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Maximization of System Loadability based Optimum Sizing and Placement of Multi-DG Units Simultaneously Using HPSO in Distribution System

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Abstract

In the future generation system, distributed generation (DG) is predicted to become more essential. Furthermore, the size and placement of DG unit that changes the flow of active and reactive power and its course in a power system will cause a significant impact on stability of bus voltages, losses of power, reliability and loadability. Maximization of the network loadability is key interest of this paper. After one DG Unit has been installed, various approaches based on sequential DG site selection cannot yield to the optimum result for peak loadability of the system. The paper presents an optimization process to determine the optimum sizing and allocation of multiple DG units simultaneously in a distribution network based on the maximizing the loadability. For multi-DG units, the optimization is carried out using a hybrid particle swarm optimization (HPSO) technique considering DG penetration level,current carrying capacity of ine and magnitudes of voltage as system constraints. Along with the financial analysis, the proposed algorithm is tested on a standard IEEE-33 radial distribution system. Results supports the necessity of simultaneous allocation of multi-DG units to ameliorate the loadability of distribution system.

Keywords

Distributed generation (DG), Hybrid Particle Swarm Optimization (HPSO), Loadability, Optimal size, Optimal location

1. Introduction

As a consequence of the use of emerging technologies and restructuring in the electricity industry, a new identity known as ”distributed generation (DG)” emerged on the power system. The DGs are sources of energy in the distribution network that are linked close to load centers [1]. The system’s power consumption is rising rapidly, leading the present transmission and distribution system infrastructure to become overburdened. The solution is to either upgrade the existing infrastructure (both generation and line capacity) or locally supplied the demand with the DG and incase of evacuation, upgrading the existing system [2]-[3]. The DG can be the active source of energy (Photo voltaic), reactive source of energy (synchronous compensators), source of active power but sink of reactive power (wind power) and source of both power (synchronous generators) [4]. The deployment of DG in distribution network has so many benefits than centralized generation system. Connecting DG units can have an effect on bus’s voltages, loadability margin, flow of power, quality of power, stability margin, dependability, and safety measures utilized in distribution networks [5]-[6]. The effect of DG integration in the system is also guided by the penetration level [7]. The optimize sizing and allocation of DG is crucial to get must return with least initial funding [8]. The usage of the DG technology is rapidly ascending in context of Nepal too as the consumer’s load is ascending exponentially [9].

Power demand in the system is growing as economy expands. As a result, distribution substation are working closer to the bounds of instability of the voltage as a consequence the reduction in loadability margin [10]. Many scholars have gone through the study of DG allocation and its consequence. To find the best position and capacity of DG in the distribution network, the Kalman filter approach is

presented [11].
The optimal locator index is a novel factor that uses power loss sensitivity to discover optimal placements in a systematic and effective manner. In [12], the authors also examined DG placement as a multi-objective problem in the fitness function, taking into account voltage stability, reduced power losses and improved load management. The DG sizing and placement problem is solved from distribution company viewpoints considering power loss, unsuccess rate of feeder, reliability and consumer's demand [13]. The use of DG is becoming more frequent, posing a challenge for maintaining power system voltage stability. To keep the voltage of the system stable, a novel placement approach for multi-DGs was developed based on Lyapunov exponent estimate in [14]. It has been found from the [15] that the best placement of DG ameliorates the power flow, voltage stability and many more. The effect of DG allocation in the loadability of the system is studied in [16]. The amount of load that can flow through a line without surpassing its restrictions is referred to as loadability. Heating margin, least point voltage, and stability at normal state are the limiting factors for line loading. In any case, the line loading must not exceed these restrictions [17]. The effect of DG's penetration level in the distribution system is briefly explained in the [18] and found that allocation must be in optimal manner. Also, in [19] the successive allocation of DG is investigated after first DG has been placed but this may not lead to the global optimum maximization of the loadability.This paper employs hybrid particle swarm optimization (HPSO) technique to evaluate best location and rating of multi-DG units, that is applied simultaneously in the network.

This paper is organized as follows: Section 2 review the DG placement and its effect in loadability. The execution of the suggested method is examined in Section 3. Section 4 discusses case studies to verify proposed algorithm. And section 5 summarized the paper.

2. DG Placement and its effect in loadability

The ability of power networks to connect maximum load in the networks without breaching system related limitations with regard to nominal rated capacity is referred to as loadability [19]-[20]. The loadability is directly related to the voltage of the system. Figure 1 show that the increasing the maximum loadability will improves the voltage of different buses. The overall voltages of network with the multi-DG implementation is better than in the base case scenario. Along with loadability the other parameters get improved after the implementation of DG units. Also, as shown in Figure 1, λ_1 and λ_2 are the corresponding loadability at Vmin for base case and with DG implementation scenario. The penetration level of DG is also key to effect the loadability of the distribution network [18]. Penetration level can be varied according to system benifit.

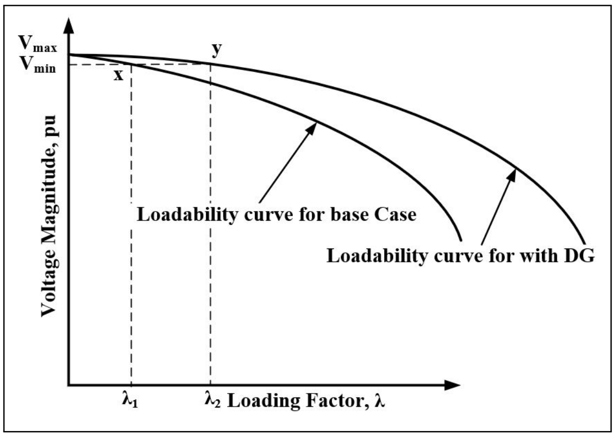

Figure 1: Voltage profile improvement with loadability

2.1 Penetration level of DG

The ratio of generation of DG to the total load provided by the DG is known as the DG penetration level as depicts in equation 1.It is varied from 0 to 100 percent.

$$Penetration\ level\ of\ DG = \frac{S_{DG}(KVA)}{S_{Load}(KVA)} \quad (1)$$

In above, $S_{DG}(KVA)$ is sum capacity of the DG units and $S_{Load}(KVA)$ is total load supplied in the system.

2.2 KVA margin to maximum loadability (KMML)

It is the extra reactive load that line can carry after from the loadability value λ_1 to extreme voltage point. The initial operating point refers to point x in base case and point y after the deployment of DG as shown in Figure 1.

2.3 Qualified load index improvement (QLI)

Reactive power deficiency in the system will cause the bus voltages to reduce from its allowable limit. It is always desirable to maintain the voltage of all buses within allowable limit. These indices will evaluate the performance of the system taking voltage and the power demand of all buses as input.

3. Methodology

The DG is considered to be synchronous generator type, which can provide both active as well as reactive power into the network. During placement of multi-DG, due to the multiple combination of position and size, the simple PSO mayn't give an optimal result. The maximum loading factor (λ_{max}) may be the same for one or multiple DG locations and sizes So hybrid PSO is proposed. As a result, a new hybrid matrix (H-matrix) variable containing the various parameters is defined in order to get the best DG placement as shown in equation 2.

$$\begin{bmatrix} X_{11} & X_{12} & X_{13} & \cdots & \lambda_{max1} & P_{loss1} \\ X_{21} & X_{22} & X_{23} & \cdots & \lambda_{max2} & P_{loss2} \\ X_{31} & X_{32} & X_{33} & \cdots & \lambda_{max3} & P_{loss3} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ X_{n1} & X_{n2} & X_{n3} & \cdots & \lambda_{maxn} & P_{lossn} \end{bmatrix} \quad (2)$$

In equation 2, X represents the size and position of the DG, λ_{max} is the maximum loadability, P_loss is the power loss incorporated in the network. These parameters are used in PSO to optimize the result as per requirement. The HPSO is the combination of continuous PSO, Discrete PSO and the H matrix parameters as shown in equation 2. The overall process overview is shown in Figure 2. The different blocks are evaluated sequentially to obtain the optimal results.

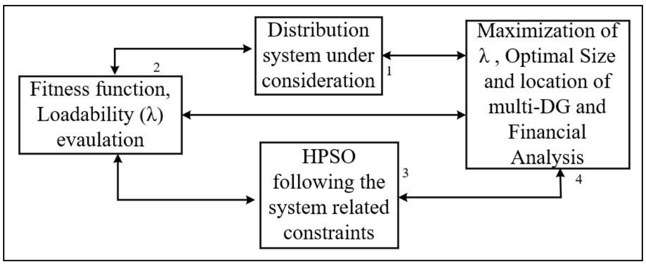

Figure 2: Overall process overview

3.1 Continuous Particle Swarm Optimization

PSO is worldwide utilized natural-inspired evolutionary metaheuristic optimization algorithms [21]. This approach is based on the intellect and mobility of swarms of animals such as birds, fishes, and other creatures. A swarm of n particles communicates with each other using search directions while flying across a search space to find a best solution in this optimization mechanism. Every particle changes its location based on its personal experience (pbest), global experience (gbest), and it's current velocity. The velocity and the position update are given with (3) and (4).

$$V_i(t+1) = \omega_t * V_i(t) + C_1 * r_1 \left(pbest_i - X_i(t)\right) + C_2 * r_2 \left(gbest_i - X_i(t)\right) \quad (3)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (4)$$

3.2 Discrete Particle Swarm Optimization

The binary form of PSO uses a particle's decision making using discrete decisions, such as "true" or "false." This method, unlike the continuous PSO, depicts each state of a particle as "0" and "1" number [19]. In the binary mode, velocity are articulate as the probability that a particle's outcomes will vary from "0" to "1". The range [0, 1] is so constricted. The sigmoid function is utilized to convert the output of the equation 5 into the velocity required for discrete PSO [21].

$$V_{ij}(t+1) = \omega_t * V_{ij}(t) + C_1 * r_1 \left(pbest_{ij} - X_{ij}(t)\right) + C_2 * r_2 \left(gbest_{ij} - X_{ij}(t)\right) \quad (5)$$

$$V'_{ij}(t+1) = sig\left(V_{ij}(t+1)\right) = \frac{1}{1+e^{-V_{ij}(t+1)}} \quad (6)$$

$$X_{ij}(t+1) = \begin{Bmatrix} 1 & if\, r_{ij} < sig\left(V_{ij}(t+1)\right) \\ 0 & Otherwise \end{Bmatrix} \quad (7)$$

In equation 3,4,5 and 6, "V" referes velocity, "X" is the position corresponds to particle, "C_1" and "C_2" refers to acceleration value, "r_1" and "r_2" are variables generated randomlay and that "ω_t" is the inertia constant. Equation 4 and 7 is used to update position of a particle. In equation 7, r_{ij} is the random number between 0 and 1, since it is the binary problem.

3.3 Objective function Evaluation

The objective is to evaluate the best capacity and location of the DG with maximization of the system loadability.

$$f = Max\{\lambda_{max}\} \tag{8}$$

In equation 8, f refers to the fitness function and (λ_{max}) refers to the system's maximum loadability. The loadability of the each buses are calculated based on algorithm shown in Figure 3. H-matrix is evaluated to optimize the result based on algorithm of Figure 4.

All the equation from 2 to 22 are used for this purpose. The active and reactive loads on all buses are found to obtain the system's maximum loadability or loading factor (λ_{max}) using equation 9 and 10.

$$P_{new} = P_0 \times Loading factor\,(\lambda_{max}) \tag{9}$$

$$Q_{new} = Q_0 \times Loading factor\,(\lambda_{max}) \tag{10}$$

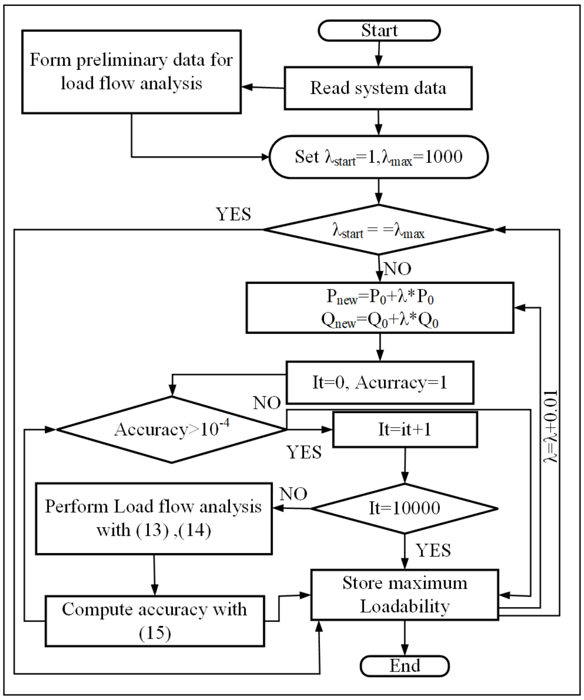

Figure 3: Flowchart for fitness function calculation of each bus

$$A(j) = P(m_2) * R(j) + Q(m_2) * X(j) - 0.5 * V(m_1))^{\frac{1}{2}} \tag{11}$$

$$B(j) = \{A(j) * A(j) - [R^2(j) + X^2(j)] *\} [P^2(j) + Q^2(j)]^{\frac{1}{2}} \tag{12}$$

$$V(m_2) = (B(j) - A(j))^{\frac{1}{2}} \tag{13}$$

$$\delta(2) = \delta(1) - \tan^{-1} \left[\frac{P(m_2) * X(j) - Q(m_2) * R(j)}{P(m_2) * R(j) + Q(m_2) * X(j) + V^2(m_2)}\right] \tag{14}$$

$$\varepsilon = V_i^k - v_i^{k+1} \tag{15}$$

$$LP(j) = \frac{R(j) * [P^2(m_2) + Q^2(m_2)]}{V(m_2)^2} \tag{16}$$

$$LQ(j) = \frac{X(j) * [P^2(m_2) + Q^2(m_2)]}{V(m_2)^2} \tag{17}$$

The overall distribution load flow is performed using equation 11 to 17, while evaluating λ .In equation 11 and 12, "j" is refered as branch number and "m_1" and "m_2" represents neighbouring bues. Equation 13 is the updated voltage and 14 calculate angle. Equation 15 evaluates the accuracy error. The active and reactive power loss is given by equation 16 and 17.

3.4 Implementation of algorithm for DG size and location

To maximize equation 8, the optimal capacity and location of DG is evaluated using the algorithm explained Figure 3. The Continuous PSO is used to evaluate size and discrete PSO is used to calculate position. Also, H-matrix is utilized to sort out the loadability corresponding to minimum loss following constraints shown in equation 18, 19, 20, 21 and 22.

$$0 \leq \sum_{k=1}^{n} P_{DG} \leq \sum P_{load} \tag{18}$$

$$2 \leq DG\ positions \leq n_{buses} \tag{19}$$

$$Pos_{DG1} \neq\ Pos_{DG2} \neq\ Pos_{DG3} \tag{20}$$

$$I_{DG}^i < I_{limit}^i \tag{21}$$

$$0.95 \leq V_{bus}^{k} \leq 1.05, \;\; where\ k = 1\ to\ n_{bus} \qquad (22)$$

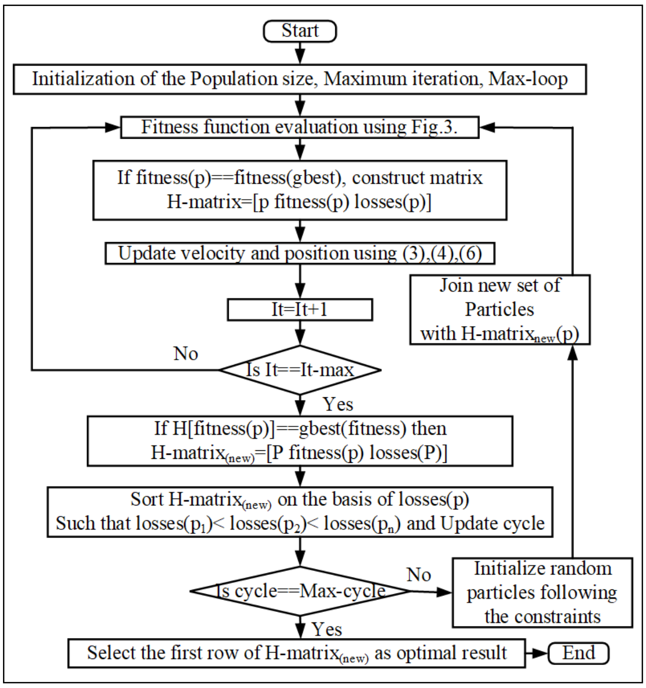

Figure 4: Flowchart of proposed HPSO algorithm

The amount of power delivered by DG should be less than load as depicts in equation 18. The equation 19 shows that position of DG should be in the bus other than substation. Also, the location of multi-DG shouldn't be in same bus as shown in equation 20. The branch current and bus voltage requirement are depicted in equation 21 and 22. The position and the size of DG is sort on the basis of maximum loadability and minimum loss. Each particle's velocity and location are updated using equations 3,4 and 6. The particle refers to the capacity and site of DG. The DG placement evaluation indices are given in Table I. The subscript '0' represents the value in base case and subscript '*DG*' represents the value after implementation of DG. Also, V_i and L_i means the voltage and power demand of i^{th} bus.The population size is taken 500 and also maximum iteration is 1000.

Table 1: DG placement evaluation indices

Index	Evaluation
$P_{lossreduction}$	$\frac{Re\{loss\}_0 - Re\{loss\}_{DG}}{Re\{loss\}_0} \times 100$
$Q_{lossreduction}$	$\frac{Imlosses_0 - Imlosses_{DG}}{Imlosses_0} \times 100$
QLLI	$\frac{(\sum_{i=1}^{n_{bus}} V_i L_i)_0 - (\sum_{i=1}^{n_{bus}} V_i L_i)_{DG}}{(\sum_{i=1}^{n_{bus}} V_i L_i)_0} \times 100$
$\lambda_{improvement}$	$\frac{\lambda_{max(0)} - \lambda_{max(DG)}}{\lambda_{max(0)}} \times 100$
KMMLI	$\frac{KMMLI_0 - KMMLI_{DG}}{KMMLI_0} * 100$
Voltage Improvement	$\sum_{i=1}^{n_{bus}} (V_{i(0)} - V_{i(DG)})^2$

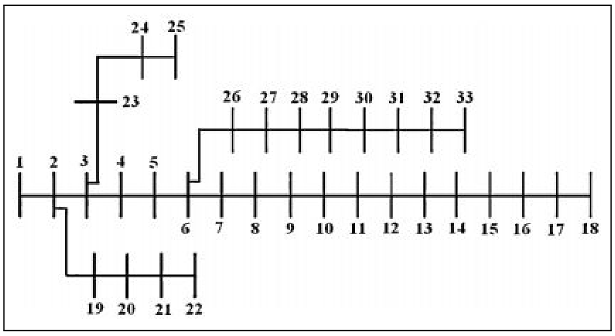

Figure 5: IEEE 33 radial bus test system

3.5 Financial analysis of the DG Placement

The proposed capacity of DG is assumed to be operated in full capacity or penetration level as stated in equation 1. The initial investment of the DG is assumed to be 20,00,000 dollar per MW. The plant load factor is considered to be 0.6357 with given load pattern [22]. The power loss reduction is calculated from the data obtained from Table 1. The energy generated per day by the DG unit is calculated using equation 23. The cost of electricity per unit (C_{el}) is assumed to be 0.094 dollar per KWH [9]. The annual income of DG is evaluated using equation 24. The operation and maintenance cost is given by equation 25, which is approximately equal to 5% of the cost of installation, shown in equation 26. The Environmental cost is given by equation 27 and it is assumed that cost of emission is 1% of the DG installation cost. The cost of depreciation is equivalent to the 5% of the cost of installation as given by equation 29. Similarly, equation 30 and 31 are used to evaluate the final income from the DG. The total study period is 20 years with discounted rate of 10% is assumed.

$$DG_{kWh} = Capacity_{DG} \times Plant\ LF \times 24 \qquad (23)$$

Where, DG_{kwh} is the energy generated by DG and LF is load factor.

$$\mathrm{DG_{aincome}} = \mathrm{C_{el}} \times 365\left(\mathrm{DG_{kWh}} + \mathrm{LF} \times 24\right) \quad (24)$$

Where, $DG_{aincome}$ is energy generated by DG in a year.and C_{el} is per unit cost of electricity.

$$C_{O\&M} = C_{omDG} \times \mathrm{DG}_{kWh} \times 365 \quad (25)$$

Where, C_{OM} is operaion and maintenace cost of DG. and C_{omDG} operation and maintenance is cost per unit energy.

$$C_{DGinst} = \mathrm{Capacity}_{DG} \times C_{capital} \quad (26)$$

Where, C_{DGinst} is the initial investment on DG and $C_{Capital}$ is the capital DG's cost per MW.

$$C_{En} = \mathrm{DG}_{kWh} \times C_{emiscost} \times 365 \quad (27)$$

Where, C_{En} environmental emmission cost of DG and $DG_{kwhemiscost}$ is per kwh emission cost in a day.

$$C_{Outage} = \mathrm{C}_{DGinst} \times R_{outage} \quad (28)$$

where,C_{Outage} is outage cost of DG. $DG_{aincome}$ is the annual income of the DG.

$$C_{dep} = R_{dep} \times C_{DGinst} \quad (29)$$

where,C_{dep} is depreciation cost of DG. R_{dep} is rate of depreciation.

$$\mathrm{DG}_{incomebtax} = \mathrm{DG}_{annincome} - C_{O\&M} - C_{Outage} - C_{dep} - C_{En} \quad (30)$$

Where,$DG_{incomebtax}$ is income from DG before implementation of tax.C_{OM}, C_{Outage}, C_{dep} and C_{En} are calculated above.

$$\mathrm{DG}_{incomeatax} = \mathrm{DG}_{incomebtax} - R_{tax} \times \mathrm{DG}_{incomebtax} \quad (31)$$

Where,$DG_{incomeatax}$ is income from DG after implementation of tax.

4. Results and Discussion

The proposed process is tested in three phase, 12.66 kV, IEEE-33 standard test bus system as given in Fig.5. The exploration is performed before and after implementation of single and multi-DG units in the feeder. The performance indices are evaluated and also financial analysis is performed to carried out the effectiveness of the proposed algorithm.

4.1 IEEE-33 bus radial bus test system

The radial test feeder has base load of 3715 kW and 2300 KVAr. From the distribution load flow before adding DG units, total of 0.2027 MW of real power and 0.132 MVAr of the reactive power loss is incorporated, i.e., total apparent power loss of 0.2418 MVA is incorporated. The voltage is minimum at bus number 18 with magnitude 0.9131 pu. There is total 21 number of bus violating equation 22. These factors get ameliorated after allocation of single and multi-DG units in the networks. From the mechanism, single DG's size is found to be 3574.6 KVA and location is at bus number 9. Also from multi-DG unit placement, the size and location of two DGs are found to be 1237.5 KVA at bus 15 and 1908.4 KVA at bus number 25 respectively. Which are placed in the network simultaneously. Also, in the case of three DG, the size and location are found to be 652.3 KVA at bus 30, 1452.2 KVA at 18 and 1567.98 KVA at bus 21 respectively. Similarly, all three DGs are paced simultaneously in the network. With implementation of the proposed algorithm, the losses get diminished with compared to the base case scenario. The QLI, KMMLI, loadability and the voltage of the all buses are also improved calculated with Table 1. The number of busses violating equation 22 becomes zero. The result of evaluation indices are shown in Table 2.

Table 2: Performance Indices of algorithmn in IEEE-33 Bus

Case	Base	Single DG	2 DG	3 DG
Size, KVA (Bus no.)	**	3574.6 (9)	1237.5 (15) 1908.4 (25)	652.3 (30) 1452.2 (18) 1567.98 (21)
P_{loss} (MW)	0.202	0.18	0.10	0.09
Q_{loss} (MVAr)	0.132	0.101	0.085	0.071
λ_{max}	3.623	4.860	5.638	5.643
KMMLI, KVAr	1342 7.04	1425 0.09	1902 3.04	1992 3.02
QLI	0.353	0.431	0.448	0.496
No. bus voilating voltage (NBVV)	21	0	0	0

The overall voltage profile in four various scenario is depicted in Figure 6. It is found that the different bus voltages are within the limit after implementation of single and multi DG units. Also, the loadability (λ_{max}) curve of the system for all three different cases is shown in Figure 7. The loadability at the base case scenario is found to be 3.623. After the implementation of single DG unit, the (λ_{max}) of the system is increased to 4.8604.

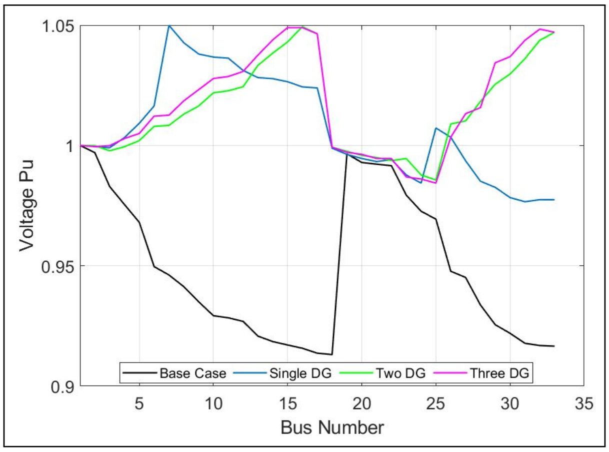

Figure 6: Voltage of each bus before and after implementation of DG

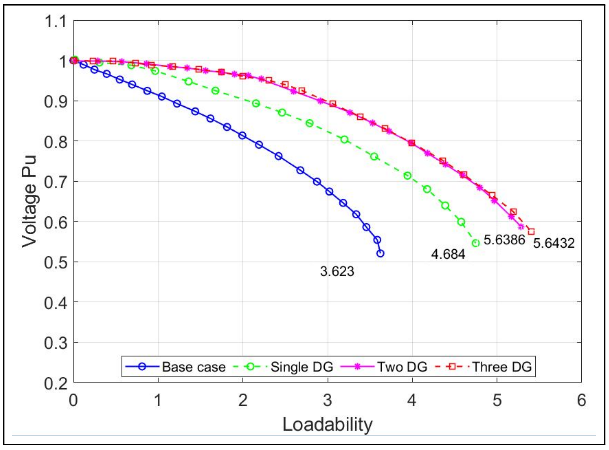

Figure 7: Loadability Curve of system for base case, single, double and triple DG Units

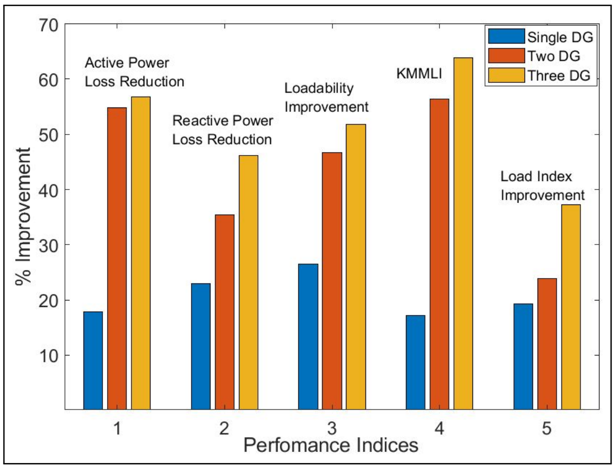

Figure 8: Improvement in the performance indices in presence of single, double and triple DGs

Also, after implementing two DG simultaneously, the maximum loadability(λ_{max}) is increase to 5.6386, which is almost double than in the base case scenario. Again, in the case of the three DG implementation the maximum loadability(λ_{max}) is found to be 5.6432. which is not that much larger than in the case of two DG case. So, it is economical to place simultaneous double DG sets in the network. The summary of the percentage improvement in the various indices with one, two and three DG implementation cases are shown in the Figure 8. The indices shown are MW loss reduction, MVAr loss reduction, loadability improvement, KMML improvement and QLI improvement. The financial analysis of the system after implementations of DG is shown in the Table III. It is found that payback period of implementing single DG unit of capacity 3574.6 KVA placed at bus number 9 is 5.284 years, which also incorporate the benefit from the loadability(λ) improvement. The payback period of incorporating simultaneous two DG with capacity 1237.5 KVA at bus 15 and 1908.4 KVA at bus number 25 is 3.139 years. While in case of three DG implementation, the payback period is 3.575 years, which is greater than in two DG implementation case. It is found that from the loadability improvement and payback period result it better to place two DG sets simultaneously instead of the three DG sets.

Table 3: Financial evaluation of DG placement

NO. OF DG	1	2	3
DG_{Cap},MW	3.038	2.674	3.509
Generation Kwh/day	46451.21	40880.34	53651.37
L.Loss Reduction, KW	40.2	123.1	127.58
DG Annual income, $	1914426.3	2384603.5	2858515.6
Inst. Cost, $	6076820	5348030	7018756
OM Cost, $	303841	267401.5	350937.8
Depreciation Cost, $	303841	267401.5	350937.8
Environmental Cost, $	60768.2	53480.3	70187.56
Outage Cost,$	60768.2	53480.3	70187.56
Income before tax,$	1185208	1742839.9	2016264.93
Income after tax, $	1125947.59	1655697.96	1915451.68
Income with Loadability improvement$	24000	48000	48000
Pay back Period, Years	5.284	3.139	3.575

5. Conclusion

This paper presented maximization of loadability based the simultaneous multi-DG unit placement in the distribution feeder in optimum manner. The proposed algorithm helps to optimize the capacity and allocation of the DG sets in IEEE 33 standard radial distribution test system. The optimize sizing and siting are investigated for single, two and three DG case scenario. The loss, maximum loadability, Bus voltages profile, KMML and QLI are analyzed. These indices are found to be improved and are within the desirable range after the implementation of DG. Also, the financial analysis is performed which also incorporate the benefits from the loadability improvement. The analysis is performed for 20 years period and it is concluded that the distribution company will get benefited from the implementation of DGs in the distribution network with maximization of system lodability.

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