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A Simplified Methodology for Determining Optimal Location and Capacity of Solar PV Distributed Generation to Reduce Losses

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This paper presents distribution load flow analysis for balanced radial system in conjunction with Solar Photo-Voltaic (PV) distributed generation. The proposed approach utilizes Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL) carried-out on forward and backward sweep iterative algorithm for the calculation of node voltages and currents flowing in radial branches. The power generated from solar PV system is determined by developing a mathematical model of solar PV modules that adopts to the Indian meteorological conditions. The distribution load flow analysis carried out by taking into the effect of this Solar PV generation. Optimal location for the distributed generation is determined by considering total system losses that can occur in 24 hours and the capacity to be installed is based on desired voltage improvement. The proposed approach has been implemented on standard 69bus radial distribution network. The simulation results obtained with and without inclusion of Solar PV generation are compared and discussed.

Keywords: *Distribution load flow; Heuristic approach, Losses, optimal, Solar PV generation, Voltage profile*

1.0 INTRODUCTION

Electricity, one of the basic needs of modern world is experiencing a consistent rise in demand. On the other hand the conventional resources used for its production are depleting at a rate faster. According to [1] approximately 39% of world's electricity generation is contributed by coal, 19% from Hydro, 15% from gas, 16% from nuclear and 10% from oil. Also, the quality and reliability of produced power is of a great importance in the present day scenario. Even with today's advanced power system technologies the losses in the system are very high which need to be decreased for higher efficiencies and better receiving end voltages. This is experienced even more in distribution system where there is a direct impact on customer, owing to long radial lines in a country like India. Hence a solution that addresses both the concerns is of a great interest. This paper proposes a solution with distributed renewable generation in the system at an overall optimal location and optimal capacity that is required/possible to be installed by solving distribution load flow.

Since renewable generation will not completely replace the conventional generation, in near future the solution to this lies in effective diversion of load demand onto distributed generation. India being a tropical country where 300-330 solar day are available in a calendar year and is one among the energies attracting lot of investors. Hence solar energy is chosen for the study presented in this paper. Solar PV modules are modeled for the study and the exact output based on the available solar insolation and temperature is calculated.

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Attempts have been made in the recent past to study the effect of distributed generation on the distribution system. Reference [2-4] show that the distributed generation was successful in reducing total system losses and also show improvement in the voltage profile. All these works are made on an hourly basis and has the disadvantage of not considering the intermittence effect of both the load and renewable energy throughout the day.

This paper makes an attempt to study the effects of both, optimal distribution generation capacity and optimal location in the distribution system on 24 hour basis taking into consideration the variable impact of load factor. The approach has been implemented on a balanced 69 bus system supplied by a 12.66KV substation [5] applying the forward/backward sweep iterative radial distribution load flow algorithm for the computation of node voltages and branch currents [6]. The solar PV modules has been mathematically modeled using the descriptions published in [7] and applied with 12 hours of solar spectrum subjected to its availability [8]. The simulation results of the proposed approach obtained with and without inclusion of Solar PV generation are presented and compared.

2.0 MATHEMATICAL MODELING FOR SOLAR PV

The electrical equivalent circuit of the PV cell can be described as a current source in parallel with a diode & leakage resistor (R_p) which are in series with resistor (R_s) where for simplicity R_p is neglected as shown in Figure 1. The output of the current source is proportional to the photons falling on the PV cell [9].

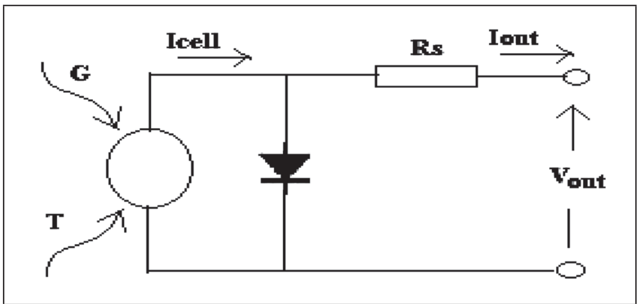

FIG. 1 EQUIVALENT CIRCUIT OF PV CELL

The I-V characteristics of a PV cell can be mathematically modeled by Shockley diode equation and the two parameters V_{OC} & I_{SC}, are determined to describe PV cell.

The mathematical modeling of a PV cell is as follows:

$$I_{Out} = I_{Cell} - I_0\left(e^{q(V_{Out}+I_{Out}R_S)/nkT} - 1\right) \quad \text{....(1)}$$

$$I_{Cell} = I_{Cell(T_1)}\left(1 + k_0\left(T - T_1\right)\right) \quad \text{....(2)}$$

$$I_{Cell(T_1)} = G * \frac{I_{SC(T_1,nom)}}{G_{(nom)}} \quad \text{....(3)}$$

$$k_0 = \frac{\left(I_{SC(T_2)} - I_{SC(T_1)}\right)}{\left(T_2 - T_1\right)} \quad \text{....(4)}$$

$$I_0 = I_{0(T_1)} * \left(\frac{T}{T_1}\right)^{\frac{3}{n}} * e^{-\frac{qV_g}{nk\left(\frac{1}{T} - \frac{1}{T_1}\right)}} \quad \text{....(5)}$$

$$I_{0(T_1)} = \frac{I_{SC(T_1)}}{e^{\frac{qV_{oc(T_1)}}{nkT_1}} - 1} \quad \text{....(6)}$$

$$R_S = -\frac{dV_{Out}}{dI_{V_{OC}}} - \frac{1}{X_V} \quad \text{....(7)}$$

$$X_V = I_{0(T_1)} * \frac{q}{nkT_1 * e^{\frac{qV_{OC(T_1)}}{nkT_1}}} \quad \text{....(8)}$$

To analyze the described mathematical model, Solarex manufactured Photovoltaic Cell of type MSX60 and 60W capacity is considered. The PV Cell specifications [10] and results obtained at a temperature of 25^0C and illumination of 1 Sun are shown in Table 1. The I-V curve and P-V curve obtained are shown in Figure 2. The inverter operation efficiency is assumed 100%.

TABLE 1

INDUSTRIAL SPECIFICATIONS VS MATLAB RESULTS

MSX60 60W PV-Cell	Industrial Specification	Matlab Results
P_{Max}	60W	60.47W
V_{Max}	17.1V	17.08V
I_{Max}	3.5A	3.5405A
I_{Sc}	3.8A	3.8A
V_{OC}	21.1V	21.06V

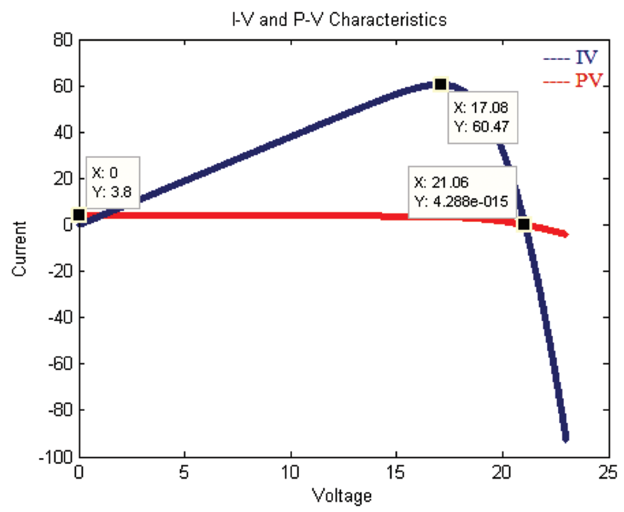

FIG. 2 I-V AND P-V CURVE

3.0 BALANCED RADIAL DISTRIBUTION LOAD FLOW

The radial distribution load flow solves algebraic equations expressed in terms of sending end voltage (V_S) and receiving end voltage (V_R), iteratively. The method of forward/backward sweep has been considered owing to its accuracy and fast convergence. The receiving end voltage can be expressed in general by equation (9).

$$V_R = V_S - I_{SR} Z_{SR} \quad ....(9)$$

Example: Consider the single line diagram of a radial distribution network with 6 nodes as shown in Figure 3.

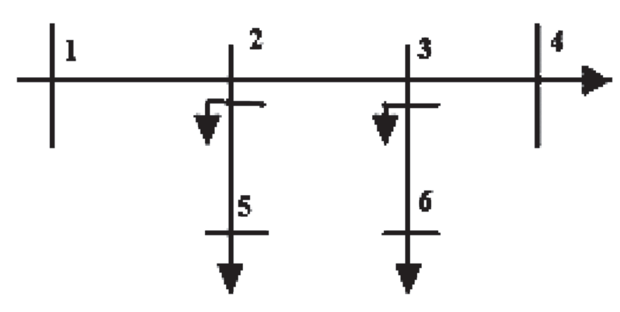

FIG. 3 SINGLE-LINE DIAGRAM OF 6 NODE NETWORK

then

$$V_2 = V_1 - I_{12} Z_{12} \quad ....(10)$$

$$I_{12} = I_{23} + I_{25} + I_{22} \quad ....(11)$$

Load current at node-i can be calculated as

$$I_{ii} = \frac{P(i) - jQ(i)}{V^*(i)} \quad ....(12)$$

The iteration procedure starts with backward sweep where node currents are calculated using Eq.12 assuming flat voltages at all the nodes at the beginning. In the successive iterations the updated voltages are used in calculating the nodal currents thereafter branch currents using Eq.11. Node-1 is considered as voltage controlled bus with a voltage of 1pu and all the node voltages are updated using Eq.9 during forward sweep utilizing the calculated branch currents from backward sweep. This iteration process of backward/forward loop continues until the maximum difference in voltage magnitude of successive iterations is less than 10^{-6}, which is the convergence criterion.

The total loss in the system is the sum of the losses in all branches. Complex power loss in any branch ij can be given as:

$$(P_L + jQ_L)_{ij} = V_i I_{ij}^* + V_j I_{ji}^* \quad ....(13)$$

The work presented in this paper considers PV generation as negative load for the modelling purpose. For a given day the 24-hours solar insolation and temperature are considered from [8] and P_{PV} is calculated. Figure 4 is considered as 24 hours load curve [3]. The load for k^{th} hour is calculated using the equation (14) and is used in the radial distribution load flow.

Net load at i^{th} node in k^{th} hour =

$$(P + jQ)_i * (Lf_k) + (P_{PV_i})_k \qquad ....(14)$$

The Distribution generation helps in the reduction of real and reactive losses and also improves the node voltages.

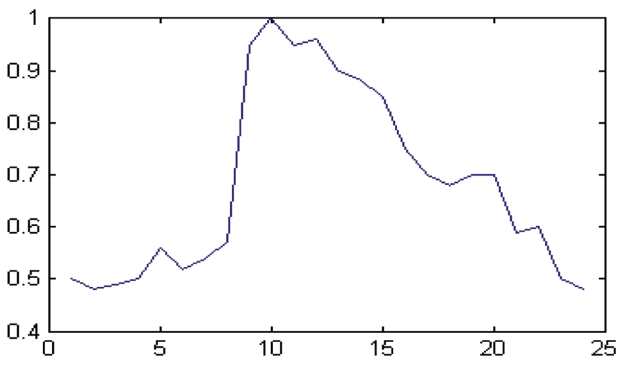

FIG. 4 24 HRS DAILY LOAD CURVE

Effect of PV generation on real and reactive loss and on voltage profile, every hour for the whole day is given by the indices [3]:

$$L_P(i) = 1 - \frac{\text{Real losses with DG in hour } i}{\text{Real losses without DG in hour } i} \qquad ....(15)$$

$$L_Q(i) = 1 - \frac{\text{Reactive losses with DG in hour } i}{\text{Reactive losses without DG in hour } i} \qquad ....(16$$

$$L_V(i) = \frac{\textit{Minimum Voltage with DG in hour i}}{\textit{Minimum Voltage without DG in hour i}} \qquad ....(17)$$

4.0 OPTIMAL PLACEMENT

For the purpose of finding optimal location and penetration capacity many methods like artificial neural networks, particle swarm optimization, genetic algorithms etc. may be used. For the simplified analysis a heuristic approach is followed here. Penetration capacity and optimal location are found by maintaining the minimum voltage greater than 0.95 and the maximum voltage less than 1.05 for the whole day. The method proposed has been implemented on a 69 bus system as shown in Figure 5. Buses between 53 and 65 (13 buses) are considered from the test system for the analysis, owing to the lowest voltages obtained at these buses by running a distribution load flow without any DG in the system. The buses are given scores accordingly from 1-13 based on the reduction in system losses, by incrementally varying the capacity of DG installed at the node, for all 24 hours. The bus having the least sum of scores throughout the day is considered as the optimal location for installing DG.

5.0 SIMULATION RESULTS

Table 2 shows the scores obtained by all the buses between 53 and 65. Bus 61 having lowest score is the optimal location for DG installation with the penetration level of DG settling at 1148kW.

In Figure 6 and 7, 6 to 18 hours indicate three days effect of PV generation in reduction of real and reactive losses with respective their insolation and temperature. Figure 8 shows the improvement in voltages. The curves attain maximum during mid-day because of high insolation. It is also seen that PV generation from 0 to 6 Hrs and 18 to 24 Hrs does not have any impact on the distribution system as the insolation during this time is zero. Table 3 shows system losses(k) and the minimum voltage (per unit) attained during day time.

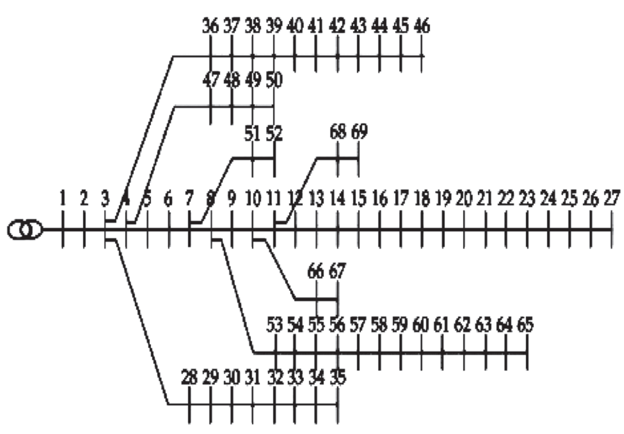

FIG. 5 SINGLE-LINE DIAGRAM OF 69BUS SYSTEM

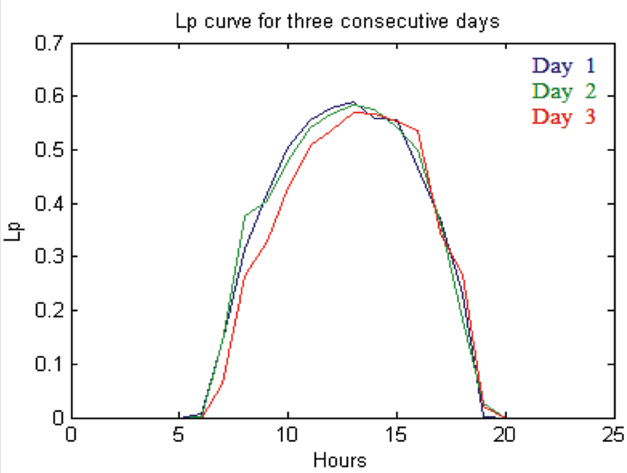

FIG. 6 L_P CURVE FOR THREE DAYS

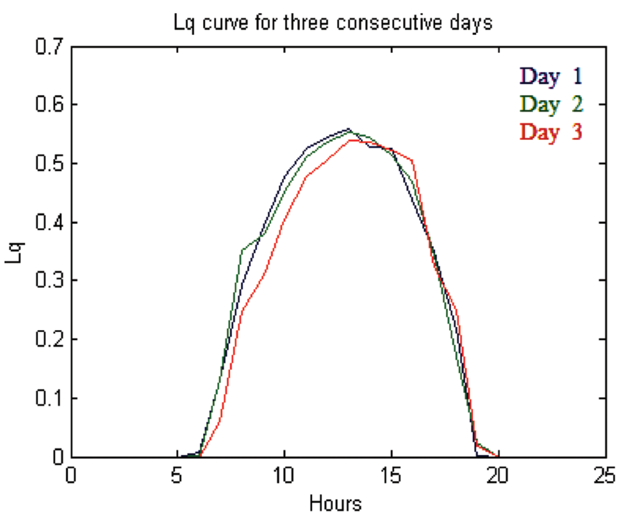

FIG. 7 L_Q CURVE FOR THREE DAYS

TABLE 2

BUS SCORES

Node	Score	Node	Score
53	312	60	100
54	286	**61**	**24**
55	258	62	48
56	234	63	75
57	202	64	137
58	165	65	210
59	133		

TABLE 3

MINIMUM VOLTAGES AND SYSTEM LOSSES

Hr	Day 1						Day 2						Day 3					
	Without solar PV			With solar PV			Without solar PV			With solar PV			Without solar PV			With solar PV		
	V_{min}	P_L	Q_L	V_{min}	P_L	Q_L	V_{min}	P_L	Q_L	V_{min}	P_L	Q_L	V_{min}	P_L	Q_L	V_{min}	P_L	Q_L
6	0.957	50	23	0.957	50	23	0.955	56	26	0.955	56	25	0.953	62	28	0.953	62	28
7	0.956	54	25	0.960	47	22	0.953	61	28	0.957	52	24	0.951	67	31	0.953	63	29
8	0.953	61	28	0.964	42	20	0.950	68	31	0.965	42	20	0.948	75	34	0.958	55	26
9	0.919	180	82	0.945	105	50	0.914	201	91	0.941	120	57	0.910	224	102	0.931	150	70
10	0.914	201	91	0.951	100	48	0.909	225	102	0.945	117	56	0.904	250	114	0.936	143	68
11	0.919	180	82	0.961	80	39	0.914	201	91	0.956	92	45	0.910	224	102	0.948	110	53
12	0.918	184	84	0.963	78	38	0.913	206	94	0.959	89	43	0.908	229	104	0.952	106	51
13	0.924	160	73	0.968	66	32	0.919	179	81	0.965	75	36	0.915	199	90	0.960	86	42
14	0.925	153	69	0.964	67	33	0.921	170	78	0.965	72	35	0.917	189	86	0.961	82	40
15	0.928	142	64	0.965	63	31	0.924	158	72	0.961	72	35	0.920	176	80	0.960	79	38
16	0.937	109	49	0.961	58	28	0.934	121	55	0.962	61	29	0.930	134	61	0.964	62	30
17	0.942	94	43	0.958	59	28	0.938	105	48	0.955	66	31	0.935	116	53	0.952	76	36
18	0.943	88	40	0.953	68	31	0.940	98	45	0.948	80	37	0.937	109	50	0.949	80	37

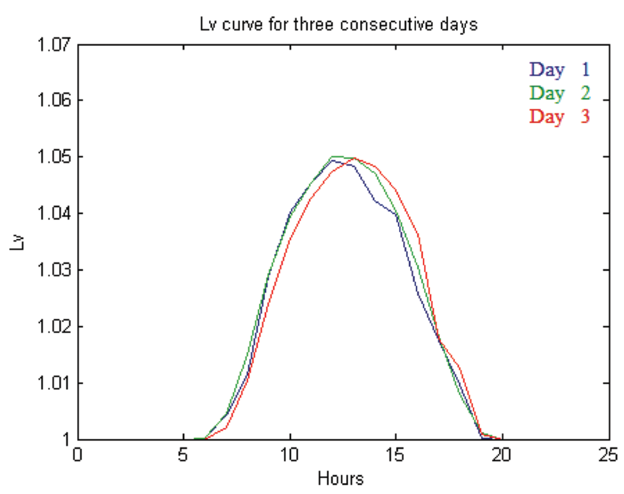

FIG. 8 LV CURVE FOR THREE DAYS

6.0 CONCLUSIONS

A simplified approach to determine the optimal location and capacity for Solar PV base distributed generation in a power system is presented in this paper. The proposed method works well on a power system that has solar PV distributed generation. It considers the 24 hours scenario while considering the impact of inclusion of renewable generation with respect to a 24 hours load for the system. The proposed approach has been implemented on a 69 bus system and results have been presented and discussed. As presented with the help of simulation results, the optimal location of the distributed generation can be achieved by the proposed simplified approach which reduces the real and reactive power losses of the system as well as improves the voltage profile of the buses where voltages were quite low. The proposed simplified approach is extendable to include other type of renewable energy source with small modification in the modelling and we are working towards including the renewable energy sources other than solar also. The proposed work will be providing a simplified way to power utilities to put renewable energy in their distribution power system.

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