Performance of a Grid-Interactive Rooftop Photovoltaic System with Battery Storage

S. Bhattacharjee, D. Debbarma, S. Sharma, and A. Das

Abstract— In North East India, there is severe power shortage and associated power quality problems; the quality of grid supply in most of the places is characterized by large voltage and frequency fluctuations, scheduled and unscheduled power cuts and load restrictions. Load shedding in many cities in North East India due to power shortage and faults is a major problem for which there is no immediate remedy in the near future since the gap between the power demand and supply is increasing every year. This led to rapid usage of stand-by petrol or diesel generator sets and conventional battery inverter sets in both urban and rural areas. Shopkeepers, house owners and offices commonly use 1-5 kW fuel generators when utility exercises load shedding. But this region is rich in sun shine and solar energy is available all over the year at free of cost. The paper analyses the performance of grid-interactive photovoltaic system with storage facility for this region. The system is installed at Tripura University campus. Online monitoring is carried out and real time data have been collected to study the feasibility of grid-interactive PV system penetration in this region particularly for the state Tripura. This paper presents the response of the various components of the system with available solar energy input.

Keywords— Grid-interactive System, Hybrid Inverter, Solar Resource, Battery Storage.

I. Introduction

ENERGY is vital for the progress of a nation and it has to be conserved in a most efficient manner. Among the nonconventional energy sources, India has made notable progress in utilizing wind energy. However, solar-based energy, the other potential and abundantly available resource, is yet to take off in the country. The solar photovoltaic energy is of the most decentralized nature among all the sources of energy in the world and harnessing power from solar energy is solely pollution free.

India receives about 300 clear sunny days in a year. This is equal to over 5000 trillion kwh/year, which is far more than the total energy consumption of the country in a year. The daily average solar energy incident over India varies from 4-7 KWh/m^2, depending upon location [1].

In spite of sufficient power potential in Tripura and other parts of N-E India, the region ranks lowest in terms of per capita energy consumption (113.7 KWh/head /year.) [2]. Setting up of conventional power plants in this region has to face a lot of difficulties due to the factor like inadequate infrastructure facilities, lack of communication facilities, difficult geographical conditions, dearth of skilled labour etc. By virtue of physical location, provision of grid electricity is neither technically feasible nor commercially viable [3]. The costs to install and service the distribution lines are considerably high for remote areas. Also there will be a substantial increase in transmission line losses in addition to poor power supply reliability. In most of the sites, extension of utility grid lines experiences a number of problems such as high capital investment, high lead time, low load factor, poor voltage regulation and frequent power supply interruptions.

Thus solar photovoltaic are one of the few options to produce electricity in this region with no emission of harmful gases and noise. Urban areas have unique and significant potential to exploit PV electricity because they not only have a focused and large energy demand, but also a physical infrastructure that can support localized power generation. The versatility and modularity of PV systems make it easy to integrate into the building.

II. System Operation

The single phase solar mains hybrid inverter system utilises a bi-directional inverter to supply conditioned power to a local load and operates as an on-line UPS. The inverter operates in parallel with the grid supply with the power to the local load supplied from the solar input via the inverter. Any excess renewable energy will be exported into the grid. In the event when sufficient renewable energy is not available to meet the local load the grid will make up the shortfall. Provided the local load is not greater than the capacity of the grid, battery charging will automatically occur from the grid to maintain the battery bank at its float voltage. In the event that the grid voltage or frequency moves out of its operating range, the grid will be disconnected and the load is supplied directly from the inverter / battery with no interruption to the power fed to the load [4]-[5].

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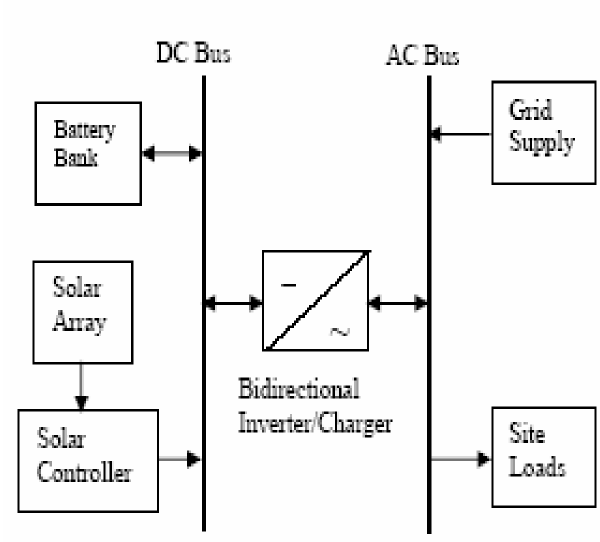

Fig. 1 System Block Diagram

A. Solar PV Panel

Make: Tata BP Solar India Ltd.
Model: TBP 1275 M
Power = 74 Watts minimum at 16.4 V
Data at STC (Standard Test Condition) 25^0C and 100 mW/cm^2
Total Max^m Power Output from PV Array =1.5 KW

Fig.2 Solar Array of the System under Study

B. Inverter

The product incorporates integrated Supervisory Control and Data Acquisition (SCADA) facilities. The use of a local operator interface with numerical keypad and LCD enables the viewing of instantaneous parameter metering, changing of operating modes and the review of system logged events. In addition, the more specific needs of station monitoring and remote communications can be accessed by using the remote system access software.

The overall system consists of up to five main sections as described below:

System Control Module (SCM): This single card contains a data acquisition section, a system control section and a digital inverter control section. AC parameters such as grid, inverter volts, amps, frequency and DC parameters such as battery volts, amps, temperature, solar/wind charge amps and various digital inputs are monitored and stored in a database for access by the control module and LCD.

The System Control Module operates various relays on the Relay Interface Card to control the output contactors . It also handles all the synchronising and supervisory requirements of the inverter including the inverter contactor control and includes local or remote system access via a separate optically isolated RS232 module.

Keypad Membrane Panel (KMP): The Keypad Membrane Panel consists of a membrane keypad and a 40 x 4 character liquid crystal display (LCD) screen, usually mounted on the front panel. The keypad can be utilised to select various operational and display modes and to enter system setpoints and parameters. The liquid crystal display (LCD) is used to indicate various modes of operation, fault conditions, system parameters, system events, system logs and system setpoints.

Relay Interface Card (RIC): These cards interface directly with the System Control Module and contains on board control relays to control the output contactors.

Half bridge IGBT power output driver stages (DRV): This consists of two half bridge IGBT driver cards driving a left and right half bridge IGBT modulel. Each driver card utilises adjustable peak current sensing for the top and bottom sections of the IGBT modules. In the event that the IGBT module peak current is exceeded for more than one second a signal is sent back to the System Control Module, which instigates an inverter fault shutdown.

Solar Regulator Module (SRM): This card drives a high current series element in a pulse-switching mode to progressively unload the current from the solar array in the event that the battery is at its preset float potential.

Fig. 3 Hybrid Inverter System

The Single Phase Solar Mains (SM) Inverter system utilises three, state of the art, high performance microprocessors that integrate real time system control and SCADA monitoring.

The power electronic inverter module supports high quality mains type sinewave generation and bi-directional operation; ie, drawing AC mains and converting to DC battery charge current or the reverse (the conversion of DC to AC mains voltage).

The SM Hybrid system behaves as an on line UPS whose output voltage is regulated to within 3% of its nominal value. The inverter module operates in parallel with either the grid supply with the power to the load being supplied by either the grid or the inverter depending on the availability of solar resources.

The SM Hybrid system operates in a variety of modes, all under software control. In parallel mode the unit tracks the external grid source and connects transparently to that source. The inverter supports high peak, short duration loads while the grid maintains the base load. Alternatively, with low grid loading, the system configures in a charge mode. The excess power is managed by charging the battery bank. The charging process is undertaken in two stages; a constant current, bulk charge period followed by a constant float voltage taper charge period.

C. Battery Storage

Make: UPLUS

Valve Regulated Lead Acid Rechargeable Battery

US 12-110 12 V 110 Ah

Constant Voltage Charge

Boost/Equalize: 14.5-15.0 V

Float: 13.5-13.8 V

Maximum Charging Current: 33.0 A

Fig. 4 Battery Bank used for Storage Purpose

Fig. 5 shows a typical two phase charge cycle. Phase 1 is the constant current bulk charge mode where the power into the battery is limited and the terminal voltage is allowed to rise. Phase 2 begins when the battery bulk potential is reached and the charge is slowly tapered down till the float voltage is reached. The float potential is then maintained with a resultant reduction in charge power into the battery.

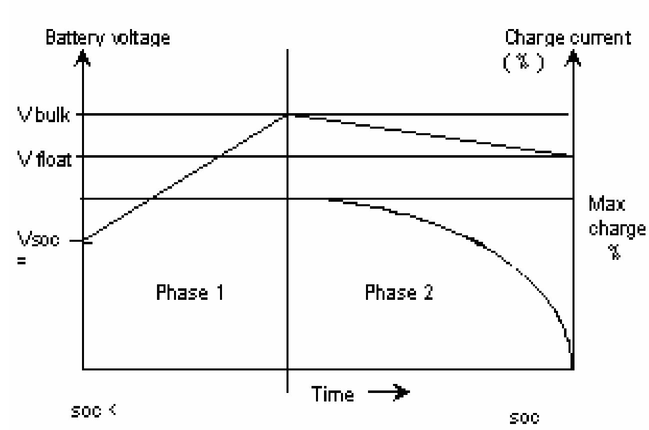

Fig. 5 Two Phase Charge Cycle

D. Site Demand

Site demand generally varies from 2.5 KW to 3.5 KW. This demand is met by solar, battery storage and grid. At present only the critical loads such as computers, sophisticated instruments and machineries of the laboratories are connected with inverter system for uninterruptible and quality power supply purpose. Since all the critical loads of the laboratories are not operated simultaneously, the usual demand of critical load is more or less 0.80 KW.

III. Availability of Solar Energy Resource

Table 1 Solar Data of the Site under Research

Month	N	G	GSRTF		
			Lat-15	Lat	Lat+15
January	7.3	4.263	1.127	1.295	1.392
February	8.2	5.161	1.092	1.201	1.244
March	7.6	5.580	1.043	1.075	1.051
April	7.8	6.108	1.006	0.980	0.907
May	7.6	6.215	0.982	0.921	0.823
June	3.2	4.492	0.980	0.922	0.835
July	4.5	4.987	0.981	0.921	0.831
August	4.6	4.908	0.995	0.955	0.877
September	5.6	4.999	1.022	1.021	0.972
October	7.2	5.046	1.067	1.137	1.148
November	8.0	4.664	1.119	1.273	1.356
December	7.3	4.094	1.140	1.329	1.445

Explanation of symbols used in the tables:
N: Actual sunshine duration a day (in hours)
G: Daily sum of Global Solar radiation (in kwh/sq.meter)
GSRTF: Global solar radiation tilt factors for south-facing surfaces for three tilt angles, Latitude, Latitude - 15 degrees & Latitude + 15 degrees.
To get 'Daily global radiation falling on the tilt surface' (in kwh/sq.m), multiply 'G' with 'tilt factor'.
Agartala, Latitude: 23.88N

The Hybrid Optimization Model for Electric Renewables (HOMER) (the micropower optimization model, developed by the National Renewable Energy Laboratory of the U.S.

Department of Energy) introduces the clearness index from the latitude information of the site under investigation. Average daily radiation in a year is shown in Fig. 6.

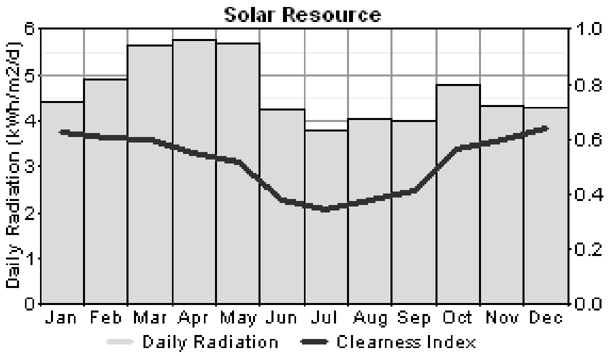

Fig. 6 Solar Resource of Study Area

The solar based design is justified in terms of earning carbon credit. It has been found that solar radiation in the state varies from 4-6 KWh/m^2/day.

IV. Observation and Analysis

A. Grid-Inverter Voltage Characteristics

Input to the Inverter is from solar panel and battery. The voltage from inverter is maintained at around 230 volt free from any harmonic distortion. As the power generated by the solar panels is being utilized locally without any transmission losses, a very good power quality is obtained from the inverter. It has been observed that for any day the grid power quality is poor.

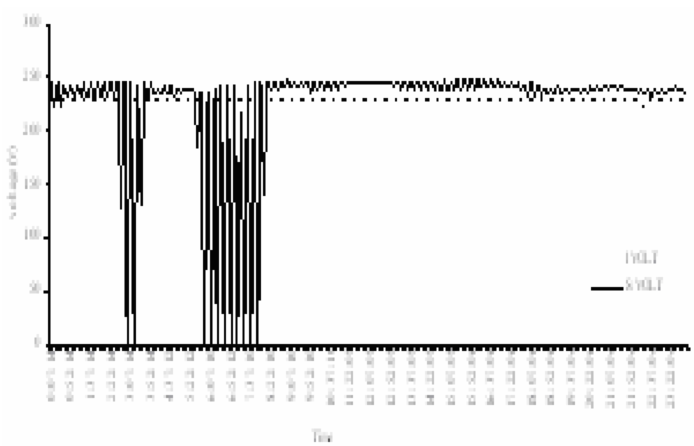

Fig. 7 Comparison of Voltage Quality from Inverter and Grid

B. Grid-Inverter Frequency Trend

Inverter frequency is always maintained at around 50 Hz. But due to occurrence of fault, the grid frequency does not always remain constant and frequency deviation prevails in the system. It was observed in a particular day that around 2:40 a.m. and 6 a.m. frequency was out of range, so the grid got disconnected for a while and the voltage dropped down to zero during that period (Fig. 8**)**.

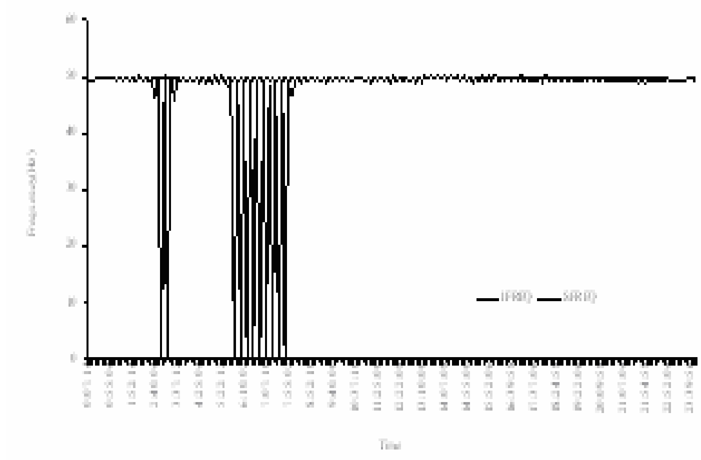

Fig. 8 Frequency Profile of Inverter Power and Source Power (Grid)

C. Grid-Inverter Power Comparison

At morning time (usually up to 8:30 a.m.) power is not delivered by inverter; rather power is being consumed from the grid to satisfy the site demand and battery charging. From 10:30 a.m. to 3:30 p.m. when high solar radiation is available, renewable current increases, thus resulting in the increase of inverter current (Fig. 9 and Fig. 10).

During this period power from both the inverter and the grid is available to meet the site demand. Gradually renewable current decreases due to low intensity of sunlight and then the source current is consumed for charging the battery and meeting the site demand.

Since out of the total site demand, inverter serves only the critical load of around 0.80 KW, therefore the power contribution from the inverter is comparatively low than the grid power supply (Fig.9).

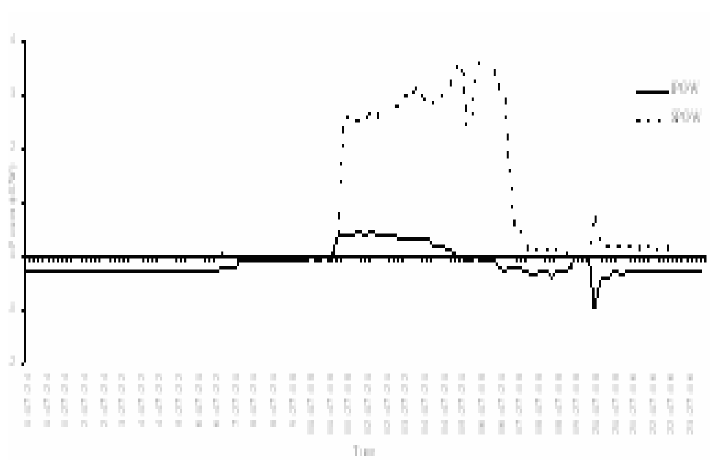

Fig. 9 Power Available from Inverter and Grid

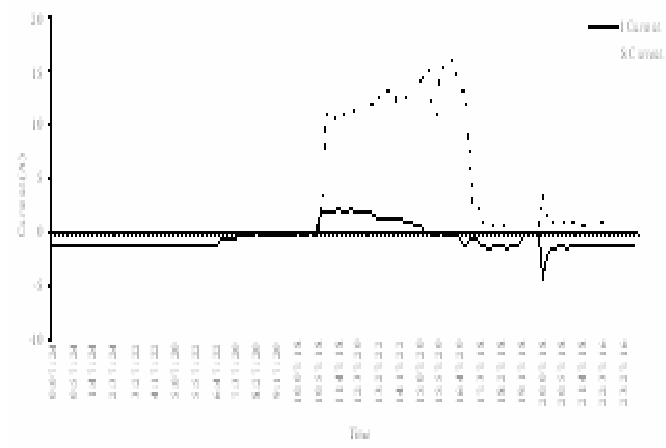

Fig. 10 Flow Pattern of Inverter and Source Current

D. Grid-Inverter Power Factor Characteristics

The graph in Fig. 11 shows the power factor trend in a cloudy condition. As seen from the graph that the source and the inverter power factor trend is almost identical for most of the time. According to the relation, $\cos\Phi = P/(\sqrt{3} \times V \times I)$, power factor is inversely proportional to system voltage and current. Since inverter voltage remains almost constant, inverter power factor mainly depends upon inverter current. On a cloudy day, the renewable current is generally very low due to bad weather condition and the site demand is mainly met by grid and the battery.

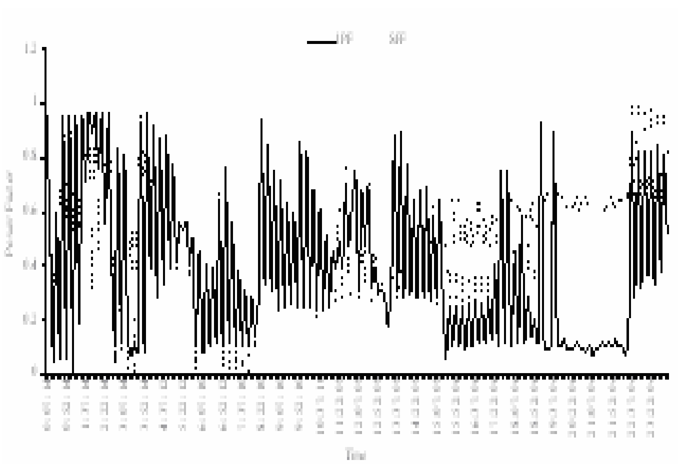

Fig. 11 Inverter and Grid Power Factor

E. Renewable Current

From the observation, it appears that generally till 8 a.m. renewable current is not available because of the low intensity of sunlight (Fig. 12). As the time progresses, with the increasing intensity of sunlight the renewable current proportionally increases. Highest solar output current is generally observed between 11 a.m. to 1:30 p.m. After that renewable current rating gradually drops off with decreasing intensity of sunlight.

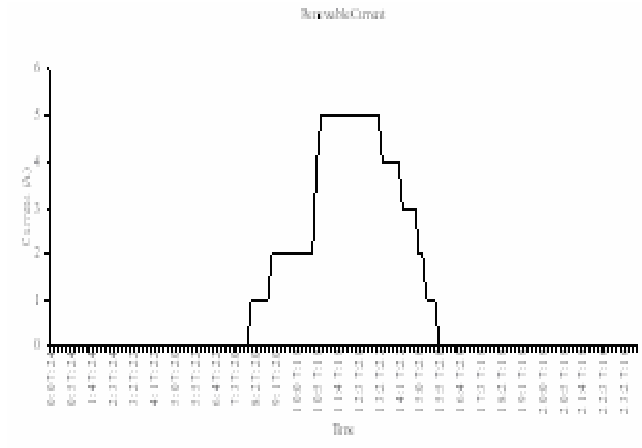

Fig. 12 Solar Current Output

F. Battery Characteristics

When either or both grid and renewable power are available to meet the demand of the site, there is no discharge of current from the battery. Following observation is illustrated to understand the contribution of battery storage which is an essential component and plays a vital role to meet the demand in the absence of grid and solar power.

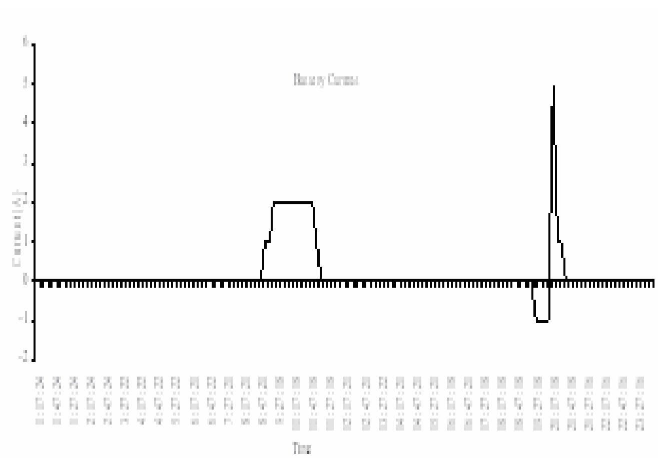

Fig. 13 Flow Nature of Battery Current

From Fig. 13, in a particular day it has been observed that till 8:30 a.m. there is no flow of current from the battery because of the adequate grid supply. During the period of 9 a.m. to 11 a.m., no power is available from the grid and renewable power is also very low. Thus the site demand is mainly met by the battery. When the renewable and grid power is restored, the battery gets disconnected. Again at around 7:15 p.m. to till 8 p.m., grid voltage becomes very low and at that time no renewable power is also available, so the site demand is again met by battery. Later that grid is again restored and the battery started recharging upto the float voltage.

The battery voltage per cell remains around the float voltage which is 2.3 V (approx) for most of the time (Fig. 14).

Battery voltage is maintained around 138 volts. As seen from Fig. 15 that between 8:30 am to 11 am when no power is available from the grid and the solar power is also very low, the site demand is met by battery. Again at around 7:15 p.m. to 8 p.m., battery is taking power from the grid for charging purpose.

Present study shows that battery temperature varies between 29ºc to 31ºc (Fig. 16).

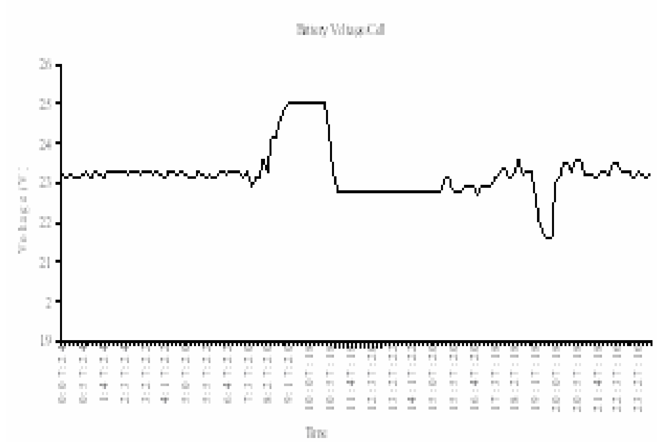

Fig. 14 Cell Voltage Profile

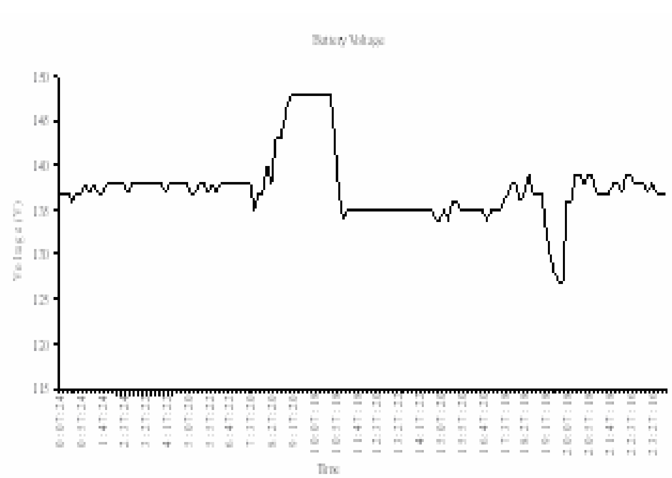

Fig. 15 Voltage Profile of Storage Battery

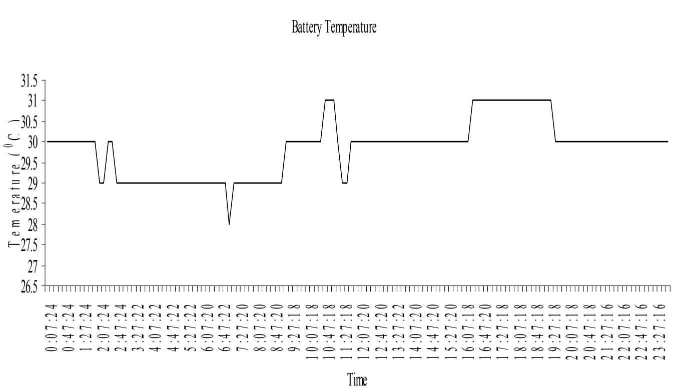

Fig. 16 Battery Temperature Profile

V. ENERGY CONSERVATION

In normal working hours, the onsite demand varies from 2.5-3.5 KW. It has been observed in most of the time that when site demand is 3.5 KW, solar and battery storage met 0.8 KW (usual demand of critical load) and remaining 2.7 KW load demand (light, fan, air conditioner and few computers) is met by grid. Thus 22-25% grid electricity is conserved in most of the days during peak hour. It has been observed in some best situations that solar and battery can contribute 2.70 KW power when site demand was 4.10 KW. Thus 66% grid electricity conservation is experienced during the monitoring with this system. Apart from the critical loads, if some other additional loads were fed from the hybrid inverter then more energy conservation could have been possible with the present system.

VI. CONCLUSION

In the grid interactive system, the solar power which may be available in excess of the demand during period of high sunshine is fed to the grid and is utilized elsewhere. This also improves the grid voltage and power factor. The grid interactive system having some storage for the energy, obtained from PV, can compensate the voltage of a pure, grid connected system. The system has been designed to supply continuous power to a dedicated local load with the power to the load carrying from the solar array, grid, or battery bank in the order of preference. It is capable of operation in a grid interactive mode and will automatically change over to the stand alone operation without break in power in the event of the grid drifting out.

It can be summarized from the analysis that grid-interactive photovoltaic power system could play a vital role to mitigate power shortage problem of the region and can enhance reliability of quality power supply which is essential for critical loads.

Performance of a grid-interactive PV system installed in the location under investigation will most likely be similar for all parts of North East India as geographical and climatic conditions are almost same in this entire region. Satisfactory steady state performance experienced from the system in terms of voltage quality, frequency profile, energy conservation, battery characteristics indicate that the grid interactive PV system is a promising and viable option for this zone and large scale penetration of this technology will be helpful to alleviate the dependence on grid.

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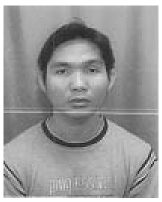

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APPENDIX 1

System Electrical Specification

Inverter	
AC Voltage output	230 V_{rms} L-N
Output voltage regulation (stand-alone mode)	±3%
Output frequency regulation (stand-alone mode)	±0.5%
Number of Phases	Single
Inverter Frequency	50 Hz
Total Inverter continuous rating	10 KVA
Inverter surge rating	17.5 KVA for 30 seconds
Peak Efficiency	93%
Nominal DC input voltage	120 V_{dc}
Total Harmonic Distortion (THD)	< 5%
Cooling	Fan forced
Protection	Electronic peak overload current and voltage detection
Control Type	Voltage source, microprocessor assisted output regulation
Solar regulation Control Type	Series element PWM control
Other AC Sources	
Grid rating	10 KVA
Battery	
Nominal battery voltage	120 V_{dc}
Float voltage	136.8 V_{dc}
Boost voltage	147 V_{dc}
Renewable Input	Photovoltaics
Total capacity	10 KW_p
Output Circuit Breaker	
Minimum continuous current rating	50 A
Voltage rating	230 V_{ac}
Number of poles	1
Battery Circuit Breaker	
Minimum continuous current rating	100 A
Overload current rating	175 A for 30 seconds
Voltage rating	250 V_{dc}
Maximum I^2t value (where I is battery short circuit current and t is time for breaker to break the short circuit current)	6×10^7 A^2s

APPENDIX 2

Data profile of BIPV system

Date	Time	Inv. Power (KW)	Grid Power (KW)	Site Power (KW)	Ren. Current (A)
24.03.09	10:46:10	0.6	0.7	1.3	6
24.03.09	10:56:10	0.7	1.8	2.5	7
24.03.09	11:06:10	0.7	2.2	2.9	7
24.03.09	11:16:10	0.7	2.3	3	7
24.03.09	11:26:10	0.7	2.5	3.2	8
24.03.09	11:36:10	0.7	2.4	3.1	8
24.03.09	11:46:10	0.7	2.4	3.1	8
24.03.09	11:56:10	0.7	2.6	3.3	7
24.03.09	12:06:10	0.7	2.6	3.3	7
24.03.09	12:16:10	0.7	2.7	3.4	7
24.03.09	12:26:10	0.7	2.6	3.3	7
24.03.09	12:36:10	0.6	2.6	3.2	7
24.03.09	12:46:10	0.6	2.6	3.2	6
24.03.09	12:56:10	0.6	2.5	3.1	6
24.03.09	13:06:10	0.6	2.6	3.2	6

24.03.09	13:16:10	0.6	2.7	3.3	6
24.03.09	13:26:10	0.5	2.8	3.3	6
24.03.09	13:36:10	0.5	2.9	3.4	6
24.03.09	13:46:10	0.5	2.9	3.4	5
24.03.09	13:56:10	0.5	3	3.5	5
24.03.09	14:06:10	0.4	3	3.4	5
24.03.09	14:16:10	0.4	3.1	3.5	4
24.03.09	14:26:10	0.3	3.3	3.6	4
24.03.09	14:36:10	0.3	3.4	3.7	4
24.03.09	14:46:10	0.6	0	0.6	3
24.03.09	14:56:10	1.3	2.9	4.2	3
24.03.09	15:06:10	2.7	1.4	4.1	3