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Impact of Photovoltaic Penetration on Voltage Stability of Radial Distribution Networks using Monte Carlo Simulation

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***Abstract*— In countries like Nepal, solar PV and wind are seen as the most efficient forms of distributed generation. Adding PV as a renewable energy source to the power distribution system has helped improve voltage levels and cut down energy losses. However, there is a limit to how much PV can be added, as it can cause various problems in the power system including increased line losses and voltage stability issues. In Nepal, most consumers are connected through radial distribution networks that can be very long, sometimes hundreds of kilometers, leading to bigger voltage drops and more line losses. Adding small amounts of PV doesn't cause any issues, but when the amount goes beyond 30-40%, some negative effects start showing up. So, there's a balance between improving voltage and reducing losses, and the main aim of this paper is to calculate the best level of PV penetration. In this research paper, the Voltage Stability Index (VSI) is utilized to locate the buses that have the lowest VSI and are at risk of collapsing under heavy loads. The PVDG is then placed at the bus which has lowest VSI, and the PV penetration level is increased from 0 to 80% in the steps of 20 to see the results. These results are then compared and analyzed to find the optimum solution. The study was carried out on the IEEE-33 radial distribution system and the East feeder of Rajbiraj DC, Saptari. The results show that with the optimal amount of PV integration, the voltage profile and VSI of the system improve significantly.**

Keywords—PV Penetration, Radial distribution system, VSI, Monte Carlo Simulation.

I. INTRODOCTION

In the last few decades, the integration of renewable energy has increased enormously. The emerging concern over the greenhouse effect and environmental issues caused by fossil fuel-based power plants, as well as concerns regarding catastrophes like earthquakes, which affected the Fukushima Nuclear plant on March 11, 2011, has forced countries to find alternative energy sources. Nepal, a country comprised of more than 70% of the Himalayas and home to 8 out of the world's 14 tallest peaks, is prone to the adverse effects of climate change caused by the greenhouse effect. Nepal has significant potential for solar power generation, with its abundant sunlight averaging around 300 sunny days per year and an average solar insolation of approximately 4.7 kWh per square meter per day. [10] It is capable of producing between 3.6 to 6.2 units of electricity per square meter. According to the "Energy" report released by the Investment Board Nepal (IBN), the total technical potential for solar energy production in Nepal is estimated at 432 GW (432,000 MW).

The assimilation of PV into the radial distribution network has not only improved the voltage of the weak buses but also reduced the line losses. The integration of PVDG in small amount has not caused any issues, but if the penetration limit is increased beyond the critical point, then some stability issues is noticeable in the distribution network. In [6], the different penetration level caused different impacts on the voltages within the network. The extent of penetration level depended on the constraints imposed by grid robustness and transformer loading capacity. Here, the optimum penetration level was achieved where the voltage improvement is maximum and the loss is minimum, and reverse flow is not recorded. In [7], the PV is integrated to the distribution side of the IEEE 14 bus test system, where transient analysis is done, and it was observed that during transient faults, the frequency does not differ much if PV can be attached inside the system. In [8], the hosting capacity of solar PV in any system was calculated using analytical method. In this paper it was found that location and sizing of PV affects the hosting capacity.

As solar radiation is dependent on many factors like geographical location, month of the year, time of day, season, and orientation of the solar cell, its output varies from time to time. So, it can be modelled as Beta function. In [9], it was shown that the solar measurements collected at various locations in Algeria can be described by beta probability distributions. Due to the inherent uncertainty in solar irradiation levels, deterministic load flow techniques are not adequate to evaluate the accurate state of the system. Also, the stochastic behavior of load has a prodigious 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.[1] A range of techniques has been developed to address load-flow uncertainty, generally grouped into Monte Carlo simulation (MCS) methods and analytical methods. MCS method has been considered as standard method for probabilistic studies. [3] In this paper the MCS method has been utilized to estimate the performance of distribution network, including the penetration of DGs. The uncertainties in locations, penetration level and states of DG units were considered as random parameters for studied system. [1]

A widely adopted method for probabilistic assessment is the Monte Carlo Simulation (MCS) combined with Probabilistic Load Flow (PLF) analysis.[2] In this approach, stochastic variables such as solar irradiance, ambient temperature, and load demand are represented by probability density functions (PDFs), and random samples are generated to simulate multiple system states. For each sample, an AC power flow is solved, and the corresponding voltage and voltage stability index are computed. Repeating the process for a large number of samples produces empirical distributions for system voltages and stability margins.

Many studies have looked at how to include solar panels in low voltage and high voltage networks. In low voltage networks, adding solar panels is considered as a beneficial because the solar panels are placed at end users. This closeness brings several advantages like less energy loss, better voltage levels, more reliable power supply, and support for goals that use more renewable energy. Most low voltage networks are shaped like branches, have uneven loads and structures, and have a high ratio of resistance to reactance. Putting a lot of solar panels into these networks is limited because of issues with voltage levels, especially too high voltages and imbalance. In [12], the research showed that the PV penetration limit on HV lines is just 20%. In this research paper the parameter for PV connection is computed from the VSI. From the research paper of Chakraworty and Das [11], the load flow of radial distribution network is unique and the terminology Voltage stability index (VSI) is proposed for radial distribution networks. Using the voltage stability index, it is possible to calculate the stability index at each node and the node with minimum stability index is most sensitive to collapse. It was tested in IEEE 69 bus network.

II. Methodology

The degree of uncertainty in solar irradiance is substantial owing to its dependency on hour of the day, season and month of the year. So, in this paper the solar irradiance is modelled into the beta function. The website https://globalsolaratlas.info/ [15] is used for collecting the solar irradiance data of Rajbiraj area. The solar irradiance data is then normalized and utilized to calculate the beta pdf parameters like mean, variance, α and β.

A. Modelling of Photovoltaic

Due to the high degree of uncertainty associated with the solar irradiance which varies as a function of different parameters such as ambient condition, time of day, month, season and orientation of the solar cell generator (SCG) to the sun radiation, beta pdf can be used to represent solar irradiance. [1] [11]

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

The parameter of beta pdf can be calculated by using the mean(μ) and standard deviation(σ) of the random variable (s) in the following manner:

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

$$\alpha = \frac{\mu \times \beta}{1-\mu} \tag{3}$$

The efficiency of a solar photovoltaic distributed generation (PVDG) system is influenced not only by the solar irradiance and ambient temperature typical of the installation site, but also by the design and material properties of the PV module. Consequently, after estimating solar irradiance using the Beta probability density function, one can determine the module's expected performance under those conditions.

$$T_C = T_A + s_a\left(\frac{N_{OT} - 20}{0.8}\right) \tag{4}$$

$$I = s_a[I_{SC} + K_i(T_C - 25)] \tag{5}$$

$$V = V_{OC} - K_V \times K_C \tag{6}$$

$$P_S(s) = N \times FF \times V \times I \tag{7}$$

$$FF = \frac{V_{mpp} \times I_{mpp}}{V_{oc} \times I_{oc}} \tag{8}$$

where,

- Tc = Cell Temperature (°C)
- TA = Ambient Temperature (°C)
- Kv = Voltage Temperature Coefficient (V/°C)
- Ki = Current Temperature Coefficient (A/°C)
- N_{OT} = Nominal Operating Temperature of cell in °C
- FF = Fill Factor
- Isc = Short circuit current in A
- Voc = Open circuit voltage in V
- Impp = Current at maximum power point in A
- Vmpp = Voltage at maximum power point in V
- Ps = Output Power of PV generator
- s = Average solar irradiance

B. Monte Carlo Simulation

MCS is a computational method that generates numerical results by repeated random sampling, it is especially helpful for modelling systems that are inherently unpredictable. The probability of various outcome in a process that is difficult to anticipate because of the involvement of random factors can be modeled using Monte Carlo Simulation. [3] It is a method for comprehending the effects of uncertainty and risk. Numerous issues in a variety of domains, such as business, physics, engineering, and investing, can be solved using Monte Carlo simulations. It is often referred to as a multiple probability simulation. Monte Carlo simulations simulate the effect of unpredictability in a system, which aids in the forecasting of a variety of potential outcomes.

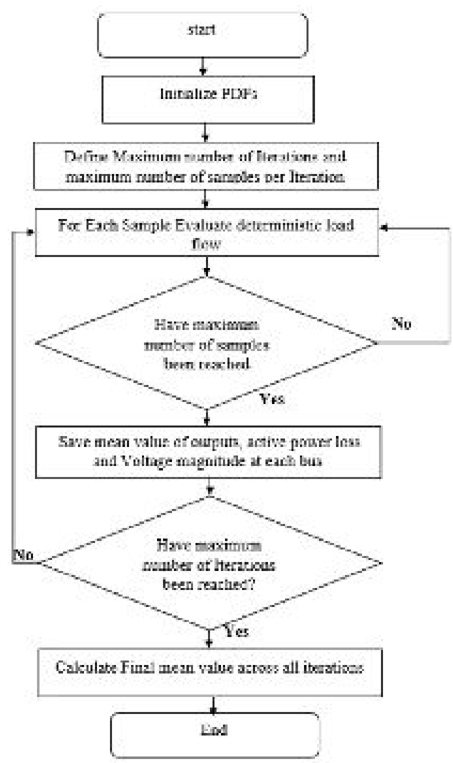

Figure 1: Flow Chart of Monte Carlo Simulation

In order to get multiple results from Monte Carlo simulation, an unknown variable must be assigned various values. The results must then be averaged to produce an estimate. perfectly efficient markets are assumed in these simulations. Artificial intelligence is increasingly being employed in conjunction with Monte Carlo simulations. Since solar irradiance is regarded as a random variable in this study work as well, MCS is used to obtain the best results. The flow chart shown above.

C. *Voltage Stability Index (VSI):*

Voltage has become an essential parameter while dealing with the quality of electricity provided to consumers. A low voltage not only hampers the electrical appliances but also the losses in the system, whereas high voltage is also undesirable for smooth operation of the distribution system. There are various major impacts of PV integration in distribution network which can be summarized as either steady-state or dynamic state impacts. [16] VSI is a parameter to indicate the state of the bus. A bus with low VSI near or equal to zero is prone to collapse.[11] So, in this paper the VSI is used as a parameter to identify the bus where PVDG is connected. To analyze voltage stability problems numerous methods have been proposed by the scholars. In real time operation the Static voltage stability analysis is used, and the computation takes little time. On the other hand, dynamic analysis is more accurate than static analysis; nevertheless, it involves the synchronization of protection, controls, and short-term voltage stability analysis and necessitates a significant amount of data for modelling. The VSI suggested by Chakravorty and Das (2001) has been used in this paper to identify the bus with the lowest VSI

From the equivalent circuit (figure 2) of radial distribution network, the following expressions can be deduced. [1] [11].

$$I_{ij} = \frac{V_i - V_j}{r_{ij} + jx_{ij}} \tag{9}$$

$$P_j - jQ_j = V_j^* I_{ij} \tag{10}$$

where i,j are sending and receiving end voltages respectively, Iij is branch current, Vi, Vj are voltages of node i and j respectively Pi, Qj are total real and reactive load power fed through node j. From equation (9) and (10), following equation can be written.

$$|V_j|^4 - \{|V_i|^2 - 2P_j r_{ij} - 2Q_j x_{ij}\}|V_j|^2 + \{P_j^2 + Q_j^2\}\{r_{ij}^2 + x_{ij}^2\} = 0 \tag{11}$$

Let

$$b = |V_i|^2 - 2P_j r_{ij} - 2Q_j x_{ij} \tag{12}$$

$$c = P_j^2 + Q_j^2 r_{ij}^2 + x_{ij}^2 \tag{13}$$

$$|V_j|^4 - b|V_j|^2 + c = 0 \tag{14}$$

The feasible solution of equation 13 is unique and can be obtained as follows:

$$|V_j| = 0.707\sqrt{b + \sqrt{b^2 - 4c}} \tag{15}$$

$$b^2 - 4c \geq 0 \tag{16}$$

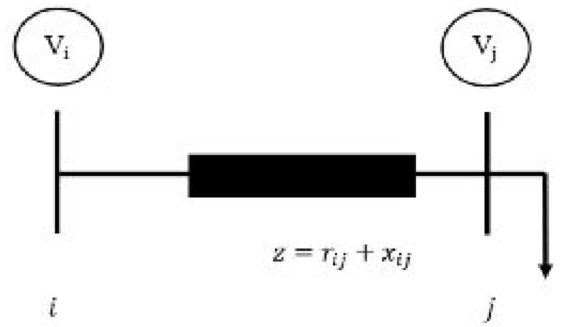

Figure 2: Equivalent circuit of radial network.

From equation (12), (13) and (16)

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

Rearranging equation (17)

$$|V_i|^4 - 4\left(P_i x_{ij} - Q_j r_{ij}\right)^2 - 4\left(P_j r_{ij} + Q_j x_{ij}\right)|V_i|^2 \geq 0 \tag{18}$$

Voltage stability index of node j can be expressed as

$$VSI = |V_i|^4 - 4\left(P_i x_{ij} - Q_j r_{ij}\right)^2 - 4\left(P_j r_{ij} + Q_j x_{ij}\right)|V_i|^2 \tag{19}$$

The condition of the node is represented by the value of the VSI at that node. The lesser the value of VSI the more the node is subtle to voltage collapse. For stable operation of radial distribution network VSI values must be higher i.e., near to 1.

D. *Proposed Algorithm:*

The algorithm used in this research paper is the same as that was used in the Chakravorty and Das (2001) [11], where the VSI was identified of each bus and the bus with with lowest bus was selected for PV integration. The MCS for both scenarios of without PV and with PV. The PV penetration is increased in the step of 10 and up to 80 percent. The results are then compared for optimal solution.

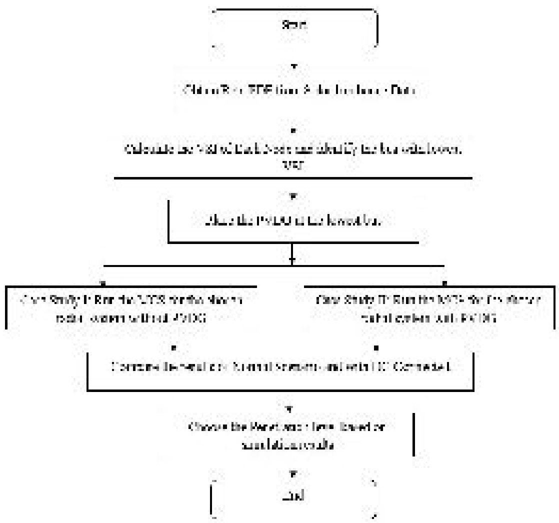

Figure 3: Algorithm of the Research Method

III. RESULTS AND DISCUSSION

The proposed algorithm is tested in the IEEE 33 radial distribution network and a case study was done in the Rajbiraj East feeder with 63 nodes. The substation voltage is taken as 1 pu in both cases. The maximum numbers of PVDG installed for these test systems is limited to two since rate of improvement of percentage loss reduction decreased when the candidate location increases.[1] To calculate the solar irradiance the site is selected at Rajbiraj and a website https://globalsolaratlas.info/ is used to estimate the irradiance thought the year. The solar irradiance data is then normalized and the mean and standard deviation is calculated from the normalized data. The graph of monthly solar irradiance and beta fit of the pdf is shown below:

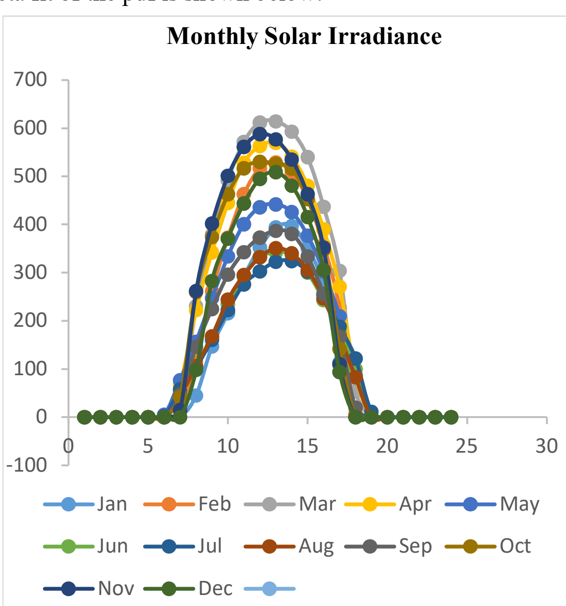

Figure 4: Graphical representation of monthly solar irradiance

The mean, variance, alpha and beta parameters of the solar irradiance data is given in the following table:

Table 1: Parameters of beta function

μ	σ	α	β
0.7533	0.0352	3.2226	1.05553

The PV module selected for this research paper has following characteristics:

Table 2: Parameters of PV module

Parameters	**Selected PV module Rating**
Peak power (Watt)	180
V_{oc}: Open circuit voltage (V)	44.2
I_{oc}: Short circuit current (A)	5.36
V_{mpp}: Voltage at maximum power (A)	36.2
I_{mpp}: Current at maximum power (A)	4.97
K_v: Voltage temperature coefficient (%/°C)	0.386
K_i: Current temperature coefficient ((%/°C)	0.044
N_{OT}: Nominal operating cell temperature	45.8

A. *Case I: IEEE 33 Node Distribution Network*

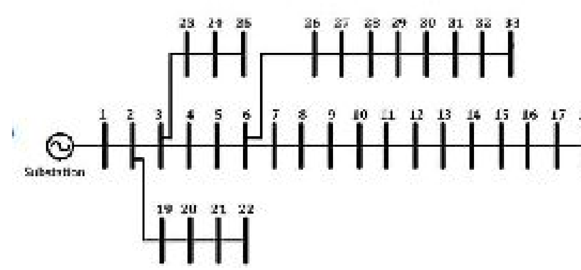

Figure 5: IEEE 33 bus system

Table 3: Critical node of IEEE 33 bus network

Node	Voltage Magnitude	VSI Index
18	0.903772	0.668523
17	0.904385	0.671341
16	0.906433	0.678056
33	0.916404	0.705751

The IEEE 33-node (or 33-bus) distribution network is a widely recognized, standardized benchmark model in power systems research, primarily characterized by the its radial topology, meaning there is only one path for power flow from the substation (slack bus) to any load bus. It consists of 33 nodes (buses) and 32 branches (lines). This is a typical real-world distribution feeders and results in specific power flow characteristics, such as high line losses and a pronounced voltage drop along the feeder, making it ideal for studies on loss minimization and voltage profile improvement. The base parameters of IEEE 33 bus are:

Nominal Voltage: Typically, 12.66 kV or 13.8 kV (depending on the specific version or modification used). Total Load (Base Case): The total active (real) and reactive power load is approximately 3.715 MW and 2.24 MVAR (or 2.3 MVAr), respectively. Slack Bus: Bus 1 is typically the slack bus, connected to the transmission system.

From Table 3, it is evident that node 18 has the lowest VSI. Since the nodes 16, 17, and 18 all lie on the same branch, placing the PV on node 18 will improve the VSI of all three nodes.

After running the MCS for both cases, i.e., with and without PV, the results show that the optimal PV penetration level is 60 percent. In figure 8, the loss reduction percentage is increasing with the penetration but after 60 percent penetration the loss reduction starts decreasing. Also from the figure 9, the feeder loss is decreasing with penetration but beyond 60 percent penetration the losses stars to increase. The voltage profile and VSI of the nodes before PV

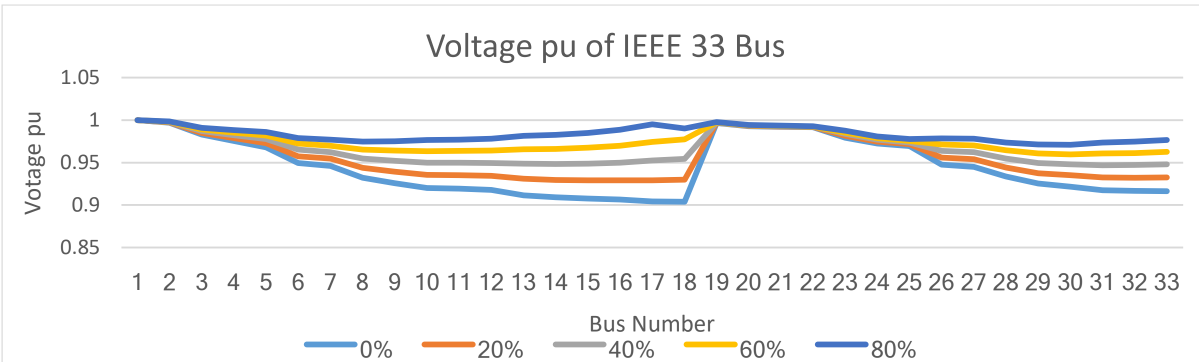

Figure 6: Voltage in IEEE 33 bus system under various penetration level

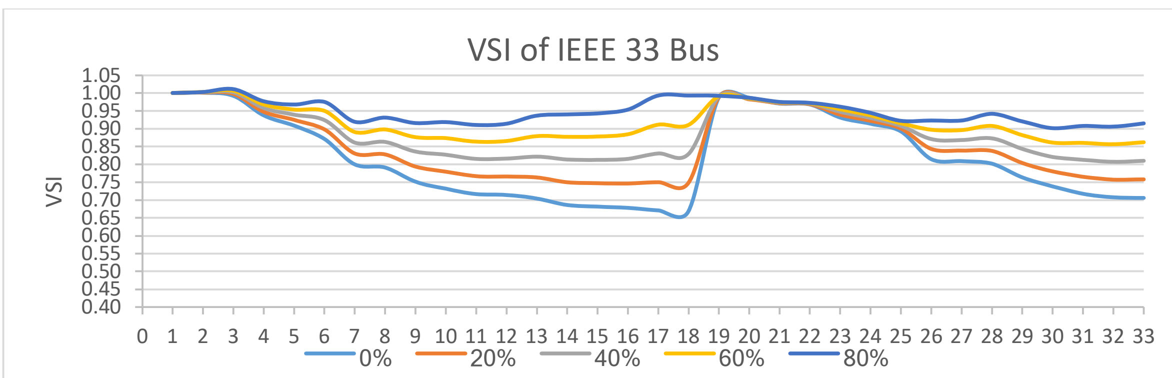

Figure 7: VSI in IEEE 33 bus under different penetration level

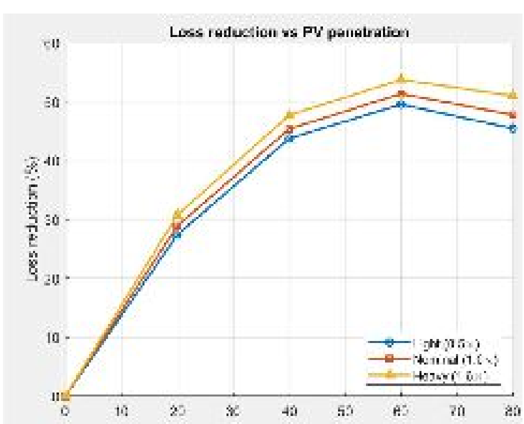

Figure 8: Loss reduction % vs PV penetration

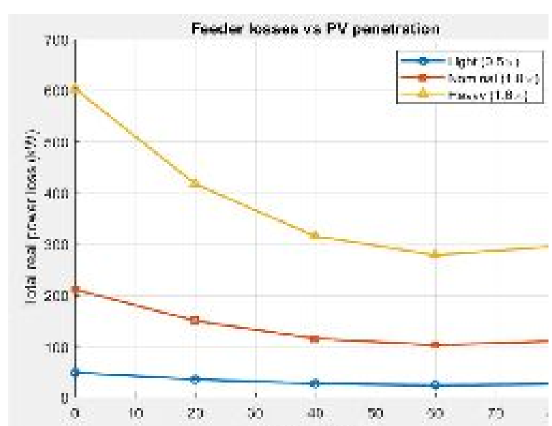

Figure 9: Total Loss vs PV penetration

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

IEEE 33 bus Study	DG Penetration Level	Items	Load Levels		
			Light load (0.5)	Nominal Load	Heavey Load (1.6)
Base Case (Case I)	-	Power Loss	48.817	211.34	603.46
		Size of DG in KW	-	-	-
		Minimum Voltage (pu)	0.95398	0. 903772	0.83601
		Minimum VSI Value	0.82899	0. 668523	0.49035
		% Loss Reduction	-	-	-
Solar Photovoltaic based DG (Case II)	20%	Power Loss	35.439	150.28	417.91
		Size of DG in KW	128.1*2	256.59*2	409.76*2
		Minimum Voltage (pu)	0.96563	0.92902	0.88101
		Minimum VSI Value	0.87057	0.74697	0.60545
		% Loss Reduction	27.403	28.89	30.747
	40%	Power Loss	27.455	115.42	315.55
		Size of DG in KW	256.34*2	512.53*2	820.02*2
		Minimum Voltage (pu)	0.97419	0.94688	0.91168
		Minimum VSI Value	0.90231	0.80692	0.69540
		% Loss Reduction	43.758	45.389	47.71
	60%	Power Loss	24.624	102.8	279.04
		Size of DG in KW	383.73*2	769*2	1231*2
		Minimum Voltage (pu)	0.9804	0.99597	0.93291
		Minimum VSI Value	0.92817	0.85685	0.76981
		% Loss Reduction	49.559	51.358	53.76
	80%	Power Loss	26.624	110.38	295.66
		Size of DG in KW	512.68*2	1023.3*2	1640*2
		Minimum Voltage (pu)	0.98612	0.97087	0.95117
		Minimum VSI Value	0.95205	0.90104	0.83786
		% Loss Reduction	45.46	47.773	51.01

connection and at various PV penetration is shown graphically in figure 6 and 7, respectively. In both figures we get improved voltage and VSI value. So, it can be said that the 60 percent penetration is the optimum level of PV penetration where the loss becomes minimum and VSI is improved to desired range.

The loss vs penetration level of all three-load condition i.e., light load, nominal load and heavy load is tabulated in table 4. It can be seen that the loss is minimum for 60% penetration.

B. Case II: East Feeder of Rajbiraj DC

The East feeder of Rajbiraj DC is one of the longest and overloaded feeders. It has 63 nodes and the lowest VSI is recorded at the node 60. The real and reactive power of East feeder is 2.132 MW and 1.6 MVAR respectively for an annual average load of 140 A. The PV is placed at node 60 and the MCS is carried out. The outputs of the VSI of nodes and voltage per unit is shown in the figure 12 and 13 respectively. The Feeder loss vs penetration graph shows that the losses continue to decrease for the penetration level 60 and starts to increase again when the penetration level is increased. In figure 15, the loss reduction percentage is increasing with increase in penetration and starts to decrease again when the penetration is increased beyond 60 percent. So, 60% is considered as optimum penetration level.

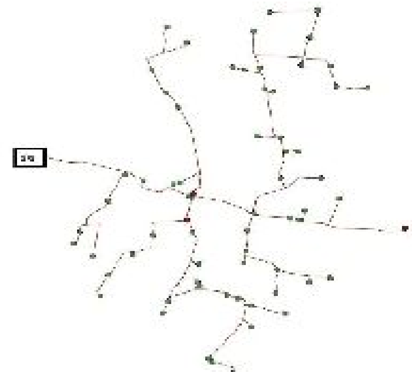

Figure 10: GIS map of East feeder

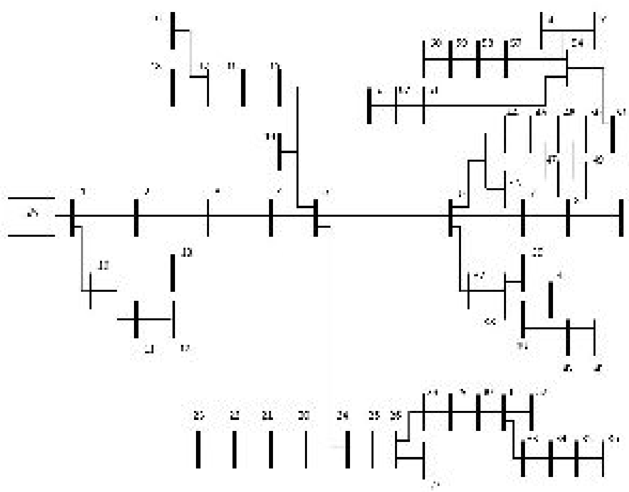

Figure 11: East feeder of Rajbiraj DC node diagram

Table 5: Critical node of East feeder

Node	Voltage Magnitude	VSI Index
36	0.947923	0.808062
15	0.948156	0.808766
60	0.942989	0.791592
63	0.943996	0.794712

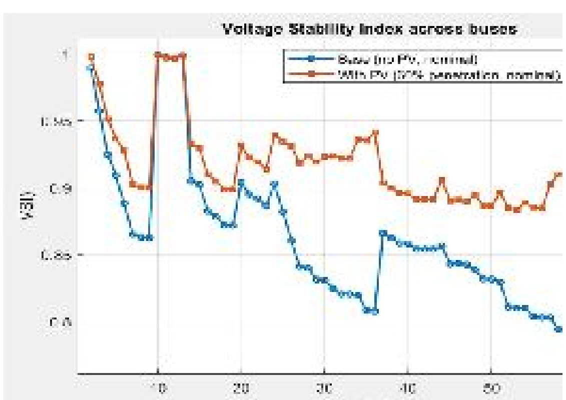

Figure 12: VSI of different nodes under 60% penetration of East feeder

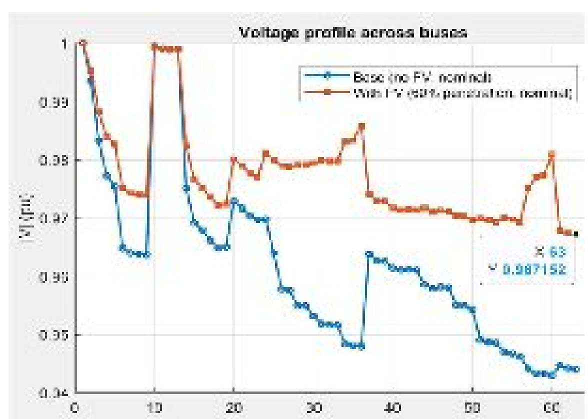

Figure 13: Voltage of different nodes under 60% penetration of East feeder

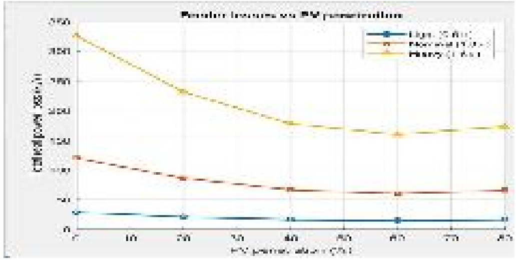

Figure 14: Total loss vs PV penetration

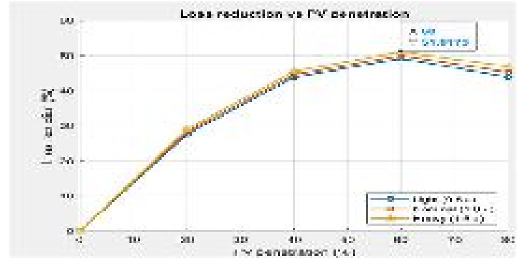

Figure 15: Loss reduction % vs PV penetration

Table 6: Result analysis of East feeder with various PV penetration levels

East feeder Study	DG Penetration Level	Items	Load Levels		
			Light load (0.5)	Nominal Load	Heavey Load (1.6)
Base Case (Case I)	-	Power Loss	28.651	120.04	326.21
		Size of DG in KW	-	-	-
		Minimum Voltage (pu)	0.97222	0. 942989	0.90565
		Minimum VSI Value	0.8939	0. 791592	0.67401
		% Loss Reduction	-	-	-
Solar Photovoltaic based DG (Case II)	20%	Power Loss	20.807	86.149	232.49
		Size of DG in KW	179.75*2	359.5*2	397.11*2
		Minimum Voltage (pu)	0. 97652	0. 95203	0. 92107
		Minimum VSI Value	0. 90966	0. 82211	0. 72066
		% Loss Reduction	27.573	28.234	28.948
	40%	Power Loss	16.098	66.577	178.21
		Size of DG in KW	359.5*2	719*2	793.08*2
		Minimum Voltage (pu)	0. 98024	0. 95972	0. 93397
		Minimum VSI Value	0. 9236	0. 84899	0. 76184
		% Loss Reduction	43.815	44.538	45.48
	60%	Power Loss	14.571	60.062	158.97
		Size of DG in KW	539.25*2	1078.5*2.	1190.4*2
		Minimum Voltage (pu)	0. 9839	0. 96712	0. 94605
		Minimum VSI Value	0. 93746	0. 87548	0. 80204
		% Loss Reduction	49.143	49.966	51.017
	80%	Power Loss	16.08	65.743	170.67
		Size of DG in KW	719*2	1438*2	1586.5*2
		Minimum Voltage (pu)	0. 98727	0. 97398	0. 9571
		Minimum VSI Value	0. 95076	0. 90112	0. 84074
		% Loss Reduction	43.877	45.233	46.861

IV. CONCLUSION:

In this paper, a method called Monte Carlo simulation is used for finding the maximum penetration level of PVDG in IEEE 33 bus and East feeder of Rajbiraj DC. In this research the VSI (Voltage Stability Index) is used to identify the weak buses and the PV is placed in the weakest bus. Hit and trial method is also done to identify appropriate bus if more than one buses have the lowest VSI. The penetration level of the PV is increased from 0 to 80 percent on the step of 20. In this paper the solar irradiance and the load is considered as random variables due to its stochastic nature. So, probabilistic load flow analysis is used in this research paper. Monte Carlo simulation which is considered as one of the best methods for probabilistic study is used in this research work.

The case study was done for the IEEE 33 bus system and East Feeder of Rajbiraj Distribution Center, Saptari, Nepal. In IEEE 33 bus network, it was observed that the lowest VSI occurred at the bus number 18 and 33. so the PVDG is placed at the bus number 18 and 33 and the results were compared with PVDG and without PV. It was found that the losses were decreasing up to the penetration level 60% and then started to increase again. The lowest VSI and V pu at the 60% penetration is 0. 99597 and 0.85685 respectively. The loss of IEEE 33 bus system without PV at normal load is 211. kW which decreased to 102.8 kW at 60% penetration.

When the PVDG is applied to the East Feeder of Rajbiraj DC, the line losses without PV were 120.04 kW which reduced to 60.06 kW after the 60% integration of PV. The lowest VSI and V pu at the 60% penetration is 0. 87548 and 0. 96712 respectively, which is between the limits. Thus, it was concluded that the integration of PVDG can reduce the loss as well as increase the voltage profile but the limitation of the penetration level must be 60%.

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