Optimal Allocation of Reactive Power Compensation in a Distribution Network with Photovoltaic System Integration

Sohair M. Allam, Tamer Fetouh and Asmaa A. Ebrahim

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Sohair M. Allam
Electrical Engineering Department
Faculty of Engineering, Menoufia University
Shebin El-Kom, Egypt
sohirallam@yahoo.com

Tamer Fetouh
Electrical Engineering Department
Faculty of Engineering, Menoufia University
Shebin El-Kom, Egypt
tamerfet@yahoo.com

Asmaa A. Ebrahim
Electrical Engineering Department
Faculty of Engineering, Menoufia University
Shebin El-Kom, Egypt
asmaa_ad2016@yahoo.com

***Abstract*— This article aims to introduce a complete design for a solar photovoltaic (PV) system integrated with a distribution network. According to the nature of solar power generation, the designed PV system would be able to supply the load only through day hours and the additional power needed for the rest of the day can be obtained from the grid. The growing level of penetration of solar power generation requires reactive power compensation to ensure the security and reliability, voltage profile and high efficiency of the system. This can be achieved through two stages. At first, backward forward sweep method (BFS) is used to calculate active and reactive power losses and the voltage profile. Secondly, particle swarm optimization technique (PSO) is applied to find the optimal ratings and locations of reactive capacitors by considering single and multi-objective functions. The proposed algorithm is applied on the 33-bus IEEE test system. The results show the capability and efficiency of this algorithm.**

***Keywords*— Renewable energy, PV system design, Particle swarm, Capacitor placement**

I. INTRODUCTION

With the continued demand for electricity, the renewable energy sources draw the world attention as the best way to generate electricity when both economic and environmental concerns are needed. Using these renewable sources, the good operation of the electrical network which means enhancing the bus voltages, reducing the power loss and improving the reliability of the grid is achieved. These sources are integrated into the electrical grid in the form of small capacity units that are distributed in a well thought out manner along the radial distribution network [1-3]. This concept is a promising area, especially when there are different types of renewable energy sources such as solar, wind and fuel cells are available and able to feed a certain load whether they are individually placed [4-5] or assembled together [6-7]. Focus on solar cells as a field of research and study as it is distinguished from the other types of clean energy in that it can be placed anywhere next to the load or away from it, depending on the amount of output power required. The intermittent nature of solar energy causes unbalance in power flow in the lines leading to voltage collapses. The fall of the voltage value and the resulted power loss are due to the reactive power lack. Therefore, this lack must be compensated for maintaining the reliability and security of the electrical network. One way to fix this problem is to connect a number of capacitors in parallel along with the distribution system. The ratings and locations of these capacitors are optimally selected to maintain the values of the buses voltages within permitted limits while compensating for the reactive power. Different algorithms were presented for solving the capacitor-locating problem in a radial distribution network. In [8] a proposed technique called modified discrete particle swarm optimization was introduced. Also, Haque used the loss saving based technique in [9] for determining the capacitor's optimal location while reducing the total losses for a radial system. Reference [10] presented a new formulation for solving the capacitor placement problem taking into consideration the load variation through the upper and lower bounds for various loads. The loss sensitivity factors were used as a first stage for capacitor placement problem in a radial distribution network and secondly they used the plant growth simulation algorithm to compute the level for the capacitive value needed [11]. For maximizing the net saving as well as improving the voltage value, the direct search algorithm has been introduced and tested on 69 bus radial distribution system and the total losses were significantly decreased [12]. A new technique namely the Bacterial Foraging technique [13] was proposed for computing the optimal ratings of capacitors needed to be placed on 34 and 85-bus test systems according to the load changes. Depending on the direct connection between the voltage and the reactive power value, the inversed reduced Jacobian matrix used in [14] could sufficiently locate the right positions for capacitors required for covering the shortage of reactive power. This paper presents a grid connected photovoltaic system designed to supply an industrial load represented by a 33-bus test system. The complete designed of PV system includes the number of modules, arrays and inverters needed to fully supply the test system and the total costs to be spent and the total area required for the PV system installation. In this paper, the allocation of reactive power compensation is also introduced for improving the system reliability and enhancing the voltage profile using particle swarm optimization algorithm.

II. DESIGN AND ECONOMICAL ANALYSIS OF PV SYSTEM

A. *Design of PV System Components*

The PV system includes various components that are designed accurately depending on the load needs, site location, climate conditions and expectations. These elements are:

- PV modules, which convert the solar radiation into electrical current. Connecting these modules together in series or parallel or both depends on the output power needed.
- Charge controller, which prevents battery from overcharging and prolongs its life cycle.

- Inverter, which converts the DC power into AC power synchronizing with the utility power.
- AC & DC loads devices and appliances, which are fed by the PV system. A grid connected PV system is shown in Fig.1

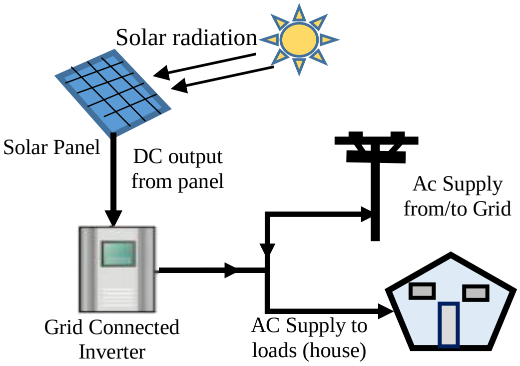

Fig. 1. Grid Connected PV System Configuration

B. Design Procedure for PV System

The daily energy demand [15-16] from the PV system, E_d (KWh/day) and the DC-watt hour per day (E_{DC}) are given by:

$$\mathrm{E_d = W * H} \tag{1}$$

$$\mathrm{E_{DC} = E_D/\eta_v} \tag{2}$$

The total daily average load (I_{tot}), the array ($\mathrm{I_{ar}}$) and string ($\mathrm{I_{st}}$) currents are given as:

$$\mathrm{I_{tot} = E_{DC}/V_{sys}} \tag{3}$$

$$\mathrm{I_{ar} = I_{tot}/(S_p * \eta_c * D_f)} \tag{4}$$

$$\mathrm{I_{st} = P_{max}/V_{max}} \tag{5}$$

Therefore, the number of series (N_s), parallel (N_P) and the total Number of modules ($\mathrm{N_T}$) are given as:

$$\mathrm{N_s = V_{mv}/V_{max}} \tag{6}$$

$$\mathrm{N_P = I_{ar}/I_{st}} \tag{7}$$

$$\mathrm{N_T = N_s * N_P} \tag{8}$$

Where,

W	The power rating for the distribution network (Kw)
H	The number of hours that the system loads is in use daily (h/day)
η_v	The efficiency of the grid connected inverter
V_{sys}	The distribution network rated voltage in volts
η_c , D_f	The columbic efficiency and the derating factors
S_p	The peak solar radiation for the PV location
P_{max}	The maximum power rating for the PV module
V_{max}	The maximum voltage for the PV module
V_{mv}	The maximum input voltage for the inverter

The DC power output (P_{Dc}), the AC power output (P_{Ac}) and the total energy produced per year (E) are given as [17]:

$$\mathrm{P_{Dc} = S_{STC} * A_T * \eta_m} \tag{9}$$

$$\mathrm{P_{Ac} = P_{Dc} * \eta_v * \eta_{d\&m}} \tag{10}$$

$$\mathrm{E = P_{Ac} * S_{av} * 365} \tag{11}$$

The total area needed for the PV system (A_T) is calculated as:

$$\mathrm{A_T = N_T * A_M} \tag{12}$$

$$\mathrm{A_M = h * w} \tag{13}$$

Where,

A_M	The area of one module
h , w	The module dimensions in (m)
S_{STC}	The solar insulation
η_m	The module efficiency
$\eta_{d\&m}$	The dirty and mismatch losses
S_{av}	The average solar radiation (Kw/m^2/day)

C. Economic Design of PV System

The Life Cycle Cost (LCC) of the PV system include the initial, inverter, the PV module costs and the maintenance and operating costs [18] can be calculated as:

$$LCC = C_{inv} + C_{PV} + C_{in} + C_{OP\&M} \tag{14}$$

Where,

C_{inv}, C_{PV}	The cost for the inverters, and the modules ($).
C_{in},$C_{OP\&M}$	Installation, operating and maintenance costs

The operating and maintenance costs, $C_{OP\&M}$ [$] for the PV system is expressed as:

$$C_{OP\&M} = C_{op\&m/y} * \left\{\frac{(1+i)}{(1+d)} * \left(1 - \frac{1+d}{1+i}\right)^N\right\} / \left(1 - \frac{1+d}{1+i}\right) \tag{15}$$

The Annualized Life Cycle Cost (ALCC) of the PV system and the Unit Electrical Cost (UEC) are given as:

$$ALCC_{PV} = LCC * \left(1 - \frac{1+d}{1+i}\right) / \left(\frac{1+d}{1+i}\right)^N \tag{16}$$

$$UEC_{PV} = ALCC_{PV}/(366 * E_d) \quad (\$/\text{kwh}) \tag{17}$$

Where,

$C_{op\&m/y}$	The operation and maintenance costs per year in $
i & d	The interest and the inflation rates (%)
N	The PV system life span in years

III. POWER FLOW CALCULATIONS USING BACKWARD FORWARD SWEEP ALGORITHM

Simplicity, robust convergence and requiring low space of memory for processing as well as efficiency and accuracy solutions are key features that make the BFS algorithm a common method used for power flow calculations for radial distribution systems [19]. The load flow analysis aims to calculate the active and reactive values for the power flowing in each line and the buses voltages with their angles too. With BFS, the load flow calculations for a single power source in a radial distribution system can be solved through two stages namely backward and forward sweep methods and both will be explained in detail in the following sub-sections. A single line diagram of the main feeder is shown in Fig.2. While, the flow chart of BFS algorithm is shown in Fig.3.

A. Backward Sweep Method

At iteration K and by applying the KCL starting from the end branches and moving towards the source, the branch current and complex power cab be calculated as:

$$\mathrm{I_{LK} = -I_{JK} - \sum_{m=1}^{M}(S_m/V_{JK})^*} \tag{18}$$

$$\mathrm{S_{LK} = \left(V_{JK} + Z_L * I_{LK}\right)(\, I_{LK})^*} \tag{19}$$

Where,

I_{LK}, I_{JK}	The flowing currents at iteration k in branches L, J
M	The branch numbers connected to bus J
S_m	The complex power at sending end of branch m
S_{LK}	The power flow in branch L
$\mathrm{V_{JK}}$	The voltage at bus J
Z_L	The branch L impedance

B. Forward Sweep Method

At iteration *K* and unlike the previous method the voltage values are calculated but starting with the first nodes and moving towards the end nodes. For a branch L, the voltage magnitude at the receiving end Q is given as:

$$V_{QK} = (V_{Pk} - Z_L * I_{LK}) \tag{20}$$

Where,

V_{QK} & V_{Pk}	The voltages at sending and receiving ends, respectively

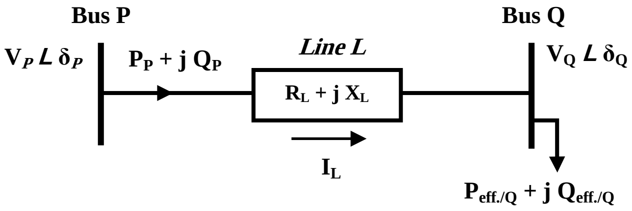

Fig. 2. Single line diagram of two nodes in a distribution system

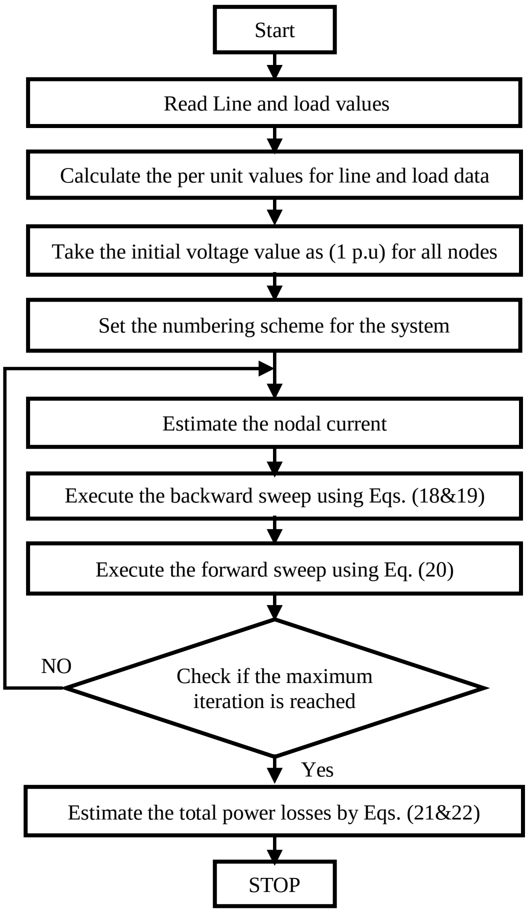

Fig. 3. Flow chart of BFS algorithm

C. Power Loss Calculation

After calculating the voltage and current magnitudes using BFS algorithm, the active and reactive power losses are calculated using the following equations:

$$\text{Total } P_{los} = \sum_{Q=2}^{N_b} \sum_{K=1}^{N_{b-1}} \{(P^2{}_{ef/Q} + Q^2{}_{ef/Q})/V_Q^2\} * R_K \quad (21)$$

$$\text{Total } Q_{los} = \sum_{Q=2}^{N_b} \sum_{K=1}^{N_{b-1}} \{(P^2{}_{ef/Q} + Q^2{}_{ef/Q})/V_Q^2\} * X_K \quad (22)$$

Where,

$P_{eff/Q}$ & $Q_{eff/Q}$	The total effective active and reactive power for loads at node Q
N_b , N_{b-1}	The number of busses and branches in the system

IV. OPTIMAL CAPACITOR PLACEMENT USING PSO ALGORITHM

A. Problem Formulation

The proposed technique is applied on a 33-bus test system shown in Fig. 4 to find the optimal ratings and locations for number of capacitors that are needed to compensate the reactive power and enhance the voltage profile. Three objective functions are considered that are minimizing the total costs of active and reactive losses and total cost of capacitors, and minimizing the voltage profile index as single objective functions and minimizing both costs and voltage profile index as a multi objective function.

1) Single Objective Functions

- *Minimization of total costs*

To minimize the total costs of energy and maximize the net savings, shunt capacitors are placed optimally in a radial distribution system considering the following objective function [20]:

$$\begin{aligned} Minimize\ \ C_t &= K_p * P_{tl} + K_C * Q_{Ct} \\ &= K_p \sum_{i=1}^{N_{b-1}} P_{li} + K_C \sum_{j=1}^{N_C} Q_{Cj} \end{aligned} \quad (23)$$

Therefore, the annual cost for the capacitors to be placed optimally is given as:

$$\text{Total cap. Cost } = K_C * Q_{C\,tot}/LE \quad (\$/\text{yr.}) \quad (24)$$

Where,

C_t	The total costs ($/yr.).
K_p	The annual cost per unit of power loss ($/kw.yr)
K_C	The total capacitor cost and installation cost ($/KVAR)
P_{tl} , Q_{Ct}	The total power loss and capacitor reactive power
P_{li}	The power loss for line i (kw)
Q_{Cj}	The value of the reactive power injected at location *j* (KVAR).
N_b&N_C	The bus numbers and the optimal number of capacitor locations respectively.
LE	The life expectancy

- *Minimization of voltage profile index (VPI)*

The voltage profile index value is an indication for the voltage profile in the system. It would be better if the VPI value closer to zero. The objective function of VPI is given as:

$$\text{Minimize VPI} = \sum_{n=1}^{N_b} abs(1 - V_n) * 100 \quad (25)$$

Where,

V_n is the voltage value at bus n and the 100 value is considered for scaling.

2) *Multi Objective Function*

A multi objective function (MO) considering equations (23, 25**)** can be formulated as:

$$\begin{gathered} Minimize\ \text{MO} = wf_1 * C_t + wf_2 * \text{VPI} \quad (26) \\ 0 \le wf_i \le 1 \quad \& \quad \sum_{i=1}^{2} wf_i = 1 \end{gathered}$$

Where,

wf_1 & wf_2 are the weighting factors for C_t % and PVI %.

All objective functions are subjected to the following constraints:

1. *Maximum capacitor number*

The number of capacitors to be placed optimally (N_c) should be limited by the number of the optimal locations (N_c^{max}) as:

$$N_c \le N_c^{max} \quad (27)$$

2. *Maximum capacitor rating*

To choose an optimal size for the capacitors to be injected at a specific bus, the reactive power value at this bus should meet this condition:

$$Q_c^{min} \leq Q_c \leq Q_c^{max} \quad (28)$$

3. *Maximum power flow in lines*

For each line (K), the power flow (PF_k) should not reach the maximum power flow value (PF_k^{max}) for this line as:

$$PF_k \leq PF_k^{max} \quad (29)$$

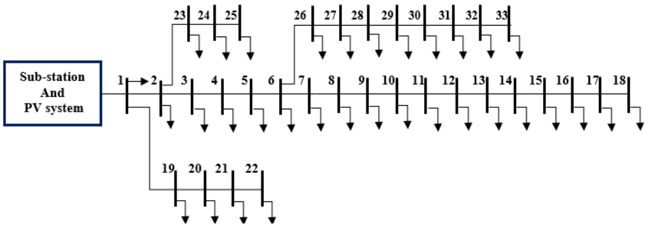

Fig. 4. Layout of 33-bus test system

B. Particle Swarm Optimization

Particle Swarm Optimization (PSO) is considered an evolutionary technique developed for programming and optimizing. It depends mainly on the flocks of birds and fish swarms' movement assuming that the distance between each particle of the swarm is changing optimally and with a synchrony behavior [21-22]. In PSO, when a particle reaches the best solution with its own, this solution is called *pbest* (personal best), but the overall best value founded by any particle in the population is called *gbest* (global best). With every time step, the velocity of each particle moving towards its *pbest* or *gbest* is changing. The PSO algorithm is running according to the following steps:

Step 1 Initialization: an array of particles is initialized with random velocities and positions in a problem space having a dimension (n).

Step 2 Evaluation: according to the objective function, the fitness is evaluated for every particle

Step 3 Comparison 1: when the fitness value obtained by each particle is considered the best when compared with the *pbest* value for this particle, then the *pbest* value is set equal to the this fitness value and its location is considered the *pbest* location.

Step 4 Comparison 2: the *gbest* value is reset to the present value of the fitness when the fitness value was founded better than the previous *gbest* [23].

Step 5 Updating: the particle's position and velocity is updating continuously depending on the following equations:

$$V_i^{T+1} = W\,V_i^T + C_1\,Rn_1\left[P_i^T - X_i^T\right] + C_2\,Rn_2\,\left[P_g^T - X_i^T\right] \quad (30)$$

$$X_i^{T+1} = X_i^T + \Delta T * V_i^{T+1} \quad (31)$$

Where,

T	The iterations number
V_i , X_i	The ith particle velocity and position
P_i	The previous best value for the ith particle
C_1& C_2	The values for cognitive and social components
Rn_1, Rn_2	Random values limited in the range [0, 1]
ΔT	The change in iterations for the updating process

W is the inertia weight value which makes a balance between the global and local search and hence a fewer iterations are required so that the algorithm is converged quickly. The weight value is updated according to the following formula:

$$W = W_{Max} - (W_{Max} - W_{Min}) * T / T_{Max} \quad (32)$$

Where,

W_{Max} , W_{Min}	The maximum and the minimum values of the inertia weight respectively,
T_{Max} , T	The maximum and the present iteration values.

Step 6 Stopping criterion: a loop is made to repeat step (2) until the maximum number of iterations is reached therefore the stopping criterion is attained.

V. APPLICATIONS

A. Design Parameters of PV Solar System and Capacitor Placement Problem

1) Solar system components and location

A PV solar module of 250 w power rating according to IEC 61730-1 & 2 is used to feed 33-bus test system with load of 3715 Kw. The module is made up of Multi Crystalline Silicon with power tolerance of [0/+5] W. The data sheet for the PV module is listed in Table I. The inverter unit cost is 1000 \$/ unit and the PV cost is 3.05 (\$ / watt). The installation and maintenance costs are taken as 10% and 2% of PV unit cost. The life span is taken as 20 years and the interest and inflation rates are 16.75% and 13.99% respectively in Egypt. The inverter used is a single-phase string inverter rated at 5 Kw with 96.5% efficiency. The inverter data sheet is given in Table II. The dirty and mismatch losses value is 3%, the columbic efficiency is taken as 95% and the derating factor is 90%. The designed PV system will be placed in a location with latitude and longitude values that are 30.565° and 31.158° respectively. This selected location has high intensity of solar radiation that is 2400 (kwh /m^2 /yr) and a daily average solar radiation of 5.31 (kwh/m^2 /day) [24]. About 9 to 11hours of sun shine are available daily and few days are overcast during the year. The maximum solar radiation reaches 8.4 hours per day of peak sun.

2) Parameters of Capacitor Placement Problem

- The rated line voltage and the rated MVA are 11kv and 100.
- The PSO parameters are:
  npop = 100 (number of iterations),
  pop = 100 (number of particles),
  W_{Max} = 0.9, W_{Min}=0.4, C_1=2.05 and C_2=2.05,
- K_p & K_C values are set as 168 \$/ (kw-yr.) and 5 \$/KVAR respectively.
- The life expectancy is assumed 10 years neglecting the running and maintenance costs.
- The number of possible capacitor sites is maximized at 3 and minimized at 1.
- The maximum and minimum values of capacitors are 1200 and 150 KVar respectively.
- The maximum power flow is taken as 5 MW.

TABLE I. MODULE DATA SHEET

PV module parameter	Symbol	Value	Unit
Maximum output power	P_{max}	250	watt
Voltage at maximum power	V_{max}	30.8	volt
Current at maximum power	I_{max}	8.12	amp
Open circuit voltage	V_{oc}	37.2	volt
Short circuit current	I_{sc}	8.96	amp
Module efficiency	η	15.4	%
Height	h	1640	Mm
Width	w	990	mm
No of cells per module	N_{cells}	60	value

TABLE II. INVERTER DATA SHEET

Parameter	Value
Type code	Growatt CP1000 Station
Size	3600/3000/2896mm
Maximum DC power	1150 KW
DC voltage range voltage	500V-1000 V
Grid connection type	Triple
Maximum efficiency	98.5%
Output Voltage	250V-362V
Output Current	1833A

B. Results and Comments

1) Results of PV System Design

Table III shows the designed PV system parameters. The PV system is designed to be a grid connected system. It supplies an AC output of 4135 kw only through day hours (from 8 am to 6 pm) while the test system needed to be supplied for 24 hours daily, therefore the designed PV system would be able to supply about 25% of the total energy needed yearly by the distribution system. The load energy and the energy produced by PV system as shown in Fig.5. Figure 6 represents one of four arrays each with its central inverter that are connected together to supply the distribution system in cooperation with the sub-station.

2) Results of optimal locations and capacitor ratings

- *PSO Algorithm Convergence*

The convergence curve of the first objective function during the optimization process is shown in Fig.7. It is clear that, the PSO algorithm gives the optimal solutions with fast convergence curves.

Figure 8 shows a comparison between the voltage profile of the distribution system with and without reactive power compensation for all cases. It is clear that, the voltage profile is improved after allocating the capacitors optimally in the test system in all cases. Figure 9 shows the active and reactive power losses in the branches of the system.

TABLE III. DESIGN PARAMETERS FOR PV SYSTEM

Parameter	Value
Total number of modules (N_T)	18000
Number of series modules (N_S)	30
Number of parallel strings (N_P)	150
Number of arrays (inverters)	4
DC power generated (P_{DC})	4508 kw
Ac power generated (P_{AC})	4135 kw
Total energy produced (E)	8 Mwh /yr.
Cost of electricity (UEC)	0.485 $ /kwh

Table IV shows the proposed technique results. With backward and forward sweep method the power losses is calculated according to 33-bus test system data then the optimal sizes and locations of the needed shunt capacitors are listed. As shown in Table IV, the total active and reactive power losses are significantly decreased by about 34% at case (1) where and the net savings records the highest value over all cases. At case (2), the minimum voltage value records the best value over all cases as the voltage regulation is improved from 16.8% at bus (18) to 6.7% at bus (30). This improvement in voltage profile came at the expense of the power loss value, which is maximized. Case (3) represents an improvement in voltage regulation by about 7.5% at bus (18) while the active power losses decreases by 29% so it is considered the best case as the voltage and the power losses are controlled with a satisfied value of the net savings.

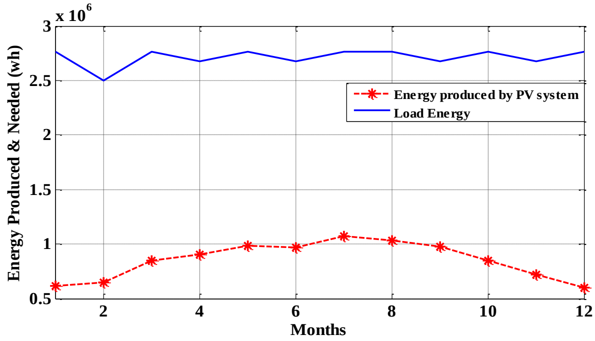

Fig. 5. Relation between the load energy and energy produced by PV system

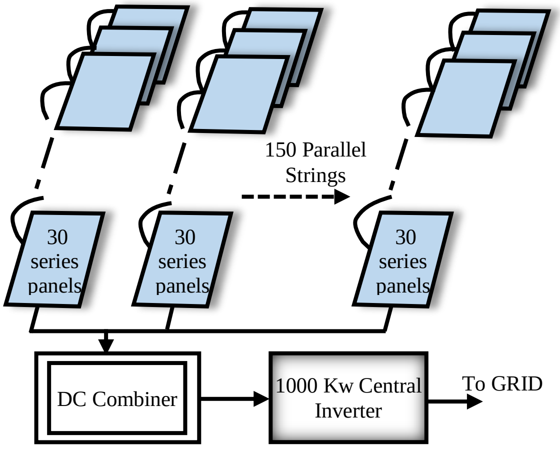

Fig. 6. One array of the PV system configuration

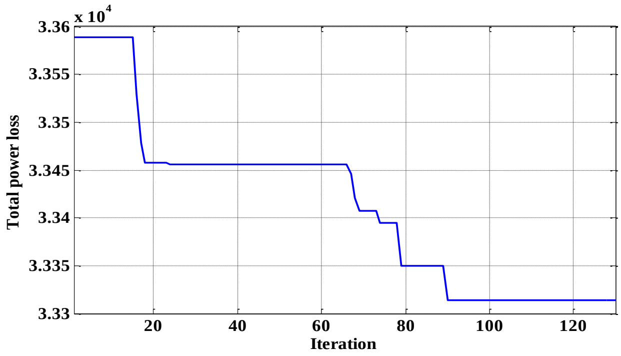

Fig. 7. Convergence curve of the PSO algorithm

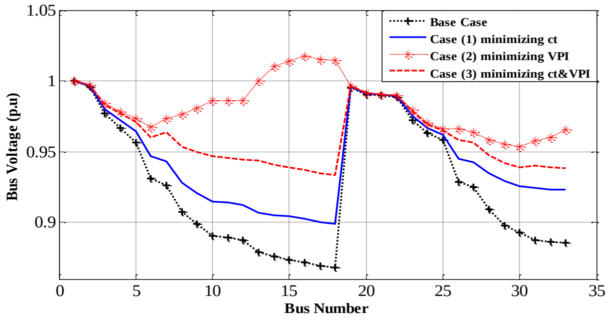

Fig. 8. Bus voltage before and after capacitor placement

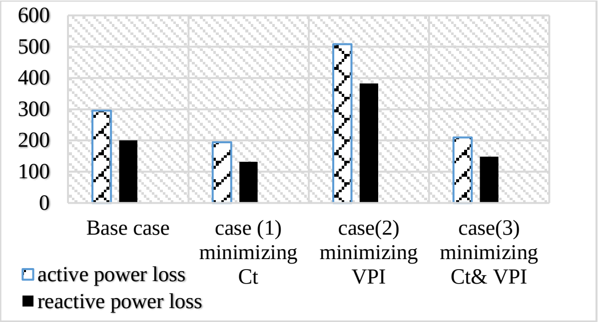

Fig. 9. Power losses before and after capacitor placement

TABLE IV. COMPARISON BETWEEN SYSTEM PARAMETERS BEFORE AND AFTER CAPACITOR PLACEMENT

Parameter	Base case	After Compensation		
		Case (1)	Case (2)	Case(3)
Total Active Losses (KW)	295.909	201.9	508.8	209.7
Total Reactive Losses (KVAR)	200.95	137.26	382.2	148.4
Minimum Bus Voltage (p.u)	0.8683 v (#18)	0.9001 v (#17)	.9532 v (#30)	0.9338 v (#18)
Optimal Capacitor Sizes and Locations (KVAR)	——	503 #31 378 #29 257 #15	1200 #33 1200 #16 1128 #14	700 #13 778 #31 838 #7
Total Capacitor Power	——	1138 (KVAR)	3528 (KVAR)	2316 (KVAR)
Annual Cost ($/yr)	49712.7	33919.2	85478.4	35230
Total Capacitor Cost ($/yr)	——	569	1764	1158
Net savings ($/yr)		15793	No savings but extra cost of 35766 $/yr.	14483

VI. CONCLUSION

In this paper, a complete design for a grid connected PV system is presented to supply a part of a distribution network. The total number of modules is 18000 connected through 4 arrays each with its central inverter to give total AC output of 4135 kW. The penetration level of PV system is calculated as 25 %. An efficient methodology has been presented based on BFS and PSO algorithms. BFS has been used for load flow calculations. PSO has been used to find optimal allocation of shunt capacitors using single and multi-objective functions. The active and reactive power losses has reduced by 34% and the net savings of power losses have significantly reduced too. The voltage profile has also improved to 6.7 %. The proposed algorithm has been applied on 33-bus IEEE test system and the results insures that the optimal allocation has been achieved.

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