Abstract— Solar PV energy is one of the most promising renewable resources that use the abundant and free energy from the sun having clean, inexhaustible and environment-friendly cyclic operations. However, the intermittent nature of the output power of PV systems reduces their reliability in providing continuous power to customers. Solar PV energy can be used mainly in standalone (off-grid) and grid connected system. A stand alone solar PV cannot provide a continuous supply of energy due to seasonal and periodic variations. Therefore, in order to satisfy consumer load demand, grid connected PV energy systems that combine solar energy and other conventional conversion units are becoming more popular in recent years. But, the fluctuations in the PV output power with climatic conditions might lead to undesirable performance of the electric network in grid connected system.

The objective of this work to study the performance analysis of grid connected solar PV system. To accomplish this, the mathematical modeling of 1kWp grid connected system is carried out and the power profile is estimated using historical environmental data collected over a number of years at Kathmandu. Identified the possible operational problems that might arise in grid connected PV system and different strategies that can mitigate these problems are studied. In addition, the performance of the system is evaluated.

Index Terms— Standalone, off-grid, grid penetration, performance ratio, Maximum Power Point Tracking (MPPT), Total Harmonic Distortion (THD), power factor (PF).

I. INTRODUCTION

In grid connected PV system, the output from the PV system is connected to utility grid by means of PV grid tied inverter. Unlike off grid system, there is no need of batteries and charge controllers but the grid tied inverter should have special functioning capability such as anti-islanding, grid synchronization etc. Out of 67GWp PV installed globally, 80% is of the grid connection type. In Nepal, 680 kWp PV system delivering energy of 560kWh/day for water pumping and 1736kWh/day is injected to NEA grid is the first grid connection project in country. 1kWp grid connected PV system has been installed at CES/IOE to study the performance analysis of it and its effect on utility system.

The fluctuating behavior of PV output with environmental condition may degrade the power quality of inverter output which may cause to degrade the performance of utility and the consumer electrical appliances? So, to study the performance of PV grid connected system, 1kWp PV system is modeled using MATLAB/Simulink and detail study has been carried out in this work.

II. SYSTEM DESIGN

A. Modeling of solar cell and module

The short-circuit current (I_{sc}) from a cell is nearly proportional to the illumination, while the open-circuit voltage (V_{oc}) may drop only 10% with an 80% drop in illumination [1]. The important result of these two effects is that the power of a PV cell decreases when light intensity decreases and/or temperature increases. The amount of power generated by a PV cell depends on the operating voltage of the PV cell array. It’s V-I and V-P characteristic curves specify a unique operating point at which maximum possible power is delivered. The point at which the PV operates at highest efficiency is called the maximum power point (MPP). The light generated current (I_{pv}) is the function of solar irradiance and environmental temperature. The little impact has also been shown by the wind speed. Irradiance has direct relation while working temperature has inverse relation to the I_{pv}.

\[ I = I_{pv} - I_{0} \left( \exp \left( \frac{V + R_{s}I}{V_{oc} + a} \right) - 1 \right) - \frac{V + R_{s}I}{R_{p}} \]  

Where,

- \( I_{pv} \) and \( I_{0} \) are the PV and saturation currents of module,
- \( V_{r} = N_{r}kT/q \) is the thermal voltage of the array with \( N_{r} \) cells connected in series,
- \( R_{s} \) = equivalent series resistance and \( R_{p} \) = equivalent parallel resistance of the array of \( N_{r} \) cells in series.

The value of the diode constant ‘a’ may be arbitrarily chosen usually \( 1 \leq a \leq 1.5 \). If the array is composed of \( N_{p} \) parallel connections of cells then the saturation currents is given by \( I_{p}=I_{pvcell} \times N_{p} \) and module current is modified to \( I_{p}=I_{pvcell} \times N_{p} \).
The effect of solar irradiance and cell temperature on light generated current of solar PV is given by the Eq. 2 as follows [4]:

\[ I_{pv} = (I_{pv,n} + n \cdot K_i \cdot \Delta T) \frac{G}{G_n} \]  

\[ I_o = \frac{I_{sc,n} + K_i \cdot \Delta T}{\exp \left( \frac{V_{oc,n} + K_v \cdot \Delta T}{a \cdot V_t} \right) - 1} \]  

This modification aims to match the open-circuit voltages of the model with the experimental data for a very large range of temperatures. The ambient temperature sets the base temperature of the module and the irradiance predominantly sets the temperature raise of the module, which is about 0.028°C per W/m². The research work reported in [6] says that wind speed and ambient humidity slightly influence the module temperature whereas the wind direction influence is negligibly small. The mathematical equation determined by the reduction and analysis work performed on a long-term collected data and regression analysis:

\[ T_{module}(°C) = 0.943 \cdot T_{ambient} + 0.028 \cdot \text{Irradiance} - 1.528 \cdot \text{WindSpd} + 4.3 \]  

Eq. 4 is used to analyze the effect of ambient temperature and wind speed on the PV output. Also, the report says that humidity coefficients for the modules range from 0.089°C to
0.181°C per RH% and it has little or no influence on the temperature of the modules [6]. The mathematical modeling of PV cell has shown in Fig. 2.

B. Modeling of MPPT system algorithms

Maximum Power Point Tracker (MPPT) is used to operate the module at the peak power point so that the maximum power can be delivered to the load under varying temperature and irradiance conditions. A DC to DC converter serves the purpose of transferring maximum power from the solar PV module to the load by changing the duty cycle of it and load impedance as seen by the source is varied and matched at the point of the peak power with the source so as to transfer the maximum power.

Among various algorithms, Perturb and Observe (P&O) algorithm is used in this work for the MPP tracking. A slight perturbation is introduced to the system, due to this perturbation, the power of the module changes. If the power increases due to the perturbation then the perturbation is continued in that direction. After the peak power is reached the power at the next instant decreases and hence after that the perturbation reverses [7][8]. The Matlab/Simulink model has shown in Fig. 4.
C. Requirements of grid connection system

Power quality, protection coordination and grid synchronization are the major issues to be concern over the grid connection of solar PV system. Harmonics, voltage regulation, power factor, EMI and DC current injection are the main power quality issues that may cause adverse effects like additional heating, reduction of transmission system efficiency, overheating of distribution transformers, malfunctioning of electronic equipment etc. in grid connected system if not properly addressed. According to IEEE1547 standard, allowable current THD is 5% (Even harmonics are limited to 25% of the odd harmonic limits), 2% for voltage THD and 1% for individual voltage harmonics in Distributive Resource (DR) connected to area Electric Power System (EPS). DC current injection shall not be greater than 0.5% of the full rated output current at the point of DR connection as per IEEE standards.

The complete model for grid connection of 1kWp PV system has shown in figure 5.

III. DATA COLLECTION

The historical data of inclined irradiance (W/m²) collected over two years, in the interval of every five minutes, reported by SWERA, are used to estimate the profile of the output power of the PV system. The two year average temperature reported by weather station Kathmandu airport has been collected and calculated the average day temperature to analyze the effect of temperature on solar PV output. Also, the effect of wind speed on soar PV output has been analyzed by using the historical value of ten year average wind at speed above 50 meter from the surface of ground at Kathmandu, reported by NASA data.

IV. SIMULATION RESULTS

A. Output from array

The IV and PV curve from array has shown in Fig. 7 under the time varying input of irradiance and ambient temperature. The open circuit voltage of array was about 250V and short circuit current was 3.9A. It has found that increase in irradiance caused array current to increase while small reduction of array voltage but ambient temperature has reverse relation unlike irradiance. At very low irradiance, array voltage has dropped below the threshold voltage level for the inverter resulting highly distorted waveform and it needs to use undervoltage protection circuit for such cases.
perturbation of the algorithms. Upon the use of small perturbation, ripple was reduced but it took more time to track the operating point.

B. Power quality

It has found that current THD is 21.35% and fundamental or 1st harmonic component (50Hz) is 4.124Apeak (2.91Arms). The even harmonics are much less than the odd harmonics and they have severe impacts on power quality. Similarly, voltage signal contained 5.01% of THD with fundamental components of 312.8 Vpeak (221.18Vrms). The details of even and odd harmonics are shown in Table I. Since the harmonics present in the inverter output are higher than the IEEE 159 standard (below 5%), harmonic filter is used for suppression of harmonics. In this work, a passive LCL harmonic filter is used for the harmonics compensation techniques.

<table>
<thead>
<tr>
<th>Even harmonics %</th>
<th>h2</th>
<th>h4</th>
<th>h6</th>
<th>h8</th>
<th>h10</th>
<th>h12</th>
<th>h14</th>
<th>h16</th>
<th>h18</th>
<th>h20</th>
<th>DC component</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.35</td>
<td>0.42</td>
<td>0.28</td>
<td>0.71</td>
<td>0.30</td>
<td>0.45</td>
<td>0.20</td>
<td>0.28</td>
<td>0.06</td>
<td>0.33</td>
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<table>
<thead>
<tr>
<th>Odd harmonics %</th>
<th>h3</th>
<th>h5</th>
<th>h7</th>
<th>h9</th>
<th>h11</th>
<th>h13</th>
<th>h15</th>
<th>h17</th>
<th>h19</th>
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</tr>
</thead>
<tbody>
<tr>
<td>8.14</td>
<td>11.42</td>
<td>5.05</td>
<td>3.96</td>
<td>1.35</td>
<td>1.37</td>
<td>0.99</td>
<td>0.71</td>
<td>0.91</td>
<td>0.36</td>
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TABLE II: Harmonic orders and magnitudes of filtered current

<table>
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<tr>
<th>Even harmonics %</th>
<th>h2</th>
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<th>h6</th>
<th>h8</th>
<th>h10</th>
<th>h12</th>
<th>h14</th>
<th>h16</th>
<th>h18</th>
<th>h20</th>
<th>DC component</th>
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</thead>
<tbody>
<tr>
<td>0.22</td>
<td>0.02</td>
<td>0.06</td>
<td>0.04</td>
<td>0.01</td>
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<td>0.00</td>
<td>0.02</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Odd harmonics %</th>
<th>h3</th>
<th>h5</th>
<th>h7</th>
<th>h9</th>
<th>h11</th>
<th>h13</th>
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<tbody>
<tr>
<td>3.07</td>
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<td>0.12</td>
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<td>0.09</td>
<td>0.04</td>
<td>0.02</td>
<td>0.04</td>
<td>0.02</td>
<td>0.01</td>
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</tbody>
</table>

After employing harmonic compensation techniques, the current THD is maintained at 4.98% with the fundamental output of 4.048Apeak (2.86rms). The voltage THD is 0.12% with fundamental component of 312.8Vpeak. The orders of filtered harmonics are presented in Table I and II.
Ideally, the reactive power generated by the inverter should be zero i.e. the power factor is unity. But, because of the inductive and capacitive components used in the energy conversion and transmission system power factor is changed. Results show that the reactive power generated by the inverter is increased with the decrease in irradiance i.e. power factor decreased with decrease in irradiance.

C. Power outputs from the array and system efficiency

The system is simulated individually for the inputs of meteorological data collected over 12 month. The array energy was 1886.1 kWh/Year at STC but the array actually produced 1699.62kWh/year out of which 1523.69 kWh/year is injected to the grid and the performance ratio is 80.76%. The least energy is generated in January and August (4.09kWh/day) and total energy in this month is 126.66kWh/month. The highest energy is produced in October with 5.68kWh/day and total of 176.2kWh/month. The average inverter efficiency throughout the year ranged from 87% to 93%. The average grid penetration throughout the year varied from 95%, in June, to 99%, in February. Similarly, the overall performance ratio is 78% to 84 %. A thesis work done by A. Bhattrai 2012 shows that average final yield is 2.31kWh/day; array yield is 2.64 kWh/day under the average 4 hours of load shedding during day time at Kathmandu. Grid penetration is the ratio of energy injected to the grid to the energy available at inverter output and performance ratio is the power at inverter output to the energy fall to the PV array.
at constant load and it has found that for most fraction of day, the power factor is acceptable. Also, the current THD became lowest at peak day but voltage THD is highest and it slowly decreased on either side.

V. CONCLUSION

Grid tied inverters convert DC power to AC power with an efficiency of 90% or more most of the time. Inverters can even work to some extent when irradiance levels up to 200W/m², but performance starts to drop off dramatically when irradiance levels falls below it.

The use of MPPT system is of great value to the array output as it (P&O algorithm) optimizes the PV power output by 23% than without the use of MPPT system. The nonlinear devices used in the converter circuits are the great source of harmonics in the PV grid connected system. The harmonics generated in the PV power converting systems greatly vary with the solar irradiance. The odd harmonics have greater impacts on power quality than even harmonics as they have higher magnitude. The current THD is more sensitive on the fluctuation of solar irradiance than the respective voltage THD. Current THD greatly decreases with the increase in the solar irradiance while voltage THD slightly increases with increase in solar irradiance. Power factor varies linearly for values of solar irradiance lower than 200 W/m² and remains close to unity for higher solar irradiance values. In addition, reactive power injection increases at low irradiance.

REFERENCES


BIOGRAPHIES

Mr. Debendra Bahadur Raut is the postgraduate of Renewable Energy Engineering form Institute of Engineering (IOE) Pulchowk Campus, Nepal after graduated from Electronics and Communication Engineering. He is the Managing Director of Peaksun Engineering Solutions Pvt. Ltd. Kathmandu Nepal. He is also involving in academics as Lecturer at Acme Engineering College, Kathmandu Nepal.

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