

# Placement of PV Units Considering Uncertainties of Generation and Load in Distribution Systems

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**Abstract** - In conventional power system the transmission and distribution (T&D) losses is a major concern. Renewable energy resources placed at load centers can reduce the T&D losses. For power system planners and researchers it is essential to find the optimal size and position of renewable energy resources to be placed in distribution networks. Renewable energy source such as solar energy is abundantly present in the environment. With the help of solar photovoltaic (SPV) system solar energy can be converted to electrical energy. Placement of SPV in distribution system is an interesting area for researchers and planners, the random placement of SPV in distribution system leads to more power losses and poor voltage profile. In this article mathematical modelling of time varying nature of SPV and variable load has been explained and particle swarm optimization (PSO) method is proposed to find the best size and location of the SPV system. This method is tested on IEEE 33 bus system. For the validation of result existing technique based on analytical expression is selected. It is found that PSO gives better result in compare to analytical method.

**Index Terms** - Solar photovoltaic system, Multi-objective index, Time varying solar irradiance, Power system optimization, Particle swarm optimization.

## I. INTRODUCTION

Owing to the technology advancement and Government policies, On Grid Solar Photovoltaic (PV) units are increasing worldwide. PV owners can receive incentives from utilities in case of surplus power [1]. In conventional distribution systems power loss is a major concern. By using Distributed Generation (DG) units near to the load center power loss can be reduced and other factors like voltage stability, loadability enhancement etc. can also be improved [2-10]. On the other hand, more and more diffusion of renewable resources with load variations may cause challenges such as increasing losses, voltage step, power fluctuations and short voltage strength [1-5]. Placement of DG in distribution system considering power loss and voltage profile improvement has been addressed separately in recent years. Some studies have been done on DG allocation by taking into account load variation and generation variations [11-13]. In the same way some studies has been done on voltage stability improvement by using DG unit's at most sensitive buses using continuous power flow (CPF) [7]. Like conventional technologies, solar PV is unpredictable, discontinuous and non-dispatchable.

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In literature [5-7] multi-objective optimization method based on active power index and reactive power index has been proposed. But the practical scenario of time dependent generation and load demand is not addressed. Different methods and techniques have been suggested in different literatures to come across the optimal allocation of solar PV. In Paper [14-20] metaheuristics techniques has been proposed to come across the optimal allocation of DG considering the peak load and fixed generation. In most of the papers the constant value of solar PV output and load is considered. From the literature survey done here, the time dependent load model and solar PV generation with multi-objective indexing for finding the optimal size and location of PV unit is not reported. This paper contributes the uncertainty of solar PV and load is modelled and multi-objective index based hybrid (MOI-PSO) method is presented to get the optimal location and size of solar PV. The other section of the paper is structured as follows; the load modelling and Solar PV modelling is explained in Section 2, problem formulation in Section 3, proposed method for optimal size and location of PV in Section 4, Test system and result for 33-bus distribution system in Section 5 and finally Section 6 presents the contributions and conclusions of the work

## II. SOLAR PV AND LOAD MODELLING:

### A. Modelling of Solar PV System:

The probabilistic nature of solar PV on hourly basis is given by beta distribution function (BDF). To find the BDF, a day is split into 24-h period and each hour has its own solar irradiance PDF. Each hour of the day is split into 20 states, standard and mean deviation from historical data for these 20 states has been found. In this study irradiance of solar with step size of 0.05 kW/m<sup>2</sup> is assumed. The BDF for each hour of a day is given as [1]

$$BDF = \begin{cases} \frac{r^{a+b}}{\Gamma(a)\Gamma(b)} (R^{a-1})(1-R^{b-1}) & 0 \leq R \leq 1, a, b \geq 0 \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where a and b are the parameters of BDF and it depends on the values of mean and standard deviation. R is the solar irradiance (kW/m<sup>2</sup>).

$$b = (1 - \mu) \left[ \frac{\mu(1+\mu)}{\sigma^2} - 1 \right] \quad (2)$$

$$a = \frac{\mu \times b}{1 - \mu} \quad (3)$$

Where,  $\mu$  is mean and  $\sigma$  is standard deviation. The mean and standard deviation is calculated using the three years historical data and given in table 1. The output from the solar PV module at any solar irradiance R. P(R) can be determined as [1]

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$$P(R) = N \times ff \times V_x \times I_x \quad (4)$$

Where, N represents module number. ff; fill factor. VX and IX are voltage and current of the module which are calculated as follows:

Fill factor ( ff) is obtained using the formula:

$$ff = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{oc}} \quad (5)$$

**TABLE I: Hourly basis irradiance data [1]**

Hour	$\mu(\text{kw}/\text{m}^2)$	$\sigma$	Hour	$\mu(\text{kw}/\text{m}^2)$	$\sigma$
1	0	0	13	0.657	0.164
2	0	0	14	0.612	0.147
3	0	0	15	0.497	0.143
4	0	0	16	0.349	0.116
5	0	0	17	0.203	0.081
6	0.007	0.021	18	0.068	0.063
7	0.081	0.036	19	0.003	0.012
8	0.237	0.056	20	0	0
9	0.400	0.087	21	0	0
10	0.523	0.127	22	0	0
11	0.632	0.156	23	0	0
12	0.663	0.162	24	0	0

Where,  $V_{mp}$  and  $I_{mp}$  are maximum power point voltage and current.  $V_{oc}$  and  $I_{sc}$  are respectively the open circuit voltage (V) and current (A).

Voltage ( $V_x$ ) of the module is given by:

$$V_x = V_{oc} - C_v \times T_{ycell} \quad (6)$$

Here,  $C_v$  is voltage temperature coefficients ( $V/^\circ C$ ) and  $T_{ycell}$  is cell temperature ( $^\circ C$ ).

Current ( $I_x$ ) of the module is given by:

$$I_x = R [I_{sc} + C_i \times T_{ycell}] \quad (7)$$

Here,  $C_i$  is current temperature coefficients ( $A/^\circ C$ ) and  $T_{cell}$  is cell temperature ( $^\circ C$ ).

Cell temperature ( $T_{ycell}$ ) is calculated using the relation:

$$T_{ycell} = T_a + \left( \frac{NOT - 20}{0.8} \right) \quad (8)$$

Here,  $T_a$  is ambient temperature ( $^\circ C$ ) and NOT is nominal operating temperature ( $^\circ C$ ) of the cell.

Now, the average output power of a module at any hour of a day can be calculated by

$$P(\tau) = \int_0^1 P(R) \times BDF \, dR \quad (9)$$

Table 2 shows different values of PV modules taken for the calculation of eqn. (4) to (8).

## B. Load Modelling:

In this study the commercial load with time varying nature [2] is considered. Which dependants on voltage and represented by active and reactive power injection.

Active power injection:

$$Pk(\tau) = P_L(\tau) \times V_k^{np}(\tau) \quad (10)$$

Reactive power injection:

$$Qk(\tau) = Q_L(\tau) \times V_k^{nq}(\tau) \quad (11)$$

Equation (10, 11), the active and reactive loads are arranged as  $P_L(\tau)$ ,  $Q_L(\tau)$ ; voltage at kth bus is  $V_k^{np}(\tau)$ ,  $V_k^{nq}(\tau)$ ;  $Pk(\tau)$  is the active power injections and  $Qk(\tau)$  is the reactive power injections at bus k. In this paper the value of

$np=1.51$  and  $nq=3.40$  is taken which is defined as commercial load voltage exponents.

## III. PROBLEM FORMULATION

### A. Active Power loss index (APLI)

The total APL in the n- branch radial distribution system without PV (Ploss) can be defined as [3]

$$P_{loss} = \sum_{i=1}^n \frac{P_i^2 + Q_i^2}{|V_i|^2} R_i \quad (12)$$

Here,  $P_i$  is active and  $Q_i$  is reactive power flow through the branch i when no PV system is connected to the radial distribution system.  $|V_i|$ ; voltage magnitude of ith bus.  $R_i$ ; resistance of the ith branch.

When a PV system is connected at kth bus, the total active power loss of the system is given by

$$P_{loss,PV} = \sum_{i=1}^k \frac{(P_i - P_{PVk})^2}{|V_i|^2} R_i + \sum_{i=k+1}^n \frac{P_i^2}{|V_i|^2} R_i +$$

$$i=1k(Q_i - Q_{PVk})^2 V_i^2 R_i + i=k+1nQ_i^2 V_i^2 R_i \quad (13)$$

The relation between active and reactive power of a PV system at bus k can be written as

$$Q_{PVk} = a_k P_{PVk} \quad (14)$$

Where,  $a_k = \pm \tan(\cos^{-1}(pf_k))$

By substituting (12) and (14) into (13), we get APLI as

$$APLI = \frac{P_{loss,PV}}{P_{loss}} \quad (15)$$

### B. Reactive Power loss index (RPLI)

The total RPL in the n- branch radial distribution network without PV ( $Q_{loss}$ ) can be defined as[3]

$$Q_{loss} = \sum_{i=1}^n \frac{P_i^2 + Q_i^2}{|V_i|^2} X_i \quad (16)$$

Here,  $P_i$  is active and  $Q_i$  is reactive power flow through the branch i when there is no PV system connected to the radial distribution system.  $|V_i|$  is the voltage level of ith bus and  $X_i$  is the reactance of the ith bus.

When a PV system is connected at kth bus, the total reactive power loss of the system is given by

$$Q_{loss,PV} = \sum_{i=1}^k \frac{(P_i - P_{PVk})^2}{|V_i|^2} X_i + \sum_{i=k+1}^n \frac{P_i^2}{|V_i|^2} X_i + \sum_{i=1}^k \frac{(Q_i - Q_{PVk})^2}{|V_i|^2} X_i + \sum_{i=k+1}^n \frac{Q_i^2}{|V_i|^2} X_i \quad (17)$$

Active and reactive power of a PV system at bus k can be written as

$$Q_{PVk} = a_k P_{PVk} \quad (18)$$

Where,  $a_k = \pm \tan(\cos^{-1}(pf_k))$

By substituting (16) and (18) into (17), we get RPLI as

$$RPLI = \frac{Q_{loss,PV}}{Q_{loss}} \quad (19)$$

### C. Multi-objective index (MOI)

$$MOI = \sigma_1 APLI + \sigma_2 RPLI \quad (20)$$

Where  $\sum_{i=1}^2 \sigma_i = 1$



The value of impact indices are given by  $\sigma_1$  and  $\sigma_2$ . It varies between 0 to 1.

Impact indices values are considered as 0.7 and 0.3 [4]. It is the experience of the engineer that decides the suitable value of weight. Now the average multi-objective index (AMOI) for time varying generation and demand can be calculated as:

$$AMOI = \frac{1}{T} \int_0^T MOI(\tau) d\tau \quad (21)$$

$$= \frac{1}{24} \sum_{\tau=1}^{24} MOI(\tau) \Delta\tau$$

Minimum value of AMOI presents the optimal allocation of DG considering minimum power loss and voltage stability enhancement.

#### D. Objective Function

The aim of the research work is to minimize the active and reactive power loss of the system using multi-objective index (MOI) i.e.

$$\text{Min (MOI)} = \min(\sigma_1 \text{APLI} + \sigma_2 \text{RPLI}) \quad (23)$$

subject to:

$$V^{\min} \leq V_k(\tau) \leq V^{\max} \quad (24)$$

$$DG^{\min} \leq DG \leq DG^{\max} \quad (25)$$

$V^{\min}$  is minimum and  $V^{\max}$  is maximum voltage limit of the bus.  $DG^{\min}$  and  $DG^{\max}$  are the minimum and maximum size of the DG.

#### IV. PROPOSED METHOD

Particle swarm optimization (PSO) approach is proposed in this paper to get the optimal size and location of solar PV considering the time varying load model and probabilistic solar PV generation. The steps used to code the problem are as follows:

- Step 1:** Algorithm specific parameters are initialized
- Step 2:** Possible solution are generated
- Step 3:** Solar panel constant parameters are initialized
- Step 4:** Size of solar PV in discrete form is generated
- Step 5:** Constraints of the problem is defined
- Step 6:** Objective function i.e. optimal allocation of DG is calculated
- Step 7:** Keeping constraints in mind fitness of the problem is determined
- Step 8:** Program termination parameter is initialized

#### V. TEST SYSTEMS AND RESULTS

In this paper 33 bus system has been used to implement the proposed work. The details about the system is given in paper [5].

**Solar PV system modelling:** In this paper the value of solar irradiance (R) is taken as 0.65 and number of modules=1. Now Eqn. (1) to (9) is calculated for each hour of a day using values from table 1-2.

**Table II: Calculated values of a, b, BDF and P for each hour of a day**

Hour	a	b	BDF	P (W)	Hour	a	b	BDF	P (W)
1	NaN	NaN	0	0	13	25.9358	13.5403	5.1703	774.4082
2	NaN	NaN	0	0	14	27.3284	17.3258	4.9367	739.4199
3	NaN	NaN	0	0	15	17.5856	17.7979	0.9136	136.8432
4	NaN	NaN	0	0	16	11.8618	22.1263	0.0084	1.2590
5	NaN	NaN	0	0	17	7.3529	28.8683	0	0
6	0.1048	14.8792	0	0	18	1.1762	16.1215	0	0
7	5.3915	61.17093	0	0	19	0.0596	19.8361	0	0
8	21.918	70.5660	0	0	20	NaN	NaN	0	0
9	29.1943	43.7915	0	0.0879	21	NaN	NaN	0	0
10	25.3053	23.0795	1.1711	175.4068	22	NaN	NaN	0	0
11	26.1538	15.2288	5.2484	786.1055	23	NaN	NaN	0	0
12	27.1911	13.8211	5.1908	777.4680	24	NaN	NaN	0	0

From Eqn. (4-8) we get,

$ff = 0.7105$ ,  $V_x = 32.0157$  V,  $I_y = 6.5840$  A,  $T_{ycell} = 38.6875$  °C and  $P(R) = 149.7775$  W.

**Location selection and sizing:** For each bus multi-objective index (MOI) is calculated using (21). The bus where the value

of AMOI is minimum is optimal location for the DG placement. For 33-bus system the value of MOI is minimum at bus 6 with industrial load model. For the 33 bus system at bus 6 the maximum output of the PV system is obtained at hour 11 which gives the optimal size of the DG. Table 4 shows the optimal location and size of solar PV system in 33- bus system

**Table IV: Optimal location and size for 33-bus system**

Load Models	Optimal bus	Optimal Size (MW)	MOI
Industrial	6	1.07	0.22

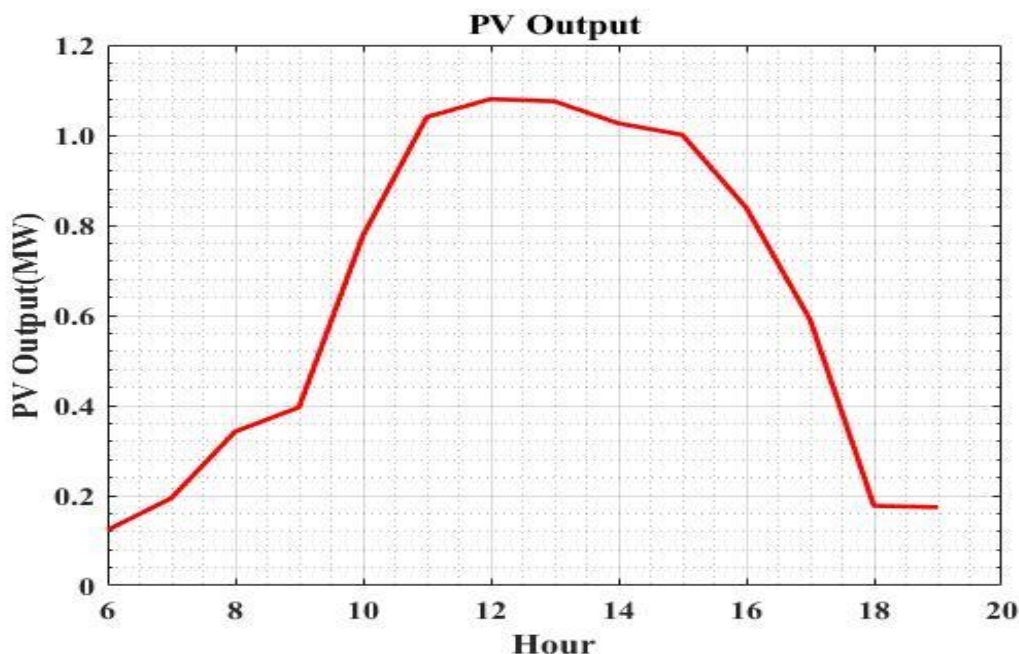


Fig.1. Expected PV output at bus 6

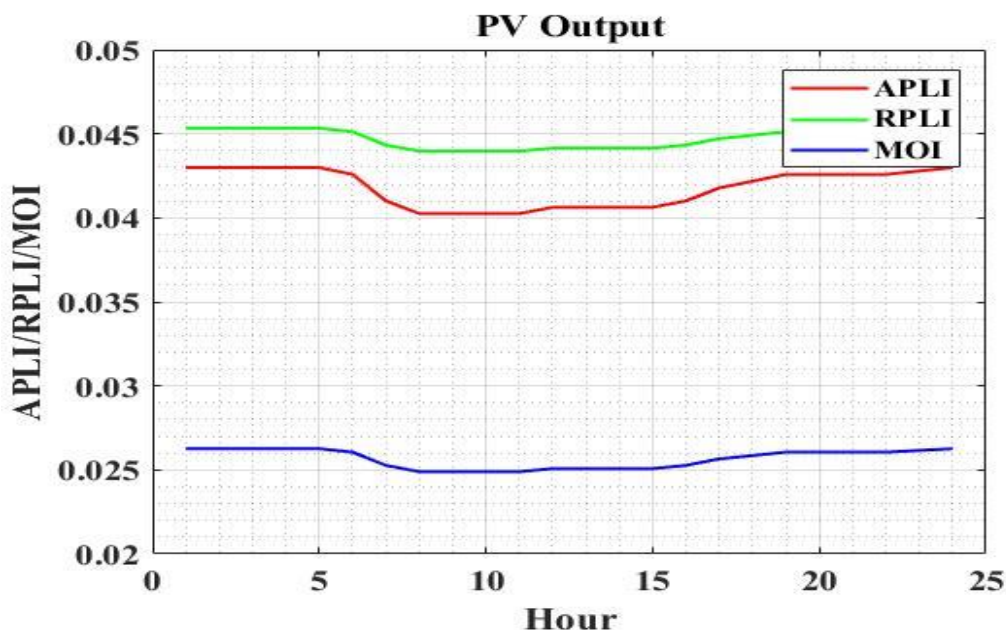


Fig.2. Loss index

VI. CONCLUSION

This paper discusses the optimal location and size of solar PV system in commercial distribution system using multi objective index (MOI) based PSO algorithm. Here, we are simultaneously reducing the active power loss and reactive power loss. The probabilistic nature of solar irradiance is

modelled using beta distribution function (BDF) and also time varying load modelled is proposed. Result obtained from the proposed method is compared with the existing analytical method. It is found that this method is fast and gives improved results.

Table V: Comparison of proposed method with existing methods

Proposed method		Existing Method	
Size (MW)	Location	Size (MW)	Location
1.07	6	1.50	6

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