A RESIDENTIAL MICRO-GRID IN AN UNRELIABLE GRID CONTEXT

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ABSTRACT: The electricity network in developing countries is often characterized by a weak stability of voltage and frequency, frequent accidental power cuts, high losses in the distribution network and regular planned load shedding schemes. All these issues prevent normal access to electricity by the population, inhibiting and impoverishing the whole country. One approach to overcoming these issues is to switch from the centralized paradigm of old power production schemes to a new decentralized generation of power. Needs and difficulties in developing countries are different compared to residential and SME in developed countries. Therefore, new inverters which are suitable in power range and settings for a decentralized residential PV system with backup are needed. In this project we explore the technical challenges to connecting small residential grid-connected (GC) PV systems with and without storage capabilities. The first five small photovoltaic residential systems (1.1kWp) were installed in the Kathmandu Valley in October 2012. Three locations reflecting the typical conditions of the electricity grid in Kathmandu were chosen. Load shedding and power cuts occur during 38.1% of the time (9.2 hrs/day and ranging from 6.7 to 12 hrs/day). In the reference location without load shedding, three PV systems produced an average of 1600 kWh/kWp annually. With load shedding, production was 44% lower. In the third location a residential microgrid with a 9.6kWh storage system generated 15% lower energy compared to the reference location but delivered energy 100% of the time.

Keywords: Small Grid-connected PV Systems, Grid Integration, Reliability, System Performance, Developing Countries, Micro-grid

1 INTRODUCTION

The availability of energy is a key element of any economy. Every civilization has developed around plentiful, readily available sources of renewable energy, be it wood, slaves, coal or oil. Our modern civilization, although dependent on fossil fuel for 78.4% of global energy consumption [1], uses electrical energy to manage most new economic activities, particularly in the area of housing (communication, lighting, cooling).

The expected lower availability of fossil fuels (oil, gas, coal) and of energy from traditional sources (wood) associated with population growth and the increase in secondary needs, has changed the use of renewable energy sources, favoring the use of electrical energy [1].

The versatility of electricity makes it an interesting vehicle for applications such as mobility (electric vehicles) and, in the Nordic countries, for heating by way of heat pumps.

Even now it is common to see small electric taxis circulating on the streets of Kathmandu.

However, the electricity network in developing countries is often characterized by a lack of stability of voltage and frequency, frequent accidental power cuts, high losses in the distribution network and regular planned load shedding schemes. Load shedding in Nepal is particularly high, ranging from 7 to 12 hrs per day (2014).

The rapid increase in energy demand cannot be met by new production facilities. Over the past five years, the domestic consumption of electricity has increased by 50% and domestic users by one million.

The production potential of hydropower in Nepal is extremely high [2], but the conditions of poverty in the country do not allow full use of its potential. The fulfillment of energy demand in the fiscal year 2013/2014 was only 4,631.51 GWh (78.4% of the estimated energy demand). 3,559.28 GWh (76.8%) was contributed by domestic generation. Domestic supply included 1,258.94 GWh (35.4%) from IPPs (Independent Power Producers), and the remaining 2,300.34 GWh (64.6%) was from NEA-owned power stations (Nepal Electricity Authority), with a share of 2,290.78 GWh from hydro and 9.56 GWh from thermal. 1,072.23 GWh (23.2%) was imported from India [2]. Technical (transformers, line losses, etc.) and non-technical losses (electricity pilferage, etc.) in the distribution lines reached 25%.

Nepal is characterized by a great deal of sunlight, with a long period of stable and predictable irradiation during the dry season, but the unstable network complicates the direct connection of a photovoltaic system. A storage system (UPS) is therefore essential to ensuring an optimum utilization of the energy fed into the grid.

Our research has explored the solutions to the connection of photovoltaic systems to the Nepalese public network, and has lead to the creation of two systems connected to the network, with and without storage, in two different locations in Kathmandu. Three additional GC PV installations have been realized and connected to a portion of the network which is not subject to constant daily load shedding.

Finally, the aim of this project was also to verify the potential impact of 100,000 roof-top, decentralized small (each system with a rated power output of 0.5 – 2 kW) solar PV grid-connected systems to support and strengthen the unreliable national electrical grid and to minimize the periods of load shedding.
2 APPROACH

A microgrid is an electrical system, within clearly defined electrical boundaries, which includes a group of interconnected loads and distributed generators, and which can be operated either in parallel with the utility grid or in "island" mode. In developing countries people usually live in extended families consisting of the immediate family living either nearby or in the same household, and with grandparents or other people. Therefore, we have called our grid-connected PV system a "residential microgrid", which provides energy for two families and a NGO office.

In the analysis and verification of PV systems connected to the electricity grid of Nepal, a comparison between the two topologies mentioned above (standard grid-connected, residential microgrid) was carried out with respect to a reference PV system connected to a stable power supply.

2.1 Design of the PV GC Systems and Micro-Grid

The two PV systems were designed with consideration given to the results of a feasibility study which had previously been carried out [3]. The energy needs of an upper-middle-class family amount to approximately 5 kWh / day. Under the climatic conditions of the Kathmandu valley, there is an annual average of 4.5-5.5 kWh / m2 of sunlight. A 1kWp energy yield of a plant corresponds to approximately 1700 kWh, given a ten-year average of sunlight.

The financial capacity of the upper middle class allows them to purchase both a photovoltaic system connected to a network of approximately 1kW and an energy storage system to address periods when the network is down.

2.2 Choice of Locations

Three locations reflecting the typical conditions of the electricity grid in Kathmandu were chosen. One location is the reference site, which is located near both a transformer and the distribution center and therefore experiences no power cuts [3].

2.3 Building of PV Systems

Local staff were employed for the construction of the plant [3]. All materials were sought within Nepal, at local prices. Skills and ways of working in the country were employed. Importing methodologies, either different from those of local operators or unknown to them, was avoided.

It was necessary only to purchase the data acquisition system abroad, while the programming was done by local staff.

The grid inverters and bidirectional battery inverters for the residential microgrid were purchased abroad.

The costs of the system mostly reflect the local costs. A cost optimization may be done in the future using existing inverters in Asia (e.g. China and India).

2.4 GC PV System with Storage

In the context of a power supply such as that of Nepal, a traditional system of connection to the network is limited by the high number of hours of load shedding, especially during the evening period. A storage system (UPS) permits optimum utilization of the energy fed into the grid by limiting any disruption caused by network downtime.

In the residential context in Nepal, the most common method to avoid running out of energy during the crucial hours of the evening is to charge a battery with a standard grid charger and consume the energy thus stored by using a low-cost unidirectional DC-AC inverter during the load shedding period.

However, the overall output of this system is low (<50%), the battery life is limited and the public network becomes even more overloaded.

The SME and businesses prefer to use a diesel generator, but in the past the supply of diesel in the country has not always been steady. In addition, the state subsidizes part of the importation of fuel, generating increasing losses to the state with the increase in consumption.

Currently, there are different types of connection to network storage. In our study, we have opted for a system with an AC connection of the PV generator on an AC bus shared with the batteries and electrical loads (see Figure 1).

![Figure 1: Schematic bloc of a residential microgrid with AC bus.](image)

In systems where usage is delayed with respect to production, a direct connection on the DC bus of the photovoltaic generator is preferable, so as to avoid a double conversion (DC-AC and AC-DC during the charge phase, and DC-AC during the usage phase). In our case, however, we want to compare this with a system of direct connection to the network in urban areas, where the PV system, after the period of battery life, provides energy to support the public network.

3 RELIABILITY OF THE ELECTRICAL GRID

The grid is weak, unable to meet the load demand and experiences frequent accidental power cuts in addition to the regular, planned seasonal load shedding schemes. Frequency is not stable. Voltages at POI do not comply with national standard grid regulations.

Moreover, the population uses inefficient systems consisting of battery-charger-inverter to overcome periods without mains power. SMEs and householders often use diesel gensets, thereby increasing the country's dependence on energy from abroad.

The current unreliability of the electricity grid and the growing demands of users, together with the high level of losses in the electricity distribution network, are a challenge for the whole country, both socially and technically. The connection of PV grid-connected inverters is possible only by appropriately changing the inverter’s setting parameters according to the local situation. The monitoring data in the three localities have
helped to define the most appropriate parameters to support the electric grid.

3.1 Nepal Power Grid and Load Shedding

The annual increase in energy demand has not been offset by the increase in global national production. In recent years, the peak load shedding during the dry season, however, was relatively low and did not exceed 12 hours a day. During the rainy season (summer) in the last three years load shedding has increased and has never dropped below seven hours a day of power cuts (Figure 2).

![Figure 2: Average monthly load shedding in hours per day, from 2010 to 2014.](image)

The daily breaks occur at all hours of the day. The duration of interruptions varies daily and is divided into two distinct periods.

![Figure 3: Duration of the outages during one year in P1 and P2. Red indicates that the grid is off.](image)

These annual blackouts in the P1 location (CES) correspond to 38.1% of the time period (9.2 hours per day and ranging from 6.7 to 12 hrs/day), Figure 3, whereas only 33 short power cuts occurred in the reference location P2.

3.2 Frequency Stability

Figure 4 shows the frequency evolution during a one-year period. The lines of NEA limits, the standard limits of the national grid code, are in green. The lines of the initial settings of the inverter (51.25 – 48.75Hz) are in red.

![Figure 4: Frequency variation at NEA P2 location (one year).](image)

Frequency doesn’t reflect an overcharge of the grid, and during several months this was either over or under 50Hz. In order to start the reconnection procedure, the inverter settings for upper and lower frequency limits for the reconnection (normally at 50 ± 0.2 Hz) must be adapted to 51.25 – 48.75Hz limits. In the five GC PV installations, the upper and lower frequency limits for the reconnection and the upper and lower frequency total limits are the same.

3.3 Voltage Stability at the Reference Location P2

Voltage at POI depends on the design of the distribution grid and on loads. In the P2 location, the reference location without load-shedding, the voltage is stable during the entire period of observation (Figure 5).

![Figure 5: Voltage at plant 2 – NEA – reference plants.](image)

Voltages are within standard NEA Grid Code limits, but lower than expected. Similar results have been found at the P1 location, where the voltages are higher and near standard 230Vac.

![Figure 6: Voltage at plant 3 – Imadol, Lalitpur.](image)
Critical situations have been found on the outskirts of the urban area in Imadol, the Lalitpur district, where the measurements in P3 (Figure 6) show voltages under 170V and ranging from 130V up to 210V during the dry season (winter). The settings of the inverters have been chosen for their possible lower limit (170V) in order to sustain the grid.

Figure 7 shows the combined effect of the loads during morning and evening and the generated solar energy injected into the grid. Voltage drops in the early morning before increasing during the hours with more radiation and after charging the batteries. Despite peak irradiance at noon, voltages are still lower than standard limits.

Figure 7: Hourly voltage at P3, RiDS-Nepal office, in green: standard limit, in red: setting of the inverter.

4 LOSSES AND PR

In the reference location (P2) without load shedding, three PV systems produced 1600 kWh/kWp on average annually. In the grid-connected PV system without storage in the middle of the town (P1) production was 44% lower. The residential microgrid with a 9.6kWh storage system, on the third site (P3), generated 15% lower energy compared to reference systems, but supplied households for 100% of the time.

4.1 Irradiation in Kathmandu

Measured monthly irradiation was lower than expected, in particular during the winter period. The ten-year average horizontal irradiation showed a mean value of Ho \(\equiv 1950\) kWh/m²/y (Meteonorm) and Ho \(\equiv 1825-2007\) kWh/m²/y (NREL and DSR with Meteosat). However, the solar irradiation measured during the winter of 2013-2014 was much lower. A lack of maintenance and daily cleaning of the sensors influenced the results, which are not reliable due to the accumulation of dirt and dust.

The measured tilted irradiation was \(Hi = 1761\) kWh/m²/y (from March 2013 to February 2014). The measured data differ by -20% from the ten-year average values.

Figure 8: Monthly irradiation (kWh/m²) and final yields AC and DC (kWh/kWp) of inverter 2 in P2 (NEA).

4.1 Undervoltage Losses

In the winter period, during the short days of the year, the morning and evening consumption increases while the dry season causes disruption in the production of hydropower. In this case the voltage at the POI varies considerably and, on the outskirts of densely populated areas, the minimum voltages force the inverter to disconnect from the grid.

Figure 9 shows the cumulative distribution of the voltages in five GC PV systems during the winter period. In P3, voltage was less than the lower limit of the inverter 37% of the time, while in P1 and P2 voltages were within the NEA standard limits for 100% of the time.

Figure 9: Cumulative distribution of the voltage in five GC PV systems during the winter period.

Figure 10: Cumulative distribution of the voltage in five GC PV systems during one year.
On average, the annual under-voltages were less than the lower limit of the inverter for 8.4% of the time (see Figure 10).

4.2 Soiling Losses

Many studies have proven that dust has a significant influence on the performance of PV systems. Dust accumulation on the surface of PV modules causes a decrease in performance. Wind speed, air temperature, and probably humidity all play a role in how dust will accumulate on the PV generator.

Routine maintenance should be performed periodically, including an inspection of the array modules to prevent dust accumulation on their surfaces. When this was not done, a decrease in performance was observed after several months.

Cleaning of the surface of the modules has shown a recovery of 48.1% of the power (Figure 11). As a result, a new cleaning procedure was introduced into the routine maintenance.

4.3 Final Yield and PR in Kathmandu

The annual production was lower than expected, in particular because of accumulated dirt, but also due to lower yearly irradiation. Despite this situation, in the reference location without load shedding, three PV systems produced 1,600 kWh/kWp on average annually.

The photovoltaic GC system in P1 produced 44% less energy during the same period, where the monthly energy production is strongly dependent on the level of load shedding and the time of the programmed interruption (see Figure 12).

Meanwhile, in the third location, a residential microgrid with a 9.6kWh storage system, 15% lower energy was generated compared to the reference location, although energy was delivered to the householders 100% of the time.

On average, a 1 kW grid-connected system without load shedding (the ideal situation) will produce at least 4.4 kWh/kW/day, meeting the daily energy demand of the upper-middle-class households.

6 IMPACT OF A 100,000 ROOF-TOP PROGRAM

The annual peak power demand of the Integrated Nepal Power System (INPS) in the fiscal year 2013/14 is estimated to be 1,201 MW, but only 791 MW of power were actually supplied. It is estimated that 410 MW of power were shed. The estimated annual peak power demand of the INPS registered a growth rate of 9.7% [3].

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Figure 12: Monthly PR during one year in the three locations.

Figure 13: Example of load profile in Nepal (Jan 13, 2012).

Figure 13 shows an example of a load profile in January 13, 2012 [3] where estimated peak demand is displayed in blue above the actual production (light blue). Peak demand occurs in the morning and evening, but not at noon when the sun is shining.
In Kathmandu, a grid-connected system of 1kW would have an average power peak of 0.65kW and a maximum peak power reaching 1 kW on a clear day (Figure 14).

If 4% of the domestic consumers (actual domestic consumers: 2.56 million), corresponding to 100,000 households, could install a 1kWp GC system, 100 MW of PV power generation could result in a very short time.

A residential microgrid would have a significant impact on supporting and strengthening an extremely unstable grid and would decrease load shedding hours.

This would not only inject energy into the grid, but also avoid unnecessary consumption for the charging of batteries.

The connection of the five small plants to the grid was possible only for the purposes of research, and so far there have been no incentive mechanisms or regulations to permit such placement on the network. In the course of 2014, however, thanks to the five demonstration plants, the political situation has changed. Currently, there is no Feed-in-Tariff grant in Nepal such as has been experienced in Europe and in other countries. However, in July 2014, the Finance Minister of Nepal announced the possibility of feed-in energy from small residential installations.

More recently, AEPC (Alternative Energy Promotion Centre, a government organization) announced a subsidy of 400 €/kWp (at 125NPR/€) for grid-connected systems ranging from 500W up to 2,000Wp. Moreover, net-metering was introduced (10-12 NPR/kWh) at the same time.

REFERENCES


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