDI (p.u)	Stability
9	1	TVAC-PSO	9.0325	16.0916	5.97E-04	0.0069
		IPSO	9.0210	16.0921	6.00E-04	0.0069
		PSO	9.2026	16.1046	5.32E-04	0.0069
	2	TVAC-PSO	9.7916	16.4972	4.83E-04	0.0246
		IPSO	9.6802	16.5030	4.99E-04	0.0245
		PSO	9.8288	16.5034	4.72E-04	0.0246
	3	TVAC-PSO	9.4796	13.7247	3.94E-04	0.0035
		IPSO	9.5026	13.7518	3.61E-04	0.0036
		PSO	9.3400	13.7889	4.01E-04	0.0035
9, 10	1	TVAC-PSO	12.0799	14.2116	4.17E-04	0.0069
		IPSO	12.1814	14.2990	3.12E-04	0.0069
		PSO	12.4724	14.1514	3.54E-04	0.0070
	2	TVAC-PSO	11.6504	14.9519	5.64E-04	0.0246
		IPSO	11.3783	15.0159	5.98E-04	0.0245
		PSO	11.4081	15.0453	3.83E-04	0.0249
	3	TVAC-PSO	16.5102	10.4218	2.90E-04	0.0036
		IPSO	16.8976	10.1903	1.98E-04	0.0036
		PSO	17.0137	10.1978	3.09E-04	0.0036
9, 10, 11	1	TVAC-PSO	18.6674	11.7165	3.33E-04	0.0069
		IPSO	17.1023	11.8714	3.09E-04	0.0069
		PSO	16.8930	12.4255	3.48E-04	0.0069
	2	TVAC-PSO	16.2117	13.7382	5.21E-04	0.0248
		IPSO	15.2969	13.9093	6.40E-04	0.0246
		PSO	16.5200	13.7597	3.51E-04	0.0252
	3	TVAC-PSO	23.9885	7.4884	1.56E-04	0.0036
		IPSO	24.1922	7.4112	1.71E-04	0.0036
		PSO	24.7293	7.2700	9.18E-05	0.0036
9, 10, 11, 12	1	TVAC-PSO	19.5493	10.7548	2.75E-04	0.0070
		IPSO	18.2866	11.1238	2.77E-04	0.0070
		PSO	18.1083	11.1520	2.75E-04	0.0070
	2	TVAC-PSO	17.8579	13.3330	6.07E-04	0.0247
		IPSO	17.9819	13.3895	4.13E-04	0.0251
		PSO	17.3985	13.4430	5.77E-04	0.0247
	3	TVAC-PSO	27.2313	6.4613	9.15E-05	0.0037
		IPSO	26.3293	6.8367	1.18E-04	0.0037
		PSO	25.5352	6.9239	9.03E-05	0.0036

CONCLUSIONS

In this paper, optimal location and sizing of different types of DG sources are optimized by optimizing real power losses and AVDI simultaneously using basic PSO, improved IPSO and TVAC-PSO. The impact of distribution generation is analyzed using different voltage stability measures namely PSI, LSI and VSI. The simulation results are performed on standard radial distribution systems and the results have shown the voltage stability improvement in radial distribution systems can be done significantly with the integration of DG sources at appropriate locations with proper rating. In addition, the solution of multi-objective non-linear power system optimization problems using PSO is well validated and TVAC-PSO has shown its superiority than other PSO algorithms in terms of convergence characteristics and by achieving global optima.

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