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Optimal Placement and Sizing of Grid-Tied SPV for Power Loss Reduction and Voltage Profile Improvement

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Abstract

Non-optimal placement and sizing of solar photovoltaic (SPV) system results in minimal gain from the SPV as a distributed generator. Operation of SPV at unity power factor (PF) results in supply of active power only from the SPV whereas reactive power supply is supplied from the feeder hence line losses due to reactive power flow. In this paper, particle swarm optimization (PSO) has been used to optimize location, size and PF of SPV with the aim of minimizing power loss and improving voltage profile. First, the SPV generator is optimally located and sized at a unity PF and then the power loss and voltage profile are monitored. Using the optimal SPV generator, the optimal PF is obtained based on the power loss. Matlab software is used for simulation, IEEE 33-bus test system and Backward forward sweep method is used in carrying out power flow. When the SPV is optimized at unity PF, there is significant power loss reduction and voltage profile improvement. However, when the SPV is optimized at an optimal PF, power loss reduction is enhanced and the voltage profile improves further.

Keywords: Backward forward sweep method, Particle swarm optimization, Power factor, power flow, Solar photovoltaic.

I. INTRODUCTION

Distributed generation (DG) is production of power close to load centers. DG integration to the grid has been increasing due to the following reasons: First, most resources used in DG are renewable energy resources, hence, there is no emission of greenhouse gases. Second, DG leads to deferral in investment on transmission and distribution network. Third, DG helps in improving power quality and power system reliability through reduction of power losses. Fourth, DG helps in diversification of energy generation. Fifth, DG promotes competition in the electricity market [1]. Some of the distributed generation technologies are: solar photovoltaic (SPV) systems, wind turbines, micro-hydro turbines and fuel cells.

SPV as a DG generates power close to the loads and therefore enhances reduction in distribution losses and improves the voltage profile. However, this is true up to some level of DG penetration above which, power losses start increasing [2]. Grid-tied SPV systems are connected to the grid either in the distribution or the transmission level through the inverter. The inverter converts DC power from solar PV modules to AC power. The AC power from the inverter can be transferred either to the loads or to the grid [3].

Integration of SPV to the grid can have positive or negative impacts depending on the size and location of the solar photovoltaic system [4]. Integration of SPV to the grid has an impact on the voltage and current profiles, the power factor of the system, power system reliability, power quality and power system protection. The extent of the impact of solar PV system on the various issues depends on the location and the penetration levels of SPV generators [5].

The power system cannot be completely efficient; however, it can be optimally operated to minimize these losses [6]. SPV generator can be installed at the distribution network to facilitate in the reduction of distribution losses. The ability of SPV to help in power loss reduction in power systems is limited by the SPV penetration. To enjoy the benefits of SPV as a DG, the SPV integration should be optimally located and sized.

Research on optimal placement and sizing of SPV has attracted interest from a number of researchers. In [7], approximate reasoning was used for optimal location and sizing of SPV to minimize power loss and maintain the voltage profile. The SPV system was optimized for active power injection at the node of connection. Authors in [8] proposed optimal placement and sizing of SPV system to improve efficiency of a rural electricity power supply using Hybrid Optimization of Multiple Electric Renewables (HOMER) based technique. Using these techniques, the solar PV was optimally located and sized to supply active power and therefore help in power loss reduction and voltage profile improvement. In reference [9], Particle Swarm Optimization (PSO) was employed for optimal placement of solar PV in the distribution network for power loss reduction. The solar PV was operated at unity power factor and therefore, providing active power only. In [10], authors employed binary particle swarm optimization in distribution systems to determine optimal number and size of solar PV units on a radial distribution system. The analysis of the system was done using active power injected and power loss per annum. Refence [11] presents optimal placement and sizing of SPV considering load ability index considering that the SPV injects active power only. Authors in [12] used GA for optimization of location and size of DG to minimize power loss. All these researches considered the SPV as an active power generator only.

Further, research on optimal sizing and location of SPV have assumed that the inverter can only generate active power, therefore, the power factor is assumed to be unity. The focus has been to identify optimal size and location; however, inverters have the ability to produce both active and reactive power. In this paper, a method is proposed that optimizes the power factor of an SPV in addition to the optimal location and sizing considering that the SPV system generates both active and reactive power through the help of inverters. The research therefore goes a step further to identify an optimal power factor for grid-tied SPV in addition to optimal size and location with the aim of reducing the power loss and improving the voltage profile. The proposed method uses particle swarm optimization (PSO) technique in the optimization process.

II. RESEARCH METHOD

II.I Problem Formulation

Optimal location and sizing of solar PV systems can lead to reduced power losses and enhanced voltage profiles in distribution networks. In this paper, a method based on particle swarm optimization to determine the optimal location, size and power factor of a grid-tied solar PV generator, is presented.

The problem formulation is based on a radial distribution network with one feeder and n buses as shown in Fig. 1 [13]. In this line diagram, v_0 and v_n are the sending end and receiving end bus voltages, and v_k is the voltage at bus k, $k = 1,2,3, \ldots, n$.

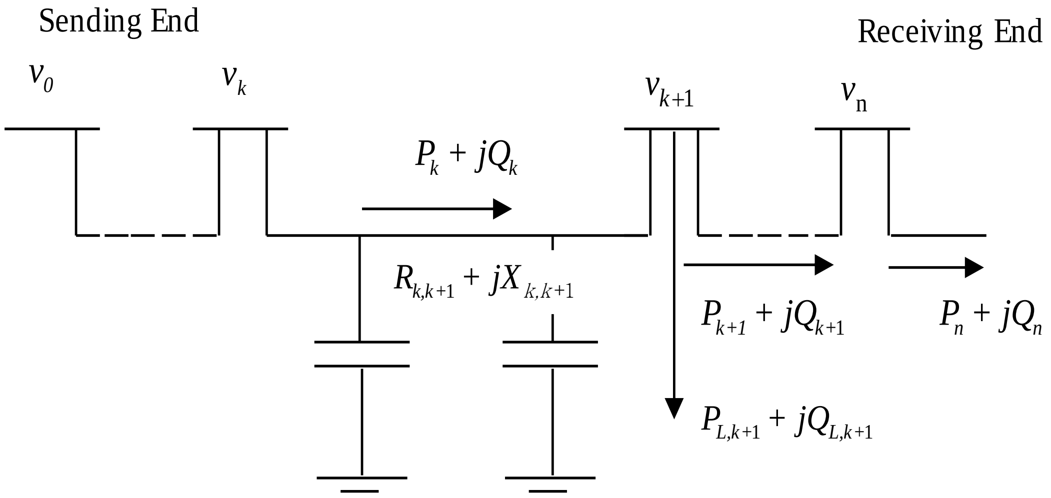

Fig 1: Single line diagram of a distribution network

The real and reactive power flowing out of bus $k + 1$ can respectively be calculated as per equation 1 and 2.

$$P_{k+1} = P_k - P_{Loss,(k,k+1)} - P_{L,k+1} \tag{1}$$

$$Q_{k+1} = Q_k - Q_{Loss,(k,k+1)} - Q_{L,k+1} \tag{2}$$

where P_k and Q_k are active and reactive power flowing out of bus k, respectively. $P_{Loss,(k,k+1)}$ and $Q_{Loss,(k,k+1)}$ are the active and reactive power losses between bus k and bus $k + 1$, and $P_{L,k+1}$ and $Q_{L,k+1}$ are the real and reactive load power demands at bus $k + 1$, respectively. The line losses between bus k and $k + 1$ are calculated as follows:

$$P_{Loss,(k,k+1)} = R_{(k,k+1)} \frac{P_k^2 + Q_k^2}{V_k^2} \tag{3}$$

$$Q_{Loss,(k,k+1)} = X_{(k,k+1)} \frac{P_k^2 + Q_k^2}{V_k^2} \tag{4}$$

where $R_{(k,k+1)}$ and $X_{(k,k+1)}$ are the resistance and reactance between bus k and bus $k+1$ respectively. Total active power lines losses $P_{T,Loss}$ and reactive power line losses $Q_{T,Loss}$ are the sum of all lines losses in the system as given by equation 5 and 6 respectively.

$$P_{T,Loss} = \sum_{k=1}^{n} R_{(k,k+1)} \frac{P_k^2 + Q_k^2}{V_k^2} \tag{5}$$

$$Q_{T,Loss} = \sum_{k=1}^{n} X_{(k,k+1)} \frac{P_k^2 + Q_k^2}{V_k^2} \tag{6}$$

The objective function to be minimized for optimal power losses (denoted by F) is given by

$$F = P_{T,Loss} = \sum_{k=1}^{n} R_{(k,k+1)} \frac{P_k^2 + Q_k^2}{V_k^2} \tag{7}$$

II.II Particle swarm optimization technique

Particle swarm optimization technique is a metaheuristic algorithm developed by Dr. Eberhart and Dr. Kennedy in 1995 and it is inspired by social behaviour of animals like bird flocking or fish schooling [14]. Particles are potential solutions to the problem being optimized, thus, starting from the randomly distributed particles, the algorithm tries to improve the solution according to a particular objective function.

PSO works on two principles: communication and learning. The algorithm contains a population of candidate solutions called a swarm of particles and every particle is a candidate solution to the optimization problem in question. Any particle has a position in the search space of the optimization problem where the search space is a set of all possible solutions of the optimization problem. PSO tries to determine the best solution amongst these possible solutions through exploitation and exploration. Exploration makes the search algorithm to move towards its global optimum whereas exploitation makes the search algorithm to move towards a local optimum. To get better results, there should be balance between exploration and exploitation.

For any particle i, its position at a time step t is denoted by vector xi(t) in the search space X. Every particle has a velocity denoted by vi (t) over the same space as the position of the respective particle. Every particle has a memory of its own best experience called personal best denoted by pi(t). Among the members of the swarm, there is a common best experience, denoted by g(t) , which is referred to as the global best [14].

With the defined concepts, the PSO vector diagram is shown in Fig. 2, where the vector from the current position to the personal best is $p_i(t)$-$x_i(t)$ and the vector from the current position to the global best is $g(t)$-$x_i(t)$. The particle moves to a new (updated) position denoted by $x_i(t+1)$ and its new velocity is $v_i(t+1)$. Thus, the position of the particles is updated as per the equation 8:

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{8}$$

where

$$v_i(t+1) = wv_i(t) + c_1(p_i(t) - x_i(t)) + c_2(g(t) - x_i(t)) \tag{9}$$

The standard PSO is described by the following equations:

$$v_i(t+1) = wv_i(t) + r_1c_1(p_i(t) - x_i(t)) + r_2c_2(g(t) - x_i(t)) \tag{10}$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{11}$$

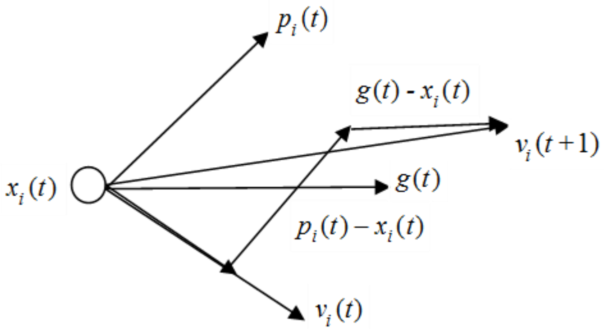

Fig 2: Vector diagram of PSO algorithm

where r_1 and r_2 are random values between 0 and 1, and c_1 and c_2 are acceleration coefficients, and w is the inertia coefficient.

To improve the performance of the basic PSO, a number of variations have been developed to improve on its speed of convergence and on the quality of the solution [14]. In one such variation, known as velocity clamping, exploration is controlled by using high values of velocity for global exploration and low values of velocity for local exploration. Another variation is based on altering the inertia weight to create a balance between exploration and exploitation [15]. Alteration of the inertia weight controls the momentum of the particles and thus helps in achieving optimum convergence.

II.III Algorithm simulation flow chart

Simulation of the optimization algorithm for the problem formulated in section II.I was carried out under Matlab environment, executed as per the flowchart shown in Fig 3. Two types of data for the IEEE 33-bus system, namely, line data and bus data, were used. Base case load flow was carried out using backward forward sweep and PSO methods and the bus and average voltages, and active and reactive power losses were noted. For all buses except bus 1 (slack bus), the optimal size of the solar PV generator (X) was obtained and the corresponding power loss recorded. The optimal size of SPV generator at unity power factor and the corresponding optimal bus for SPV integration are then identified based on recorded data. An optimal power factor was subsequently obtained by using the optimal combination of real and reactive power using the size of SPV generator that minimizes power loss at unity power factor.

III. RESULTS AND ANALYSIS

On carrying out load flow for the base case, where the base case refers to the IEEE 33-bus without SPV integrated to it, the real and reactive power losses were obtained as 210.07 kW and 142.44 kVar, respectively. Using PSO, the optimal location of a single SPV generator to realize maximum power loss reduction is identified as bus 6 and optimal size of the SPV at a unity power factor was 2605.82 kW. On integration of this generator at bus 6 and again performing load flow, the power loss of the test system reduced to 109.55 kW which is equivalent to 47.85 % power loss reduction. Using the PSO technique and the 2663.3 kW SPV, the optimal active and reactive power from the generator were identified as 2151.40 kW and 1470.30 kVar, respectively, and hence the optimal power factor is 0.826. Operating the optimal SPV generator at a power factor of 0.826 yielded real power losses at 71.09 kW representing a power loss reduction of 66.16 % on the base case.

The current profile for the three cases, namely, test system without SPV, test system with integrated SPV supplying active power only and test system with integrated SPV supplying both active and reactive power, is shown in Fig. 4. The current flow in the lines between buses 1-2, 2-3, 3-4, 4-5 and 5-6 decreases significantly on integration of SPV to bus 6. The current further reduces on the said lines on operating the SPV generator at an optimal power factor of 0.826.

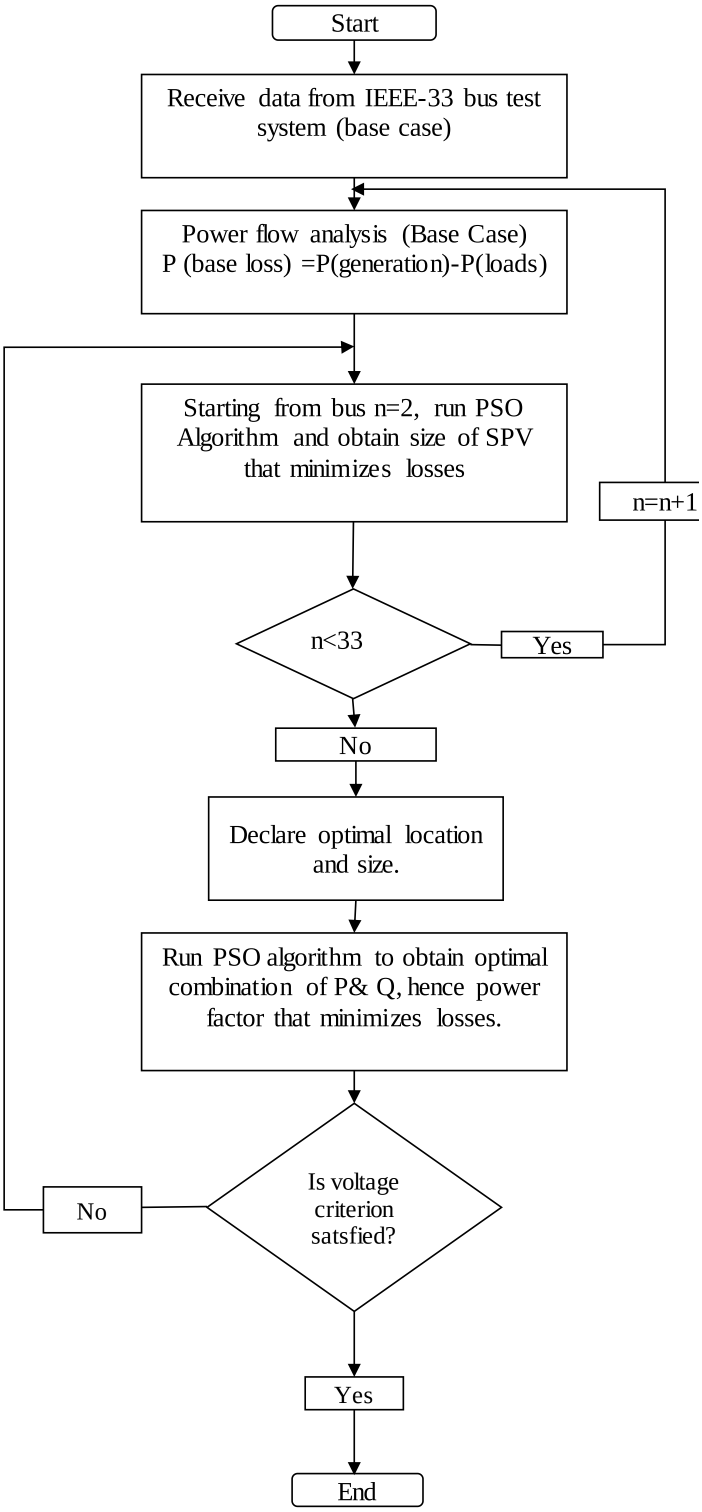

Fig 3: Flow chart for optimization

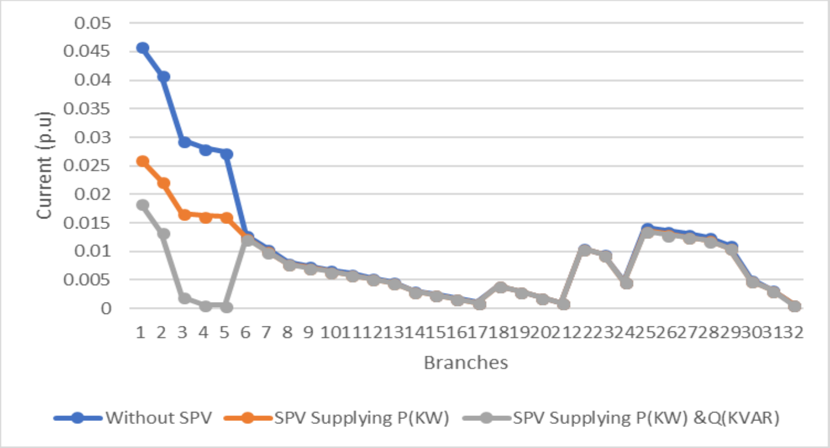

Fig 4: IEEE 33-bus current profile

Fig. 5 displays the active power loss profile on the different lines under the three scenarios above. As it is evident, the power loss reduction is between buses 1-2, 2-3, 3-4, 4-5 and 5-6. Before integrating SPV, the power loss from bus 1-6 is 141.0127 kW representing 67% of the base case power loss. On integrating SPV at unity power factor, the active power loss in the same region decreases to 45.409 kW which represents 22% of the base case. In other words, the power loss in the region between bus 1 to bus 6 reduces by 67.8%, which is as a result of the decrease of the current flowing in the region due to the SPV integration at bus 6. On operating the optimal SPV generator at an optimal power factor of 0.826, the generator is able to supply reactive power. This further reduces the current supply from the feeder to the system as the reactive power demands can be met from the SPV generator. In this case, the active power loss in the region between bus 1 to bus 6 reduces to 7.635 kW which is 4% of the base case loss in the region. The power loss in the region between bus 1 and 6 reduces by 94.59% as a result of operating the SPV generator at an optimal power factor of 0.826.

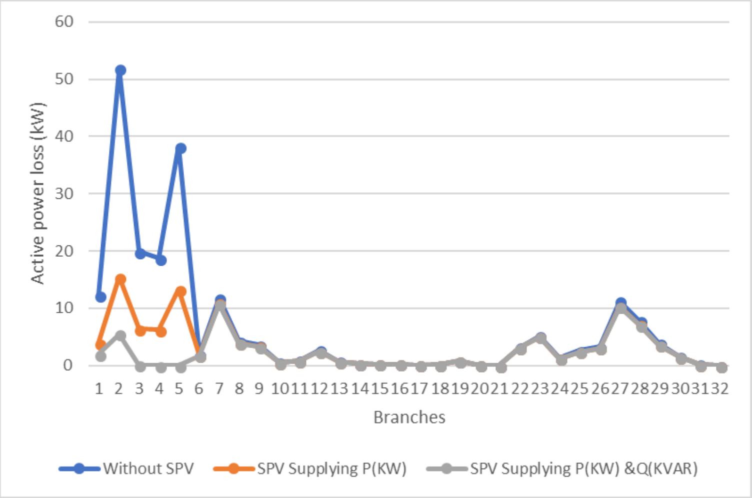

Fig 5: IEEE 33-bus active power loss

The voltage profile for the three cases is shown in Fig. 6. Without SPV integration to the system, the minimum voltage is at bus 18 at 0.9042 p.u. and the average voltage for the system is 0.9455 p.u. When the optimal SPV is connected to bus 6, the voltage profile improves across all buses, particularly in bus 18, the voltage improves to 0.9437 p.u. and the average voltage for the system is 0.9732 p.u. On operating the SPV generator at a power factor of 0.826, the voltage profile improves further, the voltage at bus 18 improves to 0.9504 p.u. and the average voltage for the system is 0.9773 p.u.

When SPV generator is operated at unity power factor, it supplies only active power, thus, the reactive power demands of the distribution system are entirely met from the feeder. The loads located far away from the feeder have to meet their reactive power demand from the feeder. This results to power losses hence voltage drop and poor voltage profile. Therefore, when the SPV generator is operated at an optimal power factor of 0.826, it is able to supply both active and reactive power which results in further reducing power losses and improving the voltage profile.

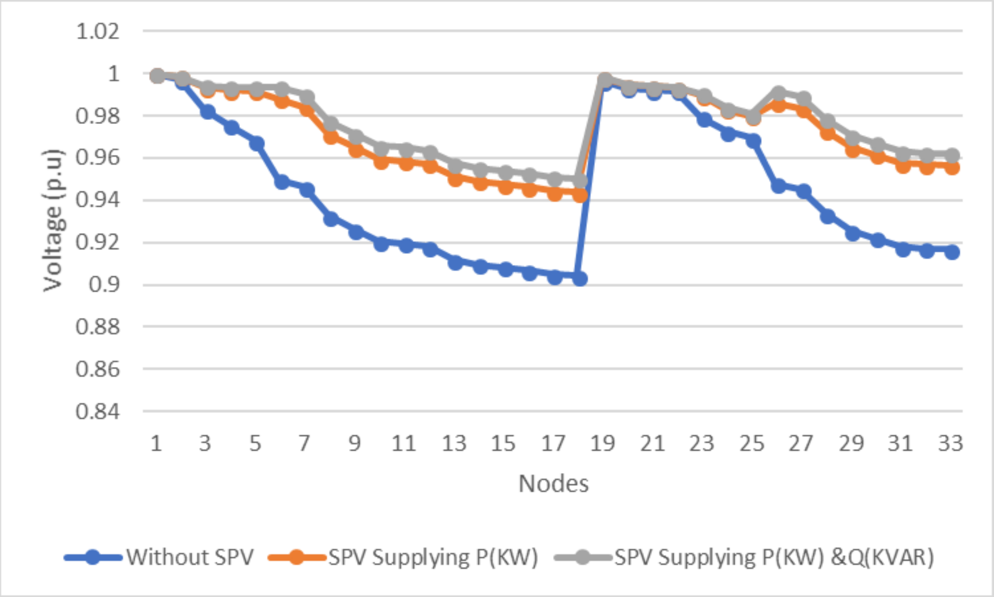

Fig 6: Voltage profile of IEEE 33-bus system

Table 1 shows a comparison of the results of the proposed method with those obtained by using different methods in previous research. It can be seen that the proposed method results in better power loss reduction of 66.16% compared to the other approaches. Therefore, it is necessary to compare both the active and reactive power capabilities of the SPV generator when determining the optimal location and size to identify the optimal power factor. By doing this, power loss reduction is enhanced as well as the voltage profile.

Table 1: Comparison of power loss results between proposed method and previous research

Specifics	Technique used			
	PSO [16]	Analytical Method [17]	Analytical Method [18]	Proposed Method
Optimal bus	8	6	6	6
Optimal size (kW)	1500	2633	2487.52	2605.82
Base Case power loss	210.1	210.25	201.906	210.07
Power loss (kW)	120.5	110.31	102.979	71.09
% Power loss reduction	42.65%	47.53%	49.00%	66.16%

IV. CONCLUSION

Optimizing location, size and power factor of solar photovoltaic system is key in improving its effectiveness in power systems. Optimization of the location and size of SPV as a distributed generator has previously been done at unity power factor. In this paper, particle swarm optimization technique has been used to solve the optimal location, sizing and power factor problem based on the IEEE 33-bus test system integrated with a single SPV generator. Optimization of the SPV system at unity power factor results in significant power loss reduction in the power system and hence, an improvement of the voltage profile. However, on optimizing the power factor, in addition to size and location, there is further reduction in the power loss and improvement on voltage profile. Thus, optimization of location, size and power factor of SPV as a distributed generator significantly improves the effectiveness and performance of the power systems. Further studies could consider solar intermittency and cost of SPV generator in the optimization process.

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