International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

December 2012 | Issue 13 | Volume 4 | Number 4 | Pages 11-16

A NOVEL OPTIMAL PLACEMENT OF PV SYSTEM FOR LOSS REDUCTION AND VOLTAGE PROFILE IMPROVEMENT

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Abstract- In this paper an optimal placement of photovoltaic systems (PV) as a source of active and reactive power in radial distribution networks is considered. The objective function of this problem is minimizing system losses and improving voltage profile. Genetic Algorithm (GA) implemented for this purpose. Photovoltaic solar systems can be used as STATCOM for voltage regulation and power factor correction during both nighttime and daytime. This novel PV solar system application, beside other useful applications, makes it very useful, so it can operate more effective by considering its reactive and active power generation in 24 hours. In this study backward-forward power flow method is applied on standard IEEE 33-bus system.

Keywords: PV-STATCOM, Optimal Placement, Total Losses, Voltage Profile, Genetic Algorithm.

I. INTRODUCTION

The photovoltaic (PV) technology is expanding by the growing demand for renewable energy mainly due to the depletion of fossil fuel. PV technology offers safe and clean energy sources. As PV systems are expensive, many researchers have been conducted to improve their efficiency and reducing their cost [1-4]. In [5] the investment of large scale PV systems in Ontario has been studied. PV solar system is a kind of Distributed Generation system (DG). PV solar units can generate active power during daytime while during nighttime are completely useless. PV solar systems generate DC voltage so they need Voltage-source inverter to be connected to the power network. Inverters are an important part of Flexible AC Transmission Systems (FACTS) which can produce reactive power for improving system voltage and minimizing losses. By appropriate control of voltage source inverter of PV solar panels, they can also produce reactive power during daytime and nighttime [6].

The active power generation of PV solar systems depends on the amount of radiation and temperature. Sun radiation during daytime varies so the output active power of PV solar panels varies during daytime. So if PV system just considered for generating active power a proportion of its inverter capacity is not used. By suitable control on PV inverter it is possible to use whole capacity of its inverter for producing active and reactive power. This new concept has been proposed as an optimal utilization of PV solar systems as STATCOM for voltage control and power factor correction during both nighttime and daytime [6].

A novel inverter controller has been proposed for operation of PV solar system as STATCOM utilizing the rated inverter capacity during nighttime and the inverter capacity remaining after real power generation during daytime. This new concept allows full utilization of PV solar panels during the entire 24-hour period. Placement of PV solar system based on this new concept can be more applicable. This proposed placement method led to more reduction of Losses and Improving Voltage Profile versus the previous PV placements that considered PV as an active power generation unit [7]. Many researchers have used evolutionary computational methods for finding the optimal DG placement [8-11]. In [12] a technique named "reverse loadability" performs negative load shedding and effectively maximizes the installed capacity of DG in power systems. In [13] optimal placement and penetration of PV system for loss reduction has been presented. In [14] optimal placement and sizing of DGs for loss and THD reduction and voltage profile improvement using PSO and sensitivity analysis has been studied. In [15] an optimal sizing of a stand-alone hybrid system including wind/PV system with battery for Ardabil area has been considered.

The impact of Distributed generation on the reliability and efficiency of system considering different loads has been studied in [16]. Almost the majority of DG placement problems have studied by considering DG as an active power generation unit. In this paper, a novel method for placement of photovoltaic systems by using whole capacity of its inverter for generating reactive power beside of active power is used. The concept of this method is based on the capability of inverter of photovoltaic system for generating reactive power.

During daytime the amount of radiation varies and during the night there is no radiation. So, a large portion of inverter capacity remains idle. The proposed method uses the remaining capacity of inverter for generating reactive power. The efficiency of this placement method for photovoltaic systems is remarkable. Voltage profile improves and losses of system reduce significantly. This study is implemented on Standard IEEE 33-bus system. In section II the capability of photovoltaic inverter for generating reactive power is stated. Objective function of problem is represented in section III. Section IV presents backward-forward power flow method. In section V, genetic algorithms and in section VI, the information about a case of study is described. Finally in section VI numerical results of this study is discussed.

II. PHOTOVOLTAIC INVERTER CAPACITY FOR GENERATING REACTIVE POWER

Photovoltaic inverters are capable to generate reactive power [17]. Injection of generated reactive power into the grid can improve voltage profile and power factor of system. Inverters have a specified capacity so the maximum current of them is limit. This capacity can be used for generating active or reactive current by independent control of active and reactive current. Figure 1 shows the operational area for the current of photovoltaic inverter based on the limits.

The blue circle in the Figure 1 represents the maximum rated current of photovoltaic inverter ($I_{\max,R}$) and the yellow circle displays the maximum overload current of photovoltaic inverter ($I_{\max,OL}$). As photovoltaic modules are inflexible faced with overload current, the maximum active current of photovoltaic inverter (I_{pv}) is limited. So, the overload capacity can be used for generating reactive current. The red area in the Figure 1 illustrates the area of inverter current.

The maximum apparent power of a photovoltaic inverter is specified. The active power generation capability of photovoltaic panels depends on the amount of radiation and varies during daytime. So, the maximum reactive power which can be generated is calculated by Equation (1).

$$Q_{\max}(t) = \sqrt{S_{\max}{}^2 - P(t)^2} \quad (1)$$

where, t is time.

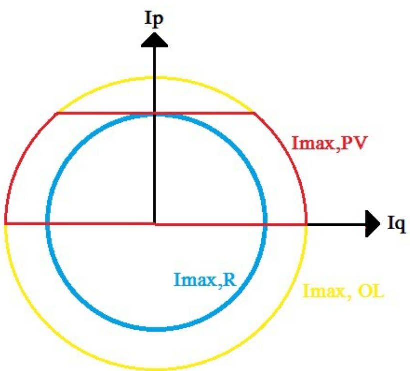

Figure 1. Current area of photovoltaic inverter

III. OBJECTIVE FUNCTION

This study is done in order to minimizing distribution system losses and improving voltage profile. The objective function of this problem is defined as follows:

A. Loss Reduction

The total losses in distribution system can be calculated as follows:

$$f_p = P_{loss} = \sum_{t=1}^{24} \sum_{j=1}^{N-1} I_j^2 R_j \quad (2)$$

$$f_{p,norm} = P_{loss,norm} = \frac{\sum_{t=1}^{24} \sum_{j=1}^{N-1} I_j^2 .R_j}{P_{loss}^{\max} .t} \quad (3)$$

where $P_{loss}^{\max}$ is maximum losses of system which has been used for normalization of P_{loss}, I_j is the current of feeder in section j, N is the number of nodes, N-1 is the number of feeder sections, R_j is resistance of feeder j, $f_{p,norm}$ is the normalized fitness function for losses of system and t is time which is equal to 24.

B. Voltage Profile Improvement

The fitness function of voltage profile improvement can be defined as:

$$f_v = \sum_{t=1}^{24} \sum_{i=1}^{N=33} (V_{nom} - V_{it})^2 \quad (4)$$

$$f_{v,norm} = \frac{\sum_{t=1}^{24} \sum_{i=1}^{N=33} (V_{nom} - V_{it})^2}{V_{nom} .t} \quad (5)$$

where $f_{v,norm}$ is the normalized fitness function for voltage profile improvement, V_{nom} is the nominal voltage of system is equal to 1 p.u., V_{it} is voltage of the ith bus at time t, N is the number of buses of network under study and t is time which varies from 1 to 24 for 24 hours.

The total objective function is minimizing the following function:

$$f = w_1 f_{p,norm} + w_2 f_{v,norm} \quad (6)$$

$$w_1 + w_2 = 1 \quad (7)$$

where f is the objective function and w_1 and w_2 are weighting coefficients.

In the above equations w_1, w_2 are considered as 0.6 and 0.4, respectively. The relation between active and reactive power of PV and its limits are as follows:

$$S = \sqrt{P^2 + Q^2} \quad (8)$$

$$P_{\min} \le P_{pv} \le P_{\max} \quad (9)$$

$$Q_{\min} \le Q_{pv} \le Q_{\max} \quad (10)$$

where $P_{\min}$ and $Q_{\min}$ are minimum active and reactive powers, respectively. $P_{\min}$ and $Q_{\min}$ are equal to zero because during the night there is no radiation so active output power is equal to zero. Also at noon PV operates in rated capacity of active power generation so its reactive output power is zero.

IV. BACKWARD-FORWARD POWER FLOW METHOD

Because of the high ratio of R/X in distribution systems power flow methods such as Newton-Raphson and fast decoupled may not converge if they used for power flow of distribution systems. According to this problem for some power flow methods for distribution systems, using backward-forward method for power flow in distribution systems is much applicable because of its convergence speed. This method includes two steps of backward-forward sweep which iterates in a loop so that the convergence of the power flow is gained [18, 19].

A. Power Flow Modeling

Numbering branches or lines of power system is the first step in this method. For do this, the network should be layered. Layering of network can be done by moving forward from main node to the ending nodes. The lines between this node and next nodes are considered as first layer. This procedure continues till network layering is completed. After layering, branch numbering will start from main node. Numbers of branches are started from 1 to N_b and the number of lower layers is bigger than the number of upper layer. In radial network the following equation shows the relation between the number of branches and number of nodes.

$$N_b = N - 1 \quad (11)$$

where N_b is the number of branches and N is number of nodes. The steps of algorithm are stated following:

1. Backward Sweep

In this stage by moving from ending buses to main bus (slack), power flow is calculated by using Equation (12):

$$S_n = S_i + \sum_{m \in M} S_m + Loss_n \quad (12)$$

where S_n is the power flowing through the nth branch, i is the last node of nth branch, S_i is The power of the load connected to the ith node, M is sum of the branches which are connected to the nth branch in ith node, S_m is power of the Mth branch and $Loss_n$ is nth branch loss (which is considered zero in the first iteration).

2. Forward Sweep

By moving from branches which connected to the slack bus to the ending branches, the branch current in sending bus of nth branch (j) and the voltage in the receiving bus of nth branch (i) is calculated using Equations (13) and (14). Calculation of branches losses can be done by using Equation (15).

$$J_n = \left(\frac{S_n}{V^j}\right)^* \quad (13)$$

$$V^i = V^j - Z_n . J_n \quad (14)$$

$$Loss_n = \left(V^j - V^i\right).J_n^* \quad (15)$$

3. Voltage Deviation Calculation

The voltage deviation of buses in each iteration can be calculated as follows:

$$\Delta V^{i^{(k)}} = \left|V^{i^{(k)}}\right| - \left|V^{i^{(k-1)}}\right| \quad (16)$$

where k is iteration number. The calculation continues until ΔV^i becomes smaller than convergence criterion.

V. GENETIC ALGORITHM

Genetic algorithm (GA) is a computational model that is based on concepts of evolutionary processes [20]. Genetic algorithm is much applicable for solving optimization problem. GA operates on a population of possible answers (individuals or chromosomes), applying selection and reproduction criteria and by then new solutions (offspring) are generated containing information from where they were originally created (parents). Obviously, the better solution, there is a higher probability one goes to the next offspring.

The first step is encoding a potential solution in a data structure type. Once the initial population is randomly generated every solution is evaluated by means an objective function. In each generation the fitness value of all individuals are calculated and those with higher fitness values have more probability to be parents of next generation. At this point, some individuals are coupled by means of a crossover operator. In continue the individuals can undergo mutation, which involves selecting a gene in a string and change it to another possible value. The probability of mutation to happen is rather small. The algorithm of this problem is illustrated in Figure 2. The number of buses in this problem are N, so the number of candidate buses for PV installation is N-1 (no PVs are installed in slack bus). The selected genetic algorithm parameters for this problem are illustrated in Table 1.

Table 1. Selected parameters for GA

Population size	100
Selection function	Roulette wheel
Crossover	Single point
Crossover rate	0.85
Mutation rate	0.3

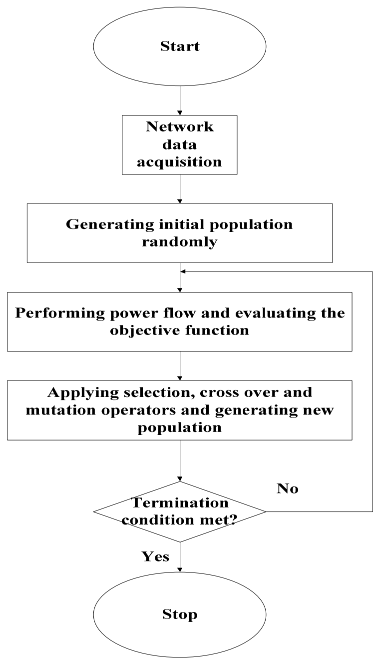

Figure 2. Genetic algorithm diagram

VI. RESULTS AND DISCUSSIONS

A. Selected Case and 24-Hour Load Profile

Standard IEEE 33-bus distribution system is selected for this study. The single phase diagram of this system is illustrated in Figure 3. In this paper placement of PV is studied in 24-hour because the purpose is using the rated capacity of inverter in 24-hour for generating active and reactive power. So 24-hour load profile is required for this problem.

The 24-hour load profile is defined by multiplication of base load of IEEE 33-bus system to a typical daily load. This typical load curve is defined as a percent of peak load in each hour, so by multiplication of this curve to the base load of IEEE 33-bus system, the 24-hour load profile is determined. The typical selected load curve has been shown in Figure 4.The information of base loads of IEEE 33-bus systems also are listed in Table 2.

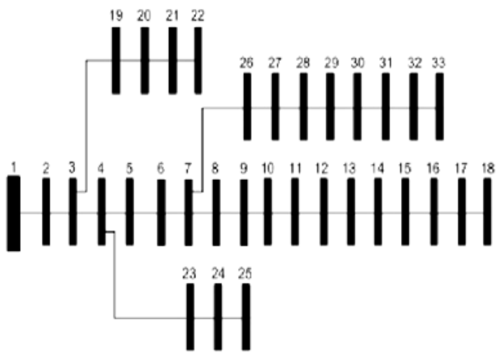

Figure 3. Single phase diagram of standard IEEE 33-bus system

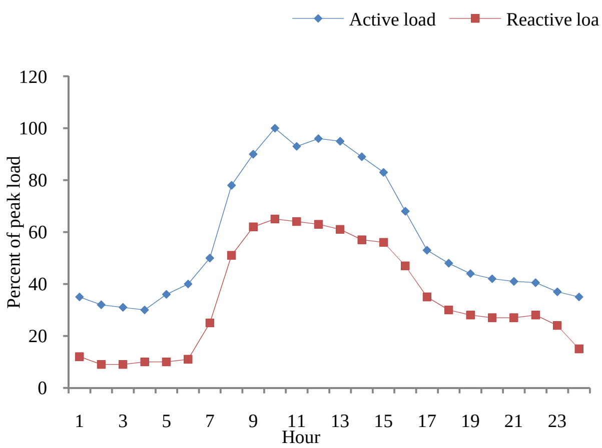

Figure 4. Typical 24-hour load curve

B. PV Capacity and Output Active and Reactive Power

The output power of PV solar system depends on some factors such as temperature and radiation. So, the output active and reactive power of PV solar system varies during daytime. The nominal capacity of PV and also its inverter is considered as 100 kVA. In this paper assumed the output active and reactive power of PV solar system varies hourly, so in 24 hours, 24 output powers are considered that are shown in Table 3.

Three PV solar systems with 100 kVA capacity are considered for this problem. Table 4 illustrates line losses without PV, with PV by considering only active power generation capability and with PV by considering active and reactive power generation capability. The result shows if reactive power capability of PV solar systems is considered, the losses of lines decreases considerably. The total loss in 24 hours is 1834.6 kW without PV.

Table 2. IEEE 33-bus base load

Bus Number	*P* (kW)	*Q* (kVAr)
1	0	0
2	100	60
3	90	40
4	120	80
5	60	30
6	60	20
7	200	100
8	200	100
9	60	20
10	60	20
11	45	30
12	60	35
13	60	35
14	120	80
15	60	10
16	60	20
17	60	20
18	90	40
19	90	40
20	90	40
21	90	40
22	90	40
23	90	50
24	420	200
25	420	200
26	60	25
27	60	25
28	60	20
29	120	70
30	200	600
31	150	70
32	210	100
33	60	40

Table 3. 24-hour output power of PV

Hour	*P* (kW)	*Q* (kVAr)
1	0	100
2	0	100
3	0	100
4	0	100
5	0	100
6	0	100
7	5	99.8
8	12	99.3
9	60	80
10	85	52.7
11	100	0
12	100	0
13	85	52.7
14	60	80
15	12	99.3
16	5	99.87
17	0	100
18	0	100
19	0	100
20	0	100
21	0	100
22	0	100
23	0	100
24	0	100

The results for improving voltage profile are shown in three hours. Figure 5 illustrates bus voltages at 9 am. This time is selected because PVs generate both active and reactive power. Three voltage profile curves are shown in Figure 5 which is related to the bus voltages without PV, with PV by considering active power generation and with PV by considering reactive and active power generation. It is clear that PV placement considering reactive power capability can improve voltage profile effectively.

Table 4. Lines Losses with & without *Q* generation capability of PV system

Number of PVs	PV with *P* generation	PV with *P* and *Q* generation
1	Selected bus:18	Selected bus:32
	Losses: 1757.46 kW	Losses: 1696.6 kW
2	Selected buses: 17, 30	Selected buses: 13, 32
	Losses: 1692.8 kW	Losses: 1580.7 kW
3	Selected buses: 17, 18, 33	Selected buses: 16, 31, 32
	Losses:1626.6 kW	Losses:1475.9 kW

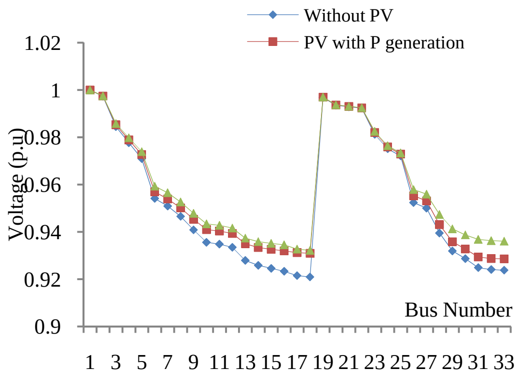

Figure 5. Voltage profile without PV, with PV with *P* generation and with PV with *P* and *Q* generation capability at 9 am

Figure 6 illustrates voltage profile at 12 pm. In this time PV just generate active power. Also the reactive power generations of PV in this time is zero but the curves of voltage profile with active generation and with active and reactive generation are not match because PVs are located in different places. Finally, the voltage profile at 12 am is illustrated in Figure 7. In this time PV can only generate reactive power because sun radiation is equal to zero. In this time (during night) if the reactive generation is not considered, the curves of voltage profile in case of with and without PV solar system are match because PV system doesn't generate active power during the night.

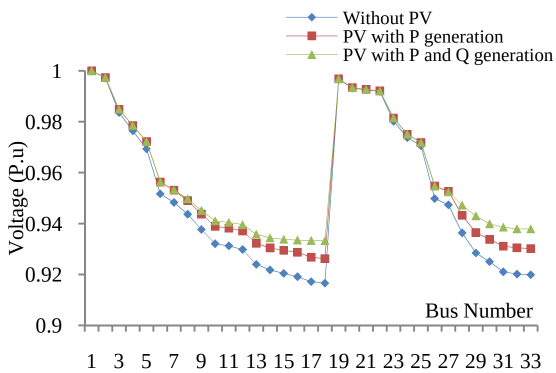

Figure 6. Voltage profile without PV, with PV and *P* generation and with PV and *P* and *Q* generation capability at 12 pm

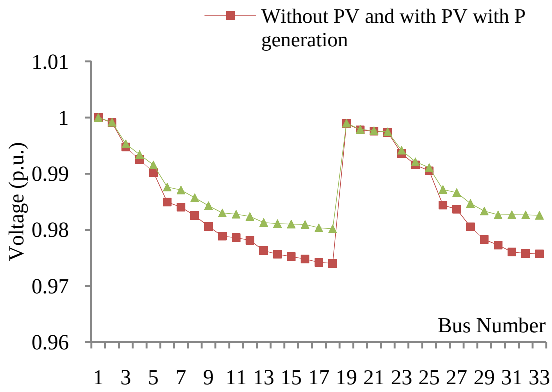

Figure 7. Voltage profile without PV, with PV and *P* generation and with PV and *P* and *Q* generation capability at 12 am

VII. CONCLUSIONS

In this paper an optimal placement of photovoltaic system considering its capability for generating active and reactive power has been studied. By the proper control of PVs inverter it is possible to use full capacity of inverter for generating reactive power beside of active power. This method of placement is based on an optimal utilization of PV system during daytime and nighttime. In this study three 100 kVA PV systems are considered. The results of this study show if the capability of generating reactive power is considered for PV placement, the losses of lines in system decrease considerably.

The results of losses reduction have been compared with and without consideration of PV system reactive power generation. This method of placement not only reduces the losses of lines in power system, but also improves voltage profile. To illustrate the effects of this placement method on the voltage profile, three different times are considered and voltage profile curves have been shown in these three times. These three times are 9 am, 12 pm and 12 am. These times have been chosen because at 9 am PV systems are able to generate active and reactive power. At 12 pm the whole capacity of inverter is used for generating the maximum active power. At 12 am, PV systems generate just reactive power. It is clear from the results that in all of these three times voltage profile has been improved when the capability of generating reactive power is considered. This is a significant concept for optimal placement of PV solar systems.

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