



## **Microgrids: Energy management by loss minimization technique**

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### **Abstract**

Energy management is a techno-economic issue, which dictates, in the context of microgrids, how optimal investment in technology front could bring optimal power quality and reliability (PQR) of supply to the consumers. Investment in distributed energy resources (DERs), with their connection to the utility grid at optimal locations and with optimal sizes, saves energy in the form of line loss reduction. Line loss reduction is the indirect benefit to the microgrid owner who may recover it as an incentive from utility. The present paper focuses on planning of optimal siting and sizing of DERs based on minimization of line loss. Optimal siting is done, here, on the loss sensitivity index (LSI) method and optimal sizing by differential evolution (DE) algorithms, which is, again, compared with particle swarm optimization (PSO) technique. Studies are conducted on 6-bus and 14-bus radial networks under islanded mode of operation with electric demand profile. Islanding helps planning of DER capacity of microgrid, which is self-sufficient to cater its own consumers without utility's support.

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**Keywords:** Differential evolution algorithms, Particle swarm optimization, Loss sensitivity index, Microgrid.

### **1. Introduction**

During the last decade, the deployment of distributed generators (DGs) in the distribution network has been growing steadily. When these DGs operate, independently, in the network, several difficulties arise with their increasing penetration. Thus concept of microgrid, where these DGs operate in co-ordination to overcome those difficulties, comes into being in the distribution system. In the context of microgrid, terms DG are replaced by distributed energy resources (DERs), which include conventional generators like microturbines, fuel cells, diesel generators etc., renewable resources like solar PV, wind generators etc., energy storages- both thermal and electric, etc. In spite of many benefits DERs possess, owners of DERs in many countries are charged with a fixed fee for interconnecting their DERs to the utility grid. At present, regulators, system operators, public utilities, consumers and society, in general, are paying a great deal of attention to identify as well as to quantify the benefits of DERs in local as well as global perspective. Actually, distributed network operators (DNO) are get directly benefited from interconnection of DERs to their own network and these benefits are like reduction of line loss, deferral of investment of network up gradation due to load growth as well as aging equipments. In Europe unbundling rules prohibits DNOs from owning generation plants and it creates a lack of integration

between network and generation planning. But in U.S. regulation, there is a provision for utility to connect DG at strategic locations on the grid. Now incentives are given to DNOs to interconnect DGs of modest penetration for reduction of losses. [1-3]

Cost is an important attribute in microgrid planning which involves identification of best DERs along with its siting, manner of interconnection to the utility and schedule of deployment. Energy management system (EMS) make best use of DERs to attain at highest economic as well as technical efficiency by analyzing various cost saving opportunities of microgrid, like line loss of network, which account for 5% to as much as 20% of generation. These losses display a U-shaped trajectory depending on the siting and sizing of DERs in the network. If DERs are placed and sized strategically a significant reduction of loss could be obtained. Injection of DER power at lower voltages tends to reduce losses but where these greatly exceed demand, overall losses may increase. Like consumers demand, loss is, also, a demand by the network itself on the utility and extra generation is required to provide by utility to meet this demand and it involves extra cost. Microgrid owner must be paid incentive by utility as its reduction of line loss benefit helps utility to avoid provision of extra generation. [1, 2, 4, 5]

Many researchers had worked on siting and sizing of distributed energy resources (DER) based on network loss minimization. Griffin et. al.[6] used loss sensitivity technique along with power system simulation for engineering (PSS/E) software package; Greatbanks et.al. [7] used both voltage and loss sensitivity indices along with reactive power compensation and capacitor bank sizing algorithm; Nara et.al. [8] used tabu search (TS) method; Abdelaziz et.al.[9] used simple genetic algorithm (GA) and evolutionary approach (EA); TS is faster and better convergence characteristic compared to simulated annealing method [8]. When simple GA [9] is compared with EA, EA is found better at all average values of losses. Heuristic and arithmetic crossover operation and two point mutation in EA is superior to any other method. Carpinelli et. al. [10] used Monte Carlo simulated based Raleigh correlated random variables, genetic algorithm (GA) and decision theory for siting and sizing of uncertain wind generator with an object of minimization of total cost of network structure, which include construction, residual, management costs and cost of losses.

The present paper conducts two separate studies for energy management decision of siting and sizing of DERs in 6-bus and 14-bus radial micro-grids. Locations of DERs are determined by loss sensitivity indices (LSI) and optimal sizes are determined using differential evolution (DE) technique with minimization of line losses in microgrid. DE is found to yield better and faster solution, satisfying all the constraints, both for uni-modal as well as multi-modal systems, using its different crossover strategies [11, 12]. It is a simple population-based stochastic parallel search evolutionary algorithm for global optimization. To compare the DE results, PSO has been used. PSO technique is conceptually simple, easy to implement, robust to control parameters and computationally efficient [13]. Optimal losses and corresponding sizing of DERs are determined at various demands of load profile under islanded modes of operations.

The contents of this paper are organized into following sections. Section 1 on introduction is followed by section 2, which provides detailed formulations of the problem. Section 3 gives a brief overview of DE technique. Section 4 details the DE algorithms in the context of present problem. Section 5 includes necessary figures, results and discussions of two study cases. The conclusion is drawn in section 6. References are appended last.

## 2. Problem formulations

Present paper has two parts –(1) optimal siting of DERs in the microgrid network and (2) optimal sizing of them. First part is handled using loss sensitivity indices and for second part DE optimization technique is used.

### 2.1 Optimal siting of DERs

Optimal siting of DERs are determined on the basis of loss sensitivity indices and its equation (1) is based on Newton-Raphson load flow method [16].

$$\frac{\partial P_l}{\partial P_i} = [J_{Ll}] * \left[ \frac{\partial P_l}{\partial \delta_i} \right] \quad (1)$$

where  $[J_{Ll}]$  is Jacobian sub-matrix of  $[J^T]^{-1}$  i.e., containing all  $[\partial \delta_i / \partial P_i]$  terms.

## 2.2 Optimal sizing of DERs [15]

$$\text{Min}P_{\text{Loss}} = \sum_{i=1}^n P_i = P_1(|V|, \delta) + \sum_{i=2}^n P_i \quad (2)$$

Subject to *PQR Constraints*:

- Bus voltage tolerance limit

$$U_{i \min} \leq U_i \leq U_{i \max}$$

- Limit on the active and reactive power generation of the DER

$$P_{i \min} \leq P_i \leq P_{i \max}$$

$$Q_{i \min} \leq Q_i \leq Q_{i \max}$$

- Line flow limits (e.g. must be below thermal limits) and takes care of internal congestion of the micro-grid

$$S_{ij} \leq S_{ij \max}$$

- Limit on active and reactive power injection to slack bus:

$P_1$  and  $Q_1$  are respectively active and reactive power injection to the slack bus. Under this constraint, the capacity of DERs obtained by simulation will be the installed capacity of micro-grid, without reserve, to meet the peak demand under islanding i.e. grid outage.

$$P_1 \cong 0; \quad Q_1 \cong 0$$

where  $P_i$  is the active power injection at i-th bus, n is total number of buses,  $P_1$  (slack bus power injection) is dependent on other bus voltage magnitudes  $|V|$  and angles  $\delta$ .

## 3. Overview of differential evolution technique

Differential Evolution (DE) is an extremely powerful optimization algorithm from evolutionary computation due to its excellent convergence characteristics and a few control parameters. DE uses a population IP of a generation 'g' of size 'NP', composed of floating point-encoded individuals (Eq.3) that evolve to reach an optimal solution. Each individual  $X_i^g$  is a vector (Eq. 4) that contains as many parameters as the problem decision variables D, called 'genes'. The population size 'NP' is an algorithm control parameter selected by the user, which remains constant throughout the optimization process.

$$\text{IP}^g = X_i^g, \quad i=1, \dots, NP \quad (3)$$

$$X_i^g = x_{i,j}^g, \quad j=1, \dots, D \quad (4)$$

### 3.1 Initialisation

The optimization process in DE is carried out with three basic operations: Mutation, crossover and selection. The first step of this algorithm is to create an initial population of 'NP' vectors, by randomly generating individuals within the boundary constraints (Eq. 5):

$$\text{IP}^0 = x_{ij}^0 = \text{rand}_{i,j} * (H_j - L_j) + L_j \quad (5)$$

where 'rand' function generates values uniformly in the interval [0,1]. The fitness function is evaluated for each individual.  $H_j$  and  $L_j$  are upper and lower limit of boundary constraint of jth population.

For each generation the individuals of the population are updated by means of a 'Reproduction' scheme. Therefore, for each individual 'ind' a set of other individuals ' $\pi$ ' is randomly extracted.

### 3.2 Mutation / differentiation

The mutation operator is in charge of introducing new parameters into the population. A set of randomly extracted individuals  $\pi = \{\xi_1, \xi_2, \dots, \xi_n\}$  is necessary for 'Differentiation'. To achieve this mutant operator creates mutant vectors by perturbing a randomly selected vector ( $\varepsilon$ ) with a difference vector  $\delta$ . the result of 'Differentiation', so called 'trial' individual, is

$$\omega = \varepsilon + F * \delta \quad (6)$$

where  $F > 0$  is the 'Constant of Differentiation'. As for example three different individuals are randomly extracted from a trial population. The updated trial individual is equal to  $\omega = \varepsilon + F * \delta$ , where

$\delta = \xi_2 - \xi_1$  and  $\varepsilon = \xi_3$ . The scaling constant,  $F$ , is an algorithm control parameter used to control the perturbation size in the mutation operator and improve algorithm convergence.  $\xi_1$ ,  $\xi_2$  and  $\xi_3$  are randomly chosen vectors and are selected anew for each parent vector.

### 3.3 Crossover/ recombination

After, the trial individual ' $\omega$ ' is recombined with updated one ' $ind$ '. 'Recombination' represents a typical case of a 'genes' exchange. The trial one inherits genes with some probability. Thus,

$$\omega = \begin{cases} \omega_j & \text{if randj} < Cr \\ ind_j & \text{otherwise} \end{cases} \quad (7)$$

where  $j = 1, \dots, D$  and  $Cr \in [0, 1)$  is the 'constant of recombination'. Crossover constant  $C_r$  is an algorithm parameter that controls the diversity of the population and aids the algorithm to escape from local optima.

### 3.4 Selection

'Selection' is realized by comparing the cost function values of updated and trial individuals. If the trial individual has lower value of the cost function, then it replaces the updated one.

$$ind = \begin{cases} \omega & \text{if } f(\omega) \leq f(ind) \\ ind & \text{otherwise} \end{cases} \quad (8)$$

It may be noticed that there are only three control parameters in this algorithm. These are 'NP' (population size), 'F' (constants of differentiation) and 'Cr' (constants of recombination). As for the termination conditions, one can either fix the number of generations ' $g_{max}$ ' or a desirable precision of a solution. DE offers several variants or strategies for optimization. These can be denoted by DE/x/y/z, where x refers to the vector used to generate mutant vectors, y the number difference vectors used in the mutation process and z the crossover scheme used in the crossover operation.

## 4. DE based algorithms for loss minimization

The proposed algorithm is implemented with MATLAB 6.5 language on a Pentium-IV PC. Gauss-Siedel load flow method has been embedded into DE algorithms for finding out the optimal solution. Let  $p_i = [P_{i1}, P_{i2}, \dots, P_{iN}]$  be the trial vector designating  $i^{\text{th}}$  particle of the population and  $i=1,2,3,\dots,n$ . The elements of  $p_i$  are real power outputs of  $N$  generating units. The objective is to minimize function as mentioned in (Eq. 2). The computational steps in respect to case of 6-bus radial system are as follows, 14-Bus case is similar:

- Read the input data:- Bus data, Line data, no. of buses ( $n$ ), no. of lines ( $nl$ ) and all other data under section 5.
- Initialize the particles of the population in a random manner according to the limits of each unit including individual dimensions, search points and velocities. These initial particles must be feasible candidate solutions that satisfy the PQR operating constraints, as mentioned in section 2.2.
- Fitness function,  $Min(P_{Loss})$  is evaluated as per equation (Eq. 2) for each individual set of the population.
- Apply the Differentiation (Mutation) operation on the population as per Eq.6.
- Apply the Crossover (Recombination) operation on the population, generated after mutation operation of Step 4, as per Eq. 7.
- The population settings after Step 4 & 5, which perform better against the fitness function, are selected to be part of the next population according to (Eq. 8).
- If current iteration is greater than or equal to the maximum iteration, keep the result in an Array and stop; otherwise repeat the Steps 3 to 6.
- Run steps 2 to 8 for 50 trials and find the best minimum loss.

## 5. Case study

This paper conducts studies, separately, on 6-bus and 14-bus radial micro-grids at two stages –(1) base case without DER connection and (2) Strategic placement of DERs in the network and its optimal sizing at various loads of daily electric load profile (Figure 1) under minimum loss. In load profile (Figure 1),

bracketed data are in MW and for 14-Bus system, whereas non-bracketed data are in kW and for 6-Bus system. The following points are considered in the studies

- Loads as per profiles;
- Zero slack bus injection constraint helps to know, at the planning stage, what exact DER capacity of micro-grid required to meet the internal demand. It is islanded operation of microgrid
- LSI at the terminal buses are usually found higher values, but due to line outage probability, there is a chance of islanding of DERs. At terminal buses these DERs are under utilized. So they are shifted from terminal buses to next higher values.
- Utility is considered as a large virtual generator connected to the microgrid at Bus no. 1, which is slack bus presently. Bus 1 is infinite bus.

The data used in two case studies are as follows:

- Price of utility electricity ( $C_e$ ) is \$ 0.12 /kWh, [14, 16]
- DE data: - Strategy used is DE/rand/1 with per-vector-dither, Population size =20, Scaling factor, or, constant of Differentiation ( $F$ ) = 0.85; Crossover constant, or, constant of Recombination ( $Cr$ ) =1;
- PSO data: - Population size: 20; Acceleration Constants:  $C1, C2 = 2$ ; Generation or iteration = 1000; Inertia weight factor:  $w_{max} = 0.95$  and  $w_{min} = 0.2$ . Constriction Factor = 1.[15-16]

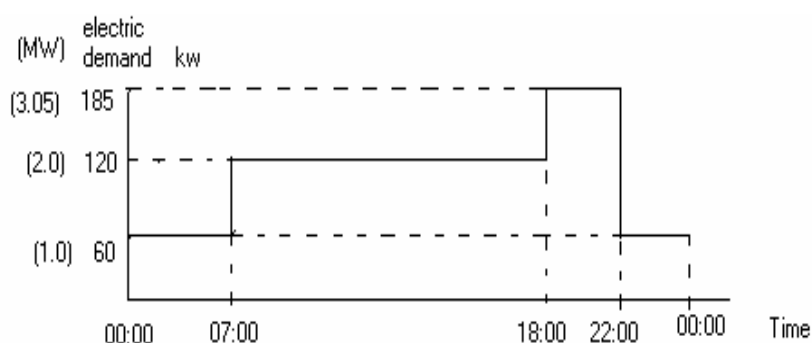


Figure 1. Electric demand profile

### 5.1 Base case i.e. without DER

#### 6-bus Radial system

The system is shown in Figure 2, where dotted lines indicate co-ordination among central controller (CC), loads controller (LC) and DERs controller (GC). Line data and bus data are shown in Table 1 and Table 2 respectively. Load flow results are shown in Table 4. System loss at peak demand of 185 kW is obtained as 12.2 kW, which is 6.59% of peak demand.

Like consumer demand loss is considered as the system demand to be supplied by the utility's generators. Therefore, its monetary value could be evaluated by utility's energy price of \$0.12/kwh. Daily energy lost due to line loss is 110.7 kWh and in terms of money \$ 13.284.

#### 14-bus system

Bus data and line data are shown in Table 2 and Table 3 respectively. Load flow results are shown in Table 4. System loss at peak demand of 3.05 MW is obtained as 293.3 kW, which is 9.62% of peak demand. Daily energy lost due to line loss is 2530.6 kWh and its monetary value is found 303.672 using the utility's energy price of \$0.12/kwh.

Table 1. Line data

Line No.	Start Bus	End Bus	R [p.u.]	X [p.u.]	B [p.u.]
1	1	2	0.01335	0.0421	0.0064
2	2	3	0.01938	0.05917	0.0264
3	3	4	0.0312	0.16	0.0282
4	3	4	0.0228	0.12	0.0071
5	3	5	0.0228	0.12	0.0071

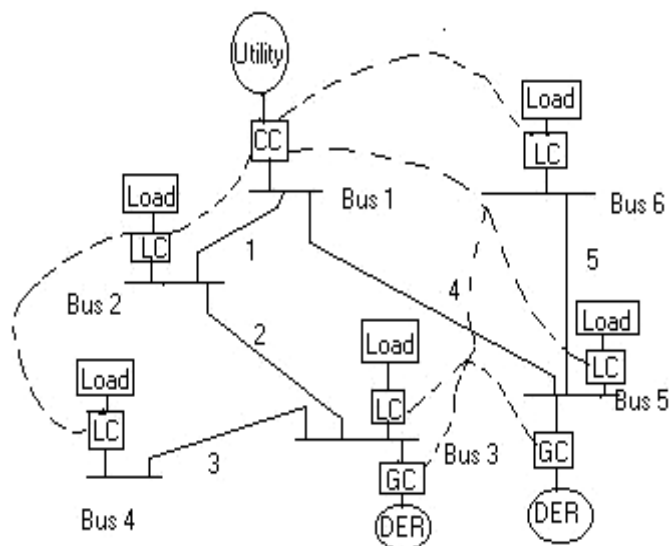


Figure 2. 6-bus radial micro-grid

Table 2. Bus Data

Bus No.	6-Bus System		14- Bus system	
	Real load demand, [kW]	Reactive load demand, [kvar]	Real load demand, [kW]	Reactive load demand, [kvar]
1	0.0	0.0	0.0	0.0
2	20.0	6.5	200.0	65.0
3	85.0	27.9	850.0	279
4	40.0	13.12	400.0	131.2
5	20.0	6.5	200.0	65.0
6	20.0	6.5	200.0	65.0
7	-	-	76.0	16.0
8	-	-	100.0	30.0
9	-	-	61.0	16.0
10	-	-	112.0	75.0
11	-	-	610.0	90.0
12	-	-	16.0	61.0
13	-	-	90.0	59.0
14	-	-	135.0	61.0

Table 3. Line data

Line no.	Start Bus	End Bus	R [p.u.]	X [p.u.]	B [p.u.]
1	1	2	0.011	0.0214	0.0045
2	2	3	0.011	0.0214	0.0042
3	3	4	0.0115	0.02211	0.0064
4	4	5	0.0127	0.0645	0.0
5	5	6	0.01538	0.05417	0.0
6	6	7	0.0224	0.092	0.0
7	6	8	0.03181	0.0545	0.0
8	7	9	0.0342	0.0917	0.0
9	2	10	0.0167	0.022	0.0085
10	10	11	0.0193	0.03417	0.0264
11	11	12	0.067	0.0817	0.0173
12	12	13	0.0549	0.0589	0.0
13	11	14	0.06135	0.0558	0.0

Table 4. Base case (5.1)

System	Load, kW	Line Loss, kW	Minimum Bus Voltage, p.u.	Maximum Line Flow, kW	Slack Bus Injection, kw
6-Bus Radial	185	12.2	0.8362	197.2	197.2
	120	4.76	0.9053	128.06	128.06
	60	1.06	0.9605	62.56	62.56
14-Bus Radial	3050	293.3	0.8085	3341.4	3341.4
	2000	100	0.8974	1990.0	1990.0
	1000	28.6	0.9536	1035.8	1035.8

### 5.2 Strategically deployed DERs

#### 6-bus system

As per LSI data (Figure 3), buses 3 and 4 have highest index value of  $-0.1424$  and  $-0.3494$ , but buses 3 and 5 are selected for DERs locations, as per reason given earlier. Terminal bus 4 is swapped with 5. In Figure 3, abscissa is shifted downward to accommodate both positive and negative LSI values. Results of simulation with DE are shown in Table 5 and with PSO in Table 6. With strategic deployment of DERs, voltage rise of 15.46%, loss reduction of 59.02%, and 79.41% line flow reduction happen at peak demand with respect to base case value. Due to line loss reduction, daily energy saving will be 78.5 kWh and corresponding monetary saving is \$ 9.42 with respect to base case value.

#### 14-bus system

On considerations of both LSI values (Figure 3) and reliability, as discussed earlier, junction bus numbers 2, 6, and 11 are selected as locations of DERs. Simulation results with DE (Table 5) are obtained at zero slack bus injection i.e. islanded condition and with PSO, results are shown in Table 6. Like 6-bus system, deployment of DERs strategically in the 14-Bus microgrid raise voltage by 17.5%, reduce line loss by 92.36% and reduce line flow by 57.16% at peak demand with respect to base case value. Loss reduction indicates that microgrid is almost a “No wires” solution to distribution system. Line flow reduction reduces internal congestion of the system. Again, voltage rise helps to maintain power quality of supply. Figure 4 indicates the voltage obtained with strategic deployment of DERs with respect to base case. Black bars indicate voltage at base case and white bars at DERs deployed case.

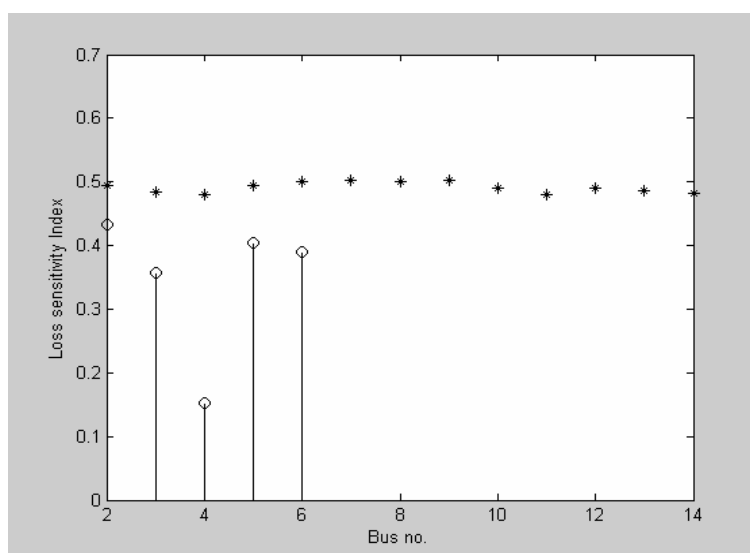


Figure 3. LSI Plot ('o' for 6-bus, '\*' for 14-bus)

### 5.3 Comparison between DE and PSO

Table 5 and Table 6 indicate that DE results are to some extent better than PSO in searching out the minimum loss. But what is noticeable in Table 7 is their iteration time. DE is much faster than PSO. Convergence characteristics of both DE and PSO are shown in Figure 5 and Figure 6 respectively with respect to 6-bus system. Within a few iterations DE reaches the convergence value.

Table 5. Results with DE – case (5.2)

System	Load, kW	Line loss, kW	Minimum Bus Voltage, p.u.	Maximum Line Flow, kW	Slack bus injection, kW
6-Bus	185	1.9	0.9656	40.84	0.0
	120	0.4	0.9788	27.23	0.0
	60	0.5	0.9909	15.55	0.0
14-Bus	3050	55.0	0.95	1201.5	0.0
	2000	1.6	0.95	828.7	0.0
	1000	1.5	0.9691	417.9	0.0

Table 6. Results with PSO – case (5.2)

System	Load, kW	Line loss, kW	Minimum Bus Voltage, p.u.	Maximum Line Flow, kW	Slack bus injection, kW
6-Bus	185	2.7	0.9656	40.77	0.0
	120	0.7	0.9788	27.24	0.0
	60	0.5	0.9909	13.45	0.0
14-Bus	3050	75.0	0.95	1207.7	0.0
	2000	6.6	0.95	829.0	0.0
	1000	2.1	0.9691	417.9	0.0

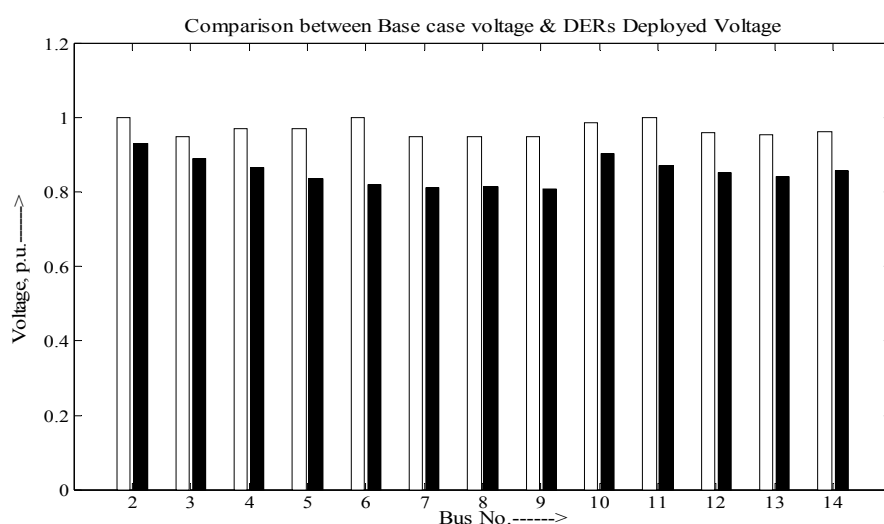


Figure 4. Voltage histogram for 14-bus system

Table 7. Results of DE & PSO – case (5.2)

System	Algorithm	Bus No.	Capacity of DERs at Load, kW			Elapsed time for 300 iterations, Secs.
			Peak Load	2/3 <sup>rd</sup> Peak	1/3 <sup>rd</sup> Peak	
6-Bus	DE	3	107.9	77.7	32.0	14.77
		5	79.0	46.0	30.0	
	PSO	3	107.7	83.0	36.0	20.16
		5	80.0	41.0	26.0	
14-Bus	DE	2	1300.0	724.1	513.2	115.4
		6	400.0	392.0	97.1	
		11	1405.0	915.5	406.2	
	PSO	2	1300.0	724.1	518.0	172.8
		6	420.0	397.0	97.8	
		11	1405.0	915.5	401.3	



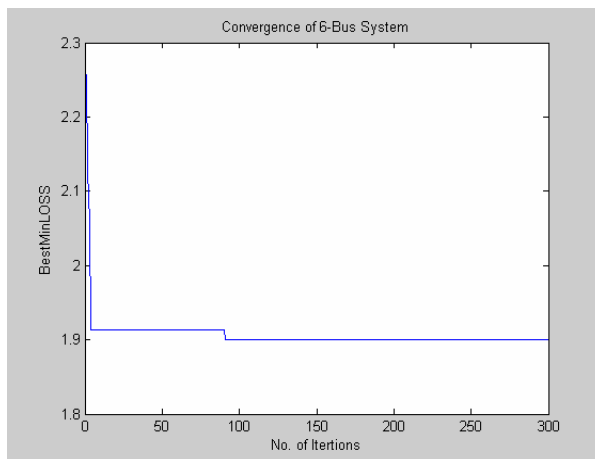


Figure 5. Convergence characteristics of DE – 6-bus system

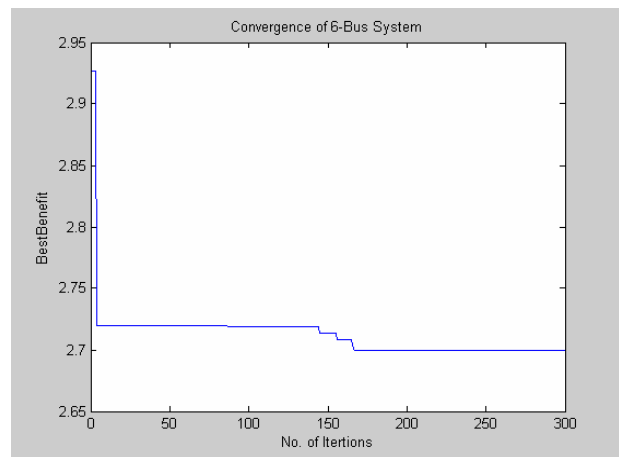


Figure 6. Convergence characteristics of PSO – 6-bus system

## 6. Conclusion

Energy management is concerned with cost saving endeavor in microgrid. Strategically deployed DERs have shown reasonable saving of cost in terms of network loss reduction. Owner of the microgrid who are the main instrumental to develop the distribution network and causing such huge saving, must be paid as an incentive for the return of their DERs investment. Voltage rise, line flow reductions are other dominant effect of DERs deployment shown in the results. Future work will be done to analyse microgrid addressing its other benefits. Results of both DE and PSO confirm each other, though DE shows slightly better minimum loss results. What is most attracting to DE is its iteration time much less than PSO.

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