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Effect of Photovoltaic Penetration on Radial Distribution Network: A Case Study of Rajgadh Feeder, Anarmani Distribution System, Jhapa, Nepal

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Abstract

Solar photovoltaic penetration to a local distribution network is one of the best ways to improve voltage profile and meet the power demand of consumers without the requirement of building a new transmission network. However, the penetration level should not be exceeded in order to prevent from serious power issues like power outage, reverse power flow, voltage fluctuations and voltage unbalance. This paper presents a simple method to obtain best location for PV penetration to improve voltage profile and reduce system loss without affecting the power factor of the supply grid. The maximum value of product sum of probability density function and voltage ratio of the distribution system with and without solar PV gives the best location for PV penetration. The effect of PV penetration on the ETAP modelled IEEE-10 Bus system is initially studied and later on again applied on 11kV Rajgadh Feeder of Anarmani distribution system, Jhapa, Nepal is analysed. The result shows, at 20% and 40% penetration, voltage at minimum voltage bus can be improved from 0.74 pu to 0.86 pu and 0.9 pu with 52% and 76.4% loss saving respectively. According to finding, 40% PV penetration at bus number 30 gives best result for Rajgadh feeder. The use of inverter that offer both active and reactive power can solve the problem of low power factor in the supply grid, also capacitor bank can aid in the improvement of reactive power.

Keywords

penetration level, probability density function, voltage ratio

1. Introduction

A rapid growth is observed in past few years in installation of solar photo-voltaic system driven by its technical and economical benefit. Integration of PV has both positive as well as negative impact on the power grid depending upon penetration level so penetration level calculations are very important in installation design to determine the maximum allowable PV power can be installed in certain system. Research shows voltage improvement at loads buses and the reduction in the system losses can be achieved by penetration of PV in distribution system [1]. In Nepalese distribution, the study of optimal location of DG unit is performed for some distribution systems[2]. For testing voltage sensitivity with load uncertainty voltage profile index is used in paper[3], which determine the best position of distributed photovoltaic generation. Higher penetration have to address different issues like reverse power flow and change of short circuit level. Power flow is unidirectional in radial feeder hence the protection scheme are designed accordingly. With increase in penetration level, variation of voltage has been found at different bus of distribution network. Voltage fluctuation due to variation in irradiance directly depends on the percentage of penetration and its concentration and affect the performance of voltage regulating equipment [4]. Different power quality issues and problem with grid limiting factors occurs with high penetration of solar photovoltaic [5].

A research has been done in Thimi- Sallagahri feeder to find optimum point for DG placement with its capacity with assessment of voltage profile and system loss[6]. After installing DG there seems to be a serious limiting factor of voltage rise at load bus.

The research shows limiting factors like conductor ampacity and rise in voltage manifest themselves on varying penetration level[7].
With rise in DG penetration on low voltage feeder it give rises to power quality issues like rise of system voltage beyond nominal value and current swing[8].
Use of distributed generation like solar photovoltaic is increasing because of its capacity to solve different energy issues, meet the power demand of consumer and no requirement of transmission line. Solar PV should be injected at optimum point of network to minimize system loss with better voltage profile rather than randomly injected solar PV[9].
A research has been done in 33KV electrical network of province 1 of Nepal for finding maximum PV hosting capacity. PV hosting size was determined on the basis of load flow during dry and wet season [10].
Different algorithm is proposed among them analytical is one which is use for optimal capacitor and DG placement[11]. DG and DSTATCOM can be optimally allocated using Cucook search optimization algorithm considering five different cases with the help of voltage sensitivity and loss index[12].
Problem like Voltage sag and system loss mainly in terai region feeder can be addressed using PV integration. This research develop the Simulink model to represent Rajgadh feeder to analyze the system voltage profile, line loss and power factor with and without PV.

2. System Modelling

The modelling approach used in this paper is discussed as network modelling and mathematical modelling.

2.1 Network Modelling

In this research IEEE 10 bus radial distribution network is used as test bus system and later analysis is done on Rajgadh 11KV feeder. The Simulink module of distribution network is modelled in ETAP software. The load data, line data and other information has been obtained from Nepal Electricity Authority (NEA). The figure 1 represent the single line diagram of Rajgadh feeder.The simulink model and load flow analysis is done using ETAP software.

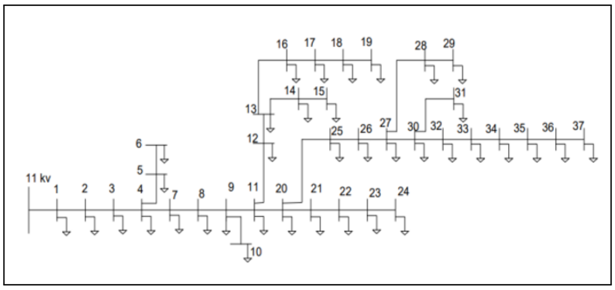

Figure 1: Single line diagram of 37 bus Rajgadh feeder

2.2 Mathematical Modelling

For load uncertainty modelling load in each bus is varied from 60% to 110%. The average and standard deviation of load at each bus is calculated. The probability density function for rated load is calculated using given equation.

$$pr = \frac{1}{\sigma * \sqrt{2\pi}} * e^{\frac{-(x-\mu)^2}{2\sigma^2}}$$

Where μ and Σ are the calculated mean and standard deviation of assumed loads respectively. X is rated load for which probability density function is calculated.[3]
The voltage ratio is calculated using given formula.

$$Vn = \frac{Bus\,voltage\,with\,DG\,on}{Bus\,voltage\,with\,DG\,off}$$

Then finally product sum of probability density function and voltage ratio is calculated using

$$\Sigma VnPr\,for\,n = 1\,to\,37$$

Maximum value of ΣVnPr represent best position for PV injection at given penetration level considering the voltage profile only. Considering the both voltage profile and loss saving we can find the best location for the PV penetration. The active loss and reactive loss of the system is calculated as

$$active\,loss = i^2 * r$$

$$Reactive\,loss = i^2 * x$$

Where i is current flowing in network and r and x are resistance ad reactance of the conductor respectively.

3. Methodology

The effect of PV penetration in the radial distribution system for voltage and loss evaluation is studied using a methodology that requires load flow before and after PV injection in the radial distribution system. Load flow analysis is used to calculate the loss and voltage profile in the system before and after PV injection in the distribution system. The load on each bus is varied from 60% to 110% for load uncertainty modeling and the mean and standard deviation is used to calculate the probability density function for rated load. Collected Line and load data are used to develop Simulink module in ETAP software for load flow analysis. The simulation result gives the total system power loss and voltage in each bus with and without PV penetration. Then product sum of probability density function and voltage ratio for PV penetration at each low voltage bus is calculated whose maximum value represent the best location of PV injection at given penetration level considering voltage profile and system loss.

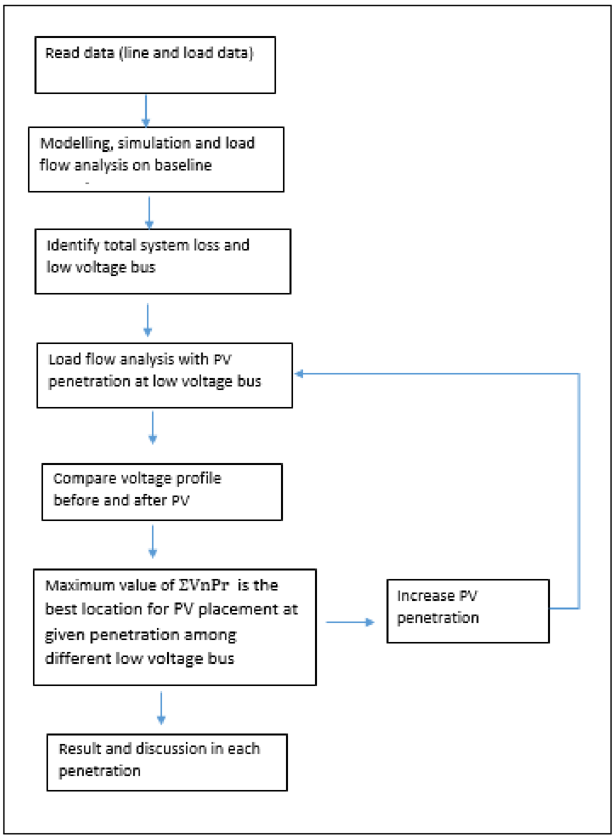

Figure 2: Methodology Flowchart

4. Grid Configuration

The distribution network use in this research is Rajgadh Feeder, one of the feeder of Anarmani distribution and consumer services (DCS). This is the 11kV feeder with 8MVA 33/11kV power transformer at Ghailadubba distribution substation. All the thirty seven 11/0.4 kV distribution transformer are taken as load bus. The total load of the system is 2769.75KW and 1340.44kVAr. The line conductor used in this radial distribution network are rabbit and weasel.

5. Results and Discussions

5.1 Effect of distance from Substation

Comparative study of PV penetration for different distance from the substation is carried and figure 3 and figure 4 shows the result obtained in each case. For 10% penetration at three different location, near substation (bus4), mid of the network (bus20) and at end of network (bus 37), Figures shows better voltage profile and maximum loss saving of around 28% for PV injection at end of the network. For the low penetration end of the network appears to be best location for the PV penetration.

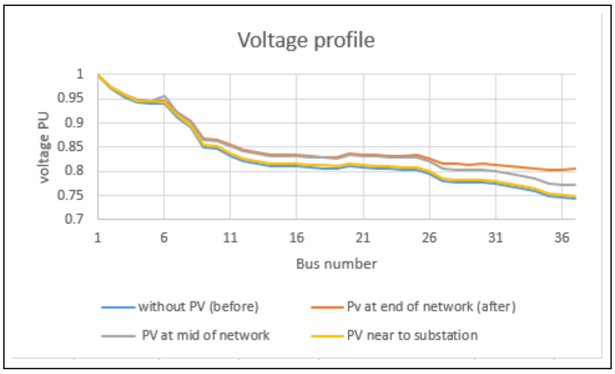

Figure 3: voltage profile of Network at 10% penetration at three different location

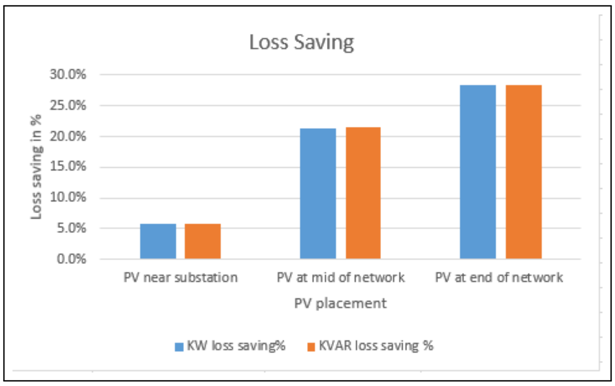

Figure 4: loss saving with PV penetration at different location

In figure 4,the lower one represents the voltage at base case (without PV) and the upper one represents the voltage profile for PV penetration at end of network at

10% penetration with minimum bus voltage improve from 0.74pu to 0.81pu. At low penetration level, better result is obtained when PV is injected near to end of the Network. This shows location is primary and important factor that effect on the performance of distributed generation on distribution system. It is necessary to find the optimal location to inject the DG like PV.

5.2 Effect of Penetration level

Comparative study of voltage profile at different penetration level-10%, 20% and 30% at end of the network. On increasing the penetration level, the lowest voltage at bus no 37 is improved from 0.74pu to 0.9 pu (21% improvement). This result shows that different voltage profile and loss profile can be obtained at different penetration level. But higher penetration level required both steady state and transient state analysis. As this research focus on steady state analysis, research focus on lower penetration.

Higher penetration may result in over voltage and results in change in power flow. When PV generation is greater than load demand. Excess power flows from PV to distribution transformer. Because of this severe problem like over voltage and reverse power flow occurs. When fault occurs in network with high penetration, high fault current flow compare to the system without PV as it continues supply until breaker open leading damage to conductor and transformer. figure 5 shows the voltage profile of the system at different penetration level.

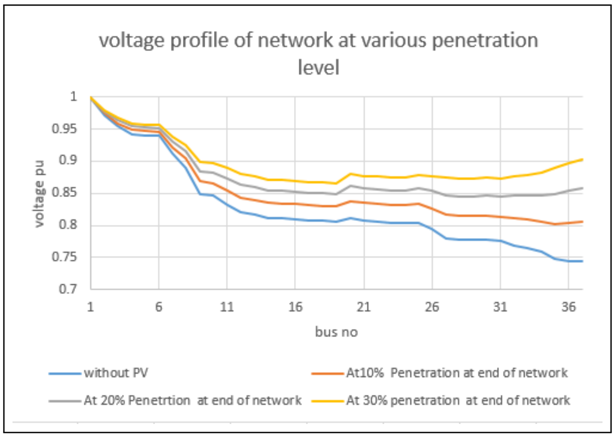

Figure 5: voltage profile of network at different penetration level

5.3 Effect on power factor of supply grid when PV is inject at different penetration at unity power factor

Most of the grid connected PV inverter are injected at unity power factor, this means inverter produce active power only. Due to this power factor of supply grid decreases and as grid has to supply same amount of reactive power but less active power. From 10% to 50% penetration grid power factor reduces from 0.88 to 0.75 lag as shown in figure 6.

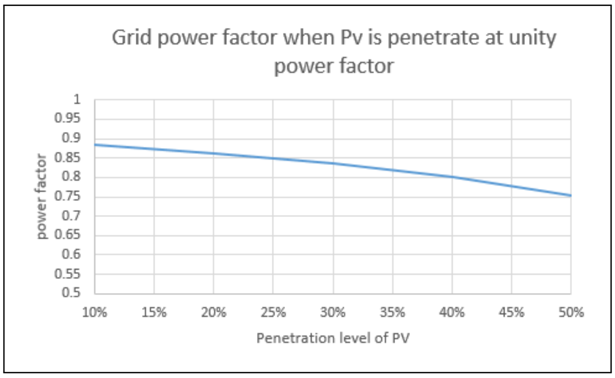

Figure 6: power factor of grid

5.4 Effect of PV penetration at different reactive power.

At 20% penetration, as the supply of reactive power is increased from 0 kVAr to 252.7 kVAr the power factor of the grid is increased from 0.86 to 0.89 lagging as shown in figure 7. Power factor is increased by around 3.21 percent on increasing kVAr from 0 to 252.7 kVAr. There is slight improvement in voltage profile of network for increment of kVAr supply 0 to 252.7 kVAr. There is kW loss saving of around 53.4%. Figure 8 and figure 9 shows voltage profile and line loss of system at different reactive power respectively.

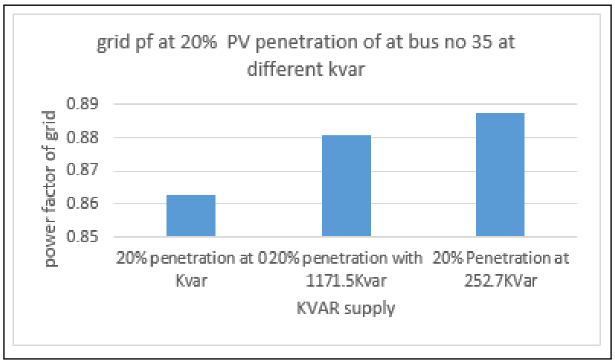

Figure 7: power factor of supply grid

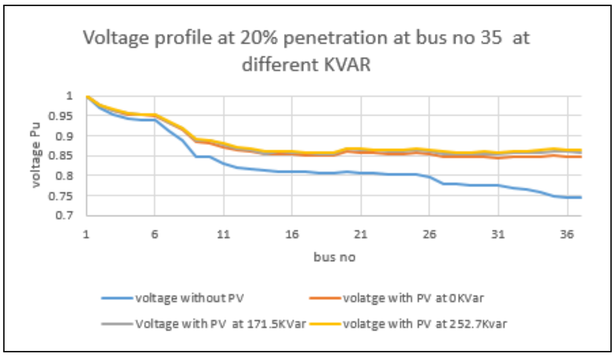

Figure 8: Voltage profile at different reactive power

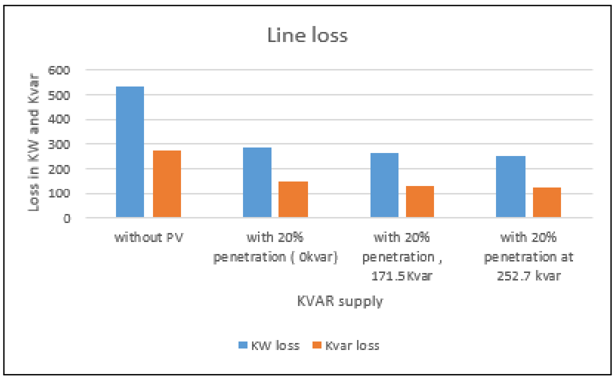

Figure 9: line loss at different reactive power

5.5 Optimal Placement for 20% penetration

For 20% penetration better voltage profile with maximum loss saving occur when PV is inject at bus number 35. With maximum loss saving of 46.1%. The voltage of lowest voltage bus improved by 16.215% from 0.74pu to .86pu. The product sum is maximum at bus no 35 for 20% penetration as shown in table 1, so product sum also suggest bus no 35 as best location for PV penetration.

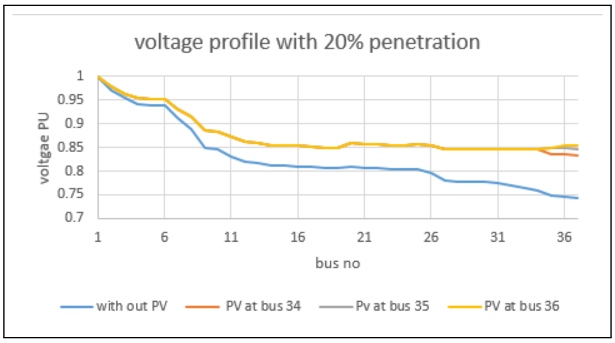

Figure 10: voltage profile with 20% penetration without kVAr supply

Result shows maximum loss saving can be achieved when distributed generation like photovoltaic integrated with both active and reactive power. At base condition (without PV), the active loss of the system is 534.25kW and reactive loss is 272.4 kVAr. At 20% penetration 46.1% active power loss saving can be made with 0 kVAr reactive power. This loss saving can be increased to 52.5 % with reactive power of 252.7 kVAr. The voltage of low bus can be improved by 13.8 percent from 0.74 pu to 0.84pu at 0 kVAr reactive power. At 252.7 kVAr, the voltage of minimum voltage bus can be improved by 16.12% from 0.74 pu to o.862 pu. Figure 10 and figure 11 shows voltage profile and loss saving at 20% penetration.

Table 1: Product sum table at 20% penetration without kVAr

PV placement	product sum A	product sum B
PV at bus 34	1.48376	0.6751108
PV at bus 35	1.485396	0.684767556
PV at bus 36	1.485589	0.675942995

Product sum A:Product sum considering Voltage profile only
Product sum B: Product Sum considering voltage profile and loss saving

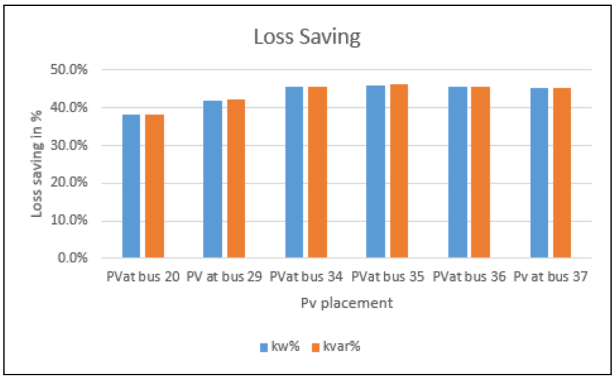

Figure 11: Loss saving without kVAr supply

5.6 Optimal Placement for 40% penetration

As in the 20% penetration bus no 30 is found to be best position for 40% PV penetration based on product sum considering both voltage profile and system loss. The value of Product sum is maximum when PV is placed at bus 30 as shown in table 2. At 40% penetration the voltage of bus 37(minimum voltage bus) can be improved by 21.6 percent from 0.74pu to 0.90 pu. The loss saving of 76.45% can be made at 40% penetration with supply of 505.4kVAr reactive power. At base case the active and reactive loss in the system was 534.25 kW and 274.4kVAr, which can be reduced to 125.85kW and 63.7 kVAr respectively. The figure 12 and figure 13 shows the voltage profile and systme loss at 40% PV penetration at bus no.30

Table 2: Product sum table at 40% penetration

PV placement	product sum A	product sum B
PV at bus 27	1.578338886	1.206539
PV at bus 30	1.579864912	1.207706
PV at bus 32	1.583288972	1.20736

Product sum A:Product sum considering Voltage profile only
Product sum B: Product Sum considering voltage profile and loss saving

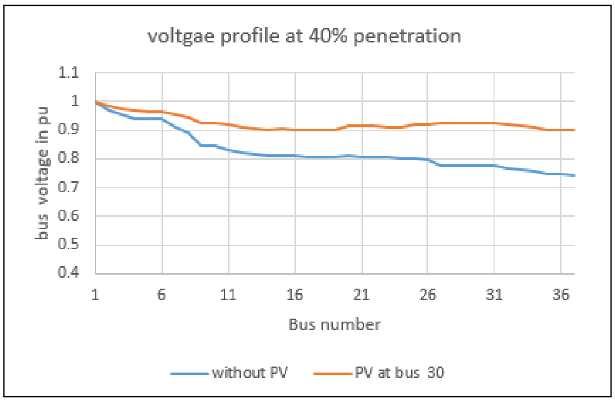

Figure 12: voltage profile at 40% penetration

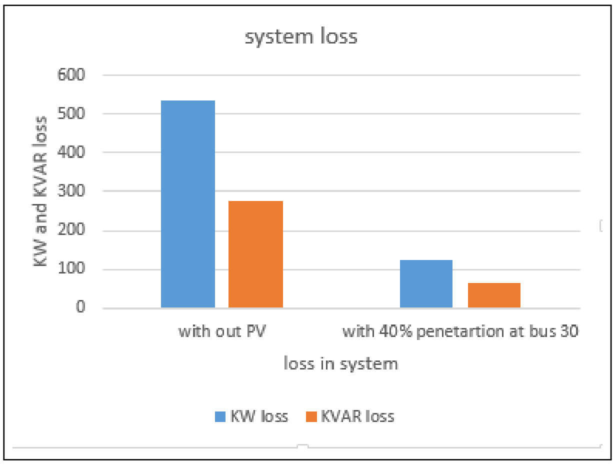

Figure 13: system loss at 40% penetration

6. Result Validation

Various studies have been conducted to penetrate the solar photo-voltaic in radial distribution network in Nepal and outside the country. Comparison is made with other similar research done on real feeder based on PV size, loss saving, and voltage profile improvement obtained from simulation result. A research done in Dodhara Chadani feeder based on analytical approach shows about 83.6% loss saving can be made with installation of 787Kwp solar PV, which is 50% of peak load. Comparing the finding of research on Rajgadh Feeder (76.4% loss saving at 40% penetration) with finding on research of Dodhara Chadani,it shows the finding obtained in this research work to be valid able[5]. Similar kind of study has been done on Thadi feeder of Lahan distribution system based on analytical approach, the voltage of lowest voltage bus improved from 0.6 pu to 0.91 pu., comparing the finding of the research done on Rajgadh feeder (voltage improved from 0.74pu to 0.9 pu) with the finding of research on Thadi feeder, it suggest result obtained to be valid able.[13]

7. Conclusion

Study shows the problem like voltage sag and line loss in radial distribution network can be solved using distributed generation like photovoltaic. Simulation result shows a significant improvement in voltage profile and line loss of radial distribution network of Rajgadh feeder. The effect of PV penetration is mainly governed by penetration level and location. The problem of low power factor of supply grid can be solved by using inverter that produce both active and reactive power, i.e. by injecting inverter at non-unity power factor. This helps to keep power factor of load and supply grid with in permissible limit. To solve protection issues of grid integrated solar PV system like change of short circuit level, reverse power flow coordination of relay and protection scheme should be designed accordingly.

8. Acknowledgements

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