TECHNICAL ANALYSIS OF GRID CONNECTED 1 kW$_P$ ROOFTOP SOLAR PV FOR RESIDENTIAL CONSUMER AT URBAN AREAS OF LALITPUR, NEPAL

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Abstract

Integration of rooftop solar PV by a residential consumer to the grid is beneficial to both consumer and grid if integrated optimally. The minimization of power loss by improving the voltage profile on the grid side and reducing the electricity bill by improving energy deficiency faced by the residential consumer is the benefit of the integrated PV system. The preparation of this paper is based on the study of grid impact analysis and performance analysis of solar among the urban areas of Lalitpur. First, the grid impact and optimum size calculation are performed in IEEE-33 and IEEE-15 bus test system, and Pulchowk feeder is taken for the study of real scenario. Improvement of voltage profile, loss reduction, and the number of houses feasible for injecting PV generation has been demonstrated graphically. The power loss is found to be reduced by 62.5% after injecting solar PV into the grid. PVsyst has been used for the performance analysis of the PV array and the performance ratios are within limits with a capacity factor of 0.177 and performance ratio of 0.74 and system yield factor of 4.24 kWh/kWp/day. From all the results and performance analysis, it can be concluded that integration of 1 kWp rooftop solar is technically feasible if the optimum number of houses are allowed to inject PV array power at the optimum location.

Keywords: Integrated PV system, Grid impact, PVsyst, Performance ratio

1. Introduction

The climatic condition of Nepal is feasible for solar energy technology (Chianese et al., 2009). The energy in Nepal is supplied by forest in about 78% of total energy requirement and with a 50% of fodder for livestock, although it has an average of 6.8 sunshine hours per day that is around 2482 sunshine hours in a year with an intensity of solar insolation ranging from 3.9 to 5.1 kWh/m^2/day (Shrestha, 2014). The total installed capacity in Nepal is around 5.6 MW for solar home systems installed in 206,152 numbers, 0.737 MW for the small solar home system in 155,574 numbers, and 0.53 MW of institutional solar PV in 415 numbers (KC et al., 2011). Having this amount of energy available from the sun, its optimum utilization has not been performed until now. So, the study of performance analysis is necessary.

Solar PV, one of the safe and clean sources of energy, can be used in standalone or grid-connected applications. If used in a standalone system, it can be used only to serve remote loads whereas grid-connected applications can be used to provide energy to local loads as well as to grid (i.e. energy trade is possible) (Farhoodnea et al., 2012). The integration of PV system to grid can help the grid by reducing energy losses of the distribution feeder (Farhoodnea et al., 2012), whereas energy injection from the demand side may cause voltage rise at low load situations (Widén et al., 2010). Power electronics plays an important role in the integration of distributed energy to grid (Hosseinipour & Hojabri, 2018). The past consideration for designing the distribution system is unidirectional power flow to the end consumer. So, for reverse power flow, the study of the impact on the existing system while injecting power into the network is necessary (Tie & Gan, 2013).

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For the study of the steady state condition of a power system, load flow or power flow studies are performed. At the design phase, load flow is carried out to check the network voltage level and at the operation phase, it is carried out to explore the required voltage profile and to minimize loss. The algorithms like Newton Raphson (NR), Gauss Seidel (GS), or Fast Decoupled methods, which are developed for transmission system load flow are not so efficient for distribution systems because they are radial and have high R/X ratio (Das et al., 1995). Many approaches for distribution networks are developed like the Ladder network theory, Compensation based power flow method, backward/forward sweep method, and direct solution method for solving radial and meshed network (Das et al., 1995). Commonly used methods are ladder network theory and backward/forward sweep method. Due to fast convergence, easy to program and requirement of minimum run time backward/forward sweep method is best for radial distribution network (Rana et al., 2014). The backward/forward sweep method uses Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL) to calculate voltage and current at each upstream bus (Rupa & Ganesh, 2014).

Technical performance includes total energy output, performance ratio, energy yields, and losses. At the generation site, it may be affected due to the shading of the panel. The real power generated from a solar PV array may fall below the design due to the small amount of shading in the panel. This may lead to a complete 'loss of load' (Anand et al., 2014, Tripathi & Murthy, 2018).

Study on technical analysis of grid-connected 1 kWp rooftop solar PV at residential consumers keeps importance by giving the number of houses who are feasible to inject energy from solar PV to grid. This analysis also shows the improvement of voltage profile and changes in branch losses of grid. In the first section of this paper, the study of the impact of solar PV connected to the grid is studied and in the second section, the study of the performance of solar PV array if installed at urban areas of Lalitpur is carried out.

2. Methodology

For the overall technical analysis of grid-connected rooftop solar PV at the residential consumer, the methodology is divided into two sections. Firstly, the grid impact analysis due to injection of numbers of rooftop solar in urban areas is carried out. It includes load flow at base case followed by calculation of the total number of houses that can inject the power from 1 kWp rooftop solar. Secondly, the study of the performance of grid-connected solar PV at the rooftop of each household is carried out based on energy yield, the efficiency of panel and inverter, and performance ratio. Each of the processes is explained as follows:

2.1. Grid impact assessment

For the grid impact analysis, the method proposed starts with the input of line data and bus data of the radial distribution system. Backward sweep propagation is used to calculate branch currents in which the voltage of each bus is set to one per unit. The branch currents are calculated using (1) and (2) (Singh, 2017). In forward sweep propagation, the magnitude of voltage is updated using (3) (Singh, 2017). The backward and forward sweep propagation is iteratively continued until the convergence criteria are satisfied. In the proposed method of load flow, the convergence criteria (i.e. number of iteration) can be input by the user and for the maximum size of Distributed Generation (DG) calculation, the convergence criterion is 0.0001. Total active power loss and reactive power loss in the radial distribution system are calculated using (4) and (5) (Das et al., 1995).

$$I_i^{(k)} = \left(\frac{S_i}{V_i^{(k)}}\right)^* - y_i V_i^{(k-1)} \quad (1)$$

$$J_l^{(k)} = -I_{lr} + \sum J_{lr} \quad (2)$$

$$V_{lr}^{(k)} = V_{ls}^{(k)} - Z_l J_l^{(k)} \quad (3)$$

$$P_l = \sum \left(\frac{P_i^2 + Q_i^2}{V_i^2} \times R_i\right) \quad (4)$$

$$Q_l = \sum \left(\frac{P_i^2 + Q_i^2}{V_i^2} \times X_i\right) \quad (5)$$

Where,

$i = 1, 2, 3, \ldots\ldots\ldots\ldots\ldots\ldots, n$

S_i is the power output at node i; V_i is the voltage at node i; y_i is the shunt admittance at node i, $l = b, b\text{-}1, \ldots\ldots\ldots\ldots\ldots\ldots 1$, I_{lr} is the current injection of node lr calculated from (1), $\sum J_{lr}$ is the currents in branches emanating from node lr, $lr = 1, 2, 3, \ldots\ldots\ldots\ldots\ldots\ldots b$, ls, and lr denote the sending end and receiving end of the branch l, Z_l is the series impedance of branch l, P_i

and Q_i are the total real and reactive power fed through i^{th} node, R_i is the resistance of i^{th} branch and X_i is the reactance of i^{th} branch.

The size of DG at each node is calculated using the analytical method in accordance with power demand at the specific node and the power factor of the DG using (6) and (7) (Elsaiah et al., 2014). After calculating the size of DG, the bus data is updated and voltage and power loss are calculated using backward and forward propagation iteratively. The bus in which the loss is minimum is identified as the optimum bus. The number of houses that can inject the solar PV to the grid in a specific node can be calculated using (8).

$$P_{DG(i)} = a_{ij}\left(P_{d(i)} + Q_{d(i)} \times apf\right) - \frac{YI \times apf - XI}{a_{ij} \times apf^2 + a_{ij}} \quad (6)$$

$$Q_{DG(i)} = apf \times P_{DG(i)} \quad (7)$$

$$N = \frac{P_{DG(i)}}{Size\ of\ solar\ PV\ at\ each\ generation} \quad (8)$$

Where,

- $P_{d(i)}$ And $Q_{d(i)}$ are the real and reactive power demand at i^{th} node,
- $apf = tan\,(acos(pf))$; *pf* is the power factor of DG
- $YI = a_{ij} \times Q_{d(i)} + b_{ij} \times P_{d(i)}$
- $XI = a_{ij} \times P_{d(j)} - b_{ij} \times Q_{d(j)}$
- $a_{ij} = r_{ij} \times \frac{\cos(\delta_{(i)} - \delta_{(j)})}{V_i \times V_j}$; $\delta_{(i)}$ is the phase angle of voltage at i^{th} node
- $b_{ij} = r_{ij} \times \frac{\sin(\delta_{(i)} - \delta_{(j)})}{V_i \times V_j}$; $\delta_{(j)}$ is the phase angle of voltage at j^{th} node
- r_{ij} is the resistance between i^{th} node to j^{th} node, *N* is the number of DG.

2.2. Performance analysis of solar PV

According to IEC and IEA standards, performance parameters of Solar PV can be evaluated using energy efficiency, yield factor, performance ratio, and capacity factor (Adaramola, 2015, Kumar & Sudhakar, 2015, Jamil et al., 2017).

a) *Array Yield*: It is the ratio of total energy output to the nominal power of solar PV in a day. It can be calculated using (9) and its unit is [kWh/kWp/day]. E_a is called array yield energy to the grid.

b) *Reference System Yield*: It is numerically equal to the incident energy in the array plane and is defined as, "the ratio of total horizontal irradiance on an array to global irradiance at standard test condition". It is expressed in [kWh/m^2/day] and calculated using (10).

c) *System Yield Factor*: It is defined as, "the ratio of final energy yield (i.e. AC output energy from solar) to the nominal power installation of the solar PV". It is expressed in [kWh/kWp/day] and calculated using (11).

d) *Capacity Factor*: Capacity factor can be calculated using (12). It is calculated because it acts as a key factor for the monetary values of the financing structure for the whole plant.

e) *System Efficiency*: The efficiency of the inverter and the efficiency of the solar PV panel differs. These two components have major roles in the application the solar PV. The formula for calculation of inverter and PV efficiency is given in (13) and (14) respectively.

f) *Performance Ratio*: This ratio determines the amount of energy that is injected into the grid (Sreedevi et al., 2017). This factor lies between relations of yield factor of the plant divided by the reference yield. It is given by the formula in (15).

$$Y_A = \frac{E_a}{P_o} \quad (9)$$

$$Y_r = \frac{H_t}{G_o} \quad (10)$$

$$Y_f = \frac{E_{AC\ out}}{P_{max,}STC} \quad (11)$$

$$CF = \frac{Estimated\ energy}{capacity \times 24 \times 365} \quad (12)$$

$$\eta_{inv} = \frac{E_{DC} \times S}{H_t} \times 100\% \quad (13)$$

$$\eta_{PV} = \frac{E_{AC}}{E_{DC}} \times 100\% \quad (14)$$

$$PR = \frac{Y_f}{Y_r} \quad (15)$$

Where,

E_a is array yield, P_o & $P_{max,}STC$ is the nominal power of solar, H_t is total horizontal irradiance on an array, G_o is the global irradiance at standard test condition, $E_{AC\ out}$ is the amount of electrical energy generated and E_{DC} is total DC energy generated by solar PV.

3. Results and Discussions

3.1. Grid impact assessment

Voltage profile and active power loss are studied for grid impact analysis. The bus data and load data of IEEE 33 bus and IEEE 15 bus system are taken which are represented in Wazir & Arbab (2016) and Sudhakar et al. (2016) respectively, and are used to study the impact on the grid on the first phase. And finally, it was studied for 16-bus system of Pulchowk feeder with real data of Lalitpur metropolitan city with data taken from NEA.

The base value of voltage 12.6 kV and base power of 500 kVA was taken for IEEE-33 bus test system to perform load flow analysis. The result of load flow for voltage was found to be 1 per unit (pu) at bus number 1 which is maximum and a minimum of 0.92 pu at bus number 18.

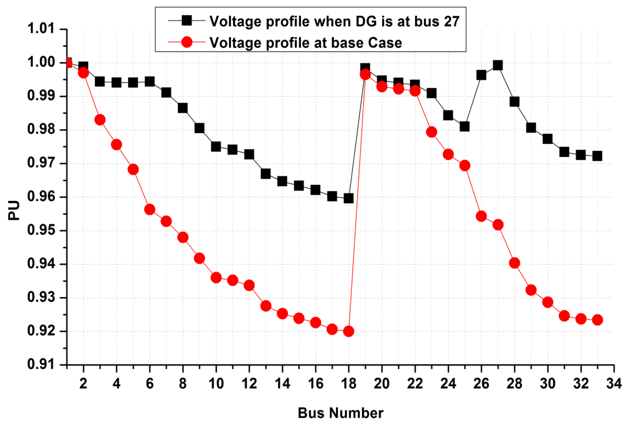

Fig. 1 Voltage profile of IEEE-33 bus test system without and with DG placement

The total active power and reactive power loss at base case were 186.404 kW and 130.667 kVar respectively. The active power loss was found to be reduced to 77.54 kW (reduction by 58.4%) and reactive power was reduced to 65.8 kVar (reduced by 49.6%) after the placement of distributed generation of size 2681.564 kVA, at 0.8 pf. at optimal bus number 27. The voltage profile was also improved above 0.95 pu at all the buses and within a limit. The bus voltage profile with and without DG placement is shown in Fig. 1.

For IEEE-15 bus test system, the base voltage and base power were 11 kV and 500 kVA respectively to perform load flow analysis. In the same manner, the load flow resulted in the maximum voltage of 1 pu at bus number 1 and the minimum voltage of 0.94 pu at bus number 13. The active power loss at the base case is 56.733 kW and reactive power loss is 52.323 kVar. By placement of DG of size 1323.45 kVA, at 0.8 pf at optimal bus number 3 can reduce the active power to 15.81 kW (i.e. by 72.13%) and reactive power to 12.53 kVar (i.e. by 76.05%). The voltage profile after placement of DG at bus 3 will improve above 0.95 and within the limit. The improvement of voltage profile is shown in Fig. 2.

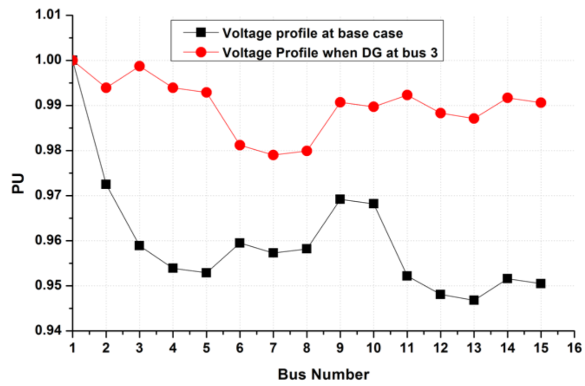

Fig. 2 Voltage profile of IEEE-15 bus test system without and with DG placement

The base voltage of 11 kV and base power of 500 kVA was chosen for 16 bus Pulchowk feeder of Lalitpur starting from Teku substation to International Labour Organization (ILO) office for load flow analysis. The maximum voltage of 1 pu is seen at bus number 1 and the minimum voltage of 0.93 pu at bus number 14. The total active power loss was 117.35 kW and reactive power loss was 95.337 kVar.

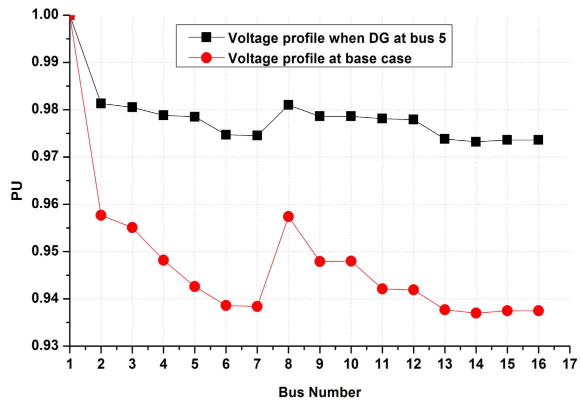

Fig. 3 Voltage profile of 16 bus distribution system at Lalitpur without and with DG placement

The optimal amount of active power that can be injected into the distributed feeder was found to be 1951.796 kW, at pf 1 (i.e. DG from Solar PV) and at an optimal bus 5. The total active power loss is reduced to 43.9 kW (i.e. reduced by 62.5 %), reactive power to 35.667 kVar (i.e. by 62.58%), and all the voltage profiles were improved above 0.95 pu. The reactive power loss is reduced because it is dependent on the current and reactance of branches. After injection of solar PV to grid current will be reduced. The voltage profile lied within the limit in all the buses and is shown in Fig. 3.

The optimum number of houses feasible to inject power from 1 kWp rooftop solar PV at bus number 5 is 1950. The number of houses that can inject power from 1 kWp solar PV if selected at only one bus at a time is shown in Fig. 4 and it also shows the respective active power loss.

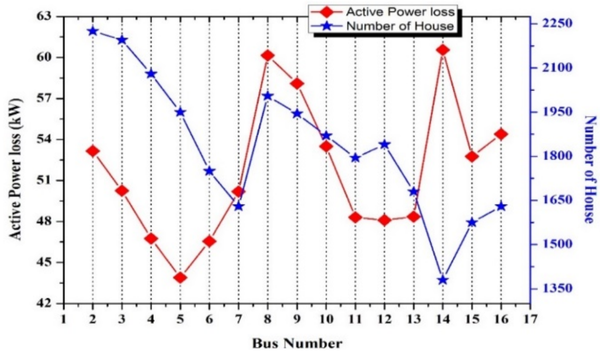

Fig. 4 Number of houses that can inject power from rooftop solar at the specific bus with active power loss at each bus in Lalitpur 16 bus DS

3.2. Performance analysis of solar PV

The major causes of effects on the performance of solar PV are shading, dust, and wind velocity. In this section, the simulation of 1 kWp solar PV at the rooftop was done using PVsyst with a consideration that all these aspects do not affect the performance. The simulation was done with consideration of grid-tie inverter to study the performance at each house at the site. The simulation result shows that normalized average production per day per kWp is around 4.24 kWh with an array loss of 1.13 kWh/kWp/day and an average system loss to be 0.35 kWh/kWp. The system production throughout the year was found to be 1547 kWh/year.

The monthly average energy that can be injected into the grid is shown in Fig. 5. In June, July, August, and September, the energy supplied to the grid is around 100 units. The energy supplied during these months is below average because the available irradiance is below the standard test condition (STC) and the temperature is above STC. Whereas, on the rest of the months the energy supplied to the grid is above the average energy supplied to the grid (i.e. 130 units) monthly.

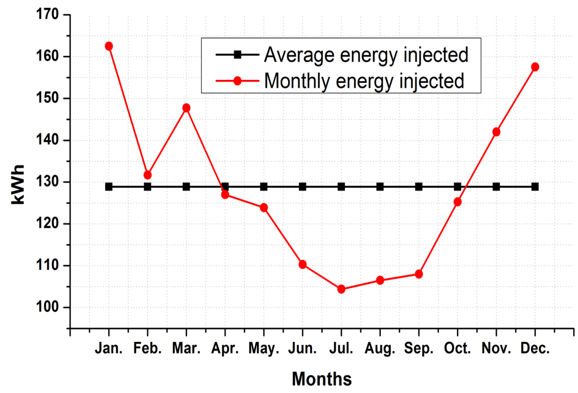

Fig. 5 Monthly actual energy and average energy injection to grid from rooftop solar PV by each house

Table 1 shows the performance factors which include array yield, reference system yield, system yield factor, and capacity factor.

Table 1 Performance factors of solar PV

S.N.	Performance factors (Unit)	Value
1.	Y_A (kWh/kWp/day)	4.59
2.	Y_r (kWh/m².day)	5.72
3.	Y_f (kWh/kWp/day)	4.24
4.	CF	0.177
5.	Performance ratio	0.74

The average yield (Y_A) of each of the residents who installed 1 kWp solar PV in Lalitpur is 4.59 kWh/kWp/day, which is a good result. Reference system yield (Y_r) is the amount of energy of solar radiation resources and orientation of PV array which is found to be 5.72 kWh/m^2.day. System yield factor (Y_f) can be used as insolation level of PV array and is 4.24 kWh/kWp/day and found to be performing well. The capacity factor is around 0.177 and is used for monetary values of the financial structure of the whole plant.

Fig. 6 shows the monthly efficiency of the panel and grid-tie inverter. The efficiency of the panel in April, May, June, July, and August is below 8% and significant in the other months. The efficiency falls on these months because of the fixed orientation of solar PV, decrease in irradiance, and rise of temperature. It can be improved by using the maximum power point tracking system.

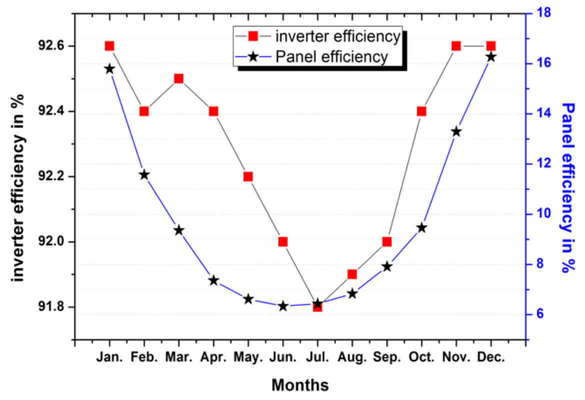

Fig. 6 Monthly Inverter efficiency and PV array efficiency

The efficiency of the inverter (which helps in the synchronization of DC energy to the grid) is between 94.5 % to 96% throughout the year. With this efficient system, the average energy injected into the grid is 130 units and this can be improved by using more efficient equipment which might be costly. The average performance ratio of installed solar PV array is 0.74 throughout the year. The performance ratio is above 70% every month which means that the losses due to panel degradation, temperature, soiling loss, inverter loss, system availability, and grid connection junction losses are about 24%. A ratio above 70% for every month indicates good performance.

4. Conclusion

The simulation of impact due to injection of power from PV array to the grid, performance analysis of rooftop solar PV using PVsyst, and shading simulation was performed. The main factor to be considered is the optimized number of households that wish to inject energy from 1 kWp solar PV as a residential consumer. The optimal number of houses that can be connected to each bus is shown. The most optimal bus is bus number 5 having a minimum active power loss and improved voltage profile. The voltages at each bus are above 0.95 pu and within the limit. The feasible number of houses that would like to connect to the grid at bus number 5 should not exceed 1950. If it exceeds, power loss increases, and the voltage limit may get violated. While moving to the performance analysis, all the factors are acceptable. In May, June, July, and August, the efficiency of the solar PV is less than 8%, but still, the performance ratio on these months is above 70%. These mentioned months had less efficiency of PV because the DC energy available is less. The overall performance of solar PV in injecting the energy from the sun to the grid can be regarded considerably good. Hence, the study can conclude that the integration of 1 kWp rooftop solar PV at residential consumers in urban areas of Lalitpur is acceptable with an optimum number of houses to be connected in optimum location and the installation areas should be shading free.

5. Limitation

The technical feasibility for connecting 1950 households in a single bus has not been studied for this work.

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