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Optimisation of distributed generation units and shunt capacitors for economic operation of distribution systems

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Abstract

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Keywords

Optimisation, distributed, generation, units, shunt, capacitors, for, economic, operation, distribution, systems

Disciplines

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Optimisation of Distributed Generation Units and Shunt Capacitors for Economic Operation of Distribution Systems

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Abstract—The integration of Distributed Generation (DG) units and shunt capacitors can be considered as an alternative approach for distribution system expansion planning not only to improve power supply quality and reliability, but also to defer major system updates. In this paper, the techno-economic issues of distribution system expansion planning with optimal sizing and siting of DG units and shunt capacitors are addressed. The minimisation of overall investment cost with the integration of DG units and shunt capacitors is assessed with the consideration of supply quality, reliability and energy loss. A new planning methodology by using Particle Swarm Optimisation (PSO) is proposed to minimise the overall cost for optimal sizing and siting of DG units and shunt capacitors. The proposed methodology is tested on a remote 11kV radial distribution feeder and results are reported.

I. INTRODUCTION

Distributed generation (DG) units have been playing an important role in distribution system planning in recent years. The integration of DG units into the distribution system defers major system upgrade and it also results in the reduction of overall energy loss and improvement in the supply quality and reliability [1].

The DG technologies can be mainly categorised as conventional type (such as micro-turbine, diesel engine) and renewable type (such as wind turbine, photovoltaic). From utilities' viewpoint, some of the main benefits of applying DG units are to support system voltage at peak load demand and to improve system reliability by reducing the number of interruptions. Utilities would prefer to use conventional DG types rather than renewable ones. The reason for selecting conventional DG types is that the power generated by these types of DG units is controllable and schedulable and the coordination of these DG types with other existing devices is relatively easy to manage.

Although DG technologies provide positive impacts on distribution system, there could be certain technical challenges with the inclusion of active DG units in conventional passive system. The benefits and challenges of applying DG units in distribution systems have been investigated in [1]. It is important that DG units should be applied in an effective

manner without causing degradation of reliability, system operation and supply quality. Therefore, the planning aspects related to the integration of DG into the distribution systems demand comprehensive techno-economic considerations.

On the other hand, shunt capacitors, which are commonly deployed by most utilities for reactive power compensation, can also be considered in parallel with DG units for distribution system expansion planning. It has been reported in literature that the reactive power injected by shunt capacitors can effectively reduce system energy losses, relieve feeder loading [2] and improve supply reliability [3]. The siting and sizing of shunt capacitors should also be investigated carefully to avoid voltage rise problem and to reduce the operating cost of DG units.

The sizing and siting of DG units and shunt capacitors in distribution systems is a very complex combinational optimisation problem. This optimisation problem involves not only integer and binary decision variables but also non-linear, non-continuous, non-differential objective functions and constraints. The problems of this type are regarded as NP-hard (nondeterministic polynomial-time hard) problems, which pose computational complexities with some conventional analytical optimisation techniques. However, some of the heuristic techniques can be capable of dealing with such complexities. The use of certain heuristic methods such as genetic algorithm (GA) [4], ant colony optimization (ACO) [5], simulated annealing (SA) [6], and particle swarm optimisation (PSO) [7] have been reported in the literature for obtaining promising results.

In this paper, an optimisation technique is developed for determination of optimal sizing and siting of DG units and shunt capacitors. The planning model of a distribution system expansion with the inclusion of DG units and shunt capacitors is presented in Section II. The PSO heuristic search method, which is used to solve the optimisation problem, is introduced in Section III. In section IV, a case study is presented for a remote 11kV radial distribution feeder.

II. DISTRIBUTION SYSTEM EXPANSION PLANNING MODEL WITH DG UNITS AND SHUNT CAPACITORS

The distribution system expansion planning problem in this paper is modelled as a constrained mixed integer nonlinear programming (MINLP) optimisation problem. The main objective function is the overall cost incurred by the distribution utility. The sizes and locations of DG units and shunt capacitors are considered as integer and binary variables, respectively. The constraints are the acceptable nodal voltages and feeder currents.

The objective function comprises of DG cost (C_{dg}), shunt capacitor cost (C_{cap}), cost of energy loss (C_{el}) and cost of reliability (C_r). The detailed description for each term is presented in following subsections. The overall cost (C_{total}) to be minimised by the distribution utility can be calculated as:

$$C_{total}(S_{dg}, S_{cap}) = C_{dg}(S_{dg}, S_{cap}) + C_{cap}(S_{cap}) + C_{el}(S_{dg}, S_{cap}) + C_r(S_{dg}) \quad (1)$$

In (1), S_{dg} and S_{cap} are two different vectors for representing the sizes of DG units and shunt capacitors, respectively. The two vectors can be expressed as:

$$S_{dg} = [S_{dg(1)}, S_{dg(2)}, \dots, S_{dg(i)}, \dots, S_{dg(n)}] \quad (2)$$

$$S_{cap} = [S_{cap(1)}, S_{cap(2)}, \dots, S_{cap(i)}, \dots, S_{cap(n)}] \quad (3)$$

where n is the total number of system nodes, $S_{dg(i)}$ is the size of DG unit installed at node i , and $S_{cap(i)}$ is the size of shunt capacitor installed at node i .

The decision variables for building new DG units (B_{dg}) and shunt capacitors (B_{cap}) can be obtained logically by using (2) and (3).

$$B_{dg(i)} = \begin{cases} 1 & \text{if } S_{dg(i)} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

$$B_{cap(i)} = \begin{cases} 1 & \text{if } S_{cap(i)} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

A. Cost Model for DG Units

The total cost of DG units includes the installation cost, the investment cost, the operation and maintenance cost. It is given by:

$$C_{dg} = \sum_{i=1}^n B_{dg(i)} (C_{ins(i)}^{dg} + C_{pri(i)}^{dg} S_{dg(i)}) + C_{op(i)}^{dg} \sum_{t=1}^T \sum_{l=1}^{TL} H_{op(l,t)}^{dg} S_{out(i,l)}^{dg} (1 + \beta)^t + \sum_{t=1}^T C_{mtn(i)}^{dg} S_{dg(i)} (1 + \beta)^t \quad (6)$$

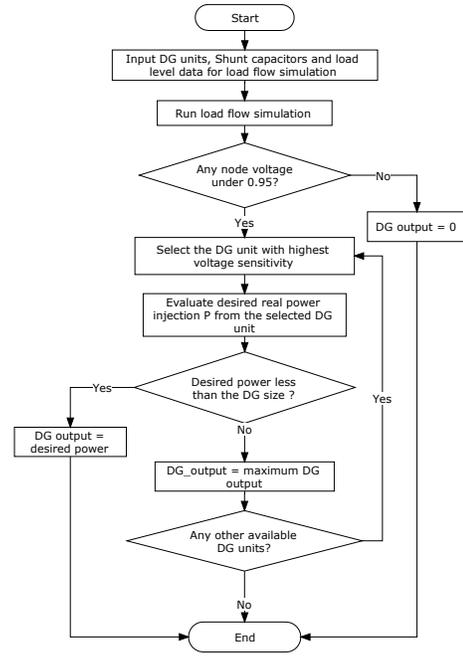


Fig. 1. Evaluation of DG output

where $C_{ins(i)}^{dg}$ is the cost for installing a DG unit at system node i (in \$/installaion), $C_{pri(i)}^{dg}$ is the capacity cost, which is associated with the size of the DG unit (in \$/kVA), $C_{op(i)}^{dg}$ is the fuel cost for DG units, which depends upon the total operating hours and output power for particular type of DG unit (in \$/kWh), $S_{out(i,l)}^{dg}$ is the power generated by DG unit at system node i for a time varying load level l (in kW), $C_{mtn(i)}^{dg}$ is the cost associated with the annual maintenance of DG units (in \$/kVA), $H_{op(l,t)}^{dg}$ is the total DG operation hours at load level l in year t over a planning period of T years, β is the inflation rate and TL is the total number of load levels.

In order to compute the fuel cost of all the DG units, it is required to evaluate the output power by each DG unit at various load levels over the planning period. The incremental power injection method [8] is selected and modified to determine the power generated by DG units for different combinations of DG sizes and locations. The flowchart for multiple DG output estimation is shown in Fig. 1. For a specified load condition with sole operation of shunt capacitors, the nodal voltage will be computed by using the load flow calculation. If any of the nodal voltage is below 0.95 pu, the voltage sensitivity $\partial V/\partial P$ at the corresponding DG nodes will be calculated and compared. DG unit with the highest voltage sensitivity will be selected to start injecting the power into the system. This process will continue until all the nodal voltages are above 0.95 pu.

The desired power from DG units can be calculated by using (7) and (8):

$$\Delta P_{dg(i)} = \frac{|V_{d(i)} - V_{node(i)}|}{\frac{\partial V}{\partial P}} \quad (7)$$

$$\Delta P_{dg(i)} = \begin{cases} \Delta P_{dg(i)} & \text{if } S_{dg(i)} > \Delta P_{dg(i)} \\ S_{dg(i)} & \text{otherwise} \end{cases} \quad (8)$$

where $\Delta P_{dg(i)}$ is the desired power generated by DG unit installed at node i , $V_{d(i)}$ is the desired voltage and $V_{node(i)}$ is the voltage at system node i .

It is assumed that the operation and control of DG units can be achieved by using supervisory control and data acquisition system (SCADA) and local measurements. There will be an additional cost for any new communication systems or a DG controller. In this paper, the additional cost for communication system update could be regarded as a part of the installation cost. The design of the DG controller is outside the scope of this paper.

B. Cost Model for Shunt Capacitors

In this paper, the static shunt capacitors are considered for reactive power compensation. The total cost of shunt capacitors includes the installation cost, the cost for purchasing shunt capacitors and the maintenance cost of shunt capacitors, as given by (9):

$$C_{cap} = \sum_{i=1}^n B_{cap(i)} (C_{ins(i)}^{cap} + C_{pri(i)}^{cap} S_{cap(i)} + C_{mtn(i)}^{cap} S_{cap(i)} (1 + \beta)^t) \quad (9)$$

where $C_{ins(i)}^{cap}$ is the cost for installing a new shunt capacitor at system node i (in \$/installation), $C_{pri(i)}^{cap}$ is the price factor associated with the size of the shunt capacitor (in \$/kVAr) and $C_{mtn(i)}^{cap}$ is the cost factor associated with the maintenance of the shunt capacitors (in \$/kVAr).

C. Cost Model for Energy Loss

The system energy loss is the summation of the losses of all feeder sections. The energy losses for feeder section are computed analytically by using balanced load flow equations [9] for different load levels with the inclusion of DG units and shunt capacitors. It is assumed that the DG units are operating with unity power factor and it can be modelled as negative P load. Similarly, the shunt capacitors are modelled as negative Q load. The load curve for a typical distribution feeder under consideration can be obtained by using historical load data and load prediction. The expression for total energy loss calculation is as given in (10):

$$C_{el} = \sum_{j=1}^m \sum_{l=1}^{TL} |I_{(j,l)}|^2 R_{(j)} H_{loss(l)} C_{loss} \quad (10)$$

where $R_{(j)}$ is the resistance of feeder section j (in Ohm), m is the total number of feeder sections, $I_{(j,l)}$ (in Amp) is the current flow in feeder section j at load level l , $H_{loss(l)}$ is the duration in which the line loss exist at load level l (in Hour) and C_{loss} is the cost associated with the energy loss for all load levels (in \$/kWh).

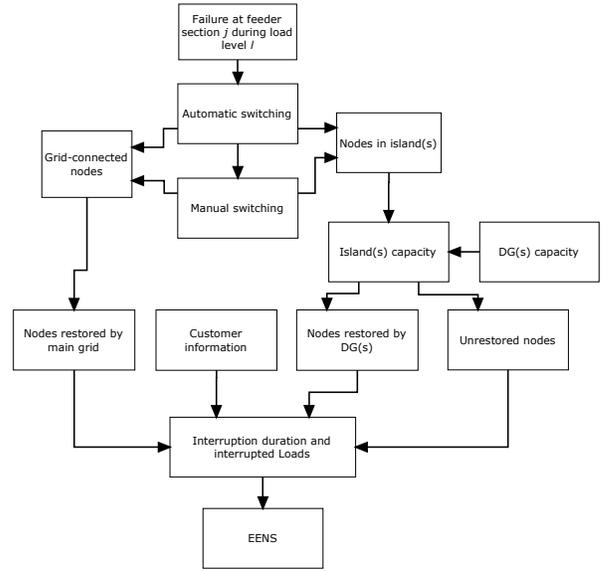


Fig. 2. Evaluation of EENS

D. Cost Model for Distribution System Reliability

The cost of system reliability is calculated analytically by evaluating the total expected energy not supplied (EENS) at different load levels in presence of the DG units.

$$C_r = F_{rate} C_{eens} \sum_{l=1}^{TL} \sum_{j=1}^m L_{fdr(j)} EENS_{(j,l)} \quad (11)$$

where F_{rate} is the average fault rate (in faults/km/year), C_{eens} is the cost associated with the value of EENS (in \$/kWh), $L_{fdr(j)}$ is the length of feeder section j (in km) and $EENS_{(j,l)}$ (in kWh) is the expected energy not supplied for fault on feeder section j at load level l .

The $EENS_{(j,l)}$ is impacted by the load levels [10], the locations and sizes of DG units [11], the operational aspects of DG units [12], the fault location and the subsequent response of system protection devices [13]. For a sustained interruption, $EENS_{(j,l)}$ is calculated by using (12):

$$EENS_{(j,l)} = \sum_{i=1}^n H_{out(i,j,l)} P_{load(i,l)} \quad (12)$$

where $H_{out(i,j,l)}$ is the outage time (in Hour) at system node i for a typical fault on feeder section j over load level l and $P_{load(i,l)}$ (in kW) is the load at system node i at load level l .

The duration of outage time is affected by many factors such as the total time required to locate the fault, to repair the faulty equipment, the response of the protection devices and the availability of backup supply. The flowchart for system reliability analysis is as shown in Fig. 2. For a specified fault on feeder section j , the fault will be isolated by automatic or manual switching. The loads located upstream of the fault will be reconnected to the main grid, while downstream loads could be restored by DG units if DG capacity is adequate. The interruption duration and interrupted customers then can

be estimated by using restoration and customer information, and therefore the final EENS can be computed.

E. System Constraints

The nodal voltage constraint and the feeder current constraint are considered in the formulation of constrained optimisation problem. The nodal voltages should be within a specified bandwidth as shown in (13). Similarly, the feeder current should be less than the overall current rating of the different feeder sections as shown in (14).

$$V_{min} \leq V_{node(i)} \leq V_{max} \quad (13)$$

$$|I_{fdr(j)}| \leq I_{rating} \quad (14)$$

III. PSO SEARCH METHOD

The PSO search method is an intelligence-based optimisation technology proposed by Kennedy and Eberhart in 1995 [14]. It can find optimal solution through the problem hyperspace by utilizing the movements of particle population and their interaction. PSO is a heuristic computation technique, which does not require gradient information about the objective function. It can be used to solve a wide range of complex optimisation problems (such as MINLP), where most conventional analytical techniques may fail to converge. Since PSO is a heuristic method, it cannot guarantee the global optimal solution. However, nearby optimal solutions can still be achieved in reasonable computational time with the proper representation of the optimisation problem. The problem variables in PSO are assembled in each particle (similar to the genes in a chromosome in case of genetic algorithm (GA)). Each particle explores the multi-dimension solution space by iteratively updating its position based on its own inertia, experience and the information provided by other particles. The behaviour of each particle can be expressed mathematically [7] as given in (15) and (16):

$$x_k(s) = x_k(s-1) + v_k(s) \quad (15)$$

As expressed in (15), $x_k(s)$ is the position of particle k at time step s while $v_k(s)$ is the velocity of particle k at time step s . The new position of each particle is based on its position at previous time step $s-1$ and the velocity at current time step s .

$$v_k(s) = v_k(s-1) + c_1 \cdot rand_1 \cdot (pbest_k - x_k(s-1)) + c_2 \cdot rand_2 \cdot (S_{best} - x_k(s-1)) \quad (16)$$

The particle updates its velocity at each time step as represented in (16), where c_1 and c_2 are the learning factors, named as cognition factor and social factor, respectively. The cognition factor expresses the confidence of each particle in itself while the social factor expresses the confidence of each particle in its neighbours. Generally, $c_1 + c_2$ will be less than 4.0 to ensure the convergency of the optimisation [15]. $pbest_k$ is the best position of each particle in explored search space

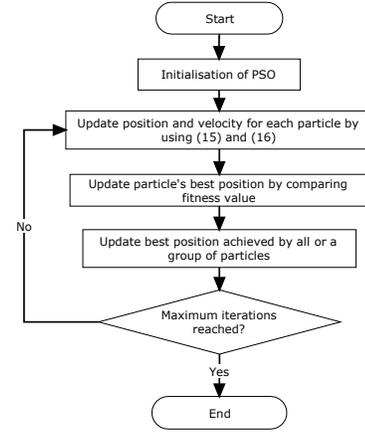


Fig. 3. PSO algorithm

while S_{best} is the best position found by all particles (Global Best PSO model) or by a group of particles (Local Best PSO model). The procedure of implementing PSO algorithm is shown in Fig. 3. The selection of different PSO models (global best model or local best model) and the learning factors are problem-specific. It has been reported by Kennedy [15] that the global version of PSO converges fast but may be easily trapped in a local minimum, while the local version of PSO may explore more space with slower convergence.

In this paper, local best PSO model is used and c_1 and c_2 are set to be 1 and 3 respectively. A penalty function is developed for constraint handling. There will be an additional penalty term in the main objective function in case of a constraint violation. Thus, the modified objective function can be rewritten as:

$$C_{total}(S_{dg}, S_{cap}) = C_{dg}(S_{dg}, S_{cap}) + C_{cap}(S_{cap}) + C_{el}(S_{dg}, S_{cap}) + C_r(S_{dg}) + C_p(V_{node}, I_{fdr}) \quad (17)$$

where $C_p(V_{node}, I_{fdr})$ is the penalty function. If the system constraints described in Section II did not get violated, the penalty will be 0. Otherwise, the penalty will be a value quantifying the violated constraints.

IV. CASE STUDY

The case study has been extracted from a distribution network in NSW, Australia, which is operated by Integral Energy, the distribution utility of NSW. The simulation is programmed in MATLAB and solved using PSO search method.

A. 86 Node Feeder Under Study

The system under study is a remote 11 kV radial distribution feeder from NSW, Australia. The topology of this feeder is as shown in Fig. 4. The entire feeder has a total length of 35km and there are 86 system nodes out of which 62 are load nodes. Most of the load served by this feeder is in terms of residential customers. A tap changing transformer is used at the zone substation for voltage regulation of the feeder (from

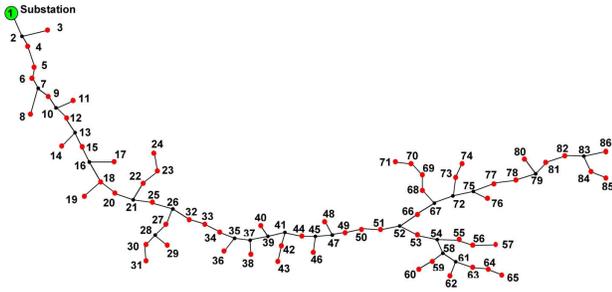


Fig. 4. 86 node test feeder

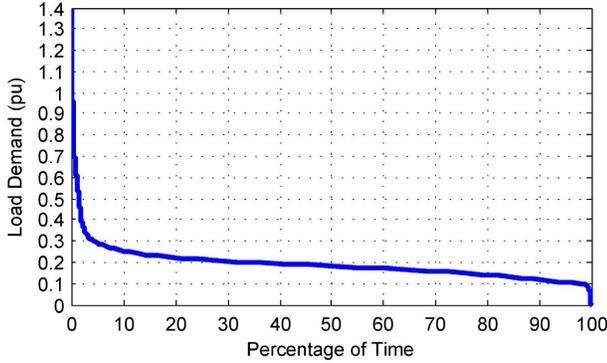


Fig. 5. Annual load duration curve

-21% to +10.5% in the step of 1.5%). The base values used in calculation are 2 MVA and 11 kV. The impedance of the main feeder sections is $0.315+j0.354 \Omega/\text{km}$. The annual load duration curve of the feeder is shown in Fig. 5.

B. Assumptions and Cost Data

For planning studies, it is assumed that all the loads are distributed in each phase so that the system is operated as a balance system. The futuristic load growth is 1% per year over a period of 20 years and feeder augmentation is not required. The inflation rate is assumed to be 4% per year. Diesel generators with unity power factor operation are considered as the only DG candidate to be used for system expansion planning. However, other DG types with different operational modes (conventional DG units as well as renewable DG units) can also be easily applied in this model if all associated costs and feasible control strategies are known. The investment of the DG unit and shunt capacitor is assumed to be proportional to their sizes. For simplicity, the installation cost of DG units and shunt capacitors is assumed to be the same for all system nodes along the feeder. However, more complex evaluation of DG installation cost, including the purchase of the land, site preparation, taxes, insurance and other auxiliary costs can be used if required. All the associated cost data used for this case study are given in Table I.

To quantify the cost of supply reliability, it is assumed that the time taken to repair faulty equipment is 10 hours and the time taken to isolate fault is 5 hours. The fault rate for the entire feeder is assumed to be 0.066 fault/km/year. It is also

TABLE I
COST DATA USED IN SIMULATIONS

Name	Value	Name	Value
C_{pri}^{dg}	70 (\$/kVA)	C_{op}^{dg}	0.6 (\$/kWh)
C_{ins}^{dg}	160,000 (\$/installation)	C_{mtn}^{dg}	7 (\$/kVA)
C_{ins}^{cap}	15,000 (\$/installation)	C_{mtn}^{cap}	3 (\$/kVA)
C_{pri}^{cap}	15 (\$/kVA)	C_{eens}	12 (\$/kWh)
C_{loss}	0.01 (\$/kWh)		

TABLE II
ALLOCATION OF DG UNITS AND SHUNT CAPACITORS

Device	Size	Location
DG Unit	1528 kVA	Node-78
Shunt Capacitor	125 kVA	Node-53

TABLE III
TOTAL INVESTMENT

Item	\$AU
DG installation cost	160,000
DG operating cost	731,503
DG maintenance cost	331,195
Investment of DG units	106,943
Shunt capacitor installation cost	15,000
Shunt capacitor maintenance cost	11,632
Investment of shunt capacitors	1,878
Cost of energy loss	5,778
Cost of reliability	1,263,008
Total cost	2,629,937

assumed that DG units can start within 15 minutes if the fault can be isolated by automatic switching in a short time. The minimum allowed system voltage is assumed to be 0.95 pu and the maximum allowed system voltage is assumed to be the voltage at the substation.

C. Results and Analysis

The proposed planning model is used to quantify the total fixed and variable cost for the integration of DG units and shunt capacitors into the system. The solution indicates that the total cost can be minimised if one DG unit and one shunt capacitor are installed. The sizes and locations of DG unit and shunt capacitor are indicated in Table II. The related costs are shown in Table III.

Fig. 6 shows the voltage profiles at peak load demand with and without DG unit and shunt capacitor at respective nodes. The lowest system voltage in the system can be improved from 0.9147 pu to 0.95 pu. The voltage at each node is within the acceptable limits.

Fig. 7 shows the feeder loading of main feeder sections at peak load demand. The loading of the feeder drops from 70% to 40%. The overall loading of the feeder has been rationalised, which could probably defer the possible T&D reinforcement. Fig. 8 shows the real power injection by DG

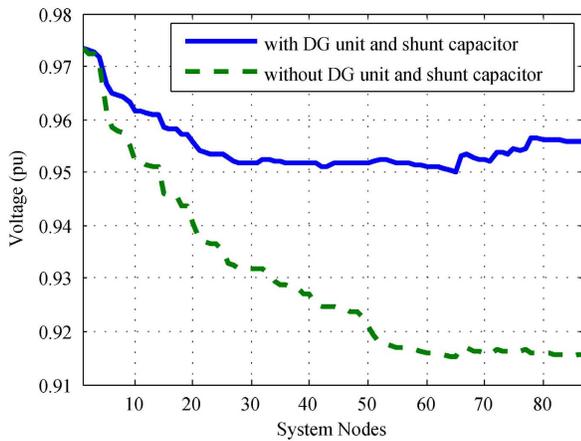


Fig. 6. Voltage profiles at peak load demand

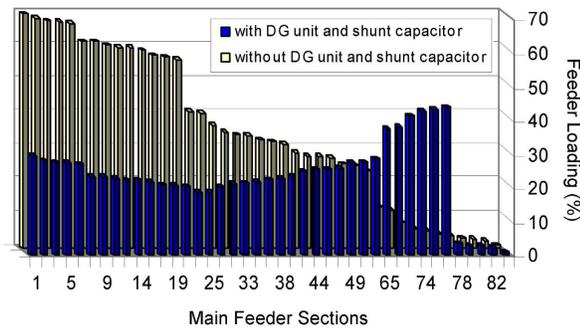


Fig. 7. Feeder loading at peak load demand

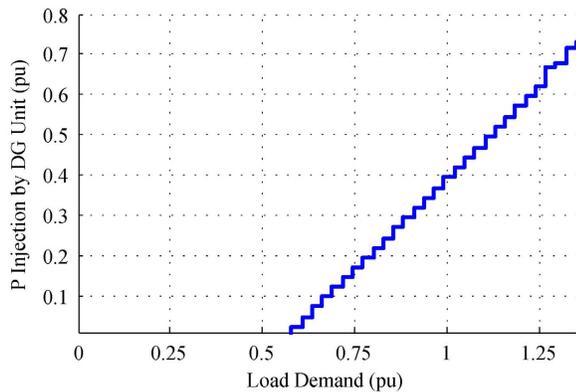


Fig. 8. Real power injected by DG unit

unit at various load levels. The DG unit starts when the load demand exceeds 0.58 pu. The reduction in the system power losses at varying load is shown in Fig. 9. During light load condition, the power losses have only reduced approximately 13% with the integration of DG unit and shunt capacitor.

The system reliability is also improved by applying DG unit into the system. The values of EENS at different load levels with and without DG unit are compared and shown in Fig. 10.

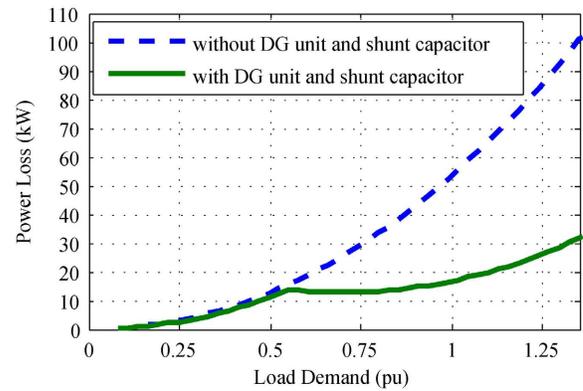


Fig. 9. System power loss

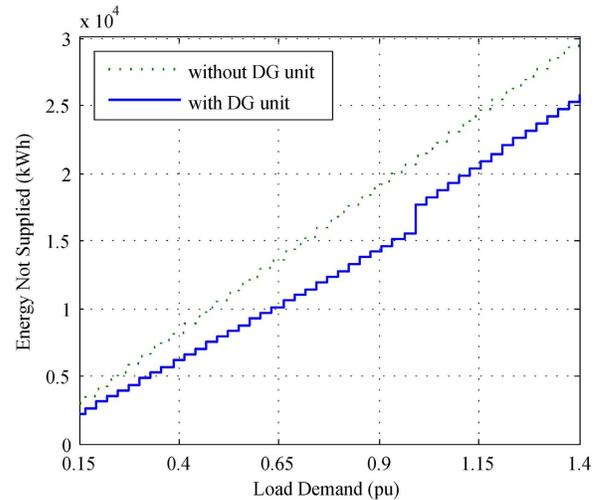


Fig. 10. System reliability

V. CONCLUSION

This paper presents a distribution system expansion planning model for the improvement in overall voltage profile and system reliability with the reduction in T&D losses. The operational strategy for DG units is described and the impact of DG units and shunt capacitors on distribution system has been quantified by minimising the total cost incurred by utilities. The total cost, comprised of DG cost, shunt capacitor cost, cost of energy loss and cost of system reliability, is then minimised by using PSO search method. The results indicate that the integration of one DG unit and one shunt capacitor with optimal sizes and locations can relieve feeder loading, improve voltage profile, reduce energy loss and enhanced system reliability. In comparison with the traditional planning methods, the application of DG units and shunt capacitors can largely reduce the investment while improving supply quality and reliability.

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