Design and Analysis of an AC Coupled Photovoltaic System for an Off-grid Community in Chittagong Hill Tracts

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***Abstract*—This paper presents the design of an AC-coupled off-grid photovoltaic (PV) system for a remote village in the Chittagong Hill Tracts of Bangladesh which has no access to national utility grid. A field survey was conducted to collect load demand data of the population for designing an optimal PV system architecture to serve that community. The proposed system consists of 18 kW PV arrays, two 6 kW grid-tied inverters, a 6 kW battery inverter and a 19.2 kWh nominal capacity battery bank. Further, the technical feasibility of the system was evaluated using HOMER (Hybrid Optimization Model for Electric Renewable) Pro software. The analytical results indicate that the proposed AC-coupled stand-alone solar system can meet a load demand of 46.58 kWh at daytime and 7.02 kWh at night in that village. Currently, the infrastructure of proposed PV plant as well as the transmission and distribution network are being developed at the selected site. Moreover, insights into the benefits of AC-coupling over DC-coupling for large off-grid systems in remote hilly areas are provided in the paper.**

***Index Terms*—Photovoltaic System, AC-coupled Off-grid Solar, HOMER Pro, Small Battery Storage, Hilly Residential Area**

I. Introduction

Bangladesh has the world's tenth highest population density with 2.11% of the Earth's inhabitants living there [1]. With the rapid growth of population, the electricity demand of the country is increasing at a rate of 10% per annum but the generation rate is not enhancing at such a rate [2]. As of 2017, only 62% of total and 51% of the rural population are connected to the national grid in Bangladesh [3]. Notably, until now, the majority of the 1.6 million inhabitants in the Chittagong Hill Tracts have no access to grid electricity due to remoteness. Although very recently, solar home systems have been introduced there, the electricity generation is far from sufficient to meet the ever-growing load demand. Hence, there is a dire need for establishing off-grid solar-powered plants to electrify these hilly areas [4].

In the last century, off-grid photovoltaic (PV) plants were mainly based on conventional DC coupling. Since the early 2000s, AC coupling has become popular for designing larger and more efficient PV systems [5]. Such systems can supply electricity to conventional AC loads. It is worth noting that depending on the application and availability, AC coupled off-grid systems can be easily expanded with additional renewable and conventional energy sources such as hydro, wind, diesel generators, etc. owing to their flexible architecture. Consequently, for retrofits, the installation of AC-coupled solar systems require less labor and time as compared to DC-coupled systems which results in a lower upfront cost. To be specific, DC-coupled configuration

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becomes quite expensive for systems above 5kW as multiple higher voltage solar charge controllers are required. Moreover, the wiring requirements of DC-coupled systems are much larger than AC-coupled ones because of the lower voltage of DC solar strings. Thus, the wire cost can be significantly reduced by employing AC-coupled systems if the solar panels need to be installed far away from the battery bank and distribution system. Therefore, for the non-electrified rural areas in developing and industrialized countries, AC-coupled systems are more suitable as compared to the DC-coupled ones [5].

In this study, we have designed an AC-coupled off-grid PV system for a remote village named Shakhoy Para at Bandarban in the Chittagong Hill Tracts, Bangladesh. Prior to designing, we have conducted a systematic survey in the selected site to collect reliable data regarding the load-demand with a view to designing an optimized system. Finally, the technical feasibility of the proposed PV system has been extensively analyzed by HOMER (Hybrid Optimization Model for Electric Renewable) Pro software simulation [6].

II. Proposed AC Coupled Off-Grid Photovoltaic System

A. Solar Irradiation and Clearness Index

In order to design the most effective and optimal PV system for a specific location, precisely measured data of solar irradiance and clearness of the atmosphere for that location should be taken in due consideration. Therefore, we have collected the Global Horizontal Irradiance (GHI) and clearness index data for our target region (Shakhoy Para, Bandarban, Bangladesh, latitude 22°02'50.7" North and longitude 92°13'26.6" East) from Nasa Surface meteorology and Solar Energy database using HOMER Pro software. The employed data are the monthly averaged values over 22 years of period (July 1983-June 2005) and hence, can be considered reliable. Notably, GHI denotes the total amount of solar radiation striking the horizontal surface on the earth which is the sum of direct normal irradiance, diffuse irradiance, and ground-reflected radiation [7, 8]. In addition to this, the clearness index indicates the fraction of the solar radiation striking the top of the atmosphere that makes it through the atmosphere to strike the Earth's surface [8]. Fig. 1 demonstrates the monthly average GHI and clearness index of Shakhoy Para, Bandarban. As can be seen, the GHI value is the maximum in April, whereas the clearness index attains its highest value in March. Typically, March and April are months with the most sunshine in Bandarban. From Fig. 1, we can estimate that the chosen site attains average daily GHI of $\sim$ 4.72 kWh/m^2/day which makes it a suitable place for installing solar-powered system.

B. Electrical Load Profile

Our selected village, Shakhoy Para consists of fifty-six residential houses, nineteen shops, a mosque, a temple, a pagoda, a church, a school and a community clinic. Currently, this remote village does not have access to national power grid and is not yet under the rural electrification scheme. Very recently, the rural people have started using solar home systems in a limited scale. Therefore, to gain a clear insight into their electricity demand, we have collected detailed information by conducting field survey. Our questionnaire mainly focused on three cases i.e. Case I: What is the current electricity consumption? Case II: What are their essential demands which they want to be fulfilled within one year? and Case III: What are their expectations for the near future (3-5 years)?

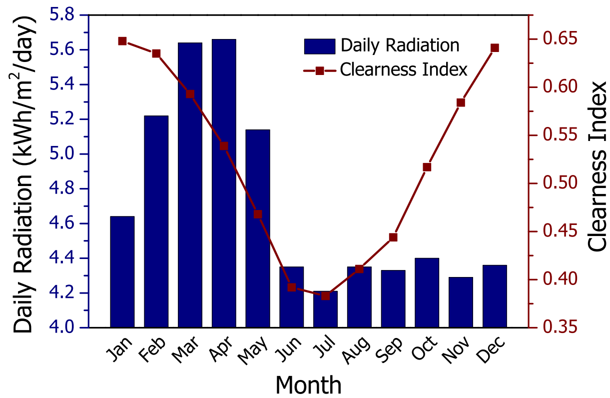

Fig. 1. Monthly average Global Horizontal Irradiation (GHI) per day and clearness index at Shakhoy Para, Bandarban, Bangladesh (latitude 22°02'50.7" North and longitude 92°13'26.6" East).

Fig. 2 shows the load profiles of the village at summer for the aforementioned three cases based on the survey data. The values of daily peak demand, daytime energy demand and total daily energy requirement for all three cases are provided in Table I. It should be noted that we have designed our AC-coupled off-grid system considering the load profile of case II. As can be seen from the Table I, the daytime energy demand for this case is 46.58 kWh and the daily peak demand is

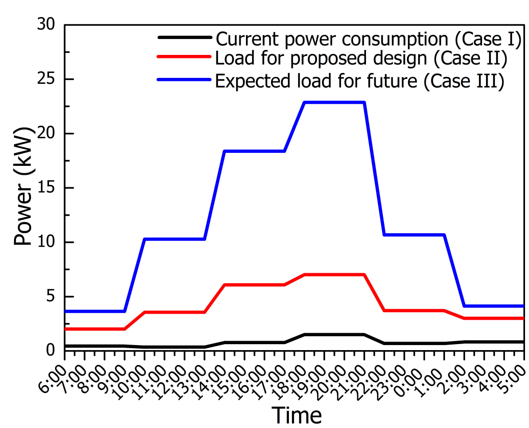

Fig. 2. Daily load profiles throughout the year for three cases.

TABLE I
ENERGY DEMAND IN THE LOCALITY FOR THREE CASES

Case	Daily peak demand (kW)	Daytime energy demand (kWh)	Total daily energy demand (kWh)
Current power consumption (Case I)	1.50	6.21	18.33
Load for proposed design (Case II)	7.02	46.58	101.48
Expected load for future (Case III)	22.86	129.15	279.79

7.02 kW. Our proposed design will meet the daytime energy demand (46.58 kWh from 6:00 up to 18:00) and can supply electricity from 18:00 to 19:00 in the evening (7.02 kWh). Notably, we intend to supply single-phase AC electric power.

C. System Architecture and Design Considerations

Fig. 3 presents the schematic diagram of our proposed AC-coupled off-grid PV system. The system architecture involves a PV array, a single-phase off-grid inverter, two single-phase grid-tied inverters and a storage battery bank. A brief description of each of the major components of our system is provided below.

1) Photovoltaic (PV) Array: The PV array is composed of 47 monocrystalline PV modules. The dimension and weight of each module are 78.27 x 39.57 x 1.57 in^3 and 49.82 lb, respectively. The rated maximum power output for each module is 390 Watts implying that we can get maximum 18.3 kW of instantaneous power output from the PV array in the sunniest day of the year.

2) Single-phase Off-grid/Battery Inverter: The rated power of the single-phase off-grid/battery inverter is 6 kW. This is a bidirectional inverter which will form the reference grid of the PV system. The proposed design will be implemented using SMA Sunny Island 8.0H battery inverter.

3) Single-phase grid-tied/PV Inverter: The power output of each single phase grid-tied/PV inverters is rated at 6 kW. In practice, two SMA Sunny Boy-6.0 PV inverters will be employed to develop the system.

4) Battery Bank: The proposed system includes a battery bank which consists of eight 200 Ah tubular plate lead-acid batteries producing a fully charged output voltage of 12 volts. Therefore, in total, a maximum of 19.2 kWh energy can be stored in the battery bank.

It should be noted that a number of principles have been taken in consideration while designing the system. For instance, the total nominal power of grid-tied inverters can not be more than double the total nominal AC power of the battery inverter. The lead-acid battery capacity per installed kWp of the PV array must be at least 100 Ah. Further, during installation, solar panels need to be connected in series (string) since the voltage window of grid-tied inverter is between 300 to 500 volts. It is noteworthy that the rated power of the grid-tied inverters will result in the nominal PV system power.

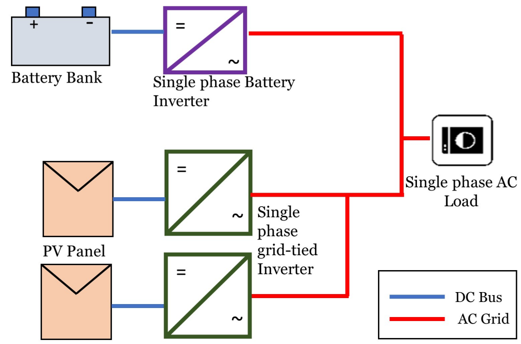

Fig. 3. Schematic of proposed AC coupled off-grid photovoltaic system.

D. System Operation

In our proposed system, the PV Array will produce DC current from solar energy. As a voltage source, the battery inverter will form the stand-alone AC grid of the off-grid system and at the same time will regulate the voltage and frequency in the AC grid [9]. Both single-phase AC electrical loads and energy generators i.e. grid-tied inverters will be connected directly to the AC grid. Further, the grid-tied inverters will directly convert the DC current produced by the PV array into grid-compliant AC current and feed this into the AC grid as a current source and thus will supply the electrical loads [10, 11].

The battery inverter will also regulate the balance between the energy fed in and energy used and will feature a management system that will manage the battery, grid-tied inverters and loads. If there is excess energy available (e.g. high solar irradiation and low consumption), the battery inverter will redirect energy from the AC grid and will use this to charge the battery. On the other hand, if there is insufficient energy available (low or no solar irradiation and high consumption), the battery inverter will supply the AC grid with energy from the batteries. The battery inverter will automatically check the availability of the AC grid and system components [12]. Therefore, additional control- and monitoring units will not be required. This will simplify system operation and reduce capital expenditure [12].

III. SIMULATION BY HOMER PRO SOFTWARE

Fig. 4 demonstrates the PV system model which has been simulated by HOMER Pro software for feasibility analysis. As can be noticed, the simulation model does not exactly match our proposed system architecture. This is due to the fact that although HOMER Pro can provide detailed economic analyses, it does not allow much flexibility in defining system architecture [13]. To be specific, our proposed AC-coupled off-grid system involves two grid-tied inverters and a battery inverter connected with battery bank. However, two different

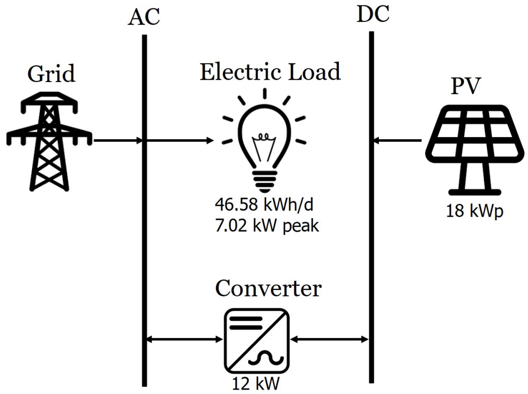

Fig. 4. Schematic diagram of PV system model as simulated by HOMER Pro software.

types of inverters are not allowed in a single system in HOMER Pro. Therefore, we have developed a simplified simulation model which can effectively perform the same operation as our proposed design. It can be seen in Fig. 4 that the model consists of 18 kWp solar panel, a 12 kW grid-tied inverter having 95% efficiency, electric load corresponding to the local demand and a grid. Here, the grid is serving the purpose of the battery inverter along with the battery bank. As was mentioned earlier, the battery inverter will create a reference grid for the grid-tied inverter and regulate the frequency and power whereas the battery bank will act as a backup. Hence, to perform simulation, we have replaced these two components i.e. battery inverter and battery by the grid.

IV. Results and Discussion

Fig. 5 shows the power generated by 18 kWp PV array, AC primary load profile and power purchased from grid at 6:00 to 19:00 of two typical sunny days in March and April which has been obtained by HOMER Pro simulation. As mentioned earlier, the off-grid and battery bank of our proposed design is modeled by an AC grid during simulation. Therefore, the grid purchases in the simulation can be considered as the power output from the battery bank via battery inverter in the actual design. The green patterned area in Fig. 5 indicates the excess energy generated by the PV array throughout the day. For the sunny day in March [Fig. 5(a)], integrating the green patterned area, we have found that the employed 18 kWp PV array can generate about 69.92 kWh of excess energy than the demand. Therefore, during high solar irradiation and low consumption, the excess energy will be stored in the 19.2 kWh battery bank. If the battery is fully charged, the grid-tied inverter will not pull the excess energy by adjusting the output voltage of PV modules. Later in evening, when the PV generation will be less than the demand, the battery bank will supply the necessary load. The blue patterned area represents the energy required from the battery bank at 6:00 to 19:00 which has been calculated to be 18.85 kWh by integration in Fig. 5(a). Likewise, for the sunny day in April as shown in Fig. 5(b), the excess generation has been calculated as 44.06 kWh whereas

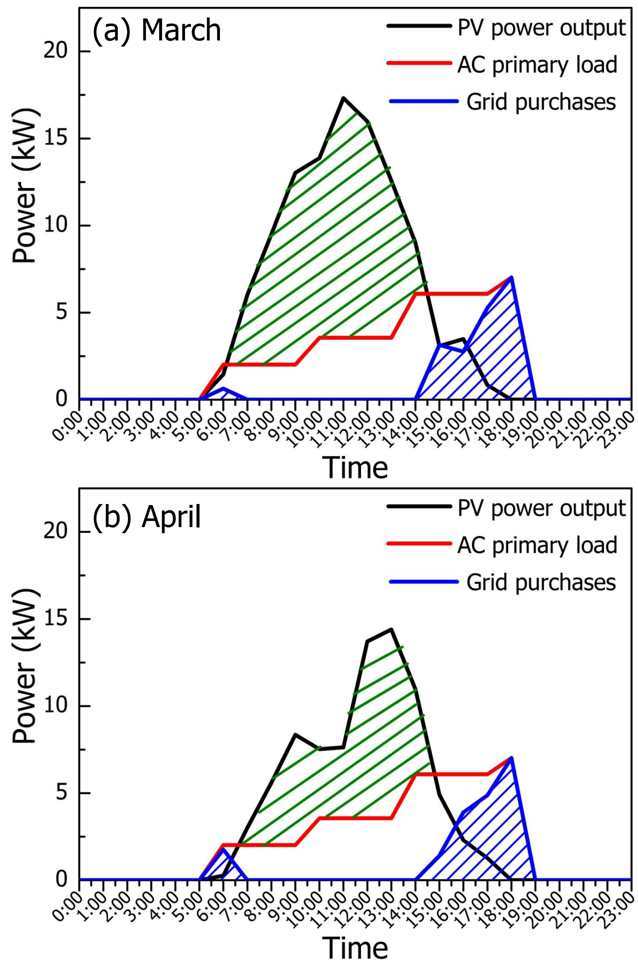

Fig. 5. HOMER Pro simulation results. Power output from PV array, AC primary load and grid purchases at 6:00 to 19:00 in a typical sunny day of (a) March and (b) April.

the energy required from the battery bank is 18.96 kWh. Since our battery bank has a storage capacity of 19.2 kWh, it can be concluded that the proposed AC-coupled off-grid system will be able to supply the load demand uninterruptedly at daytime and one hour at night.

V. Conclusion

An AC-coupled off-grid photovoltaic system has been designed for a remote off-grid village in the Chittagong Hill Tracts of Bangladesh. We have performed a technical feasibility analysis of the proposed system using HOMER Pro software and inferred that our system is capable of meeting the entire daytime load demand of 46.584 kWh and can provide required 7.02 kWh electrical energy at the night. In this system, an artificial AC grid is created using a battery inverter connected with battery. Two single-phase grid-tied inverters have been connected to the AC grid which will convert the solar power directly to AC current and supply to the single-phase AC load. Our proposed system has a number of significant advantages over the traditional DC-coupled off-grid system such as smaller storage battery bank, higher conversion efficiency and greater flexibility for expansion. The PV system along with the transmission and distribution network is currently under construction to serve the users. In the second phase, we would combine additional solar panels, hydro storage and water turbine to generate and supply electricity during night. This would enable us to replace the battery all-together and run the system for years without any major replacements and associated costs.

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References

[1] "World Population Prospects- Population Division-United Nations", Population.un.org, 2020. [Online]. Available: https://population.un.org/wpp/Download/Standard/Population/. [Accessed: 07- Sep- 2020].

[2] M. Islam, S. Shahir, T. Uddin and A. Saifullah, "Current energy scenario and future prospect of renewable energy in Bangladesh", Renew. Sust. Energ. Rev., vol. 39, pp. 1074-1088, 2014.

[3] B. Das, N. Hoque, S. Mandal, T. Pal and M. Raihan, "A techno-economic feasibility of a stand-alone hybrid power generation for remote area application in Bangladesh", Energy, vol. 134, pp. 775-788, 2017.

[4] J. Alam, M. Islam, R. Sharmin, M. Iqbal, M. Chowduray and G. Munna, "Impact assessment due to rural electrification in hill tract of Bangladesh for sustainable development", Int. J. Environ. Sci. Te., vol. 3, no. 4, pp. 391-402, 2006.

[5] Jorge E. Solorzano, and M. Á. Egido, "Simulation of AC , DC and ACDC coupled hybrid mini-grids In search of the most efficient system", 2012.

[6] S. Bhattacharyya, "Mini-grid based electrification in Bangladesh: Technical configuration and business analysis", Renew. Energy, vol. 75, pp. 745-761, 2015.

[7] S. Qazi, "Solar Thermal Electricity and Solar Insolation", Standalone Photovoltaic (PV) Systems for Disaster Relief and Remote Areas, pp. 203-237, 2017.

[8] J. Brownson, "Measure and Estimation of the Solar Resource", Solar Energy Conversion Systems, pp. 199-235, 2014.

[9] I. Serban, C. Marinescu, "A solution for frequency control in islanded three-phase micro-grids supplied by Renewable Energy Sources", Optimization of Electrical and Electronic Equipment 2008. OPTIM 2008. 11th International Conference on, pp. 327-332, 2008.

[10] P. Strauss and A. Engler, "AC coupled PV hybrid systems and microgrids-state of the art and future trends," 3rd World Conference onPhotovoltaic Energy Conversion, 2003. Proceedings of, Osaka, 2003, pp. 2129-2134 Vol.3.

[11] G. Cramer, M. Ibrahim and W. Kleinkauf, "PV system technologies", Refocus, vol. 5, no. 1, pp. 38-42, 2004.

[12] Ritu Raj Shrivastwa, Ahmad Hably, Kaouthar Melizi, Seddik Bacha, "Understanding Microgrids and Their Future Trends", Industrial Technology (ICIT) 2019 IEEE International Conference on, pp. 1723-1728, 2019.

[13] T. Lambert, P. Gilman, P. Lilienthal, "Micropower system modeling with HOMER", Integration of alternative sources of energy, 1(1), pp. 379-85, 2006.