Power loss minimization and voltage profile improvement of radial and mesh distribution network using sine cosine optimization based DG allocation

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Abstract

Due to the increasing population and emerging technologies, energy requirements are increasing progressively. Distributed generation (DG) is an excellent option to handle the increased power demand. A well optimized DG can help to reduce power losses, CO_2 emission and improve voltage profiles. This paper uses sine cosine algorithm to find the optimal location and best size ofDG with power loss minimization as its objective function. It presents the comparison of power loss reduction and voltage profile enhancement due to allocation of DGoperating at 0.85, 0.95 power factor lag andthe optimal power factor that has been obtained by sine cosineoptimization. IEEE 15, 69 bus radial and 33, 69 bus weakly meshed systems with five tie lines are used for power loss analysis. Annual energy saving due to allocating DG with different power factors have been analyzed. All the results are simulated in MATLAB 2021a.

*Keywords:*Distributed Generation (DG), Distribution System (DS), Sine Cosine Algorithm (SCA), Direct Load Flow (DLF), Loss Minimization.

1. Introduction

Electrical power system compromises of generation, transmission and distribution system (DS). A lot of research has been done on the generation and transmission side in the early stage of power system evolution. Researchers have been focusing on electrical power distribution systems (EPDS) for the last few decades because of very high losses associated with it. Transmission anddistribution (T&D) losses in India are about 20.66% of total generated power in FY 2018-19 (Executive summary on power sector,march2021). EPDS contributes about 70% ofT&D losses combining primary and secondary distribution systems(Ang et al., 2018).EPDS is mainly radial in nature due to its economic reason, or sometimes it may be meshed structure to increase its

reliability. Due to the radial nature of EPDS, voltage fluctuations and power losses at the end consumers are high. It is nearest to the consumer, so as a power system engineer, one has to take care of its reliability. All these problems can be tackled by the implementation of distributed generation (DG) in EPDS.

DG can be defined as a power generation unit with the maximum capacity of 50-100 MW which is typically connected to the distribution network near the consumer end(Acharya et al., 2006). In the EPDS, the placement of DG must be optimized to enhance reliability, power quality, voltage profile and reduce power losses. If the placement of DG is non-optimal, then it can increase the system loss, voltage regulation, harmonics and bring the system in instability (Prakash & Lakshminarayana, 2018). DG can be classified as renewable and non-renewable energy sources. By using renewable DG, greenhouse gas emissions can also be controlled, which will help to protect the environment. Different types of DG can be used according to the requirement like type I to type IV DG(Kansal et al., 2013).The optimized allocation of DG will reduce thetotal active power loss (TPL) and enhance the voltage profile.

The optimization is a tool to solve mathematical problems for obtaining minimum or maximum positions. Optimization algorithm can be deterministic or stochastic. Deterministic algorithm follows same procedure to solve any problem, solutions are repetitive in this, example newton method, gradient method, linear programming and quadratic programming. The stochastic approach defines a random variable and then stochastically work on the random variables to optimize the objective function, example bat algorithm, ant colony optimization and sine cosine algorithm. Sine cosine algorithm (SCA) was introduced by Syed Lili in 2016. It is a stochastic population-based optimization. SCA convergence rate is very high.

Various optimization methods have been already used to optimize the location and size of DG. Genetic Algorithm is used to find optimal location of DG in(Biswas et al., 2012; Singh et al., 2008). Artificial ecosystem-based optimization is used for optimal placement of DG in (Khasanov et al., 2020). Intelligent water drop (IWD) is used in (Rama Prabha et al., 2015). A novel transient search optimization (TSO) is used for DG allocation in (Bhadoriya & Gupta, 2021), grey wolf optimization is used for reducing power loss in (Ansari et al., 2020). Artificial bee colony algorithm is used in (Abu-Mouti & El-Hawary, 2011) for allocation of DG.

For optimal placement of Distributed Generation Bat algorithm is used in (Sudabattula & M, 2016) and a new Hybrid Genetic Dragonfly Algorithm is used in (Lakshmi et al., 2021). A hybrid GA-PSO algorithm is used in (Moradi & Abedini, 2012) for optimal placement of DGs. DG allocation in meshed is described in (Al-Sakkaf & AlMuhaini, 2018; Gupta, 2021).

SCA is used in this paper to optimize the location and size of DG for EPDS. The direct load flow (DLF) method was used for load flow analysis (LFA) (Teng, 2003). In section 2 sine cosine algorithm is briefly expounded. In section 3 problem formulation is mentioned, in section 4 simulations and results are given for this paper, finally conclusions are added in section 5.

2. Sine Cosine Optimization

Sine cosine optimization is a stochastic optimization technique.The main advantage of stochastic optimization is that it treats the problem as a black box, so it does not require an exact mathematical model for optimizing that problem. It is highly flexible, and it can optimize most problem with some modification. SCA is a population-based technique wherein, random solutions are generated stochastically and improves it according to equation (1) and (2).

$$X_i^{(t+1)} = \left\{ X_i^t + r_1 \times \sin(r_2) \times | r_3 P_i^t - X_i^t | \right\} r_4 < 0.5 \quad (1)$$

$$X_i^{(t+1)} = \left\{ X_i^t + r_1 \times \cos(r_2) \times | r_3 P_i^t - X_i^t | \right\} r_4 > 0.5 \quad (2)$$

Where,
$X_i^{(t+1)}$ is the solution in $(t+1)^{th}$ iteration
X_i^t is the solution at t^{th} iteration,
P_i^t is the best solution obtained so far,
r_1, r_2, r_3, r_4 are random variables,

3. Objective Function

The main objective is to find the optimal size and location of DG in the EPDS to minimize losses. DG can be placed at PV bus or PQ bus. At PV bus, DG helps to maintain voltage by providing variable reactive power to bus according to requirement and constant active power is given. At PQ bus DG helps to minimize power losses and improve voltages for the entire system by providing constant active and reactive power(Gallego et al., 2011).

Power loss can be calculated as

$$P_{loss} = I^2_{Branch} \cdot R \,(3)$$

$$Q_{loss} = I^2_{Branch} \cdot X \,(4)$$

Where,
R is resistance of that branch,
X is reactance of that branch.

Total active power loss (TPL) can be found out by adding all the power losses at each node.

$$Total_{Ploss} = \sum_1^n P_{Loss} \,(5)$$

$$Total_{Qloss} = \sum_1^n Q_{Loss} \,(6)$$

Where, n is total no. of nodes

For meshed distribution system (MDS) tie line losses are added in branch losses(Sharma & Murty, 2014),

$$P_{lossTie} = I^2_{tie} \cdot r_{tie} \,(7)$$

$$Q_{lossTie} = I^2_{tie} \cdot x_{tie} \,(8)$$

*3.1 Annual Energy Saving:*Annual energy saving (AES) is defined as net energy saving (KWh) in a year due to addition of DG. It can be expressed as

$$AES = [(TPL\ before\ allocating\ DG) - (TPL\ after\ allocationg\ DG)] \cdot T \,(9)$$

Where,
TPL= Total active power loss in KW,
T=8760 total time in hour in a year.

*3.2 Optimal Power Factor:*Optimal power factor can be found by generating a new parameter in SCA optimization as variable pf and run the algorithm given in Figure 1 for power loss minimization

$$0.80 \leq p.f\ limit \leq 0.90 \,(10)$$

3.3 Constraints

- *Voltage Constraints*: Voltage should not exceed the tolerance of ±5% of supply voltage.

$$0.95\ p.u. \leq V_i \leq 1.05\ p.u. \,(11)$$

- *Current Constraints*:Current constraints are made so that the temperature of the conductor should not exceed to already defined limit. The maximum current is defined as ten times the rated current in this paper.

$$I^k_i \leq I^{k,max}_i \,(12)$$

- *DG Constraints*: The voltage of applied DG must be under specified limit. The total size of DG should not exceed the maximum load on that system otherwise, instead of supplying power to the system, DG starts taking power from the system, and EPDS may go to instability(IEEE, 2003).

$$V^{min}_{DG} \leq V_{DG} \leq V^{max}_{DG} \,(13)$$

$$P^{min}_{DG} \leq P_{DG} \leq P^{max}_{DG} \,(14)$$

3.4 Algorithm for SCA

1. Read line and load data for the given system
2. Initialize all the parameters for SCA like population, maximum iteration, and number of DG, upper and lower limits of size, pf and location of DG.
3. Run the sine cosine algorithm(by using equation (1) and (2) it explores and exploits randomly)
4. Store totalactive power losses (TPL), size, pf and location of DG found out by step 3.
5. Algorithm compares TPL with previously obtained TPL, if the present value is minimum then it stores that value in X_{best} else move forward.
6. Update the population to the best result obtained so far, increase the number of iteration.
7. Run the algorithm until tolerance reached or maximum iterations have done.
8. End

The optimized DG size and location can be found by the following algorithm, which can reduce TPL and enhance the voltage profile. The complete flowchart for the following steps is given in Figure 1.
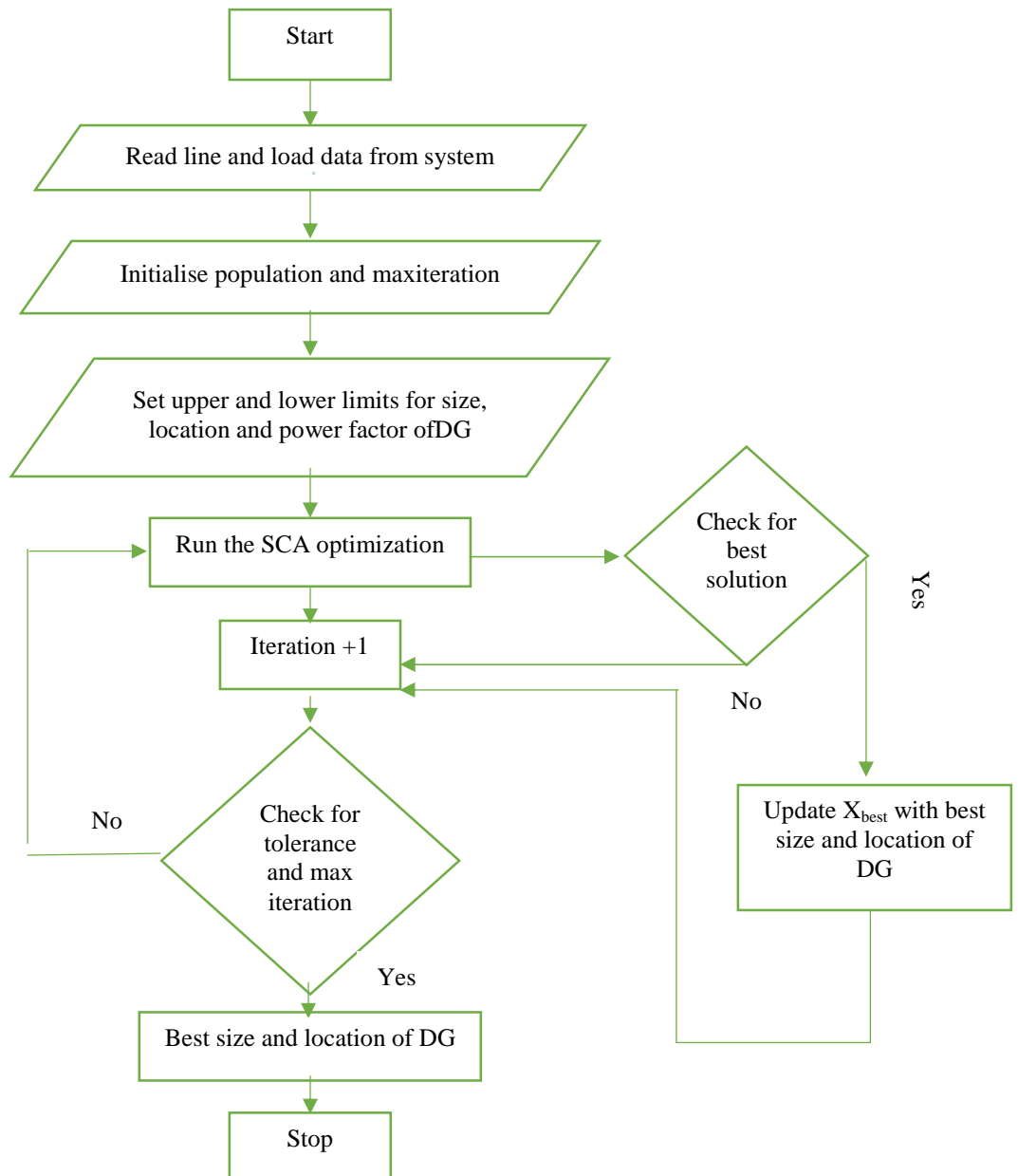
Figure 1: Flowchart for allocation of DG using SCA

4.Simulations and Results

In this paper, IEEE 15, 69 bus balanceRDS and 33, 69 bus weakly MDS are considered forallocation of DG operating at 0.85 and 0.95 pf lag. The bus system is taken base as 10 MVA and 11 KV. The line data, load data and network configuration is referred from (Das et al., 1995; Sharma & Murty, 2014; Sivanagaraju et al., 2005). The main objective of this paper is the analysis of power loss minimization with voltage profile improvements. SCA is taken with population size of 100 and 600 as maximum iterationfor optimization process. First bus is ignored for DG placement because it is a reference bus (PV bus).

4.1 Radial Distribution System:
15 bus system: Total active power loss (TPL) before implementing DG (base case) is 61.78 KW and total reactive power loss (TQL) is 57.28 KVAr. Voltage for six buses (5,11,12,13,14,15) come below the acceptable limit (0.95 p.u.). The impact of varying the pf value from 0.85 to 0.95 on voltage profile and TPL is shown in Figure2 and Figure3 respectively. Optimal pf comes out to be 0.80 lag. At optimal pf, a 1429 KVA DG at 3rd bus can reduce TPL to 12.46 KW. All the result values along with AES and % TPL savings are depicted in Table 1.

Table 1. Effect of DG at different pf on 15 bus RDS

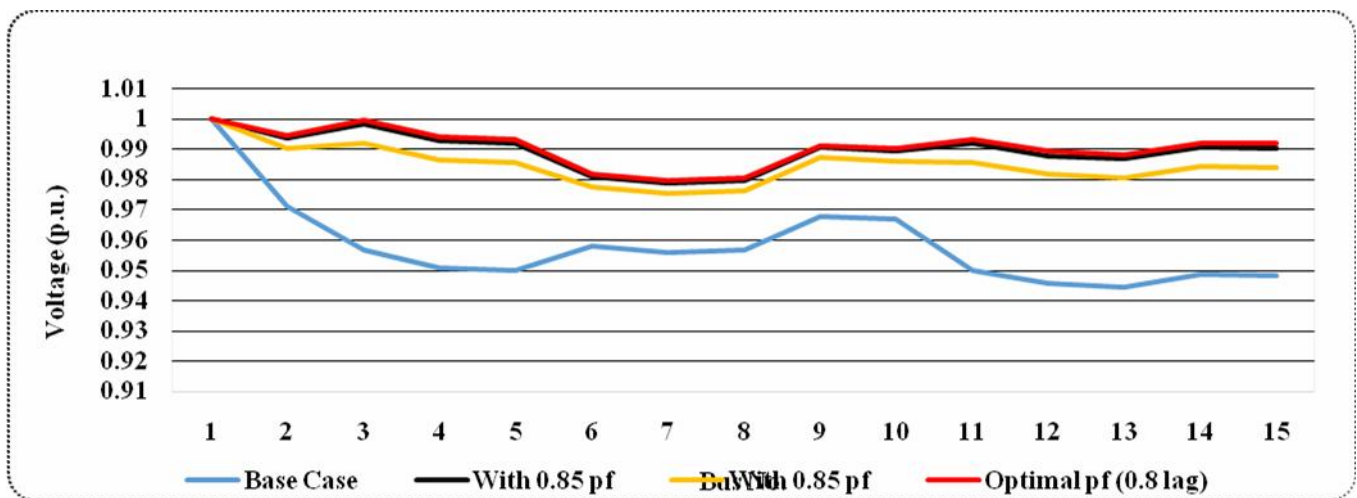|	Base Case	0.85pf	0.95pf	Optimal pf (0.80 lag)
Bus No.	-	3rd	3rd	3rd
Size (KVA)	-	1405	1289	1429
Min Voltage(p.u.)	0.9445 @ 13th	0.9787 @ 7th	0.9752 @ 7th	0.9795 @ 7th
TPL (KW)	61.78	17.24	24.12	15.76
TQL (KVAr)	57.28	13.90	20.61	12.46
AES (KWh)	-	390170.40	329901.60	403135.20
%TPL Savings	-	72.09	55.56	74.49

Figure 2. Effect on Voltage Profile of 15 bus RDS with DG at different pf
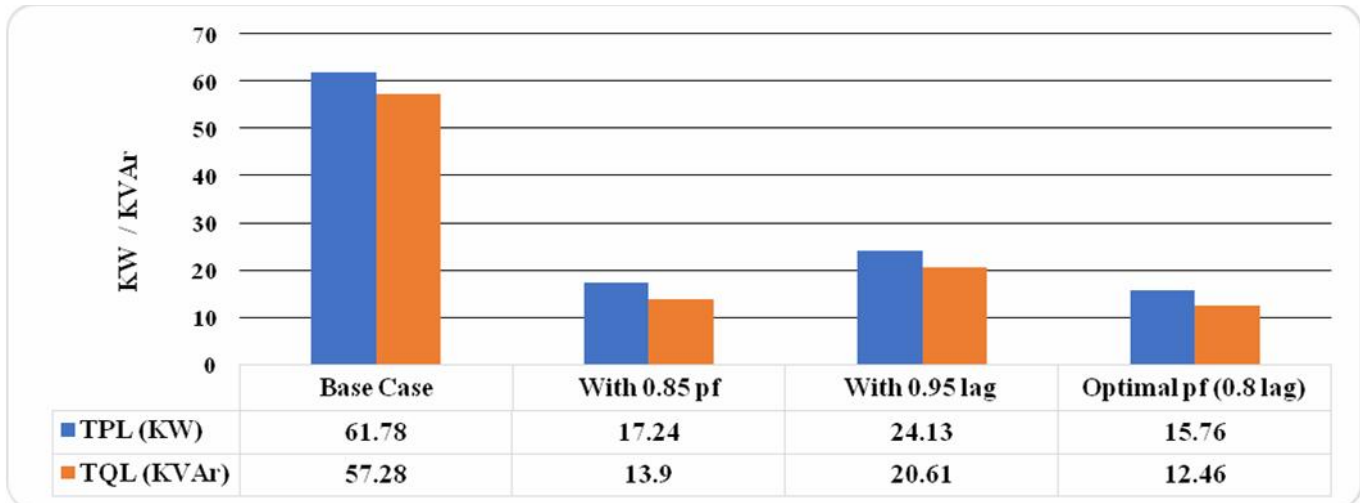
Figure 3. Effect on Power Loss of 15 bus RDS with DG at different pf

69 Bus System: TPL before implementing DG (base case) is 224.99 KW and TQL is 102.16 KVAr. Voltage for nine buses (57 to 65) come below the acceptable limit (0.95p.u.). The impact of varying the pf value from 0.85 to 0.95 on voltage profile and TPL is shown in Figure 4 and Figure 5 respectively.Optimal pf comes out to be 0.8139 lag. At optimal pf, a 2226 KVA DG at 61st bus can reduce TPL to 23.18 KW. All the result values along with AES and % TPL savings are depicted in Table 2.

Table 2. Effect of DG at different pf on 69 bus RDS

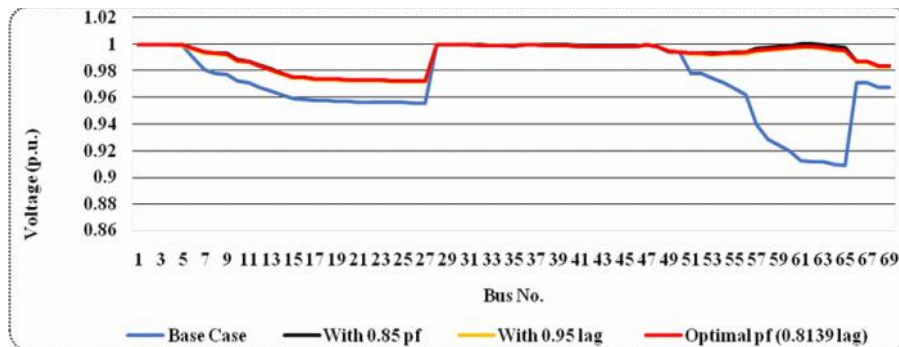|	Base Case	0.85pf	0.95pf	Optimal pf (0.8139 lag)
Bus No.	-	61st	61st	61st
Size (KVA)	-	2238	2157	2226
Min Voltage (p.u.)	0.9091 @65th	0.9725 @27th	0.9716 @27th	0.9723 @27th
TPL (KW)	224.99	23.86	38.41	23.18
TQL (KVAr)	102.16	14.68	21.01	14.41
AES (KWh)	-	1761898.80	1634440.80	1767855.60
%TPL Savings	-	89.39	82.92	89.69

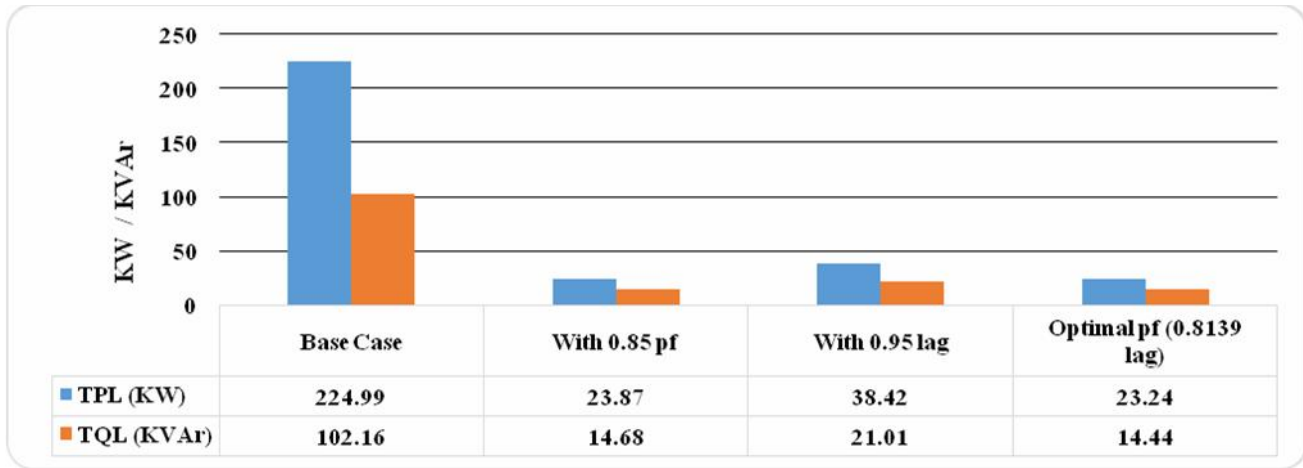**Figure 4.** Effect on Voltage Profile of 69 bus RDS with DG at different pf

Figure 5. Effect on Power Loss of 69 bus RDS with DG at different pf

4.2 Meshed Distribution System:

33 Bus System With 5 Tie Line: TPL before implementing DG (base case) is 241.71 KW and TQL is 171.25 KVAr. Voltage for no bus comes below the acceptable limit. The impact of varying the pf value from 0.85 to 0.95 on voltage profile and TPL is shown in Figure 6 and Figure 7 respectively. Optimal pf comes out to be 0.8198 lag. At optimal pf, a 3159 KVA DG at 6th bus can reduce TPL to 71.06 KW. All the result values along with AES and % TPL savings are depicted in Table 3.

Table 3. Effect on 33 bus MDS with DG at different pf

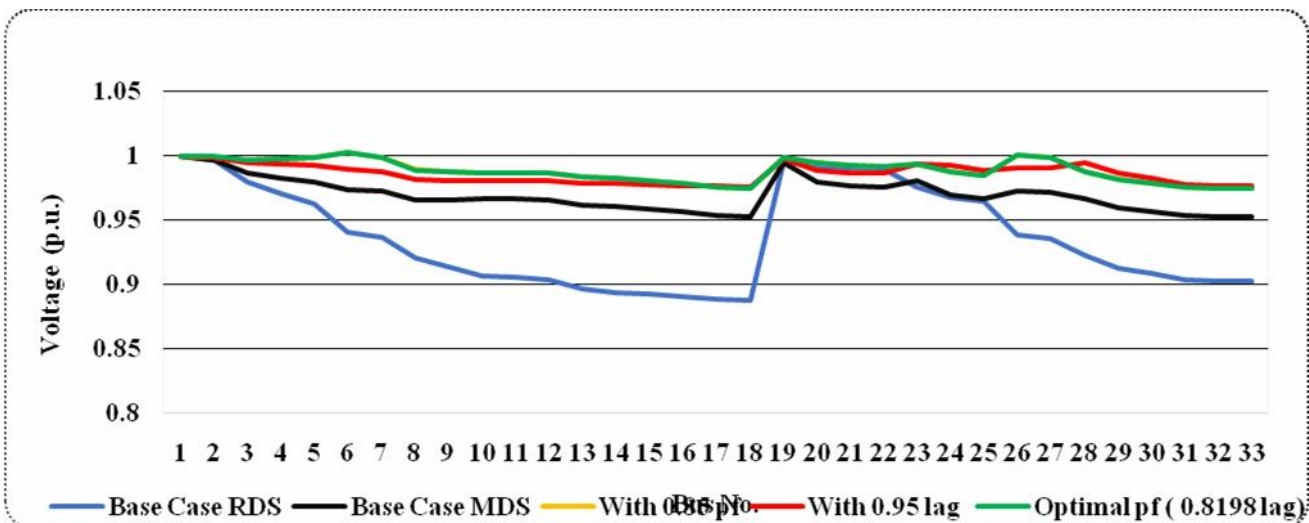|	Base Case	0.85pf	0.95pf	Optimal pf (0.8198 lag)
Bus No.	-	6th	28th	6th
Size (KVA)	-	3197	2589	3159
Min Voltage (p.u.)	0.9526 @33th	0.9743 @33th	0.9755 @18th	0.9741 @33th
TPL (KW)	241.71	71.50	80.87	71.06
TQL (KVAr)	171.25	58.99	63.62	58.60
AES (KWh)	-	14791477.60	14693969.40	1495279.40
%TPL Savings	-	70.42	66.54	70.62

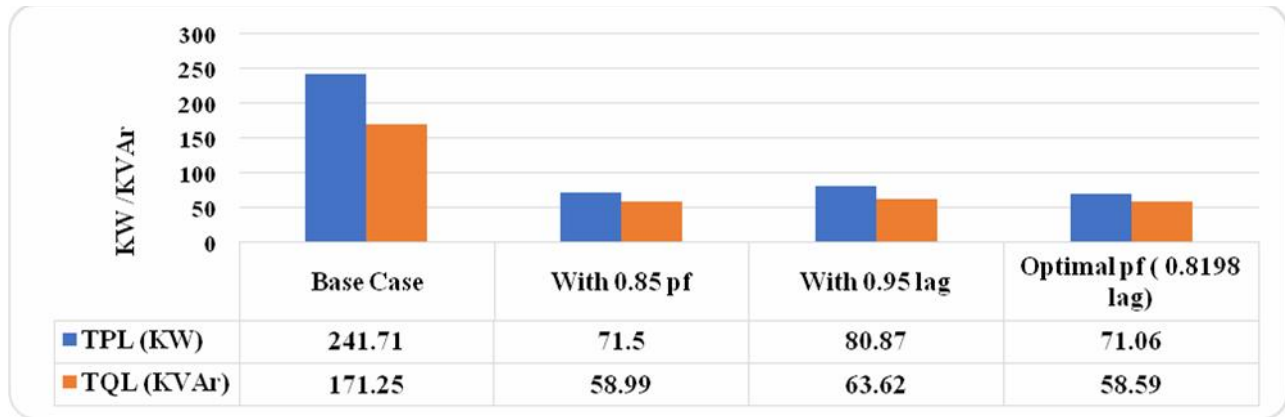**Figure 6.** Effect on Voltage profile of 33 bus MDS with DG at different pf

Figure 7. Effect on Power Loss of 33 bus MDS with DG at different pf

69 Bus System With 5 Tie Line: TPL before implementing DG (base case) is 205.96 KW and TQL is 110.34 KVAr. Voltage for no bus comes below the acceptable limit. The impact of varying the pf value from 0.85 to 0.95 on voltage profile and TPL is shown in Figure 8 and Figure 9 respectively.Optimal pf comes out to be 0.8389 lag. At optimal pf, a 2274 KVA DG at 61st bus can reduce TPL to 23.39 KW. All the result values with AES and % TPL savings are depicted in Table 4.

Table 4. Effect on 69 bus MDS with DG at different pf

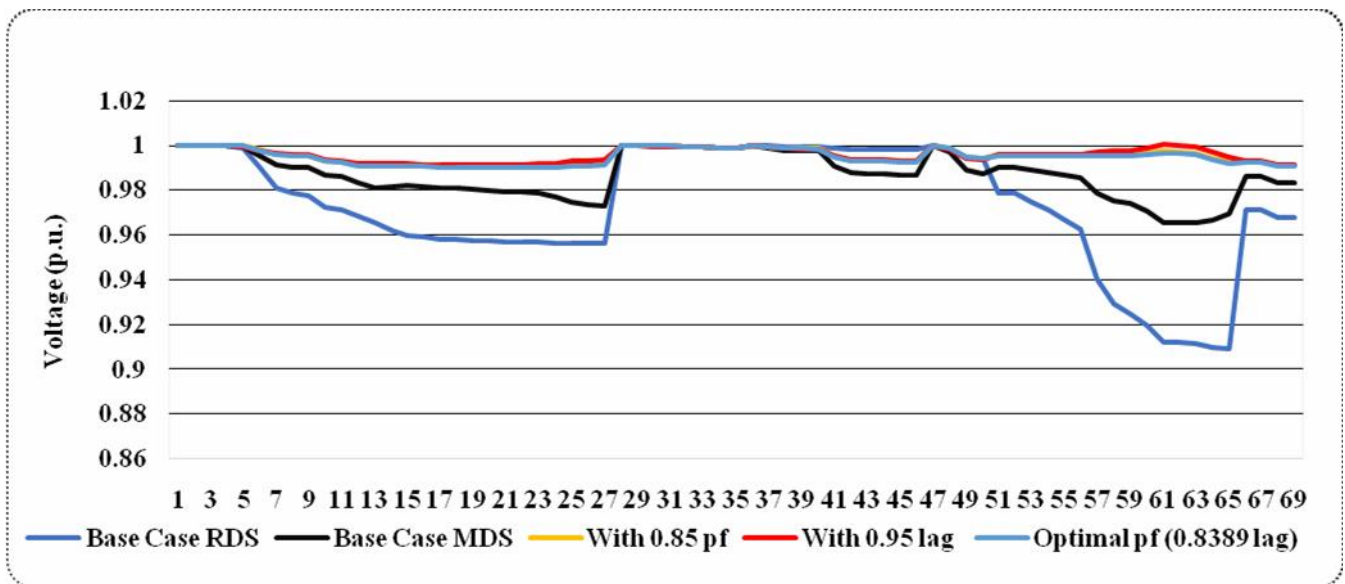|	Base Case	0.85pf	0.95pf	Optimal pf(0.8389 lag)
Bus No.	-	61st	61st	61st
Size (KVA)	-	2309	2606	2274
Min Voltage (p.u.)	0.9652 @61st	0.9907 @20th	0.9913 @18th	0.9905 @18th
TPL (KW)	205.96	23.47	32.52	23.39
TQL (KVAr)	110.34	15.46	18.72	15.58
AES (KWh)	-	1598901.50	1519246.80	1599313.20
%TPL Savings	-	88.60	84.21	88.64

Figure 8. Effect on Voltage Profile of 69 bus MDS with DG at different pf
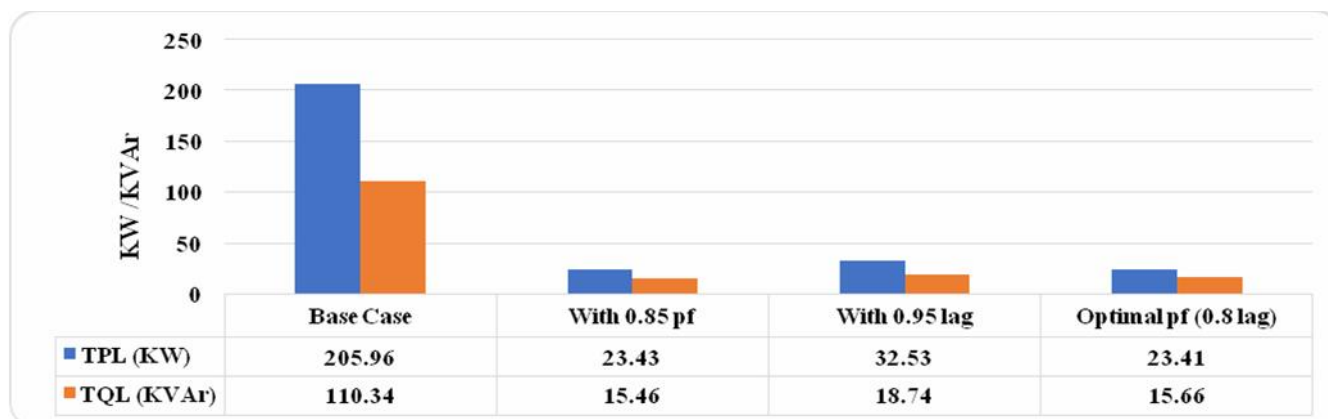
Figure 9. Effect on Power Loss of 69 bus MDS with DG at different pf

5. Conclusions

In this paper, Analysis of power loss minimization of IEEE 15 and 69 bus system in RDS and IEEE 33 and 69 MDS with single DG placement for 0.85 and 0.95 pf have been done. After implementing DG in different cases, power quality problems have been rectified. The voltage profile came within range and improved very well. Power loss reduction comparisons for different cases have been tabulated in Table 1 to 4, and the highest TPL reduction is for optimal pf found out by SCA optimization. Power loss and voltage profile have been compared with the base case (without allocating DG), 0.85 pf,0.95 pf and optimal pf lag for different bus system in RDS and MDS. In base case, voltage comes down to 0.91 p.u., but using DG with power factors, the voltage profile improved, as shown in the Figure 2 to 9. Annual energy saving for each case have been analyzed. The highest AES is coming with optimal pf. A weakly meshed network improves voltage profile and reliability. Voltage fluctuation in meshed network is much less than the radial system, but by using meshed network complexity of system increase, cost of feeders increases,finding fault locations will be difficult, and short circuit current in mesh DS is large. There is a trade-off between simplicity, reliabilityand voltage improvement.

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