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Intelligent Placement of Multiple DG's in Distribution Networks for Loss Reduction, Reliability and Voltage Improvement using IPSO

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Abstract
Distributed Generation (DG)) is a promising solution to many power system problems such as voltage regulation, power loss, etc. This paper presents multi-objective function for optimally determining the size and location of distributed generation (DG) in distribution systems for power loss minimization, reliability and voltage improvement. The objective function proposed in this paper includes reliability index, active power loss index, DG's investment cost index and voltage profile index which is minimized using improved particle swarm optimization algorithm (IPSO). The effectiveness of the proposed method is examined in the 33 and 69 bus IEEE test systems and comparative studies are conducted before and after DG installation in the test systems. Results illustrate significant losses reduction and voltage profile and reliability improvement with presence of DG units.

Keywords— Improved PSO, Reliability, Distributed Generation, Interruption cost, Loss minimization, Unavailability, Investment cost index.

INTRODUCTION

A distribution system links the bulk electric system to the customers. Distribution systems include sub-transmission lines, distribution substations, primary and secondary feeders, lateral distributors, distribution transformers, protection and sectionalizing equipments and secondary circuits related to supplying power to the customers. Most distribution systems are radial in nature because of their low cost and simple design. Most low voltage distribution systems are operated radially. A radial system consists of a series of components between the substation and the load points. Failure of any of these components may result in outage at the load point. In power distribution systems, the optimal sitting and sizing of DG units is a significant project, which has been continuously studied in order to achieve various aims. The installation of DG at non-optimal places can result in an increase in system losses and costs. Authors in [5] were presented an improved particle swarm optimization algorithm (PSO) for optimal placement of multiple distributed generation sources to minimize real power losses. Kang and his coauthors in [6] proposed a novel efficient population-based heuristic approach for optimal location and capacity of DG in distribution networks, with the objectives of minimization of fuel cost, power loss reduction, and voltage profile improvement. Objective can also be the reliability improvement. Authors in [7] were presented an innovative approach to increasing reliability and reducing power loss with placing DG resources in an actual network.

Distributed generation units (also called decentralized generation, dispersed generation, and embedded generation) are small generating plants connected directly to the distribution network or on the customer site of the meter. In the last decade, the penetration of renewable and nonrenewable distributed generation (DG) resources is increasing worldwide encouraged by national and international policies aiming to increase the share of renewable energy sources and highly efficient micro-combined heat and power units in order to reduce greenhouse gas emissions and alleviate global warming.

Some of the main applications of DG are to provide support and reliability to the power system in a grid-connected mode or isolated mode. With the growing use of DG, it is very important to study its impact on radial distribution network operation. The power loss is significantly high in distribution systems because of lower voltages and higher currents, when compared to that in high voltage transmission systems. Electricity networks are in the era of major transition from stable passive distribution networks (without DGs) with unidirectional electricity transportation to active distribution networks (with DGs) with bidirectional electricity transportation.

In this paper, a multi-objective optimization is used for the placement and sizing of multiple DG units simultaneously using improved particle swarm optimization algorithm. The objective function is used for minimization of power losses, DG's investment cost and also voltage profile and reliability improvement of distributed system. The reminder of the paper is structured as follows: problem description for reliability assessment and effects of multiple DG installation on reliability indices in distribution systems is presented in section 2, briefly. Section 3 describes the formulation of the objective function. Improved particle swarm optimization is illustrated in Section 4, briefly, and simulation results for multiple DG installation in 33-bus and 69-bus IEEE test systems are presented and discussed in section 5. Finally, section 6 summarizes the main points and results of this paper.

PROBLEM FORMULATION

A. Reliability Analysis of Distribution System

Reliability indices of a distribution system are functions of component failures, repairs and restoration times which are random by nature. As factors are random in nature, reliability indices are also random in nature.

Because of customer satisfaction, the utility of individual customers to get the best service with the least amount of power failure is important. The majority of customer reliability problem is caused by distribution system. Utilities often monitor the reliability of customers by using a reliability index. Therefore, calculating the reliability index is interesting for their customers. The use of index to indicate the average number of times of the power failure and power outage per year per one customer makes it possible to compare between different systems and can also be targeted. The predictive reliability assessment of distribution systems requires the evaluation of two groups of indices namely, load point indices and system performance indices. The load point indices are, the average load point failure rate (λ failures/year), the average load point outage rate (r hr/failure) and the average annual load point outage time or average annual unavailability (U hr/year). Analytically, these indices are calculated using the following equations:

$$\boldsymbol{\lambda}_s = \sum \boldsymbol{\lambda}_i \quad (1)$$

$$\mathbf{r}_s = \frac{\sum \boldsymbol{\lambda}_i \mathbf{r}_i}{\sum \boldsymbol{\lambda}_i} \quad (2)$$

$$\mathbf{U}_s = \boldsymbol{\lambda}_s \mathbf{r}_s \quad (3)$$

Where i is the number of feeder sections (main or laterals) connecting the load point to the supply and s is the name of this load point. These indices do not always give a complete representation of system behavior and response. The system performance indices are the weighted averages of the load point indices. The most common system indices are

System Average Interruption Frequency Index (SAIFI):
The average number of interruptions per customer served per year.

$$SAIFI = \frac{Total\ Number\ of\ Customer\ Interruptions}{Total\ number\ of\ customers\ served} = \frac{\sum \boldsymbol{\lambda}_i \mathbf{N}_i}{\sum \mathbf{N}_i}$$

System Average Interruption Duration Index (SAIDI):
The average interruption duration per customer served per year. $SAIDI = \frac{Sum\ of\ Customer\ Interruption\ Durations}{Total\ number\ of\ customers} = \frac{\sum \mathbf{U}_i \mathbf{N}_i}{\sum \mathbf{N}_i}$

Expected Interruption cost (ECOST):

ECOST is a comprehensive value based reliability index and is used for this study

$$\mathbf{ECOST} = \sum_{i=1}^{n} \mathbf{L}_i \mathbf{C}_i \boldsymbol{\lambda}_i$$

Average Energy Not Supplied (AENS):

The average energynot supplied per customer served per year.

$$AENS = \frac{Total\ Energy\ not\ supplied}{Total\ number\ of\ customers} = \frac{\sum \mathbf{U}_i \mathbf{L}_i}{\sum \mathbf{N}_i}$$

Where λ_i is the failure rate (fails/year)
N_i is the number of customers of load point i
U_i is the annual outage time
L_i is the average load connected to load point i
C_i is the cost of interruption (Rs/KW) for the i^{th} bus
n is the number of load points in the feeder
C_i is evaluated using Composite Customer Damage Function (CCDF) and. CCDF shows the cost of interruption as a function of interruption duration.

B. Impact of DG Placement on Reliability Enhancement

Customer interruptions are caused by a wide range of phenomena including equipment failure, animals, trees, severe weather, and human error. Feeders in distribution systems deliver power from distribution substations to distribution transformers. A considerable portion of customer interruptions are caused by equipment failures in distribution systems consisting of underground cables and overhead lines [4].

Resistive losses increase the temperature of feeders which is proportional to the square of the current magnitude flowing through the feeder. For underground cables, there is a maximum operating temperature which if exceeded would cause the insulation problem and an increase in component failure rates [4]. The life expectancy of the insulation material decreases exponentially as the operating temperature raises [10]. On the other hand, A major reliability concern pertaining to underground cables is water treeing. Treeing occurs when moisture penetration in the presence of an electric field reduces the dielectric strength of cable insulation. When moisture invades extruded dielectrics such as cross-linked polyethylene (XLPE) or ethylene-propylene rubber (EPR), breakdown patterns resembling a tree reduce the voltage withstand capability of the cable and the probability of dielectric breakdown increases, and consequently, the failure rate of the cable is increased. The severity of treeing is strongly correlated with thermal age since moisture absorption occurs more rapidly at high temperatures [11].

Temperature also has impacts on the reliability of overhead lines. High currents will cause lines to sag, reducing ground clearance and increasing the probability of phase conductors swinging into contact. Higher currents can cause conductors to anneal, reducing tensile strength and increasing the probability of a break occurring [12].

DG placement can supply part of the reactive and active power demands, respectively. Therefore, due to the reduction of the magnitude of current, the resistive losses decrease. As a result, destructive effects of temperature on the reliability of overhead lines and underground cables are moderated. These impacts on reliability take into consideration as a failure rate reduction of distribution feeder components.

OBJECTIVE FUNCTION

The selection of the best places for installation and preferable size of multiple DG unit banks is a complex discrete optimization problem. The first step in an optimization procedure is to define the objective function. In this paper, a multi objective function is stated on the basis of active power loss index, reliability index, DG's investment cost index and voltage sensitivity index as below.

1. Active Power Loss Index (PLI):

DG can normally but not necessarily, helps reduce current flow in the feeders and hence contributes to power loss reduction. The magnitude loss depends on amount of current flow and the line resistance. Therefore, line loss can be decreased by reducing either line current or resistance or both. When DG is used to provide energy locally to the load, line loss can be reduced because of the decrease in current flow in some part of the network. However, DG may increase or reduce losses, depending on the location, capacity of DG and the relative size of load quantity.

The active power loss index is

$$\mathbf{PLI} = \frac{P_{\mathbf{LOSS\ with\ DG}}}{P_{\mathbf{LOSS\ without\ DG}}} \qquad (4)$$

Where $P_{LOSS\ with\ DG}$ is the total active power loss of the distribution system in presence of DG and $P_{LOSS\ without\ DG}$ is the total active power loss without DG in the distribution system.

2. Reliability Index (RI):

Reliability Index used is

$$\mathbf{ECOST} = \frac{\mathbf{ECOST}_{\mathbf{with\ DG}}}{\mathbf{ECOST}_{\mathbf{without\ DG}}} \qquad (5)$$

where $ECOST_{withDG}$ and $ECOST_{withoutDG}$ is expected interruption cost of system before and after DG installation.

3. Voltage Sensitivity Index (VSI):

One of the justifications for introducing DG is to improve the voltage profile of the system and maintain the voltage at customer terminals within an acceptable range. Voltage profile can be improved because DG can provide a portion of the real and reactive power to the load, thus helping to decrease current along a section of the distribution line, which in turn, will result in a boost in the voltage magnitude at the customer site.

When DG is connected at bus i, VSI for bus i is defined as

$$\mathbf{VSI_i} = \sqrt{\frac{\sum_{k=1}^{n}(1-V_k)^2}{n}} \qquad (6)$$

Where V_k is voltage at k^{th} node and n is the number of nodes.

4. DG's Investment Cost Index (DICI):

Multiple DG are appropriate selections for minimizing both the line loss and improving the network reliability and voltage profile. However, the investment cost of DG's is a significant problem that prevents engineers using them widely. This index is calculated with the following equation:

$$\mathbf{DICI} = \frac{\mathbf{COST_{DG}}}{\mathbf{COST_{MAXDG}}}$$

where COSTDG is the cost of DG, COSTMAXCDG is the cost of DG in its maximum capacity.

5. DG Cost Evaluation

The cost components relevant to DG analyses are capital and installation cost (total initial investment), operation and maintenance cost and fuel cost [13]. Capital and installation cost of DG depends to total investment and installed costs and annual amortized installed cost. The operation and maintenance (O&M) cost of DG consists primarily of plant operating labor and periodic inspection, replacement, and repair of system components, as well as consumables computed directly from the DG plant material balance. The fuel cost component is simply the cost of the fuel required to generate electricity with the DG technology. Fuel cost component varies with the efficiency (or heat rate) of the equipment and with the cost of fuel. These costs are given in [13].

6. Multi Objective Function:

The multi objective function in order to find the size and placement of DG unit and capacitor bank is a combination of mentioned indices. The multi objective function of the problem is expressed as

$$\mathbf{MF = PLI + RI + VSI + DICI} \qquad (7)$$

This function is minimized subject to operational constraints.

C. Load Flow Analysis

Distribution systems are fed at one point and have a radial structure. Due to its low memory requirements, computational efficiency and robust convergence characteristic, the load flow is computed by Forward-Backward Sweep method [10] applied to radial distribution networks.

D. Loss sensitivity factor: Mathematical Formulation

The main objective of the proposed approach is to minimize the total system active power loss by Optimal Sizing and sitting of Distributed Generation in radial distribution system.

Total Active Power loss in a Radial distribution system is given by

$$\mathbf{P_{loss} = min\left(\sum_{i=1}^{n}(I_i)^2 * R_i\right)}$$

Where, n is the number of lines at bus i, I_i is the line current at bus i, R_i is the line resistance in ohms. The loss sensitivity factor is used for the placement of DG is explained as, the Real power loss in the system is given by

$$\mathbf{P_{loss} = \sum_{i=1}^{n}\sum_{j=1}^{n}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j + P_iQ_j\right)\right]}$$

Where

$$\mathbf{\alpha_{ij} = \frac{R_{ij}}{V_iV_j}\cos\left(\delta_i - \delta_j\right)} \ \& \ \mathbf{\beta_{ij} = \frac{R_{ij}}{V_iV_j}\sin\left(\delta_i - \delta_j\right)}$$

And $\mathbf{Z_{ij} = R_{ij} + jX_{ij}}$ are the ij^{th} elements of $[Z_{bus}]$ matrix.

$P_i = P_{Gi} - P_{Di}$ & $Q_i = Q_{Gi} - Q_{Di}$

P_{Gi} & Q_{Gi} are power injection of generators to the bus

P_{Di} & Q_{Di} are loads to the bus

P_i & Q_i are the active and reactive powers of the bus.

The sensitivity factor of real power loss with respect to real power injection from the DG is given by

$$\mathbf{\alpha_i = \frac{\partial P_L}{\partial P_i} = 2\alpha_{ii}P_i + 2\sum_{\substack{j=1\\ j\neq i}}^{n}\left(\alpha_{ij}P_j - \beta_{ij}Q_j\right)}$$

Sensitivity factor are evaluated at each bus by using the values obtained from the base case load flow. The bus having lowest loss sensitivity factor will be best location for the placement of DG (Acharya et al, 2006). Conventional load flow studies like Gauss seidal, Newton raphson and fast decoupled load flow methods are not suitable for distribution load flows because of high R/X ratio. A load flow method for distribution systems i.e backward sweep and forward sweep method for load flow that offers better solution was proposed.

E. Optimal Sizing of DG

The total power loss against injected power is a parabolic function and at minimum losses, the rate of change of losses with respect to injected power becomes zero [9].

$$\alpha_i = \frac{\partial P_L}{\partial P_i} = 2\alpha_{ii}P_i + 2\sum_{\substack{j=1 \\ j\neq i}}^{n}\left(\alpha_{ij}P_j - \beta_{ij}Q_j\right) = 0$$

It follows that,

$$P_i = -\frac{1}{\alpha_{ii}}\left(\sum_{\substack{j=1 \\ j\neq i}}^{n}\left(\alpha_{ij}P_j - \beta_{ij}Q_j\right)\right)$$

Where P_i is the real power injection at node i, which is the difference between real power generation and the real power demand at that node: $P_i = P_{DGi} - P_{Di}$,

Where PDGi is the real power injection from DG placed at node i, and PDi is the load demand at node i. By combining the above we get.

$$P_{DGi} = P_{Di} - \frac{1}{\alpha_{ii}}\left(\sum_{\substack{j=1 \\ j\neq i}}^{n}\left(\alpha_{ij}P_j - \beta_{ij}Q_j\right)\right)$$

The above equation gives the optimum size of DG for each bus i, for the loss to be minimum. Any size of DG other than PDGi placed at bus i, will lead to higher loss.

F. Optimal Location of DG

The optimal location can be found for the placement of optimal sizes of DG as obtained from above equation which will give the lowest possible total loss due to placement of DG at the respective bus. The bus having least power loss will be optimal location for the placement of DG.

Assumptions and constraints:

The following are the assumptions and constraints for optimal allocation and sizing of DG.

- The maximum number of DG units is three, with the size each from 250 kW to the total load plus loss.
- The maximum DG penetration is 100%.
- The voltage of the system is in between 0.90 and 1.05 pu.

PARTICLE SWARM OPTIMIZATION

G. Algorithm to find size of DG using PSO

Step 1: Generate an initial population of velocities and DG sizes randomly.
Step 2: Initialize the iteration with k = 1.
Step 3: Calculate the objective function at each bus.
Step 4: For first iteration, p_{best} will be equal to the values of the objective function obtained for each particle/bus and g_{best} is the value with minimum value in the values of p_{best}.
Step 5: Increment the iteration count and update the values of velocities and DG sizes.
Step 6: Compare the objective value obtained at a particular bus with its previous iteration. If it is less than value obtained in previous iteration, set this value as current p_{best}. g_{best} is the best value (i.e. with minimum objective value) among current p_{best} values.
Step 7: If iteration = maximum iteration, go to step 8. Otherwise go to step 3.
Step 8: g_{best} gives the optimal DG sizes.

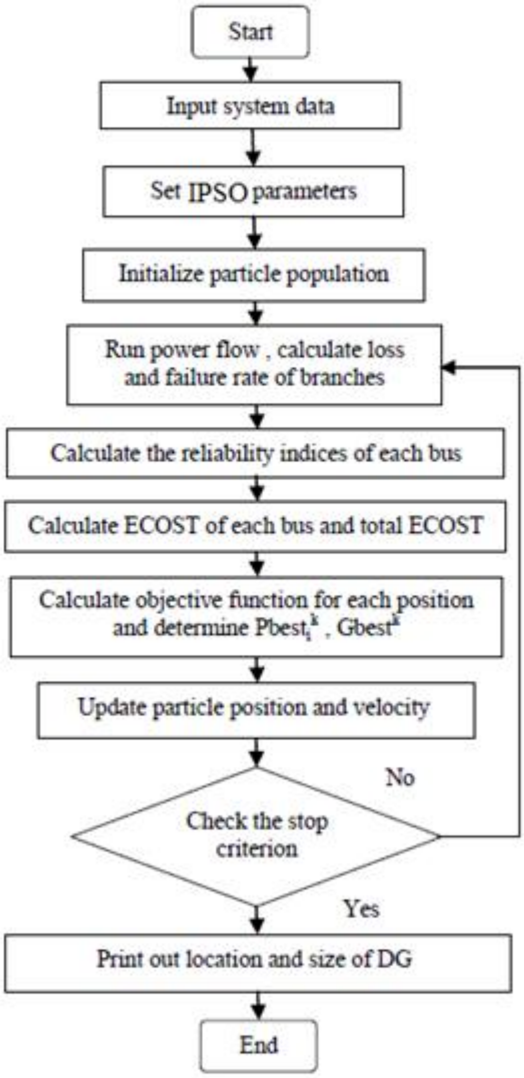

Figure 1: Flow Chart of the proposed approach

RESULTS & DISCUSSION

This work presents the results obtained after the implementation of the algorithms discussed previously. The algorithms have been developed in MATLAB environment. They are tested on 33-bus and 69-bus radial distribution systems.

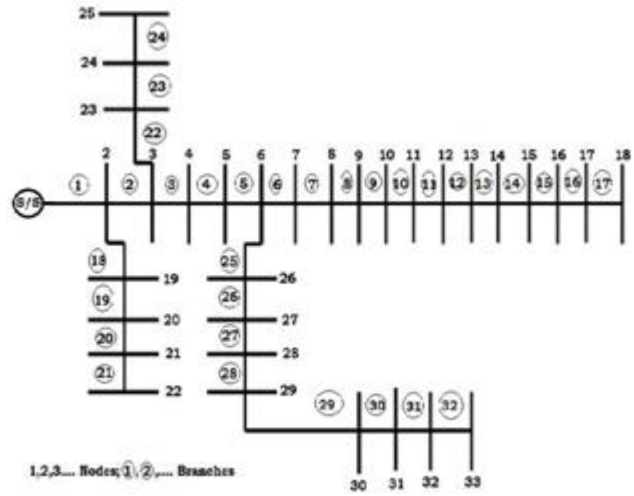

Figure 2 33 bus radial distribution system

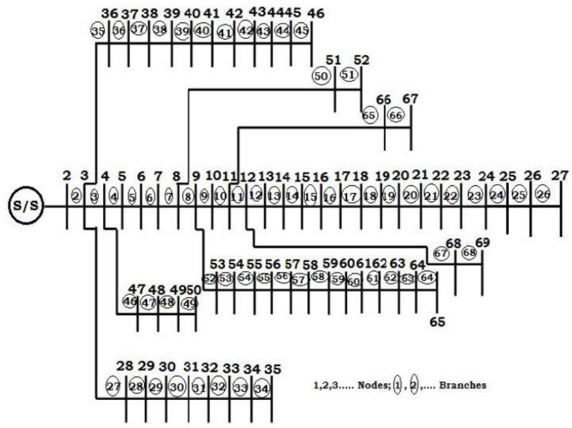

Figure 3 69 bus radial distribution system

The method based on analytical expressions incorporating PSO & IPSO is used to find out the optimal sizes and optimal locations of DG. The percentage of loss reduction after placing single, two and three DG units are presented. It is observed that high loss reduction is achieved by placing three DG units in distribution system.

The optimal size and location of DG units are given in Table 1. In order to indicate and compare the effects of DG placement in the test system, the results are compared to the case which there is no DG in the system and the results are presented in Table 2. It can be seen from this Table that determination of optimum size and location of DG has considerable effects on loss reduction, voltage and reliability improvement in the test system.

It is observed from Table 2 that the using DG installation, ECOST is decreased and ENS is also reduced. On the other hand, the DG installations at optimum locations reduce active power losses and reactive power loss significantly reduced. Moreover, VSI index is improved; therefore voltage deviations of nodes from 1.0 per unit in the test system are reduced by DG installation.

Table 1: Optimum size and location of Multiple DG units in 33 bus system

	Location of the DG (BUS NO.)		Size of the DG (kW)		Remarks
	Using PSO	Using IPSO	Using PSO	Using IPSO	
No DG	-----	-----	-----	------	
1 DG	6	15	696.2	610	IPSO results are better than PSO
2 DG	6, 15	6, 19	472.59, 181.72	469.59, 174.68	IPSO results are better than PSO
3 DG	6, 15, 25	6, 15, 25	263.15, 156.81, 84.19	261.08, 155.36, 80.95	IPSO results are better than PSO

Table 2: Comparison of Results Before and After DG Installation in 33 Bus System

	ECOST ($)		ENS (kWh/Year)		TOTAL P_{LOSS} (kW)		TOTAL Q_{LOSS} (kVAr)		VSI (p.u.)		Minimum voltage P.U	
	Using PSO	Using IPSO	Using PSO	Using IPSO	Using PSO	Using IPSO	Using PSO	Using IPSO	Using PSO	Using IPSO	Using PSO	Using IPSO
No DG	275195	273090	89966	89933.6	220.94	220.94	135.80	134.64	0.6988	0.69	0.837	0.837
1 DG	269247	267853	87523	87380	155.97	144.26	101.63	99.44	0.587	0.575	0.898	0.899
2 DG	253478	251890	82590	82265	101.15	96.09	75.63	73.77	0.468	0.459	0.915	0.917
3 DG	248490	245710	80850	80762	86.29	85.91	65.97	64.49	0.3635	0.3535	0.965	0.966

Table 3: Optimum size and location of Multiple DG units in 69 bus system

	Location of the DG (BUS No)		Size of the DG (kW)		Remarks
	Using PSO	Using IPSO	Using PSO	Using IPSO	
No DG	----	---	---	----	
1 DG	61	61	786.5	785	IPSO results are better than PSO
2 DG	61, 17	61, 19	596.1, 202	594.1, 196	IPSO results are better than PSO
3 DG	61, 17, 11	61, 15, 21	365, 196.3, 86.8	365, 194.8, 85.2	IPSO results are better than PSO

Table 4: Comparison of Results Before and After DG Installation in 69 Bus System

	ECOST ($)		ENS (kWh/Year)		TOTAL P_{LOSS} (kW)		TOTAL Q_{LOSS} (kVar)		VSI (p.u.)		Minimum voltage P.U	
	Using PSO	Using IPSO	Using PSO	Using IPSO	Using PSO	Using PSO	Using IPSO	Using IPSO	Using PSO	Using IPSO	Using PSO	Using IPSO
No DG	396205	395890	98975.4	98860	224.59	224.59	101.99	101.25	0.725	0.72	0.859	0.86
1 DG	381562	380430	97135.1	97005.3	112.12	111.15	89.56	88.51	0.659	0.65	0.890	0.890
2 DG	361230	360586	95261	94983	100.57	100.22	68.24	67.16	0.512	0.509	0.915	0.910
3 DG	348560	345225	92486.2	92253.1	94.83	92.16	49.27	49.10	0.315	0.303	0.956	0.96

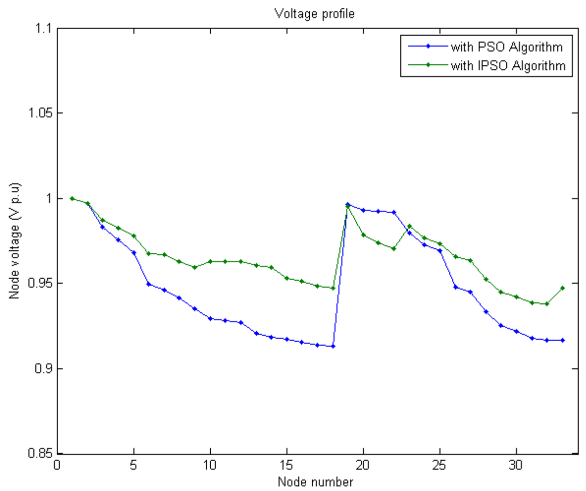

Figure 4 Voltage profile at each bus of 33 bus system after DG installation

CONCLUSION

In this paper optimum placement and sizing of distributed generation banks determined by a multi objective function using improved particle swarm optimization algorithm method. In the objective function proposed in this paper, reliability improvement, loss reduction and voltage profile improvement of electricity networks are considered. The proposed method has been applied on 33 bus and 69 bus distribution systems. The results illustrate that optimal placement of DG in the distribution systems causes to significant power losses reduction and also reliability and voltage profile improvement. The location in the power system for DG placement is found to be very important. Allocation of distributed generation at non-optimal places leads to increased power loss and reduced bus voltage profiles. The optimization of each objective function proposed in this paper has been summarized by focusing on the reliability of traditional distribution system without DG and the case that DG is connected to the distribution system.

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