Optimal Sizing and Placement of Solar Photovoltaic based DGs in the IEEE 9 bus system using Particle Swarm Optimization Algorithm.

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***Abstract*—Solar energy is one of the most commonly exploited renewable resource globally. Integration of power from solar to the main grid can either bring positive or negative impact which normally depends on their size and location. The size and location is very crucial if they will have to solve any problem because not all parts of the system needs more power. In this paper the most appropriate size and location of the solar photovaltaic (SPV) was obtained using Particle swarm optimization (PSO) technique. The IEEE 9 bus system was used and the main objective of this optimization problem was reducing active power losses. The algorithm was applied in a number of cases each with different number of locations of the SPVs. Two different locations proved to be a good option and bus 9 the most optimal.**

***Index Terms*—Solar photovoltaic (SPV), Particle swarm optimization (PSO), 9 bus.**

I. Introduction

Solar power can be connected in the distribution system and hence be utilized as distributed generation (DG). DGs have many advantages over centralized power generation such as reduction in power losses, improved voltage profile, system stability improvement, pollutant emission reduction and relieving transmission and distribution system congestion. After deregulation of power system, many power companies are investing in small-scale renewable energy resources such as wind, photo-voltaic cells, micro turbines, small hydro turbines, CHP or hybrid to meet the active power demand (MW) as well as to earn a profit [1]. The addition of distributed generation (DG) in this case solar power in power system offers a number of advantages such as reduces power losses in the system. However this improvement depends on the size and the location of these units. Integrating DG units may lead to negative impacts on a distribution system, especially for large scale installations, if they are not optimally placed. For example, DG may result in high voltage causing currents that exceed the line's thermal limit, harmonic problems, noticeable voltage flicker and instability of the voltage profile of some of the customers. In addition, the bi-directional power flows can lead to voltage profile fluctuation and change the short circuit levels. Negligible effects can be observed in the network with a low penetration level and serious effects may cause due to sizeable penetration level. To address these problems, optimal placement and sizing of DGs is necessary [1], [2]. Since utilities are already facing technical and non-technical issues, they cannot tolerate such additional issues. Therefore an optimum placement and sizing of DG is needed in order to minimize overall system losses and improve voltage profiles [1].

II. POWER FLOW AND OBJECTIVE FUNCTION FORMULATION

In a power system, power flows from the power generating plants to the loads by means of transmission lines. This flow of power (both active and reactive) is known as load flow or power flow [3]. The main objective of the power flow (or load flow studies) is to determine the steady state conditions. It mainly involves finding the power system operating condition based on a particular of system parameters of a given that the system parameters are known in advance [4]. Load flow is very importance and usually provide the starting point for other power system analysis such as transient stability, short circuit (of faults) analysis and contingency analysis [5], [6]. The purposes of load flow calculations include

- Continuous evaluation of the operation of power systems [5].
- Power system expansion which may involve investigation of alternatives for extension of the network to meet increased load demand and
- Operational planning (i.e. real-time security assessments of the system, for present and projected operating states) [5], [7].
- Control and economic scheduling in a power system and exchange of power between utilities [8].

The power system is modeled by an equivalent electric circuit which consists of generators, transmission network and distribution network. Load flow studies provide an appropriate analytical approach to determine different bus voltages, their phase angles, active and reactive power flows in all the lines, generators, transformer loadings and load under steady state conditions [3].

Four quantities are associated with each bus which are the voltage magnitude ($|V|$), voltage phase angle (δ), real (active) power (P) and the reactive power (Q) [4].
Depending on the parameters specified in a particular bus the system buses are generally classified into three types as summarized in table I.

TABLE I
POWER SYSTEM BUSES CLASSIFICATION

Bus	Known Parameters	Unknown Parameters
Slack	$\|V\|$ and δ	P and Q
Generator	P and $\|V\|$	Q and δ
Load	P and Q	$\|V\|$ and δ

It is not possible to predict the transmission line losses, the presence of the slack (swing) bus makes up the difference between the scheduled loads and generated power that is caused by the losses in the network. This is done by emitting or absorbing active/reactive power to or from the system. There is only one bus of this type in power system, chosen as the most important bus in a power system where mainly the biggest generator is connected [5]. Power flow calculations gives the unknowns in each of the buses. Therefore the main information obtained from the load flow or power flow analysis are the voltage magnitudes ($|V|$), voltage phase angles (δ) of load (P-Q) buses, reactive powers (Q) and voltage phase angles (δ) at generator (or P-V) buses, real and reactive power flows on transmission lines together with power at the slack bus [3].

A. Formulation of Power Flow Equation

Consider a typical bus of a power system network as shown in Figure 1 [5], [9], [10].

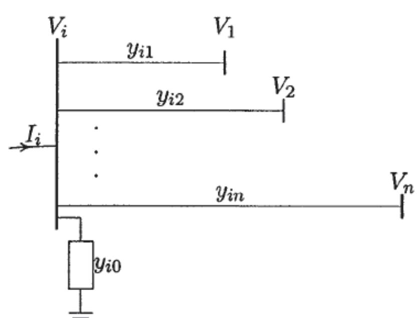

Fig. 1. *A typical bus of a power system .*

In this circuit the transmission lines have been represented by the equivalent π models where impedances have been converted to admittances in per unit and on common MVA base [5], [10].
Application of KCL to this bus results in

$$\begin{aligned} I_i &= y_{i0}V_i + y_{i1}(V_i - V_1) + y_{i2}(V_i - V_2) + \cdots + y_{in}(V_i - V_n) \\ &= (y_{i0} + y_{i1} + y_{i2} + \cdots + y_{in})V_i - y_{i1}V_1 - y_{i2}V_2 - \cdots - y_{in}V_n \end{aligned} \quad (1)$$

Therefore the current entering bus i can be obtained by simplifying equation 1 into equation 2

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij}V_j \qquad j \neq i \quad (2)$$

Equation 2 can be rewritten in terms of the bus admittance matrix as shown in equation 3.

$$I_i = \sum_{j=1}^{n} Y_{ij}V_j = \sum_{j=1}^{n} |Y_{ij}||V_j|\angle(\theta_{ij} + \delta_j) \quad (3)$$

The complex power at bus i is

$$P_i - jQ_i = V_i^* I_i = |V_i|\angle(-\delta_i) \sum_{j=1}^{n} |Y_{ij}||V_j|\angle(\theta_{ij} + \delta_j) \quad (4)$$

The load flow Mathematical formulation (known as the power flow equation) as given by equation 5 [5], [9].

$$\frac{P_i - jQ_i}{V_i^*} = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij}V_j \qquad j \neq i \quad (5)$$

The resulting equations as can be seen in equations 4 and 5 are non-linear and must be solved by iterative techniques using numerical (iterative) methods only [9], [11], [12]. The main iterative methods used in power flow studies are:

1) Gauss Siedel method
2) Newton Raphson method
3) Fast decoupled method.

B. Newton Raphson Load Flow Solution.

This method was named after Isaac Newton and Joseph Raphson. The origin and formulation of this method was dates back to late 1960s [3]. The Newton Raphson technique is the most successful power flow calculation method because it has superior convergence characteristics and is less likely to diverge even in large systems [5], [13], [14]. Separating real and imaginary parts in equation 4 gives:

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \quad (6)$$

and;

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) \quad (7)$$

The equations 6 and 7 constitute a set of nonlinear algebraic equations in terms of the independent variables, voltage magnitude in per unit, and phase angle in radians. There are two equations for each load bus (PQ bus), given by (P_i) and (Q_i), and one equation for each voltage-controlled bus (PV bus), given by (P_i). Expanding (P_i) and (Q_i) in Taylor's series about the initial estimate and neglecting all higher order terms results in the jacobian matrix equation. In that equation, bus 1 is assumed to be the slack bus. The Jacobian matrix gives the linearized relationship between small changes in voltage angle $\Delta\delta_i^{(k)}$ and voltage magnitude $\Delta|V_i^{(k)}|$ with the small changes in real and reactive power $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$. Elements of the

Jacobian matrix are the partial derivatives of (P_i) and (Q_i), evaluated at $\Delta\delta_i^{(k)}$) and $\Delta|V_i^{(k)}|$. In short form, it can be written as shown in equation 8.

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_{P\delta} & J_{PV}\\ J_{Q\delta} & J_{QV}\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta|V|\end{bmatrix} \tag{8}$$

For voltage-controlled buses, the voltage magnitudes are known. The details on how all the elements of the Jacobian matrix are obtained from equations 6 and 7 is as highlighted below [5], [15]:

- For $\mathbf{J}_1$ ($J_{P\delta}$)
  The diagonal and the off-diagonal elements of are;

$$\begin{aligned}\frac{\partial P_i}{\partial \delta_i} &= \sum_{j\neq i}|V_i||V_j||Y_{ij}|\sin(\theta_{ij}-\delta_i+\delta_j)\\ \frac{\partial P_i}{\partial \delta_j} &= -|V_i||V_j||Y_{ij}|\sin(\theta_{ij}-\delta_i+\delta_j) \qquad j\neq i\end{aligned} \tag{9}$$

- For $\mathbf{J}_2$ (J_{PV})
  The diagonal and the off-diagonal elements of are;

$$\begin{aligned}\frac{\partial P_i}{\partial |V_i|} &= 2|V_i||Y_{ii}|\cos\theta_{ii} + \sum_{j\neq i}|V_j||Y_{ij}|\cos(\theta_{ij}-\delta_i+\delta_j)\\ \frac{\partial P_i}{\partial |V_j|} &= |V_i||Y_{ij}|\cos(\theta_{ij}-\delta_i+\delta_j) \qquad j\neq i\end{aligned} \tag{10}$$

- For $\mathbf{J}_3$ ($J_{Q\delta}$)
  The diagonal and the off-diagonal elements of are;

$$\begin{aligned}\frac{\partial Q_i}{\partial \delta_i} &= \sum_{j\neq i}|V_i||V_j||Y_{ij}|\cos(\theta_{ij}-\delta_i+\delta_j)\\ \frac{\partial Q_i}{\partial \delta_j} &= -|V_i||V_j||Y_{ij}|\cos(\theta_{ij}-\delta_i+\delta_j) \qquad j\neq i\end{aligned} \tag{11}$$

- For $\mathbf{J}_4$ (J_{QV})
  The diagonal and the off-diagonal elements of are;

$$\begin{aligned}\frac{\partial Q_i}{\partial |V_i|} &= -2|V_i||Y_{ii}|\sin\theta_{ii} - \sum_{j\neq i}|V_j||Y_{ij}|\sin(\theta_{ij}-\delta_i+\delta_j)\\ \frac{\partial Q_i}{\partial |V_j|} &= -|V_i||Y_{ij}|\sin(\theta_{ij}-\delta_i+\delta_j) \qquad j\neq i\end{aligned} \tag{12}$$

The terms $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are the difference between the scheduled and calculated values, known as the power residuals, given by

$$\begin{aligned}\Delta P_i^{(k)} &= P_i^{sch} - P_i^{(k)}\\ \Delta Q_i^{(k)} &= Q_i^{sch} - Q_i^{(k)}\end{aligned} \tag{13}$$

C. Calculation of Line Flows and Losses

After the iterative solution of bus voltages, the next step is the computation of line flows and line losses. Consider a line connecting the two buses i and j as shown in figure 2 [5].
The line current I_{ij}, at bus i in the direction $i \rightarrow j$ is given by,

$$I_{ij} = I_\ell + I_{io} = y_{ij}(V_i - V_j) + y_{i0}V_i \tag{14}$$

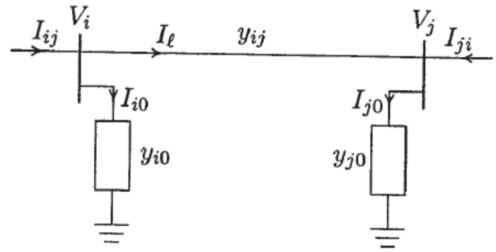

Fig. 2. *Transmission line model for calculating line losses*

Line current I_{ji} measured at bus j in the direction j→i is given by

$$I_{ji} = -I_\ell + I_{jo} = y_{ij}(V_j - V_i) + y_{i0}V_j \tag{15}$$

The complex power S_{ij} from bus i to j is

$$S_{ij} = V_i I_{ij}^* \tag{16}$$

The complex power S_{ji} from bus j to i is

$$S_{ji} = V_j I_{ji}^* \tag{17}$$

The power loss in line $i \rightarrow j$ is the algebraic sum of the power flows determined

$$S_{Lij} = S_{ij} + S_{ji} \tag{18}$$

The total power loss in the whole network can then be determined by the summation of the losses in all the benches i.e:

$$\sum S_{Lij} \tag{19}$$

The real part of equation 19 gives the total active power loss which is the objective function to be minimized.

III. PARTICLE SWARM OPTIMIZATION (PSO)

Particle Swarm Optimization (PSO) is a meta-heuristic method used by many researchers for optimization. This method was developed in 1995 by Dr.Russell C. Eberhart and Dr. James Kennedy. Lately, this method has come up as one of the most promising algorithm for giving solutions to many optimization problems in the science and engineering fields [16]. Particle swarm optimization technique is inspired by natural movements of animals like birds or fish in a search space in order to fulfill their needs such as food. The main concept of the PSO method involves the generation of random particles having random positions and velocities representing the members of the population or swarm [17], [18]. Each particle has memory and a potential solution and is moved randomly in the search space. They interact with each other and move towards global solution position by changing their velocity and position. The best position achieved so far by the moved particle is called the personal best *(pbest)* and the best solution found so far by the entire swarm or particles is called the global best *(gbest)* figure 3 [16], [19].
PSO algorithm has the advantage of being simple, precise, easy to implement [17].

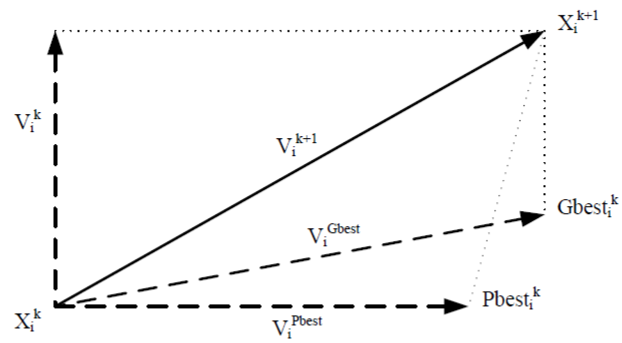

Fig. 3. *PSO search mechanism in multidimentional search space. [16].*

The PSO algorithm as customized to this problem is as follows:

Step 1: *Initialization of parameters:*
The first parameters that should be initialized are *N* particles to represent the initial sizes of the SPV, $X_i^{(k)}$ and their associated velocity $V_i^{(k)}$ where *i* = 1 ,2, 3 , ... , *N*. Other initialized parameters are the inertia weight, ω and the acceleration factors c_1 and c_2 and the particle.
The most commonly used initializations of PSO algorithm are as follows [16]:

- Inertial weight, ω: 0.9 to 0.4
- Acceleration factors (c_1 and c_2): 2 to 2.05
- Population size: 10 to 100
- Maximum iteration (Maxite): 500 to 10000
- Initial velocity: 10% of position

Step 2: *Definition of objective function, pBest and gBest:*
Each of these initialized particles is stored as personal best ($pBest_i$) and its associated fitness is labelled as F_pBest_i. The best fitness value and the corresponding particle will be stored as global best ($gBest$) and F_gBest respectively. The fitness function in this case is obtaining the real power loss (real part of equation 19) solved by newton raphson technique.
Step 3: *Setting the initial iteration counter:* i.e. set k = 1.
Step 4: *Updating Velocity and Particle Position:*
For each of the initialized particles their velocity is initialized according to equation 20

$$V_i^{(k+1)} = \omega * V_i^{(k)} + c_1 * R * \left(p_{best_i} - X_i\right) + c_2 * R * \left(p_{best_i} - X_i\right) \tag{20}$$

where R is a random number.
The particle position is then updated according to equation 21

$$X_i^{(k+1)} = X_i^{(k)} + V_i^{(k+1)} \tag{21}$$

Step 5: *Fitness Evaluation:*
Here the fitness (objective) function is calculated using the updated parameters of X obtained in step 4.
Step 6: *Updating pBest and gBest:*
If the fitness obtained in step 5 is better than the earlier stored value then that becomes the $pBest_k$ and $gBest_k$ else the earlier values are retained.
Step 7: *Termination criterion test:*
If the termination criterion is met then go to ***step 8*** else go to ***step 4.***
Step 9: *Ending the Algorithm:*
The values obtained after the termination criterion is met are stored as $gBest$ for the best particle (best size of the SPV) and F_gBest as the most optimal solution (minimum minimum active power loss)

The above steps can be summarized in the detailed flow chart in Figure 4.

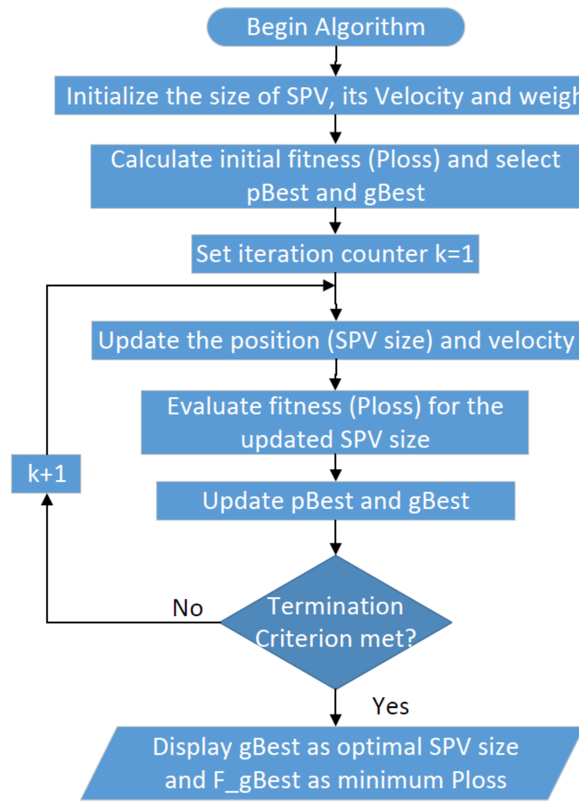

Fig. 4. *PSO flowchart.*

IV. TEST SYSTEM RESULTS AND DISCUSSIONS

The PSO algorithm was applied in obtaining the optimal size and location of the solar photovoltaic (SPV) in the 9 bus system (Figure 5 and data in appendix) so as to minimize the total active power loss in the entire system. There are a number of possibilities in terms of the number of the SPVs that can be located in this system. Results that will be shown here are considering four options i.e.

1) The initial (base case) system that does not have any SPV,
2) A case of a single source of SPV at the most appropriate location,
3) The case of two SPVs plants at their optimal locations and
4) The a case considering three SPV plants at their optimal locations

The total active power losses in each of the above four scenarios is as shown in table II.

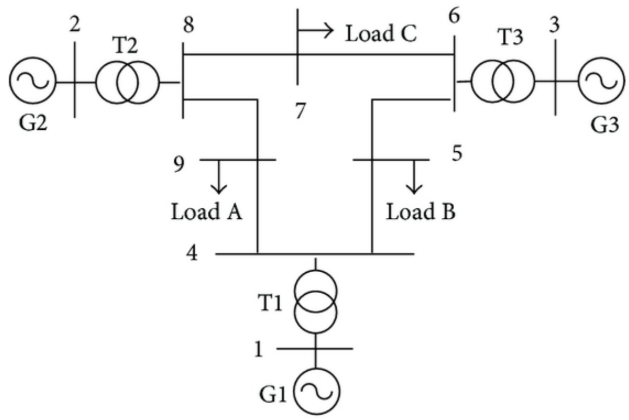

Fig. 5. *IEEE 9 bus test system*

The PSO algorithm was used to obtain the size and location of the SPV in the 9 bus system so as to minimize the total active power loss. Three scenarios were used i.e.

1) A case of a single source at the most appropriate location and
2) Two locations
3) Three locations

Table II shows the most optimal sizes and locations of the SPVs so as to minimize the total active power loss of the entire system. These losses can be plotted as shown in figure 6. From table II and figure 6 it can be seen that as the number of SPVs is increased from the base case up to two there is a significant reduction in the total power loss. However further increase to three SPVs there is no much reduction in the active power loss. With two SPVs the loss was 4.599 kW while with three sources we have a loss of 4.586 kW. This therefore means that for the 9 bus system even two SPVs are enough to minimize the active power losses in the system. This is because further increase of the number of the solar PV plants will only increase the cost without having a significant reduction in the active power loss.

TABLE II
TOTAL POWER LOSS COMPARING DIFFERENT CASES

No	Location	Size	Total Losses	Reduction
Base case	-	-	4.955	-
One SPV	9	48.4564	4.7183	4.777 %
Two SPVs	5	37.7636	4.5988	7.188 %
	9	36.0769		
Three SPVs	4	37.5279	4.5858	7.451 %
	5	28.2221		
	9	40.4792		

The individual branches contribution to the active power losses experienced in the three cases is as shown in figure 7.

Figure 7 indicates that the maximum active power loss is experience in branch 8-9. This can be because bus 9 has the largest load in the system therefore the power and hence current flowing through the branch from the slack bus (bus 1) is highest. There is also a significant reduction in power loss in branch 8-9 when one centralized SPV of 48. 46 MW was placed at bus 9. This is because the load at the same bus gets less power through bus 8, hence less current flows through that bus reducing the active power loss (I^2R) in the branch.

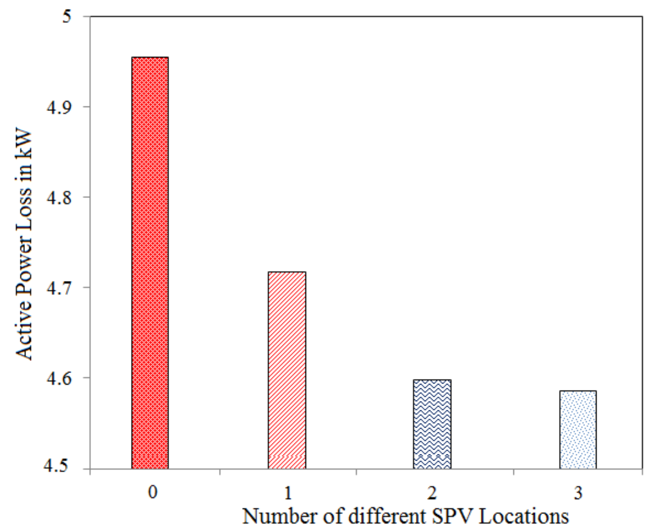

Fig. 6. Total active power loss for the three cases

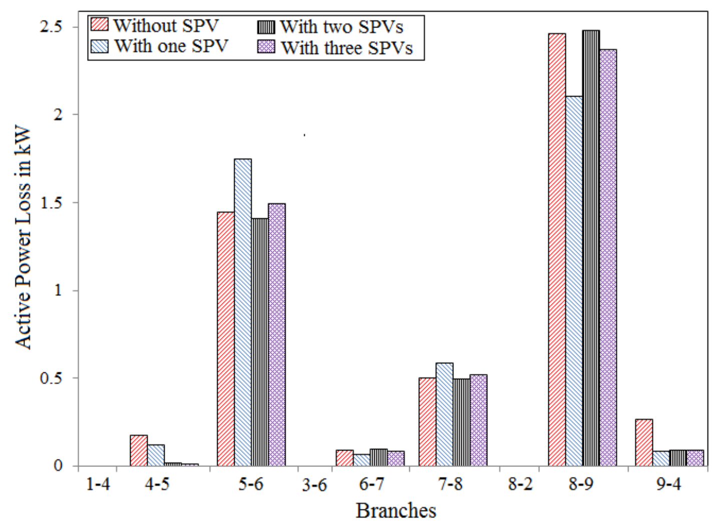

Fig. 7. Active power loss for the three cases in each branch

V. CONCLUSION

This paper investigated an efficient method of siting and sizing of SPV based distribution generation systems using the particle swarm optimization technique with an objective of minimizing active power losses. The proposed algorithm has been tested on IEEE 9 bus system. It was applied in different scenarios with different number of SPVs in the system. Our results shows that there is a significant reduction of active power losses when the SPVs are optimally located and this reduction is better when 2 different optimal locations are used instead of a single location. Increasing the number beyond 2 locations does not result is any significant further reduction but it can lead to unnecessary increase in cost. This means that in the IEEE 9 bus system it is sufficient to just consider two optimal locations to reduce the active power

VI. RECOMMENDATIONS FOR FUTURE WORK

The authors would like to recommend that this methodology be applied in a distribution network and broaden the analysis to other considerations such as voltage profile improvement and reactive power loss reduction. The determination of the best algorithm parameters to give the best solution is the main weakness of the classical PSO algorithm, therefore its recommended hybridizing PSO with an evolutionary technique to try overcoming this weakness.

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APPENDIX.

IEEE 9 BUS SYSTEM DATA:

All data in per unit at the bases of 100 MVA and 345 kV.

TABLE III
GENERATOR DATA

Bus	**Pg**	**Qg**	**Vg**	**Pmin**	**Pmax**	**Qmin**	**Qmax**
1 (**SLK**)	0	0	1	10	250	-300	300
2	163	0	1	10	300	-300	300
3	85	0	1	10	270	-300	300

TABLE IV
BRANCH DATA

From (Bus)	To (Bus)	R	X	B
1	4	0	0.0576	0
4	5	0.017	0.092	0.158
5	6	0.039	0.17	0.358
3	6	0	0.0586	0
6	7	0.0119	0.1008	0.209
7	8	0.0085	0.072	0.149
8	2	0	0.0625	0
8	9	0.032	0.161	0.306
9	4	0.01	0.085	0.176

TABLE V
LOAD DATA

Bus	Load (MW)	Load (MVAr)
5	90	30
7	100	35
9	125	50