Original Article

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Optimal DG Placement for Voltage Stability Enhancement by Intelligent Method and Modal Analysis

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Abstract

Determining the optimal size and location of several DG units based on the renewable energies has become an important subject in achieving the stability of the power systems. This paper presents a comprehensive comparison between the intelligent method and modal analysis in optimal sizing and locating of the DG units in order for improving the network voltage stability and the other aims; and then, it shows the efficiency of each of the methods. The final aim of this paper is to provide reactive power requirement of buses for increasing the loadability of the system as well as enhancement the system's ability against disturbances through determining the optimal location and size of DG units. Various types of DG units from the view of injecting and absorbing the active and reactive power is considered in simulation; and then, effectiveness of each of these units is obtained in loadability and other issues. Utilized intelligent technique in this study is PSO-GA method which is implemented on IEEE 33-bus standard distribution system to solve the mentioned problem.

Key word: Distributed Generation, voltage stability margin, Modal analysis, PSO-GA hybrid intelligent algorithm

INTRODUCTION

Intense increase in demand saturates the existing power networks; and placing appropriate sized and localized DG units in the distribution networks is a suitable solution in the performance of the modern power systems and achieving their stability [1]. Lack of good loadability of network in the heavy network load conditions causes instability problems and collapse of the distribution networks. The loadability is in fact the same stability margin of the system; and the main factor of decrease in loadability is the inability of the power system in dealing with the demands for the reactive power. Voltage stability has been described by the IEEE power system engineering committee as follows: "voltage stability is the ability of a system to maintain voltage so that, when admittance is increased, load power will increase, and so that both power and voltage are controllable" [2]. Also, IEEE/CIGRE Joint Task Force proposes definition for voltage stability as: "Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition"[3].

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DG unit with proper size and location can be used to clear voltage stability problems, as a cause of the most recent blackouts [4]. Various methods and indices have been introduced in assessing the voltage stability and investigating the impact of changing parameters on the stability level of the network's voltage. Such as smallest eigenvalue of Jacobian matrix [5], voltage stability factor (VSF) [6], loading margin [7], voltage controllability index (VCI) [8], closest loadability limit (CLL) [9], voltage instability proximity index (VIPI) [10], etc.

In [4], a DG placement problem has been solved based on voltage stability analysis as a security measure. Modal analysis and continuous power flow are used in a hierarchal placement algorithm. In [11], PSO algorithm has been used for identifying proper location and size of DG units to enhance the loadability of distribution system by improving static voltage stability. In [12], a method has been proposed by selecting candidate buses which are sensitive to voltage profile and thus improve the voltage stability

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margin. In [13], wide-area measurement-based voltage stability sensitivity and its application in voltage control have been used. A comprehensive review of the voltage stability indices has been developed in [14]. A comparison of the voltage stability indices have been presented in some papers [15-22].

In this paper, we performed a comprehensive comparison between the PSO-GA intelligent algorithm and modal analysis in locating the DG units in order to increase the stability level of the system as well as improving the other objectives in the network. First, the modal analysis is performed on the network, the candidate buses are determined using eigenvalues and critical modes in order to allocate the DG units, and the DG units are placed in the most appropriate

bus. Then, using the PSO-GA intelligent algorithm, the optimal allocation of DG units is performed in order to reduce the reactive power losses and improve the stability of the network; and ultimately, the efficiency of each of the methods is shown in improving the results and they are compared with each other. Also various type of DG units from the view of injecting and absorbing the active and reactive power is considered in simulation; and then, effectiveness of each of these units is obtained in loadability and other issues.

The rest of this paper is organized as follows: At first, Section II presents problem formulation. Then, in section III, result and discussion have been raised. Finally, conclusion is presented in sections IV.

PROBLEM FORMULATION

Objective Functions

In this paper, objective functions include voltage stability margin improvement and reduction of reactive power losses. Also other benefits are improved during DG placement problem.

Voltage Stability Margin

Voltage stability is one of the most important issues that has limited the distribution companies to provide increased load. Voltage stability problem has caused many outages around the world, because instability of distribution systems spread to transmission lines and causes blackout in the power system. Therefore, lack of proper planning for the voltage stability of the grid may cause the blackouts and therefore leads to enormous costs via system interruption. Voltage stability margin (VSM) is the distance from the point of the system operation and by increasing VSM, the system will have more loadability.

$$Pi = \delta Po,i \tag{1}$$

$$Qi = \delta\, Qo,i \tag{2}$$

$$\text{VSM} = \delta \backslash\max - \delta \tag{3}$$

Po,i BASE-CASE LOAD ACTIVE POWER
Qo,i Base-case load reactive power
δ Scaling factor of the load demand
Which δ = 0 is considered, therefore:
δ max Maximum load factor before system collapse

REACTIVE POWER LOSS

DG with optimum size and location could reduce system reactive power losses dramatically.

$$Qloss = \sum_{i=1}^{n}\sum_{j=1}^{n}[\gamma ij(PiPj + QiQj) + \xi ij(QiPj - PiQj)] \tag{5}$$

$$\gamma ij = \frac{xij}{vivj}\cos(\delta i - \delta j) \tag{6}$$

$$\xi ij = \frac{xij}{vivj}\sin(\delta i - \delta j) \tag{7}$$

Zij = rij+xij ijth element of [Zbus] impedance matrix;
Pi,Pj active power injections at the ith and jth buses, respectively;
Qi,Qj reactive power injections at the ith and jth buses, respectively;
N number of buses;

DG Variables

In this paper DG variable is location of DG.

DG Technology

In this paper all types of DG units are used as follows:
Type1) DG injects active power only, e.g. photovoltaic.
Type2) DG injects reactive power only, e.g. synchronous compensators.
Type3) DG injects active power but absorbs reactive power, e.g. induction generators.

Relation between reactive and active power in induction generators is given in [11] as:

$$Q_{DG} = -(0.5 + 0.04P_{DG}^{2}) \tag{8}$$

Type4) DG injects both active and reactive power, e.g. synchronous generators.

Constraints

Voltage limits at each bus

$$V\backslash min \ \backslash le\ Vi \backslash le\ V\backslash max \tag{9}$$
$V\backslash min = 0.9$
$V\backslash max = 1.1$

Line capacity limits

$$Sij \backslash le\ Sij\backslash max \tag{10}$$

Sij MVA flow in the line connecting bus i and j

DGs penetration limit

$$DGPenetration \le_{0.3} * Sload \tag{11}$$

Maximum size of DG in each bus

Maximum power generation of DG units at every bus should not be further than power consumption of the same bus, otherwise the direction of power flow is reversed and results in disruption of protection setting. Because in the case of utilization of DG units, just in the case of existing fault, the direction of power flow would reverse, in the event of reversed power flow in the presenting of DGs, it is necessary to update the protection equipment settings.

Proposed Technique

In this paper, proposed techniques for solving DG placement problem are PSO-GA hybrid intelligent algorithm and modal analysis.

Modal Analysis

A modal analysis can discover the instability characteristics of the system and can identify best location for reactive power compensation. Reduced Jacobian matrix of system is obtained as:

$$J_R=J_{QV}-J\_Q\theta\ JP\theta^{-1}\ J_{PV} \tag{12}$$

$$J_R = \xi\Lambda\eta \tag{13}$$

ξ: right eigenvector matrix of J_R;
η: left eigenvector matrix of J_R;
Λ: diagonal eigenvalue matrix of J_R;

$$\upsilon = \Lambda^{-1} q \tag{14}$$

υ : the vector of modal voltage variation;
q : the vector of modal reactive power variation;

Then, for the *i*th mode is obtained as:

$$\nu_i = \frac{1}{\lambda_i} q_i \tag{15}$$

If $\lambda_i > 0$, system is stable; and $\lambda_i < 0$ refers to instability of the system.

Then, the participation of bus *k* in mode *i* is given by participation factor as:

$$Pki = \xi_{ki}\ \eta_{ki} \tag{16}$$

RESULT AND DISCUSSION

Part 1: Analysis of results using PSO-GA intelligent algorithm

In this part, we have performed locating and sizing of a DG unit in the IEEE 33-bus standard distribution system in order to increase the loadability of the network and improve the voltage stability with four different types of DG unit through using the PSO-GA hybrid intelligent algorithm. Simulation has been carried out with the objective function of reducing the reactive power losses; and the voltage profile and the thermal capacity of lines limitations have been considered. In this part, in designing the DG unit, two constraints have been considered for the size of DG that one of them is the protective limit of the power reverse flow that considers the maximum DG capacity at each bus, and the other is the limitation of the maximum penetration level of 30% of DG capacity. The results of this part are shown in Table I.

From the results of the Table I and Figure 1, it is observed that the unit type 4 causes the most loadability and stability level as well as the most voltage profile in the network and the unit type 2 provides the best conditions after the unit type 4. The reason is that these two types of units inject the reactive power to the network and the network will have better behavior when faced with the reactive power shortage and the heavy load conditions in it. Then, the units type 1 and 3 are respectively placed in the next positions in terms of the loadability improvement and voltage profile.

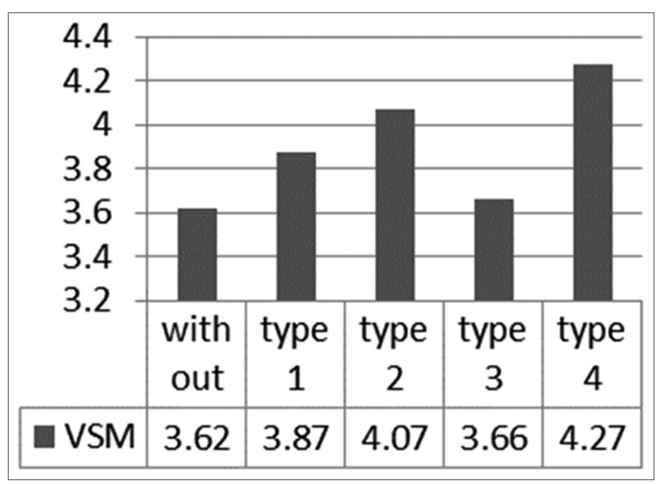

Figure 1: voltage stability margin by PSO-GA method

The unit type 3 has the least impact on the improvement of loadability and voltage profile due to its reactive power absorption. Moreover, according to the results of Table I and Figure 2, in addition to the abovementioned advantages, the DG units type 4, 2, 1, and 3 respectively have the most decrease in active and reactive power loss in the network. The percentage of active and reactive losses reduction of the network in the unit type 4 is 32%; in unit type 2, it is 22%; 12% stands for the unit type 1; and in the unit type 3, no reduction of losses has occurred compared to the mode without using the DG units. Hence, from the results of PSO-GA method, it is concluded that the DG units type 4, 2, 1, and 3 will respectively have better results.

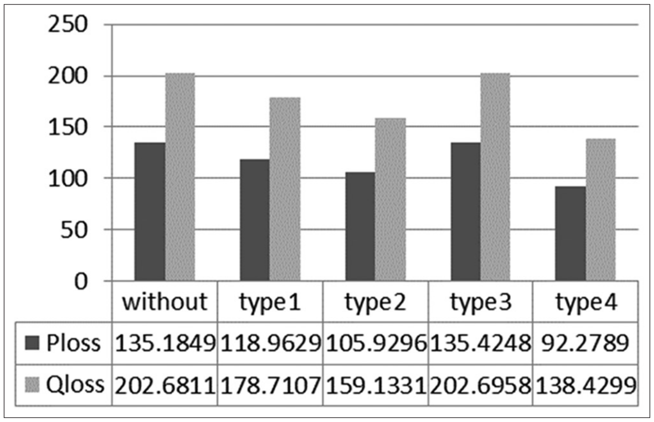

Figure 2: Active and reactive power losses by PSO-GA method

Part 2: Analysis of results using Modal analysis

In this part, locating of the DG units has been conducted by using modal analysis in order to increase the loadability of the network. The reason of using modal analysis is that this method is able to discover the instability characteristics of the system; and through using it, we can find the best location for installing DG units. Five of the smallest eigenvalues of the Jacobian matrix have been considered as the critical eigenvalues, the critical modes related to these eigenvalues and buses with the most participation have been determined in these modes. The number of eigenvalues and critical modes depends on the size and topology of the network and investigating more than five modes in this method is not analytical, but it is more like the trial and error in all buses of the system. In each of these critical modes, the bus with the most participation in that mode will be selected as the candidate bus. Then, the DG unit is added in each of the candidate bus and the voltage stability improvement of the network is examined through using continuous power flow. Finally, the bus with the most improvement in voltage stability is considered as the final bus to add the DG unit. All of these steps are

Table I: Results of DG placement by PSO-GA method

	Without DG	DG-type 1	DG-type 2	DG-type 3	DG-type 4
Location	-	32	30	24	30
Active size of DG (MW)	-	0.21	0	0.42	0.2
Reactive size of DG (MVAR)	-	0	0.6	–0.5071	0.6
Reactive Power Loss (kvar)	135.1849	118.9629	105.9296	135.4248	92.2789
Active Power Loss (kw)	202.6811	178.7107	159.1331	202.6958	138.4299
Reactive Power Loss Reduction (%)	-	12	22	0	32
Active Power Loss Reduction (%)	-	12	22	0	32
Minimum voltage (Bus)	0.9131 (18)	0.9165 (18)	0.9194 (18)	0.9137 (18)	0.9225 (18)
VSM	3.62	3.87	4.07	3.66	4.27

Table II: Placement of DG-type 1 by modal analysis

The smallest eigenvalues	The most participating bus	VSM in the presence of DG	Ploss in the presence of DG	Qloss in the presence of DG	Vmin (bus) in the presence of DG
$\lambda1, \lambda2$	18	3.66	190	126.4	0.9181 (33)
$\lambda3$	33	3.64	195	130.2	0.9141 (18)
$\lambda4$	22	3.62	202	134.4	0.9131 (18)
$\lambda5$	25	3.63	185	124.8	0.9148 (18)

Table III: Placement of DG-type 2 by modal analysis

The smallest eigenvalues	The most participating bus	VSM in the presence of DG	Ploss in the presence of DG	Qloss in the presence of DG	Vmin (bus) in the presence of DG
$\lambda1, \lambda2$	18	3.63	199	133	0.9157 (18)
$\lambda3$	33	3.63	199	133	0.9135 (18)
$\lambda4$	22	3.62	202	135	0.9131 (18)
$\lambda5$	25	3.62	198	132	0.9135 (18)

performed for each of the four types of DG units and the results are investigated as follows:

From the results of the Table VI, it is observed that with adding the DG unit type 1, the voltage stability level, voltage profile, and the active and reactive power losses have been improved compared to the without DG mode. Nevertheless, compared to the PSO-GA method, the voltage stability level is very lower and the power losses reduction is lesser about 50%. These results indicate that however during the use of modal method the results are improved through identifying the critical modes and installing the DG units in the candidate buses, but despite five of the most critical modes have been considered, the candidate buses obtained from the modal method are not necessarily optimal and there are also more optimal buses that have been identified by the PSO-GA intelligent method in the previous step. Hence, in order to find the optimal answers in modal method, we should investigate much more modes and this is not applicable in analytical aspects and in terms of the time of solving the problem; and this is like trial and error in many buses in the system.

In locating the second type DG unit, the voltage stability level and the other technical subjects have been worsened compared to the first part. In addition, regarding to the fact that the second type DG unit injects reactive power to the network, it should have more loadability compared to the first type DG unit; but the loadability has decreased according to the results of Table IV. Thus, the modal method has not identified the optimum bus for optimal allocation of the second type unit. Also in locating the unit type 3, the losses have increased compared to the without DG mode and the results have been worsened compared to the previous method. In locating the unit type 4, compared to the PSO-GA method, the results have not been improved, too; but in the same comparison, the results have improved in terms of loadability, voltage profile, and losses compared to the other types of DG and the without DG mode. This indicates that in this section, the DG unit type 4 is the most efficient type in every respect.

Anyway, from the results of these two sections and comparing them with each other, it is concluded that however locating the DG unit with modal analysis which has been also conducted in [4] improves the results, but it is not necessarily achieve the optimal response. In addition, regarding to the fact that the modal analysis does not achieve the optimal buses for DG, unlike the PSO-GA method, we cannot accurately rank the efficiency of the types of DGs in this method. Nevertheless, from the results of PSO-GA method, it was observed that the units type 4,

Table IV: Placement of DG-type 3 by modal analysis

The smallest Eigenvalues	The most participating bus	VSM in the presence of DG	Ploss in the presence of DG	Qloss in the presence of DG	Vmin (bus) in the presence of DG
λ1, λ2	18	3.47	258	177	0.886 (18)
λ3	33	3.47	261	177	0.8993 (33)
λ4	22	3.63	210	142	0.913 (18)
λ5	25	3.62	204	137	0.9137 (18)

Table V: Placement of DG-type 4 by modal analysis

The smallest eigenvalues	The most participating bus	VSM in the presence of DG	Ploss in the presence of DG	Qloss in the presence of DG	Vmin (bus) in the presence of DG
λ1, λ2	18	3.67	187	124	0.9185 (33)
λ3	33	3.65	191	127	0.9145 (18)
λ4	22	3.62	201	134	0.9132 (18)
λ5	25	3.63	181	122	0.9153 (18)

Table VI: Results of DG placement by modal analysis

	Without DG	DG-type 1	DG-type 2	DG-type 3	DG-type 4
Location	-	18	18	22	18
Active size of DG (MW)	-	0.09	0	0.06	0.09
Reactive size of DG (MVAR)	-	0	0.09	–0.5	0.04
Reactive Power Loss (kvar)	135.1849	126.3992	132.9179	141.7318	124.1711
Active Power Loss (kw)	202.6811	190.2788	199.4074	209.6121	187.0577
Reactive Power Loss Reduction (%)	-	6.5	1.7	–4.8	8.1
Active Power Loss Reduction (%)	-	6.1	1.6	–3.4	7.7
Minimum voltage (Bus)	0.9131 (18)	0.9181 (33)	0.9157 (18)	0.9130 (18)	0.9185 (33)
VSM	3.62	3.66	3.63	3.63	3.67

2, 1, and 3 respectively are efficient in terms of loadability and the other advantages.

CONCLUSION

In this paper, the optimal allocation of all types of DG units in the distribution networks has been provided in order for increasing the system loadability. With optimal locating and sizing the DG units, the required power by buses for increasing the loadability of the system as well as enhancement the system's ability against disturbances were provided. Locating the DG units was first carried out by using the PSO-GA intelligent algorithm and the results were analyzed. Then, the determination of the candidate bus for installing the DG unit was investigated through using modal analysis. The different types of DG units from the view of injection and absorption of the active and reactive power were used in simulations; then, the efficiency level of each of these DG types was obtained in the network loadability, voltage profile, and power losses. It was concluded that the DG units type 4, 2, 1, and 3 respectively have the most loadability, voltage profile improvement, and losses reduction in the distribution networks. From comparing the results of PSO-GA algorithm and the modal analysis, it was concluded that however locating DG unit by modal analysis improves the results, but modal analysis does not necessary achieve the optimal response. In addition, from the results obtained from the candidate buses in the modal analysis, it was found that the network loadability does not necessarily improve with increasing the power production as well as increasing the voltage amplitude. In this paper, the PSO-GA hybrid intelligent algorithm was used that was tested on the 33-bus standard distribution system in order to solve the proposed problem.

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