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Impact of Photovoltaic Penetration on Static Voltage Stability of Distribution Networks: A Probabilistic Approach

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Abstract: Increased penetration of renewable energy sources in distribution networks has imposed a significant challenge for power system stability. In this paper, the uncertainty associated with solar irradiation and load demands are modelled as probabilistic distribution functions (PDFs). The static voltage stability index (VSI) is used to find the optimal locations of distributed generation (DG). To investigate the impact of photovoltaic (PV) based DGs on distribution network, Monte Carlo Simulation (MCS) method, a probabilistic load flow method, is used in this work. Distribution test networks i.e. IEEE 33 and 69 bus networks are used for case study. The results obtained are presented and discussed.

Key words: Photovoltaic system, Monte Carlo simulation, distributed generation, beta probabilistic distribution function.

Introduction

According to Paris Agreement 2017 on climate change, each country will regularly reports its own contribution in order to mitigate global warming. To achieve this, global greenhouse gas emission shall need to be cut by an estimated 40-70% by 2050 and by 2100 the planet must be carbon neutral. The electrical energy system has major contribution in greenhouse gases. On this pathway, generating the electricity from renewable energy sources such as wind and solar is one of the useful solutions. Owing to uncertainty associated with wind and solar, deterministic load flow techniques are not able to evaluate accurate state of system. Also stochastic behaviour of load has great impact on static voltage stability. In this paper, probabilistic load flow method has been utilized to determine static voltage stability of distribution system considering uncertainties. Various methods have been proposed to study uncertainty in load flow and broadly categories as Monte Carlo simulation (MCS) and analytical methods.

MCS method has been considered as standard method for probabilistic studies (Rubinstein and Kroese, 2016). To evaluate the performance of distribution network including penetration of DGs, MCS method has been employed (El-Khattam et al., 2006).

The uncertainties in locations, penetration level and states of DG units were considered as random parameters for studied system. In Hajian et al. (2006), Latin supercube sampling (LSS) which includes correlation in input variable was used with MCS method. To evaluate the influence of photovoltaic (PV) generation uncertainty on transmission network, a cumulant based probabilistic power flow method has been considered

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in Fan et al. (2012). The Garm-Charlier expansion, Edge worth expansion, and Cornish-Fisher expansion have been compared for studied system. Since DG has small generation capacity as compared to central power plant, its impact is minor if the penetration level is low (5-10%). However, if penetration level of DG is more than 30-40% the impact of DG will be profound. The major cause for blackout in S/SE Brazilian system in 1997 was voltage instability in distribution network (Al Abri et al., 2013).

To access the voltage collapse, probabilistic power flow method has been used by Hatziarayriou and Karakatsanis et al. (1998). To consider uncertainties of wind power and load, two-point estimation method (2PEM) and continuous power flow (CPF) has been used to evaluate static voltage stability of system (Liu et al., 2013). For determination of probabilistic distribution voltage stability margin, maximum entropy method has been adopted (Zhang et al., 2010). In this study, only random variation of loads is considered. Ram and Miao (2015) have proposed a nonlinear three-phase maximum loading model considering wind power uncertainties, load uncertainties and probabilistic static voltage stability for distribution network. Two-point estimation method (2PEM) and CPF in distribution network have been used to evaluate the static voltage stability and compared with MCS and first order second moment method (Liu et al., 2015).

The impact of large PV plants on voltage stability of Jordan's national grid has been investigated by Feilat et al. (2018). It was found that maximum penetration level of renewable energy should not increase beyond 10% of system annual peak demand. In Sheng et al. (2017), unstable hopf bifurcation has been utilized to investigate the voltage stability of large scale PV plants connected to three-node system. The minimum value of hopf bifurcation index is proposed based on support vector machine (SVM) including particle swarm optimization (PSO) and genetic algorithm (GA). In Wang et al. (2017), the impact of PV penetration under specific integration structure (star and chain topology) on voltage stability has been investigated. It was found that the static voltage stability depends upon topological structure of PV generation at common point.

In Joshi and Pindoriya (2017), increasing penetration of PV generation on distribution network has been studied. Investigation considers the effect of feeder specific factors such as geo electric size, feeder spread, load density and phase unbalancing. Impact of photovoltaic generation on distribution network containing large population has been investigated by Westacott and Candelise (2016). Maximum penetration and overvoltage issues in low voltage distribution network due to large penetration of solar PV was investigated by Watson et al. (2016). To achieve minimum loss operation of distribution network with PV generation sources, a method based on Mixed Integer Linear Programming (MILP) was proposed for coordinating network reconfiguration, switching capacitor settings and inverter reactive power output of PVs (Jabr, 2014). In Ruiz-Rodriguez et al. (2012), analytical methods based on method of cumulant with Gram-Charlier expansion and Monte Carlo method investigated probabilistic power flow in radial distribution network with PV generators. Emmanuel and Rayudu (2017) have used PV and PQ model of single phase grid connected PV based DG to study its impact on distribution network.

In this research paper, a voltage stability index is utilized to find the optimal solar PV based DG location. Objective of the research is to minimize the power losses, improve the voltage profile and improve voltage stability index. The next section elaborates solar PV generator modelling, MCS method and VSI used in analysis. The third section describes the algorithm used to study impact of solar PV based DGs. In fourth section, case study is performed in 33 and 69 node radial distribution network. Finally, the last section concludes the research work.

Problem Formulation

Photovoltaic Modelling

Solar irradiance has high degree of uncertainty and varies as a function of several factors such as environmental conditions, time of day, month, season and orientation of the solar cell generator (SCG) to the sun radiation. As a result solar irradiance can be modelled as Beta pdf.

$$f_b(s) = \begin{cases} \dfrac{\Gamma(\alpha+\beta)}{\Gamma\alpha\,\Gamma\beta} \times s^{(\alpha-1)} \times (1-s)^{(\beta-1)} & \text{for } 0 \le s \le 1, \alpha \ge 0,\ \beta \ge 0 \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

To calculate the parameter of Beta pdf, the mean (μ) and standard deviation (σ) of the random variable s are utilized as follows:

$$\beta = (1-\mu) \times \left(\frac{\mu(1-\mu)}{\sigma^2} - 1 \right) \tag{2}$$

$$\alpha = \frac{\mu \times \beta}{1-\mu}$$

The power output from photovoltaic generator is functions of solar irradiance and ambient temperature of geographical location of site as well as characteristics of module itself. Therefore, once the solar irradiance data is generated from Beta pdf, the output power from PV generator can be calculated as follows:

$$T_c = T_A + s_a\left(\frac{N_{OT}-20}{0.8}\right) \quad (3)$$

$$I = s_a\left[I_{sc} + K_i(T_c - 25)\right] \quad (4)$$

$$V = V_{oc} - K_v \times T_c \quad (5)$$

$$P_s(s) = N \times FF \times V \times I \quad (6)$$

$$FF = \frac{V_{mpp} \times I_{mpp}}{V_{oc} \times I_{oc}} \quad (7)$$

where

T_c = Cell temperature (°C)
T_A = Ambient temperature (°C)
K_v = Voltage temperature coefficient (V/°C)
K_i = Current temperature coefficient (A/°C)
N_{OT} = Nominal operating temperature of cell in °C
FF = Fill factor
I_{SC} = Short circuit current in A
V_{oc} = Open circuit voltage in V
I_{mpp} = Current at maximum power point in A
V_{mpp} = Voltage at maximum power point in V
P_s = Output power of PV generator
s = Average solar irradiance

Probabilistic Load Flow Methods: Monte Carlo Simulation (MCS)

MCS is an iterative method which utilizes cumulative density function (CDF) of input random variable to determine final result. The step by step process of probabilistic load flow analysis using MCS method is given as follows:

Step 1: Probabilistic density function (PDF) of all random variable should be obtained from historical data. Loads are assumed to be normally distributed random variable. The stochastic variations in solar irradiance are assumed to be Beta distribution function.

Step 2: MCS method utilizes samples to evaluate objective function. Hence, maximum number of iterations and maximum number of samples to access acceptable convergence should be set in this step.

Step 3: Objective function which is deterministic load flow in probabilistic load flow (PLF) studies should be evaluated with each sample taken from all PDFs.

Step 4: Check whether maximum number of samples have reached. If yes algorithm will go to step 5 otherwise repeat from step 3.

Step 5: Mean values of each output such as active power loss, voltage magnitudes at each bus etc. should be saved in current iteration.

Step 6: Check whether maximum number of iteration has reached. If yes algorithm will go to step 7 otherwise repeat from step 3.

Step 7: Calculate the mean values of outputs from each iteration and terminate algorithm.

Voltage Stability Index (VSI)

With the development of economy and sharp increase in load demand, voltage stability has become a major concern in modern distribution system. The critical point of voltage instability is determined from instability techniques such as PV-QV curve method, bifurcation analysis, modal analysis, voltage stability index (VSI) which are helpful to measure voltage stability of system or to find out critical buses and lines in the network. Among different techniques VSI based technique has emerged as very fast and effective tool for off line voltage stability analysis. In this work VSI proposed by Chakravorty and Das (2001) was utilized for finding weak buses in network from voltage stability point of view.

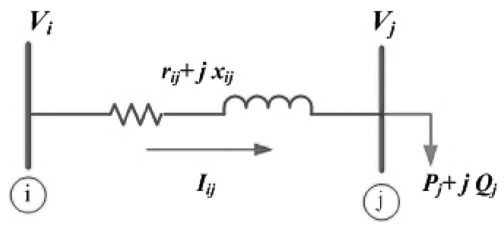

Figure 1: Equivalent circuit of radial network.

From the equivalent circuit (Figure 1) of radial distribution network, the following expressions can be deduced.

$$I_{ij} = \frac{V_i - V_j}{r_{ij} + jx_{ij}} \quad (8)$$

$$P_j - jQ_j = V_j^* I_{ij} \quad (9)$$

where i, j are sending and receiving end respectively, I_{ij} is branch current, V_i, V_j are voltage of node i and j respectively and P_j, Q_j are total real and reactive load power fed through node j. From Equations (8) and (9), following expression can be written.

$$|V_j|^4 - \left\{|V_i|^2 - 2P_j r_{ij} - 2Q_j x_{ij}\right\}|V_j|^2 + \left\{P_j^{\,2} + Q_j^{\,2}\right\}\left\{r_{ij}^{\,2} + x_{ij}^{\,2}\right\} \quad (10)$$

Let

$$b = |V_i|^2 - 2P_j r_{ij} - 2Q_j x_{ij} \quad (11)$$

$$c = \left\{P_j^{\,2} + Q_j^{\,2}\right\}\left\{r_{ij}^{\,2} + x_{ij}^{\,2}\right\} \quad (12)$$

$$|V_j|^4 - b|V_j|^2 + c = 0 \quad (13)$$

The feasible solution of equation (13) is unique and can be obtained as follows.

$$|V_j| = 0.707\sqrt{b + \sqrt{b^2 - 4c}} \quad (14)$$

$$b^2 - 4c \geq 0 \quad (15)$$

From equations (11), (12) and (15)

$$\left(|V_i|^2 - 2P_j r_{ij} - 2Q_j x_{ij}\right)^2 - 4\left(P_j^2 + Q_j^2\right)\left(r_{ij}^2 + x_{ij}^2\right) \geq 0 \quad (16)$$

Rearranging equation (16)

$$|V_i|^4 - 4\left(P_j x_{ij} - Q_j r_{ij}\right)^2 - 4\left(P_j r_{ij} + Q_j x_{ij}\right)|V_i|^2 \geq 0 \quad (17)$$

Voltage stability index of node j can be expressed as

$$VSI = |V_i|^4 - 4\left(P_j x_{ij} - Q_j r_{ij}\right)^2 - 4\left(P_j r_{ij} + Q_j x_{ij}\right)|V_i|^2 \quad (18)$$

The minimum value of stability index at any node represent that node is more sensitive to voltage collapse. For stable operation of radial distribution network VSI value must be ≥ 0.

Algorithm

This section explains the proposed probabilistic formulation for static voltage stability analysis in radial distribution network. For analyzing the effect of DGs on voltage stability and power losses in network, various penetration levels up to 40% has been taken into consideration. Realistic solar irradiance has been utilized in this study. Kamuthi Solar Project, Tamilnadu, India was selected for solar irradiance data. Variations of solar irradiance data for selected sites in four seasons of a year is shown in Figure 2.

The corresponding best fit probabilistic density functions (PDFs) are mapped into realistic data and shown in Figure 3. Table 1 shows all the available modules for selected sites. PV module B has highest capacity factor (0.3196), therefore module B type is used for this study.

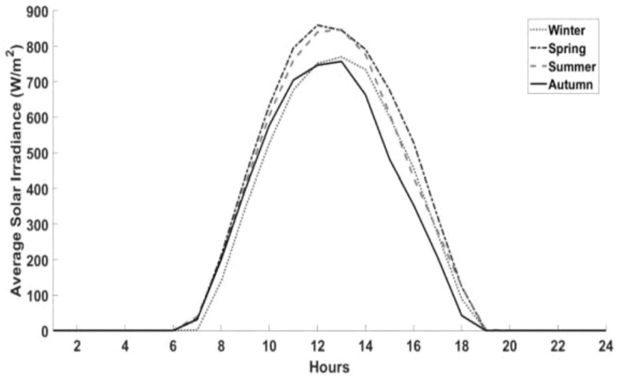

Figure 2: Variation of solar irradiance data for different seasons.

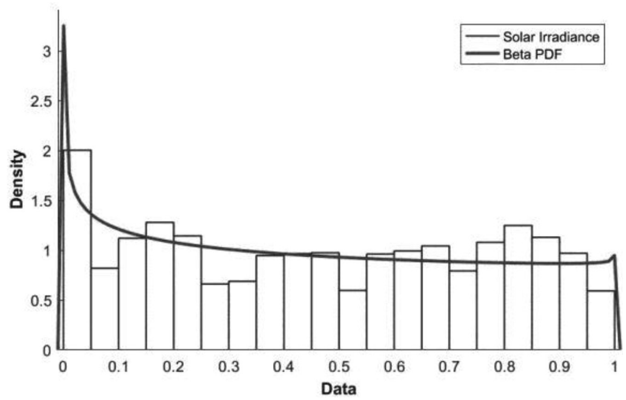

Figure 3(a): Solar irradiance data mapped into Beta PDF.

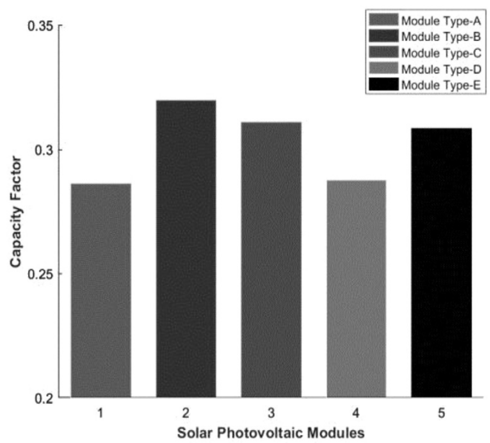

Figure 3(b): Capacity factor for various PV modules.

Table 1: Characteristics of the PV modules

Module characteristics	Module type				
	A	*B*	*C*	*D*	*E*
Peak power (Watt)	145	180	230	245	265
V_{oc}: Open circuit voltage (V)	37	44.2	37.1	37.2	38.27
I_{sc}: Short circuit current (A)	5.21	5.36	8.18	8.62	8.91
V_{mpp}: Voltage at maximum power (V)	29.8	36.2	29.9	30.2	31.41
I_{mpp}: Current at maximum power (A)	4.87	4.97	7.65	8.1	8.44
K_v: Voltage temperature coefficient (%/°C)	0.366	0.386	0.361	0.369	0.32
K_i: Current temperature coefficient (%/°C)	0.046	0.044	0.102	0.087	0.04
N_{OT}: Nominal operating cell temperature	48.6	45.8	47.4	49.9	45.6

The steps for algorithm are as follows:

Step 1: For probabilistic study, Beta PDF was utilized for solar irradiance data respectively. The variations of loads are studied using normally distributed PDF. Nominal load at each node was taken as mean and 5% standard deviation.

Step 2: For studied case network, connected loads at each node have to increase in steps until VSI at any node falls to near zero value. The nodes with lowest value of VSI are considered as weak bus from stability point of view and also considered as optimal locations for DG placement.

Step 3: All the DG units are operating at unity power factor. To study impact of renewable based DG penetration on distribution network, following cases are proposed.

Case Study I: No DG units are connected to distribution network and treated as reference case.

Case Study II: Solar photovoltaic based DG is connected to distribution network.

Step 4: Monte Carlo Simulation based probabilistic load flows are used for each scenario.

Step 5: The issue associated with performance of distribution network due to renewable based DG penetration such as voltage stability, network power loss reduction are analyzed for cases.

Results and Discussion

In this section, the applicability of proposed algorithm has been demonstrated and examined through IEEE 33 and 69 node radial distribution networks. For both the test system substation voltage is considered at 1 pu. The maximum number of DG installed for given test system is limited to three since rate of improvement of percentage loss reduction decreases when the candidate locations increase more than three.

Case I: IEEE 33 Node Distribution Network

The IEEE 33 bus distribution network includes 37 branches, 32 sectionalizing switches and five tie switches. The total real and reactive power loads of the system are 3.72 MW and 2.3 MVAr respectively. The VSI index (Eq. 18) is applied to identify weak nodes of the test network. The minimum values of VSI at base and critical loading condition are shown in Table 2.

It is identified that nodes no. 16, 17, 18 and 33 are critical (Figure 4). The critical nodes in test system are those nodes which are more prone to voltage collapse. Since nodes no. 16, 17 and 18 are on same lateral and node 18 is farthest node, power injected on this node will improve the voltages at nodes no. 16 and 17. Hence, nodes no. 18 and 33 should be considered as optimal location for DGs. Due to uncertainties associated with solar irradiance; the corresponding random variables are

Table 2: Critical node in 33 bus distribution network

System under nominal load condition			System under critical load condition		
Node	*Voltage magnitudes*	*VSI values*	*Node*	*Voltage magnitudes*	*VSI values*
18	0.9131	0.6969	18	0.4667	0.0492
17	0.9137	0.703	17	0.471	0.0553
16	0.9157	0.7072	16	0.4667	0.0598
33	0.9166	0.7067	33	0.4931	0.06

mapped into Beta PDF. Parameters for mapped PDF are shown in Table 3.

Table 3: Parameters values for solar irradiance data

Solar irradiance (kW/m²)		*Parameters for Beta PDF*	
μ	σ	α	Β
0.4579	0.08832	0.8291	0.9814

In this study solar PV based DG are placed at nodes 18 and 33 of studied network. DG penetration levels are increased upto 40% in steps of 10%. MCS technique is applied for calculating voltage magnitude and VSI values at each node of 33 bus network and is shown in Figures 5 and 6 respectively. As the penetration level is increasing, voltage magnitude and VSI values are improving for all nodes of the network at different load condition. Three types of load levels (i.e. light, nominal and heavy) are taken into consideration. In this work, light load is considered as 50% of base load, nominal load as base load of network and heavy load as 1.6 times the base load. It is observed that active power loss and reactive power loss are decreasing with increase

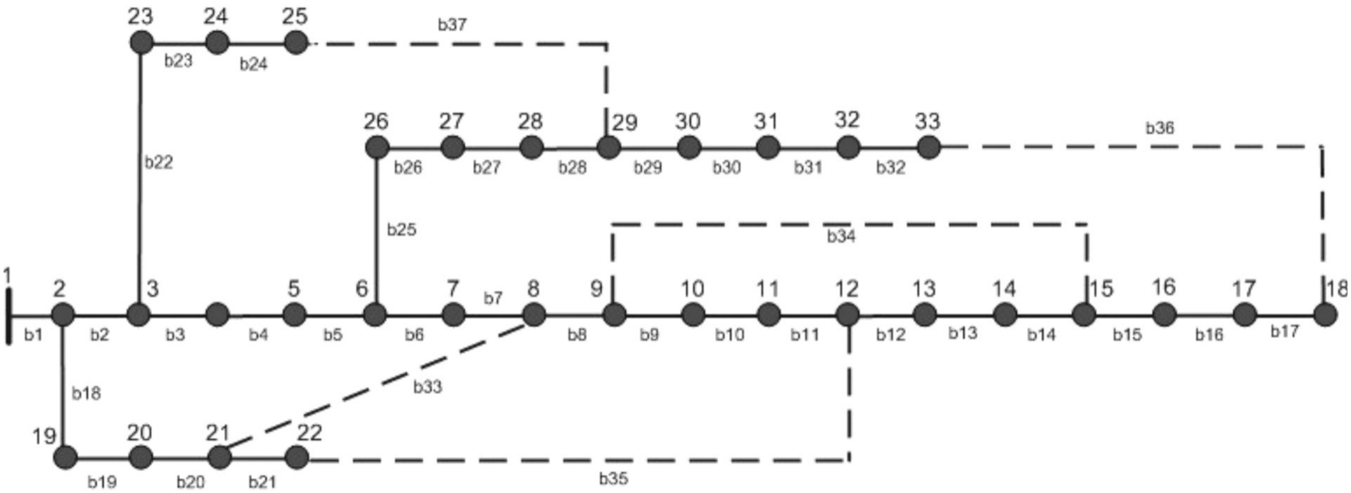

Figure 4: IEEE 33 node distribution network.

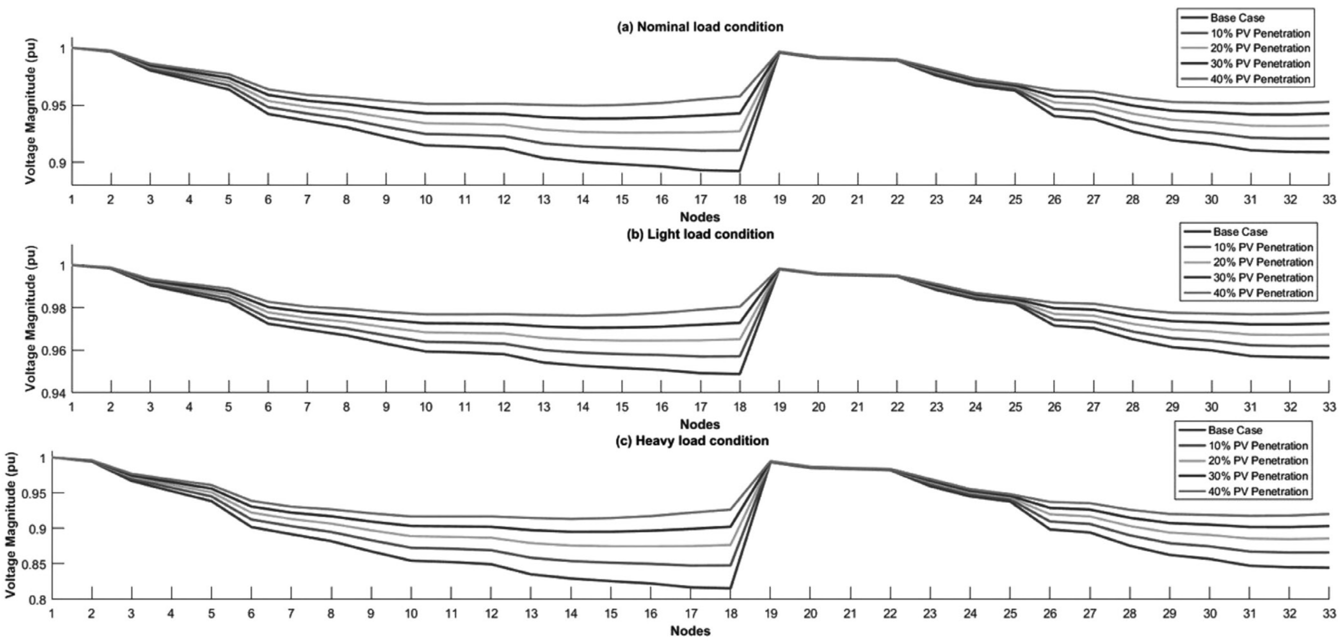

Figure 5: Voltage magnitude in 33 node distribution network under different load conditions.

in penetration level of PV generators. The maximum penetration of solar based DG is found 30.36% under light load, 34.61% under nominal load and 30.14% under heavy load conditions.

Figure 7 shows total active and reactive power loss in distribution network at various penetration studies of solar PV based DGs. As the penetration level is reaching near to 40% penetration level the loss are increasing in the networks which is considered as penetration limit. The calculated parameters for base case (no DG) and with Solar PV based DGs are shown in Table 4 for 33 node distribution network. Percentage loss reduction is calculated using Eq. (19).

$$ALR = \frac{P_{loss\,0} - P_{loss_{DG}}}{P_{loss_0}} \tag{19}$$

where ALR is Active loss reduction, P_{loss0} and P_{lossDG} are active power loss in the system with and without DG.

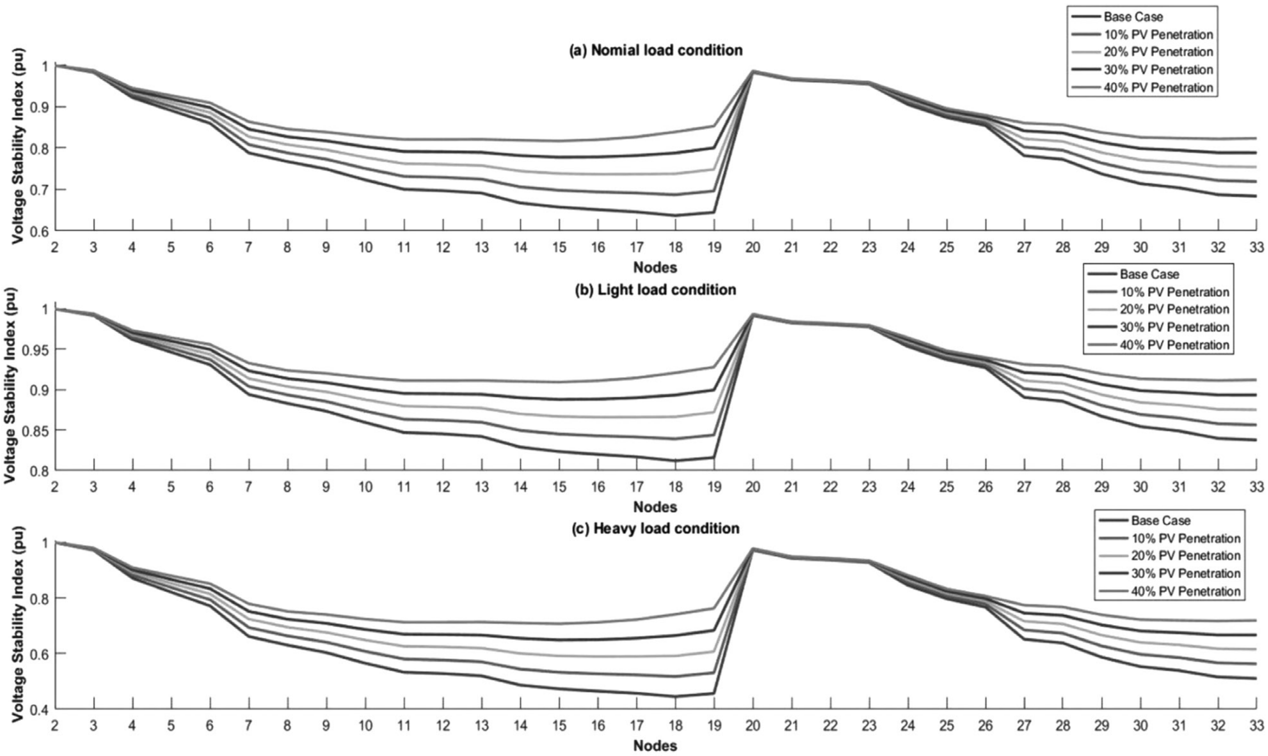

Figure 6: Voltage stability index (VSI) in 33 node distribution network under different load conditions.

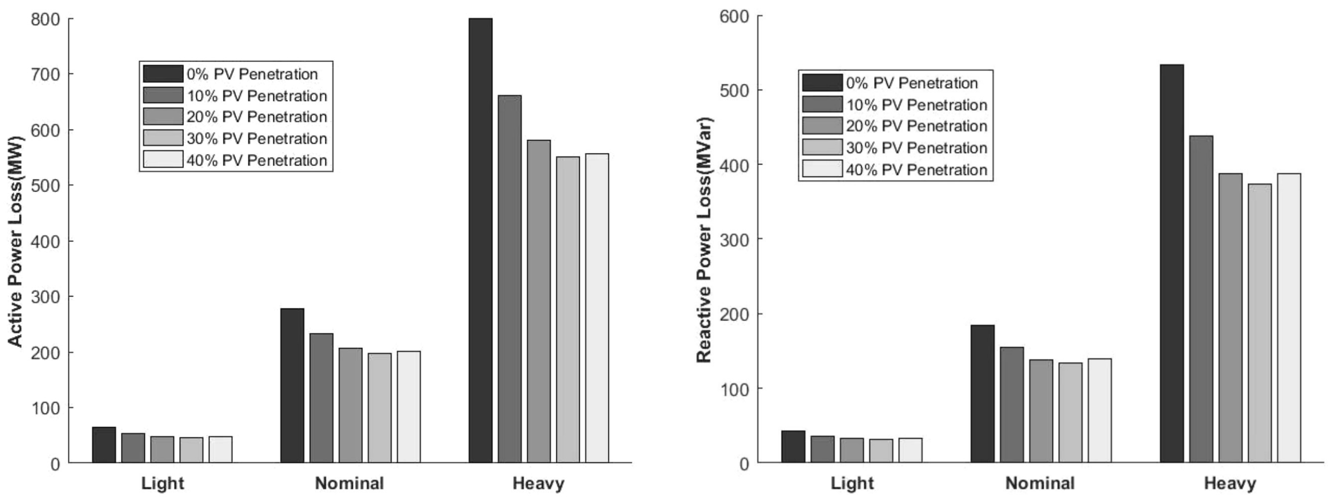

Figure 7: Total active and reactive power loss in 33 node distribution network under different load conditions.

Table 4: Result analysis of 33 node distribution network with various PV penetration levels

Case study	*DG penetration level*	*Items*	*Load levels*		
			Light Load (0.5)	*Nominal Load*	*Heavy Load*
Base case (Case I)	-	Power loss	63.70	276.93	799.70
		Size of DG in kW	-	-	-
		Minimum voltage (pu)	0.9488	0.8925	0.8154
		Minimum VSI Value	0.8118	0.6368	0.4450
		% Loss reduction	-	-	-
Solar photovoltaic based DG (Case II)	10%	Power loss	54.22	233	660.31
		Size of DG in kW	187.20	373.69	596.86
		Minimum voltage (pu)	0.9570	0.9103	0.8475
		Minimum VSI Value	0.8390	0.6871	0.5172
		% Loss reduction	14.88	15.86	17.43
	20%	Power loss	48.54	207.23	580.69
		Size of DG in KW	374.76	748.25	1196.7
		Minimum voltage (pu)	0.9645	0.9260	0.8747
		Minimum VSI Value	0.8658	0.7367	0.5890
		% Loss Reduction	23.79	25.17	27.38
	30%	Power loss	46.51	197.32	549.66
		Size of DG in KW	558.22	1115.2	1784.6
		Minimum voltage (pu)	0.9705	0.9383	0.8951
		Minimum VSI Value	0.8878	0.7777	0.6485
		% Loss Reduction	26.98	28.74	31.26
	40%	Power loss	47.66	200.69	555.34
		Size of DG in kW	745.03	1483.9	2385.4
		Minimum voltage (pu)	0.9762	0.9495	0.9133
		Minimum VSI Value	0.9093	0.8170	0.7066
		% Loss reduction	25.18	27.53	30.55

Case II: 69 Node Distribution Network

The IEEE 69 bus distribution system includes 69 nodes, 73 branches and five tie switches. The total system loads are 3.802 MW and 2.696 MVAr respectively. The VSI index (Eq. 18) is applied to identify weak nodes of the test network. From Table 5, it is observed that nodes no. 27, 61 and 65 are identified as weak nodes and optimal location to place the DGs in 69 bus distribution network (Figure 8). DG penetration levels are increased upto 40% in steps of 10%. MCS technique is applied for calculating voltage magnitude and VSI values at each node of 69 bus network and is shown in Figures 9 and 10 respectively. As the penetration level is increasing, voltage magnitude and VSI values have shown improvement for all nodes of the network for various loading conditions. Figure 11 shows total active and reactive power loss in distribution network at various penetration studies of solar PV based DGs. As the penetration level of DGs has increased beyond 55%, the increased value of active power loss has been observed which is considered as penetration limit.

The calculated parameters for base case (Case I) and with solar PV based DGs (Case II) are shown in Table 6 for 69 node distribution network.

Table 5: Critical node in 69 bus distribution network

Critical load			*Normal load*		
Node no	*VSI*	*Voltage*	*Node no*	*VSI*	*Voltage*
65	0.0655	0.5025	65	0.6851	0.9092
66	0.0676	0.8665	66	0.6858	0.9713
61	0.0997	0.5207	61	0.7153	0.9124
27	0.4311	0.8102	27	0.8367	0.9563

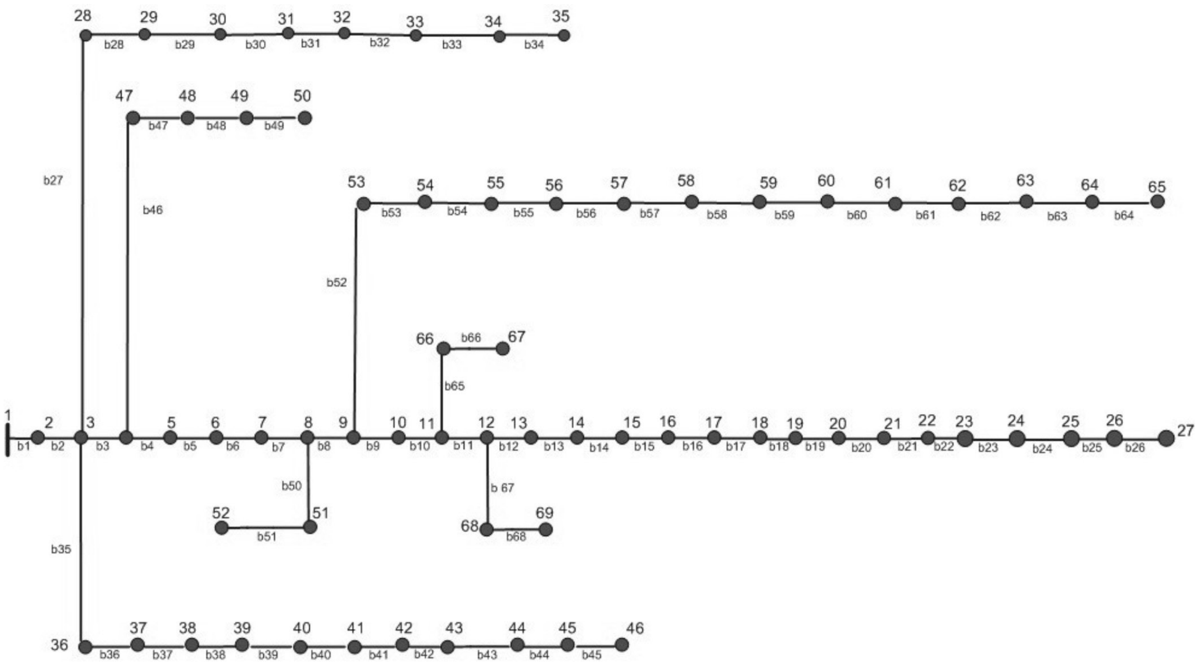

Figure 8: IEEE 69 node distribution network.

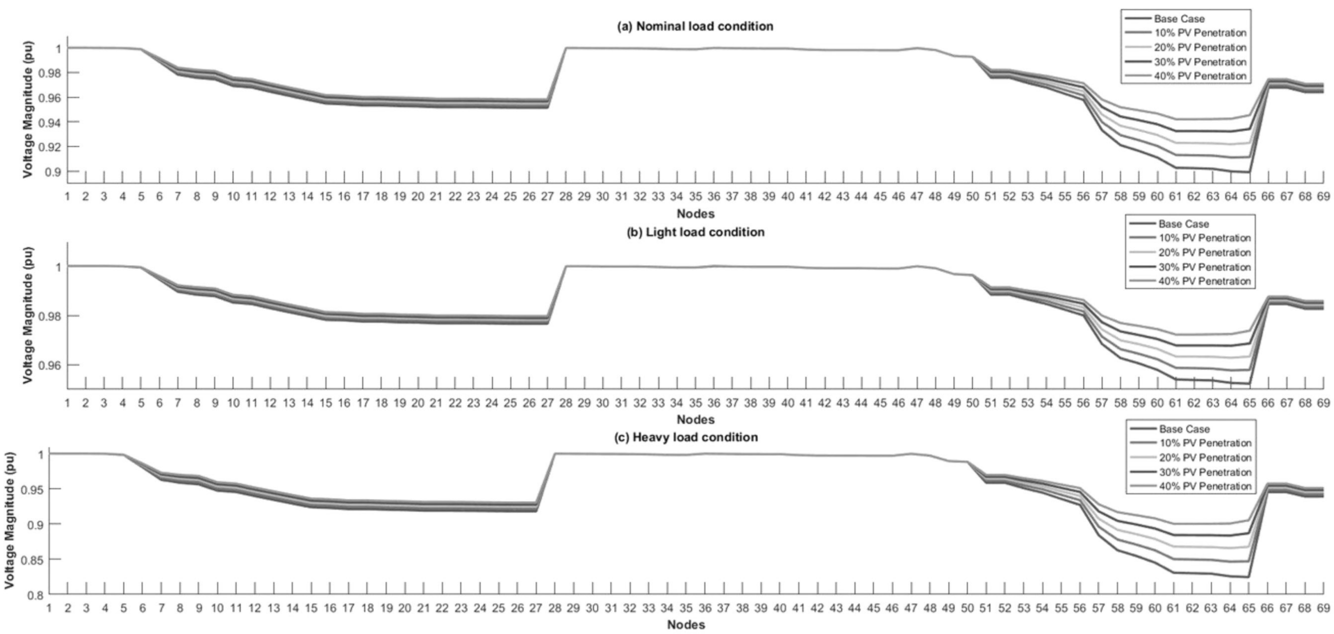

Figure 9: Voltage magnitude in 69 node distribution network under different load conditions.

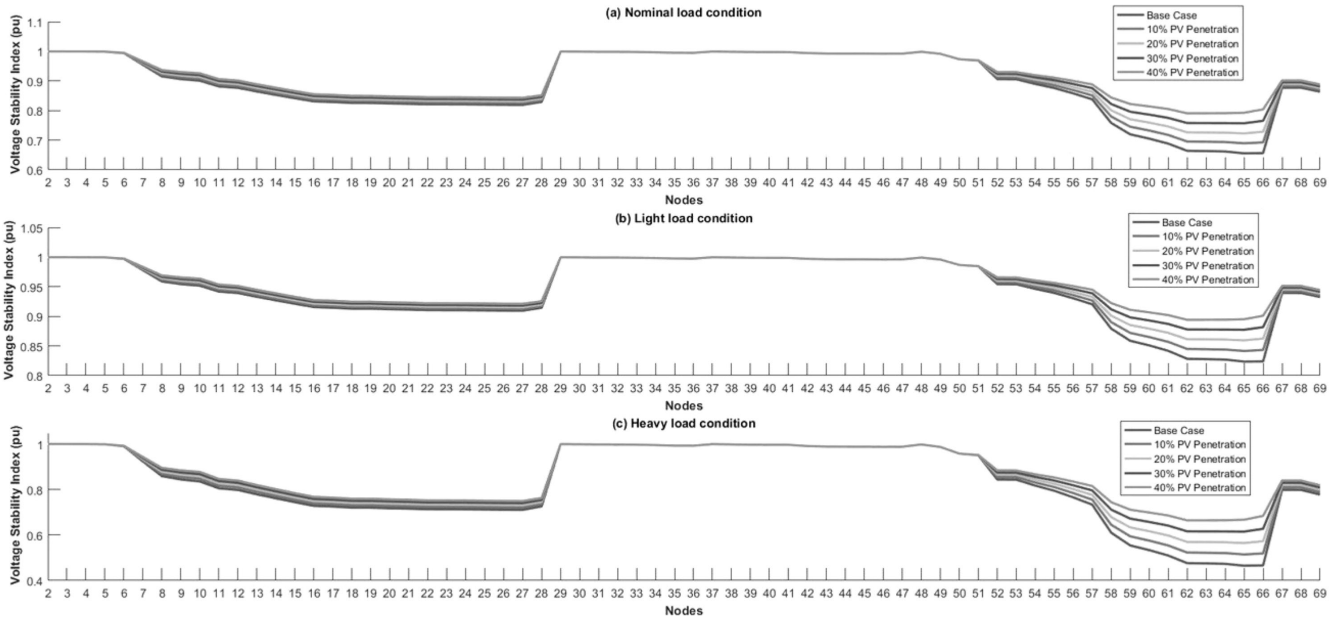

Figure 10: Voltage stability index (VSI) in 69 node distribution network under different load conditions.

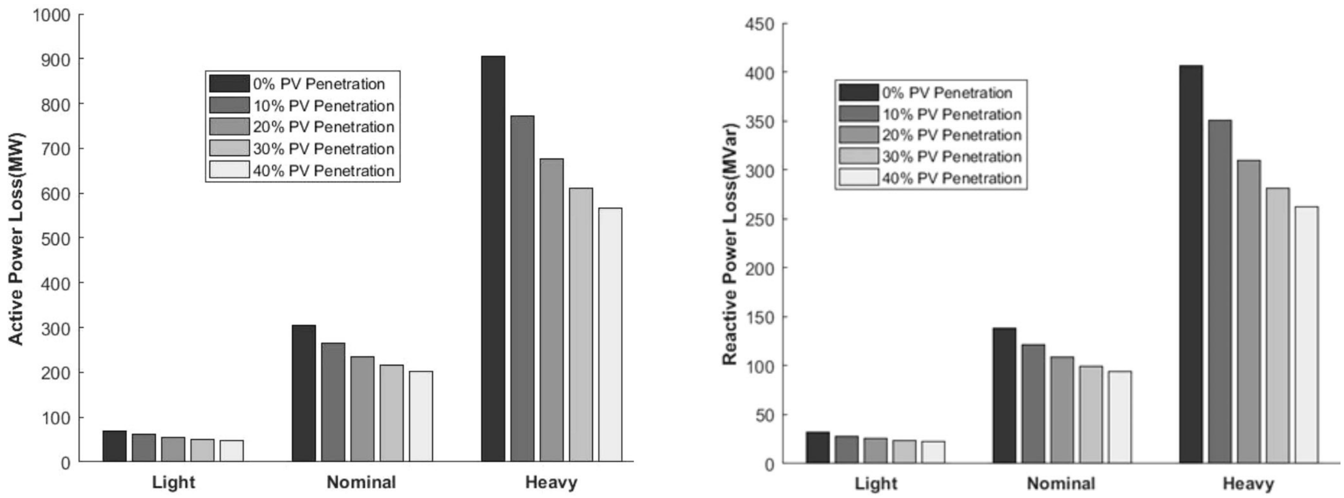

Figure 11: Total active and reactive power loss in 69 node distribution network under different load conditions.

Conclusions

In this research, static voltage stability index is used to identify the optimal location of solar PV based DG. Different penetration levels e.g. 10%, 20%, 30% and 40% of solar based DG in distribution networks and their effect on total power loss, voltage profiles and voltage stability has been investigated. IEEE 33 and 69 node distribution networks are analysed for case study. Since solar irradiance and load demand have stochastic nature, probabilistic based load flow method is used in this research work. Monte Carlo simulation which is identified as standard method by various researchers is used for probabilistic studies. From the analysis, it was found that as solar PV penetration in network is increasing, improved voltage profile, reduction in power loss and improved voltage stability index have been identified. Maximum penetration level for 33 nodes distribution network is around 30% and for 69 node network is around 50%.

Table 6: Result analysis of 69 node distribution network with various PV penetration levels

Case study	*DG penetration level*	*Items*	*Load levels*		
			Light Load (0.5)	*Nominal Load*	*Heavy Load*
Base case (Case I)	–	Power loss	69.25	305.19	904.65
		Size of DG in KW	–	–	–
		Minimum Voltage (pu)	0.9523	0.8992	0.8246
		Minimum VSI Value	0.8235	0.6555	0.4650
		% Loss reduction	–	–	–
Solar Photovoltaic based DG (Case II)	10 %	Power loss	60.84	265.04	771.51
		Size of DG in KW	192.76	388.84	612.42
		Minimum Voltage (pu)	0.9577	0.9111	0.8466
		Minimum VSI Value	0.8414	0.6894	0.5145
		% Loss reduction	12.14	13.15	14.71
	20 %	Power loss	54.44	235.65	675.45
		Size of DG in KW	385.16	766.92	1224.5
		Minimum Voltage (pu)	0.9628	0.9218	0.8658
		Minimum VSI Value	0.8594	0.7228	0.5646
		% Loss Reduction	21.38	22.78	25.33
	30 %	Power loss	50.05	215	610.07
		Size of DG in KW	576.74	1150.3	1824.5
		Minimum Voltage (pu)	0.9677	0.9322	0.8836
		Minimum VSI Value	0.8773	0.7571	0.6149
		% Loss reduction	27.73	29.55	32.55
	40 %	Power loss	47.43	201.56	567.25
		Size of DG in KW	246.49	1545.6	2436
		Minimum Voltage (pu)	0.9421	0.9722	0.9002
		Minimum VSI Value	0.7907	0.8941	0.6642
		% Loss reduction	31.50	33.95	37.29

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