A Novel Low-Cost Solution for Mitigating the Loss of Power Supply Probability in Grid-Tied Solar PV Systems during Daytime Grid-Outage Scenario

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Abstract- In this paper, a novel method has been proposed and implemented to mitigate the loss of power from grid-connected solar PV systems during daytime grid outage condition. This loss during daytime grid outages usually occurs because of the built-in islanding feature of the commercially available grid-tied solar inverters. Unlike other grid outage mitigation methods, such as; using expensive hybrid inverters and other battery backup inverters, the proposed method introduces a battery-less topology that can avoid the significant cost of the battery pack itself and associated auxiliary control circuits, its operation and maintenance. An optimized capacity (as low as 5-10% of grid-tied inverter rating) DC-AC interface system in form of a stand-alone inverter without using external battery has been introduced to provide the reference AC bus for keeping the grid-tied solar inverter operational even during the daytime grid outage. The interface system is energized from a solar PV-powered DC bus instead of the commonly used high-capacity battery backup. The method also ensures the maximum available energy extraction from a grid-connected solar PV Plant without renovating the existing grid-tied solar inverters. The experimental validation has been done by a practical $2kW_p$ grid-tied inverter and a 200VA stand-alone inverter interfaced solar PV system operation and control under sunny and cloudy day scenarios. The proposed low-cost grid outage mitigation method is a generalized one and hence can be very useful for scalable grid-connected solar PV power plants also, for the rural consumers with emergency loads to be satisfied even during day-time grid-outage scenario.

Keywords Grid outage, energy outage mitigation, scheduling of inverters, demand management

1. Introduction

In the present era of accelerated growth of implementing renewable energy sources (solar, wind, biomass, etc.), solar energy contributes to most of the sources because of its abundant availability. Starting from the grid-connected rooftop solar power plant to commercial solar power plants, the injection of solar power into the national grid is rapidly growing up. The uneven energy distribution reduces the power-sharing capability of conventional thermal and hydel power plants [1]. Very high penetration of solar PV into the existing grid may cause uncertainty to its stability [2,3]. Due to the imbalance in demand and generation, there is a rapid extra generation and withdrawal of solar PV power, also known as duck-curve [4]. The duck curve [5] represents a power generation profile throughout the day and compares it with the peak load demand with respect to time [6]. In the countries like India, a gap is rising between energy demand and energy generation, especially in rural areas [7]. The issues of variable load demand profile, weak and/or unstable distribution grid, unreliable energy distribution, and heavy penetration of renewable energy (RE) have been rising in recent days [8-17].

The most crucial component of a solar power plant apart from solar modules is the solar grid-tied inverter, which takes the dc energy from the array of solar cells and injects energy into the local AC grid. Amongst the established electrical features of a grid-tied solar inverter across the globe, it has been observed that the grid-connected solar power plants fail to inject energy into the grid during grid failure conditions because of the built-in islanding feature in the solar grid-tied inverter [18]. This type of protection can be found in all commercially available grid-tied solar inverters (module/string/central), such as ABB, SMA, KACO, FRONIUS, etc. [19,20]. This phenomenon results in a significant loss of energy available from the solar PV power plant even in the presence of adequate solar irradiance leading to inconvenience and dissatisfaction among the users and beneficiaries of solar power plant. The occurrence of these types of energy outages is quite frequent in countries like India, where the grid is relatively unstable. In rural areas, grid fluctuation is persistent also; there is a problem of grid swelling or sagging due to un-balance generation-demand management [7,21]. This is one of the main reasons not to export PV power to the grid due to the functional limitation of the grid-tied solar inverter [22].

However, the grid-tied solar inverter is overcoming some of its limitations to support the utility grid by controlling the reactive power injection to the grid [23], as per requirement [24-28]. In the AC-coupled inverter configuration, an additional battery backup inverter is incorporated with the system to mitigate the grid and peak demand management [29,30]. The additional AC-coupled configuration cost is higher due to the additional DC-AC bi-directional conversion and a battery bank. So, this system turns into an expensive, complex system. Most importantly, the system disabilities in grid outage conditions cannot be denied, which makes the method, to a great extent, unreliable. This drawback can also be seen in DC-coupled configurations [30-33], whose costs are a bit lower than the AC-coupled configurations.

The unpredictability of the solar irradiance fluctuations can be mitigated using a ramp-rates controller [34]. That can lead to significant voltage fluctuations with different ramp rates at the point of common coupling. Traditionally, these energy buffer units are used to smooth out the exported power fluctuations using the moving average or PV power gradient control. However, these methods can only smooth out the power at the output of the grid-tied inverter without considering the local load. Deployment of a battery energy storage system (BESS) for the photovoltaic (PV) application has been increasing the chances of reliability and cost [35-38]. To increase PV system flexibility and to provide more energy to the consumer, the integration of battery storage with the inverters has been considered a viable solution. But the initial and recurring costs involved in the battery storage pack have been the main barrier to its deployment in practice.

Few inverter manufacturing companies claim that AC Coupling inverters can be used with off-grid and battery-based photovoltaic systems. In this application, a battery-based inverter creates a “microgrid” where the solar inverters can be connected. In another case, an AC coupling PV hybrid system has been demonstrated where AC coupling power-sharing is possible with a diesel generator [39] and a battery-based system [29].

This paper proposes a solution to the above-mentioned problem. Herein, a small stand-alone inverter creates a reference AC bus at the point of common coupling (PCC) to keep the grid-tied solar inverter operational even during the daytime grid failure, keeping in mind the energy unavailability due to non-operational grid-tied solar inverter during a daytime grid outage. The major advantage of this solution over the existing one is the absence of a battery, which involves a high cost and maintenance for its own and the auxiliary control circuits. Here a stand-alone inverter gets power from a solar PV source-fed DC bus, which is a unique advantage of the proposed system. In this work, a novel, cost-effective solution has been developed and deployed for mitigating the power loss due to grid outages during daytime when the availability of solar irradiance is significant. A small stand-alone inverter charged from the solar PV-powered DC bus-only will replace the battery backup inverter, and a reference will be generated by the stand-alone inverter in order to keep the grid-tied string solar inverter operational, even during grid failure and to serve the local/critical AC loads, where the grid outage is frequent. The scheduling of all events and drives of the critical/local loads is controlled by a central controller. Thus, solar energy harvesting can be significantly enhanced without renovating an existing grid-tied solar PV inverter, even at grid failure conditions. The design and methodology for the developed solar energy outage mitigation controller have been demonstrated in this paper. The proposed topology can also be suitable for rural applications such as; rice processing mills [40,41], Water treatment plants [42], and various other mills where the power consumption is high and the necessity for backup power during the daytime. One of the major applications of this grid outage mitigation solution is hundreds of schools and healthcare centres installed with grid connected solar power plants in rural areas where the availability of power is necessary at daytime during grid-outage period.

The rest of the paper is organized as follows; section 2 includes the functional architecture of the proposed system, section 3 comprises of modeling and simulation study of the parallel operation of two different types of inverters and their design consideration, section 4 describes the experimental validation of the proposed system performance; finally, section 5 includes the conclusion of this paper.

2. The Architecture of the Proposed Topology

The proposed system architecture and the operation schematic are shown in Fig. 1.

Table 1. Comparison table of proposed method with other existing solutions

Parameter	AC-Coupled System [28-29]	DC-Coupled System [28, 30-33]	Hybrid-Inverter [50,51]	Proposed Solution
Operation during Grid-outage	No	No	Yes	Yes
Battery Requirement	Yes	Yes	Yes	NO
Fabrication Cost	High	High	High	Low

A solar PV array source is connected with a single-phase solar grid-tied inverter to integrate the utility grid through an AC bus and a protection circuit at the PCC. The local loads and the distribution grid are connected to the AC bus through different relays. A small stand-alone inverter is connected to the same solar PV source via a DC-DC boost converter. This stand-alone inverter is powered by a DC-DC converter instead of battery storage as an equivalent source powered by the same PV source. The DC-DC converter works in a constant voltage (CV) and constant current (CC) mode with 'zero' under-voltage protection (UVP) to avoid multiple times on/off during inrush load-changing conditions, which is similar to an equivalent battery source. The stand-alone inverter is connected to the AC bus (PCC) via a protection relay and a line reactor, a crucial part of the proposed system.

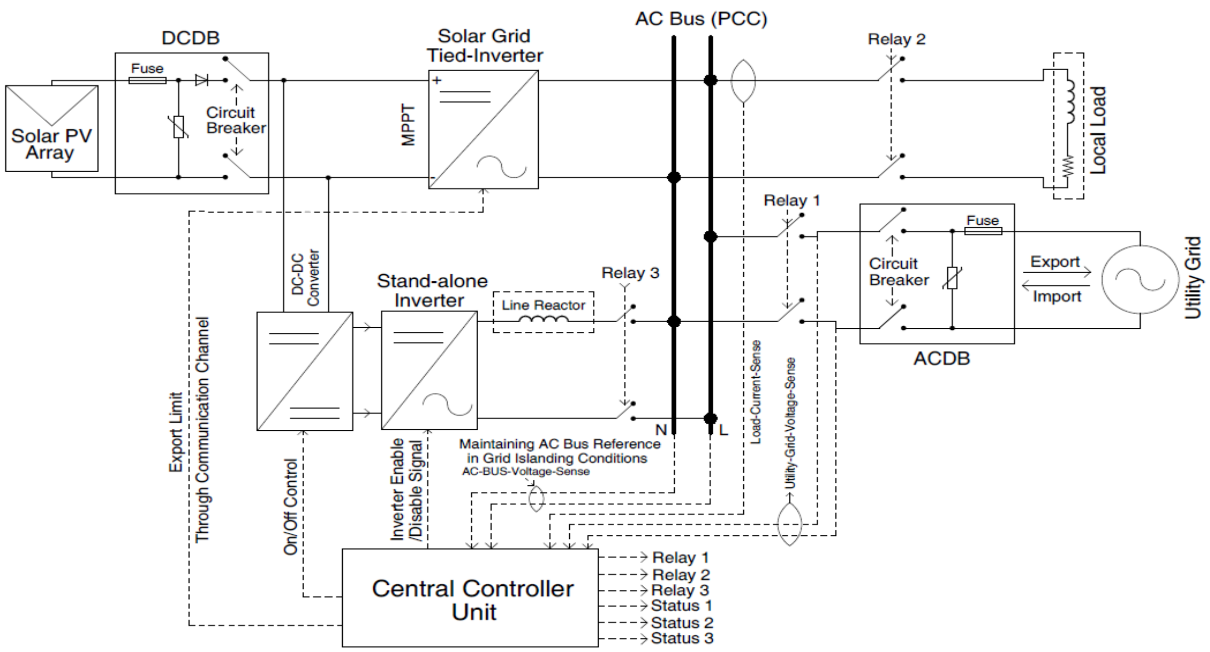


Fig. 1. The architecture of the proposed grid outage mitigation unit

The line reactor plays a vital role in maintaining a stand-alone inverter output power quality [43-46] during the grid outage scenario. The entire energy outage mitigation unit's switching operation is maintained by a sequential logic circuit implemented on a central control unit based on an 8-bit PIC microcontroller. The relays (relay 1, relay 2 and relay 3) are shown in (Fig. 1). are connected to isolate and reconnect the local loads, stand-alone inverter, and the utility grid using the central controller. Two voltage sensors and a current sensor have been used to sense the utility grid side voltage, AC bus (PCC) voltage, and load current, respectively. The current sensor is used to sense the load current, which is directly fed back to the central controller unit to maintain the power injection balance between the two inverters. The power balance is necessary to avoid voltage swelling or sagging at the PCC. The power-sharing between the two inverters strictly depends on the same current sensor's feedback during grid outages.

Figure 2 describes the different operational states of the proposed system. There are two major, one intermediate and one critical state.

The two major states are the utility grid present state and the utility grid absent state. A timer is set to measure the utility grid state (whether it is available or not). In the utility grid's present state, the specific relays are connected to the load, and the grid-tied inverter is connected to the common coupling AC bus.

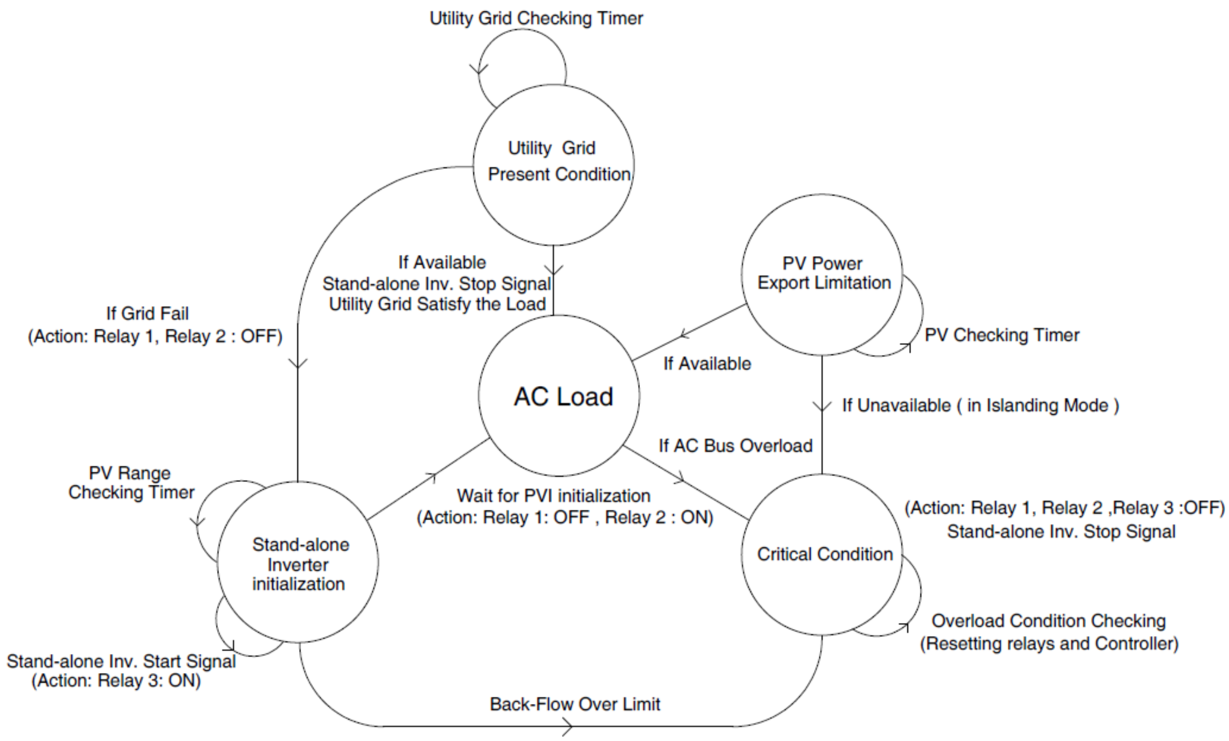


Fig. 2. State flow diagram of the proposed system

In the absence of the utility grid, the stand-alone inverter gets activated; a timer is kept to start counting and waiting for the grid-tied inverter to export the energy to the common coupling AC bus. All the necessary actions have been taken by the central controller unit. In the critical state, relay signals have been processed to protect the system, as shown in Fig. 2.

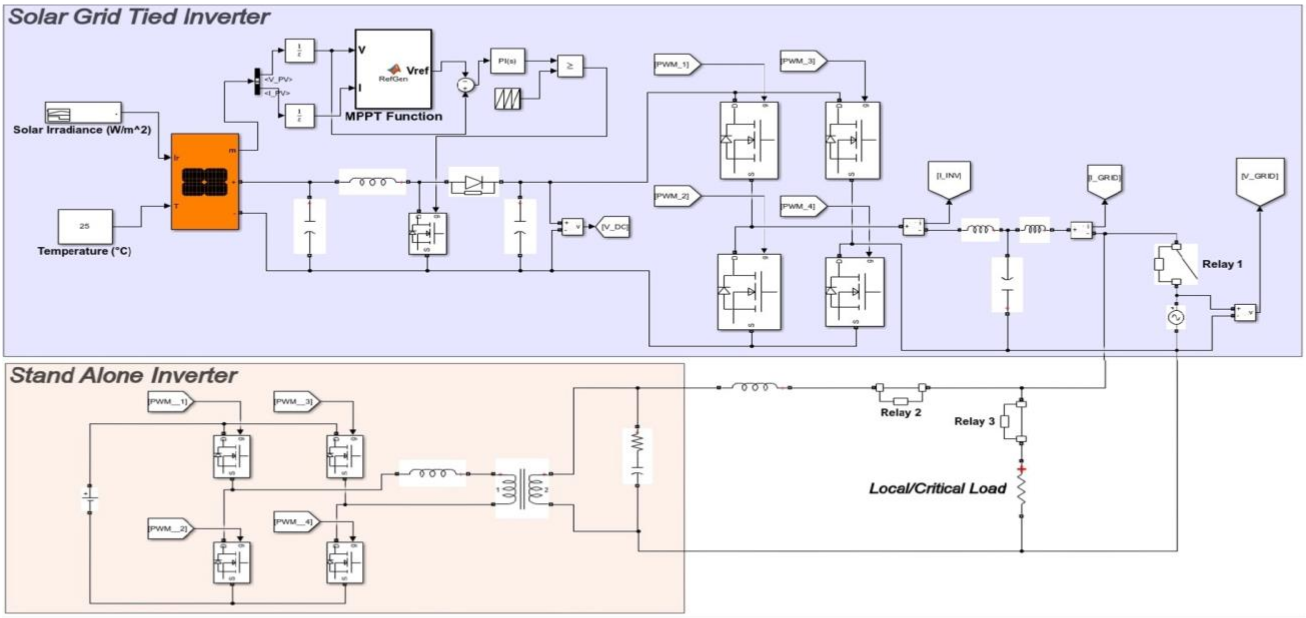
2.1. Modeling & Simulation

To verify the proposed technique, the required simulation studies have been done in MATLAB/Simulink environment. Fig. 3(a) shows the overall model of the proposed system with interconnection. The internal sub-system blocks have been represented in Fig. 3(b)-3(f), respectively. In the overall system simulation model, a standard AC bus is created to connect all the sources and local load. A coupling reactor with a value of 10mH/10A is placed in series with the stand-alone inverter to eliminate the generated harmonics [47], which can affect the grid-tied inverter operation during the grid outage time.

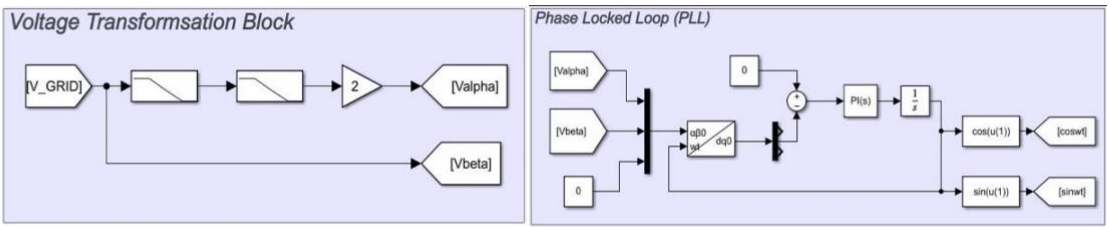
In this simulation study, one single-phase grid-tied inverter and a stand-alone inverter are connected to an AC bus through suitable interfacing circuitry in order to realize the operation of load power-sharing during the daytime grid outage period. The solar PV module is connected to an MPPT controller to ensure the maximum power point tracking at corresponding irradiance and ambient temperature level. A suitable LC filter is also incorporated into the system before sending the AC power into the grid to improve power quality.

Here, active power is controlled by using the DC bus voltage control. Grid side single-phase voltage is first converted into dq axis reference voltage by using the Clarke and Park transformation block, for which the angle reference "wt" is generated by using a phase-locked loop (PLL). Those dq axis references are then used for DC bus voltage control. Sinusoidal PWM techniques are implemented to control the operation of the inverter. At the stand-alone inverter side, a 12 V DC voltage is converted into equivalent 12 V AC voltage by use of an inverter, and then by use of a single-phase 12/230 V booster transformer, the voltage is fed to the common AC bus (PCC).

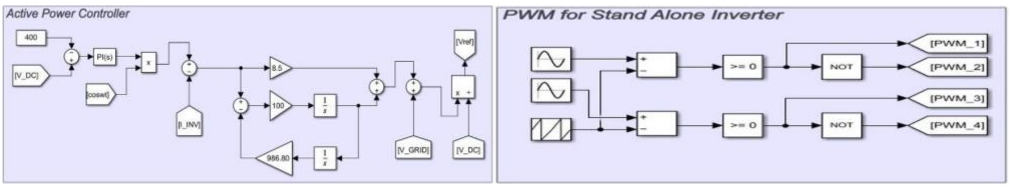
In parallel operation of inverters depends on the number of inverter terminals connected to a common bus and the control stability of each inverter when in operation. For the stable operation of the inverters, control of active power (P) & reactive power (Q) should be well maintained. P is controlled by the line frequency, and Q is controlled by the droop in the voltage. When an inverter feeds the power in an AC system, the P & Q fed to the system is governed by the time integral of the inverter output voltage space vector. The individual control loops of each inverter and the drooping of output frequency, voltage, and harmonics [48] of each module help to share the load in ac power lines in parallel operations [43-46]. In another report [45], the parallel operation of the voltage source inverter has been shown.



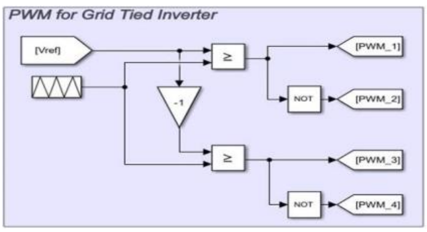
(a)



(b) & (c)



(d) & (e)



(f)

Fig. 3. Modeling of power-sharing between two parallel inverters; a grid-tied inverter and a stand-alone inverter: 3(a) represents the overall model and connection of the proposed system, 3(b) represents the voltage transformation model sub-system, 3(c) shows the PLL operation model sub-system, 3(d) illustrates the active power controller sub-system, 3(e) PWM operation for stand-alone inverter and 3(f) PWM operation for the grid-tied inverter

In this paper, the inverter forms output reference bus voltage as there is no active AC terminal. The load current is shared by multiple inverters. The control of the unbalanced current is achieved by the control of the frequency and voltage components so that the active and reactive components of the circulating current can be minimized.

3. Power-Sharing Optimization Between Two Parallel Inverter (Grid-Tied and Stand-Alone Inverter)

The simulation study describes the power-sharing between two inverters (grid-tied and stand-alone) connected in parallel, considering the daytime grid outage scenario and shown in Fig. 4-8. To evaluate the power-sharing performance of the grid-tied and stand-alone inverter during grid outage conditions, five sets of load patterns have been chosen (10%, 25%, 50%, 75%, and full load 100%). As the two inverters are in parallel, the representation has been made in terms of current and power shared by the two inverters to meet the corresponding load demands. It has been observed from the results that during the grid outage period, the power transmitted by the stand-alone inverter is around 5% of the power shared by the grid-tied inverter under various levels of load demand. Based on the simulated capacity optimization, the experimental setup has been selected [49].

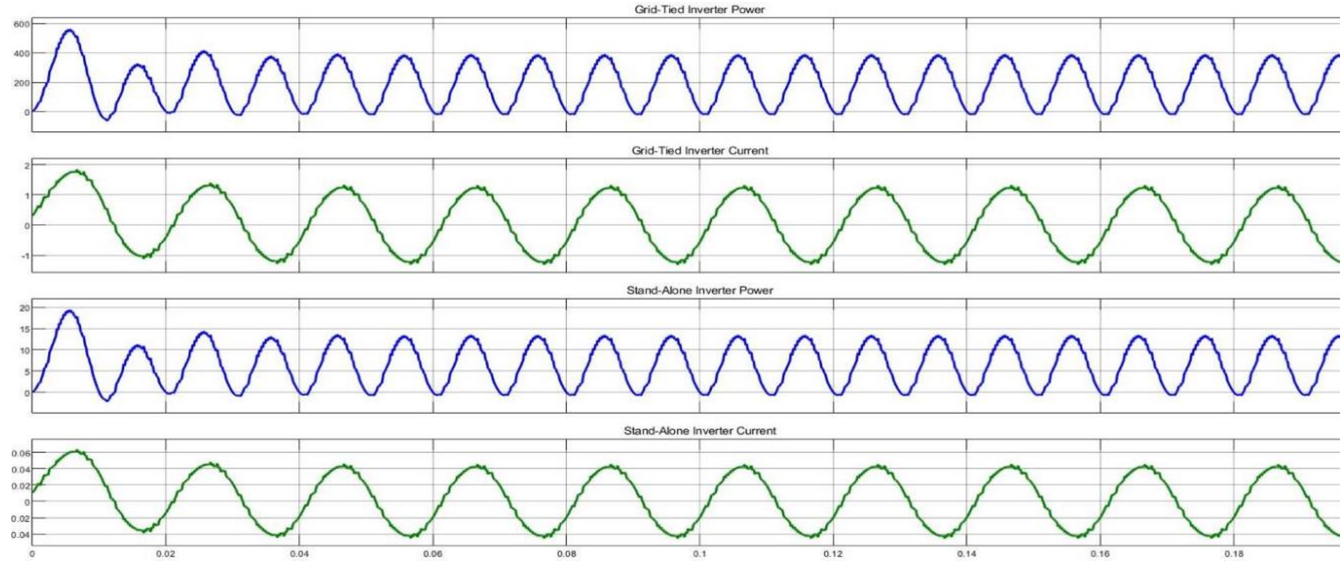


Fig. 4. Simulation result: shows the power-sharing between two inverters at 10% Load

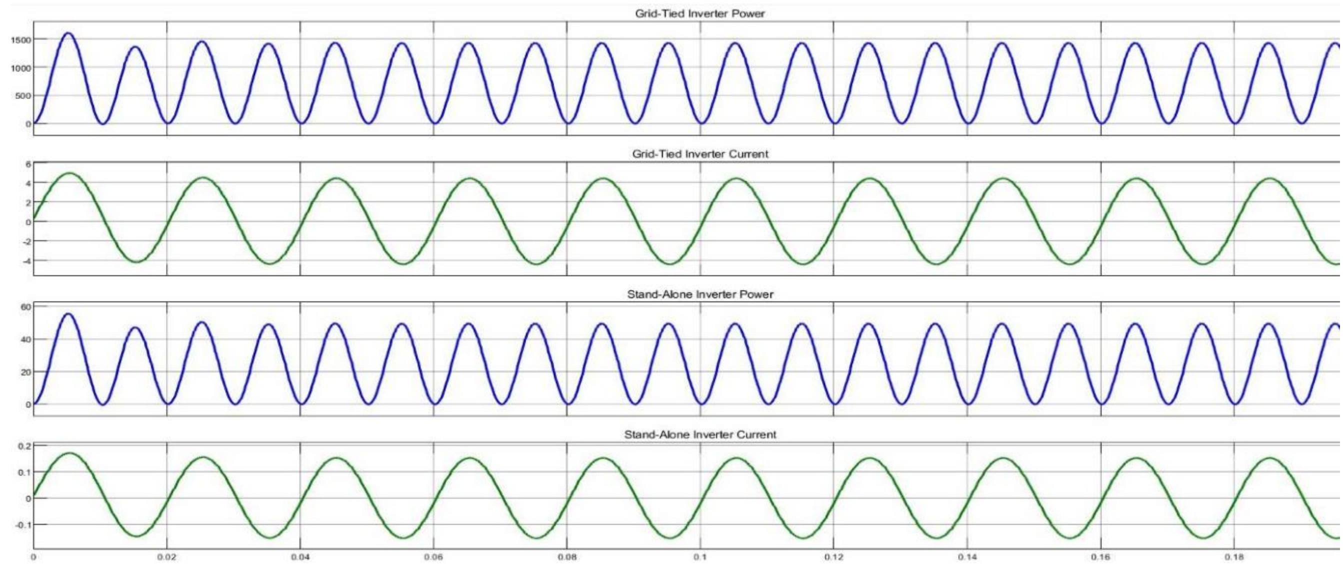


Fig. 5. Simulation result: shows the power-sharing between two inverters at 25% Load

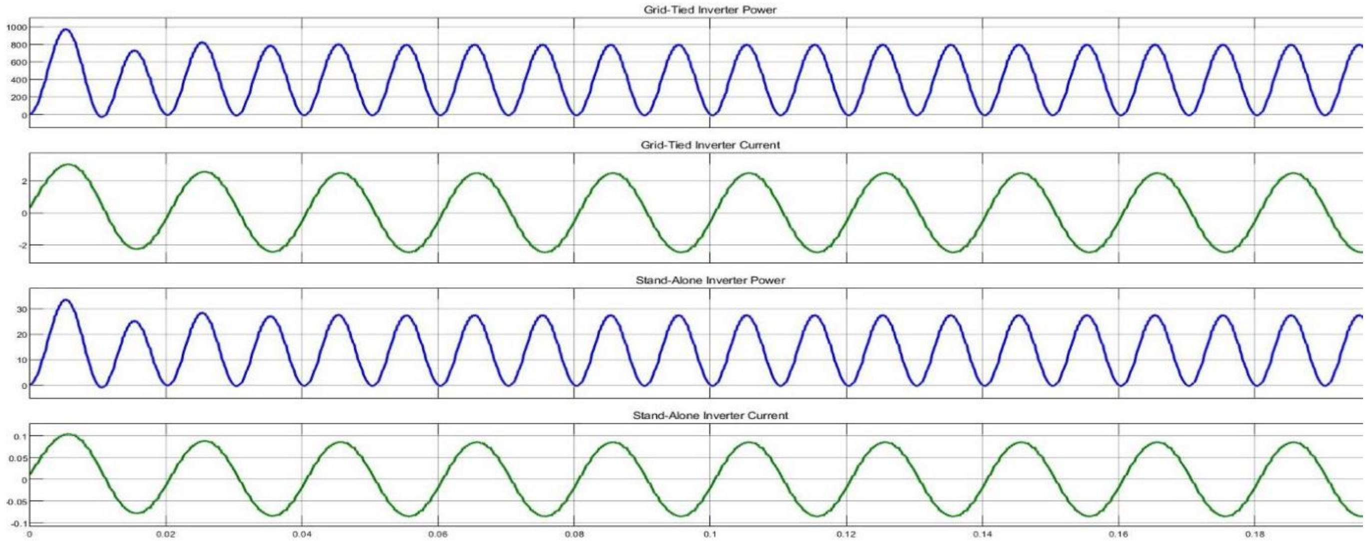


Fig. 6. Simulation result: shows the power-sharing between two inverters at 50% Load

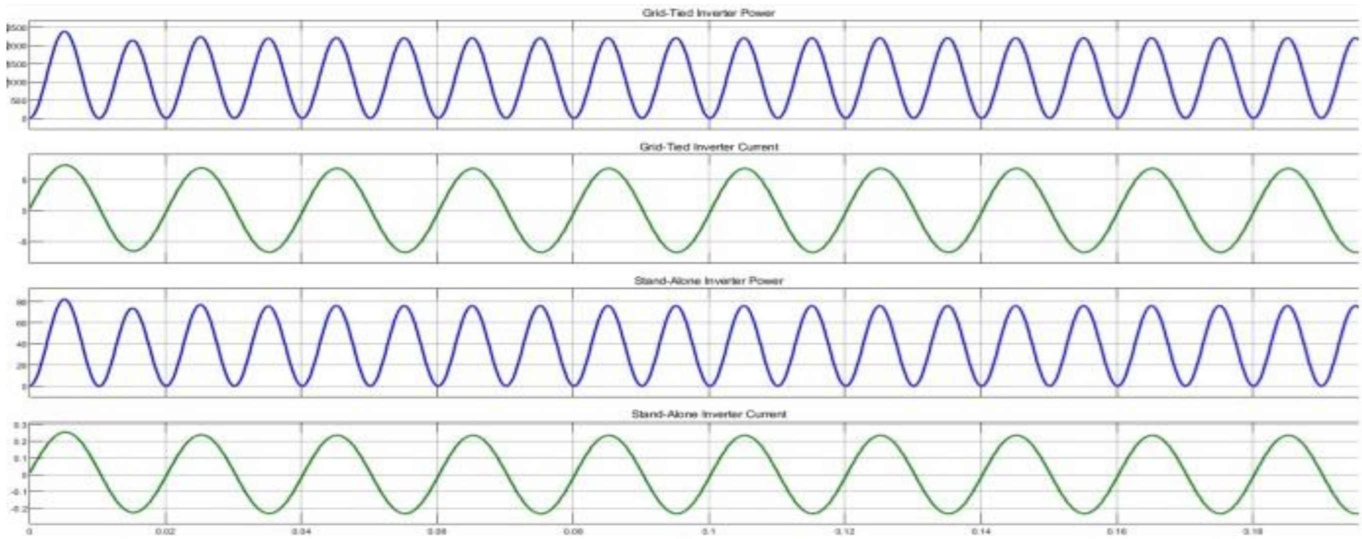


Fig. 7. Simulation result: shows the power-sharing between two inverters at 75% Load

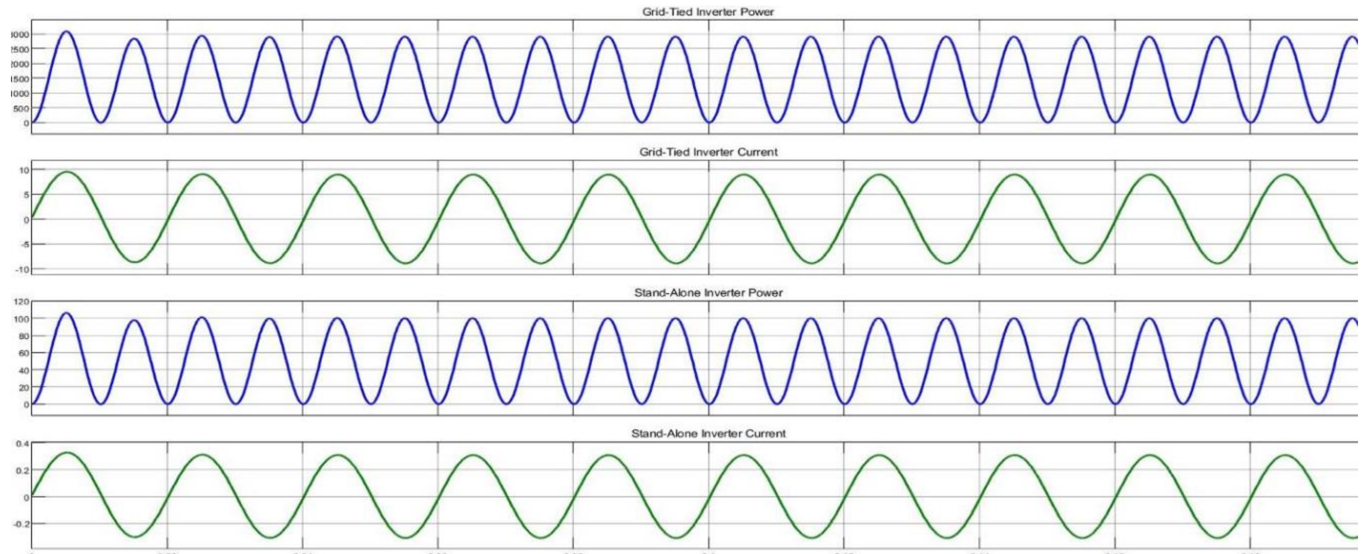


Fig. 8. Simulation result: shows the power-sharing between two inverters at 100% Load

4. Experimental Validation

4.1 Experimental Setup

In this paper, a solar PV system with a grid power loss mitigation unit has been set up at the microgrid centre within the IIEST, Shibpur campus to study the proposed approach, as shown in Fig. 9. The mitigation system consists of a solar PV Array Simulator, 2kW grid-tied solar inverter, 200VA stand-alone inverter, a DC-DC converter, and a state transition controller unit. In this system, a solar PV source of 2kW$_P$ capacity is connected with a single-phase grid-tied inverter for integration with the local/utility grid. An AC bus connects the local grid with the local loads through controllable relay switches. A stand-alone inverter having a capacity of 200VA is powered by a 12V DC-DC converter connected to the same solar PV source. A relay is used to connect the output of the stand-alone inverter to a common AC bus. Relay 1 and relay 2 are responsible for isolating and reconnecting the load and the utility grid with the AC bus using a controller unit. Two voltage sensors are used to sense the grid side voltage and the AC bus voltage, respectively. A current sensor is used to sense the load current to measure the overload situation for the stand-alone inverter until the grid-tied inverter starts.

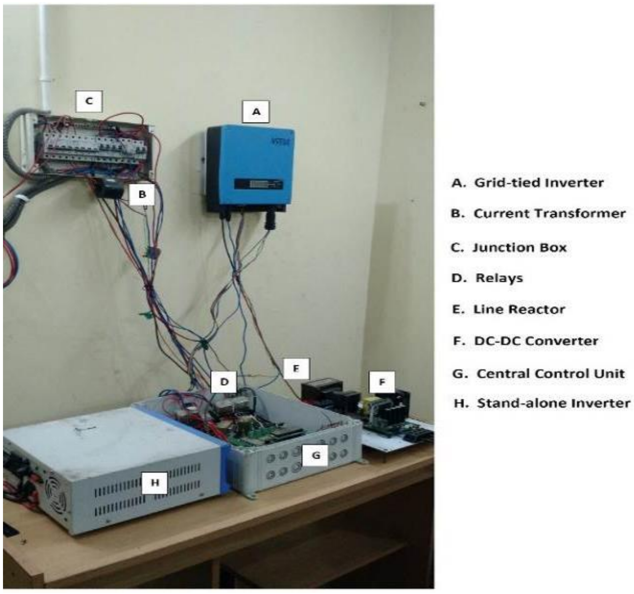
This current sensor also plays a significant role in balancing both inverters when the system runs on grid outage mode, thus enabling the seamless operation of two parallel inverters. Here a control unit is operated using sequence logic. The said controller comprises processor PIC18F46K22, an 8-bit high-performance RISC CPU, wherein the switching operations of the entire solar energy outage mitigation during grid failure are maintained by sequential logic.

Table 2. Technical specifications of the major sub-systems used in this work

Components	Specifications
Grid-tied Inverter	2kW/230V/50Hz Inverter
Stand-alone Inverter	200VA/160W/12V
Line Reactor	10mH/10A (Iron Core)
DC-DC Converter	Isolated Output (1kW/13.2VDC), Input (180V-415VDC)
Relays	230V/ 16A
Controller unit	PIC18F46K22, 8-bit high performance RISC CPU

The load management algorithm for the entire operation of the grid outage mitigation unit is described in Fig. 10. When the utility grid is available, relay 1 and relay 2 are closed. i.e., the PV power is exported to the grid via an AC bus, and the local load is connected to the same AC bus. Relay 1 and relay 2 are immediately opened at the instance of grid outage to isolate the grid from the AC bus and isolate the local load circuit. After a certain period of around 10 seconds, the DC-DC converter and the stand-alone inverter are triggered by the central controller unit. To energize the AC bus, relay 3 is closed with a delay of 5 seconds. Now the grid-tied inverter exports the limited power to the AC bus to cater to the required load demand. The export limit of the grid-tied inverter is set by the central controller unit after fetching the load current, followed by a look-up table.

Fig. 9. Experimental set-up of the proposed system



4.2 Power Sharing Between Two Inverters- A Case Study

In this study, the power-sharing between the two types of inverters has been shown in Fig. 11, where the grid-tied inverter extracts the available solar PV power shares the majority of the load power demand compared to the stand-alone inverter. It is to be noticed from Fig. 11 that with the increasing load demand, the grid-tied inverter sharing also gets increased, whereas the stand-alone inverter sharing can be limited to a small value of around 5% of the grid-tied inverter capacity. This power-sharing demonstration gives a clear decision that a small stand-alone inverter can be used to maintain the virtual AC bus to ensure the grid-tied inverter operation during the grid outage condition, even for high capacity (kW to MW) solar power plant applications also. A look-up table has been set inside the controller unit to control/regulate the grid-tied inverter's power export limitation.

4.3 Experimental Results

The proposed solution has been validated by experimental results shown in Fig. 12, 13 and 14. Two practical conditions of sunny and cloudy weather also have been considered for performance validation.

- During the availability of the utility grid, the grid-tied solar inverter delivers the power into the AC bus (PCC), which is coupled with the utility grid and the local load as well. The performance of the developed system has been validated with a constant practical load over a period of time.
- When the utility grid outage occurs, the grid-tied solar inverter gets deactivated because it goes into the

islanding condition. The AC bus (PCC) also gets de-energized, and the bus voltage decreases to 0V. Then relays 1 & 2 isolate the AC bus (PCC) from the grid.

- Sequentially the small stand-alone is activated and takes power from the same solar PV-powered DC bus. The stand-alone inverter re-energizes the AC bus (PCC) within 10 seconds through relay 3. The grid-tied solar inverter now senses the AC bus (PCC) voltage and frequency, then compares it with its reference in order to re-synchronize with the AC bus (PCC).
- The reference checking takes a finite time of 60-65 seconds, as observed. The stand-alone inverter runs on float mode in order to maintain the AC bus (PCC) reference for the grid-tied inverter but does not carry full local load power in order to overcome the probability of sudden overloading.
- The load side relay (relay 2) remains open till the grid-tied solar inverter is activated. Once the grid-tied inverter is ready to deliver power to the AC bus (PCC) at around 60 seconds, the load sides relay reconnects the loads which are shared by the grid-tied inverter and the stand-alone inverter.
- The utility grid comes back at around 160th seconds and the stand-alone inverter is deactivated by the controller signal. As a consequence, the grid-tied inverter gets islanded because of the non-availability of the AC bus (PCC).

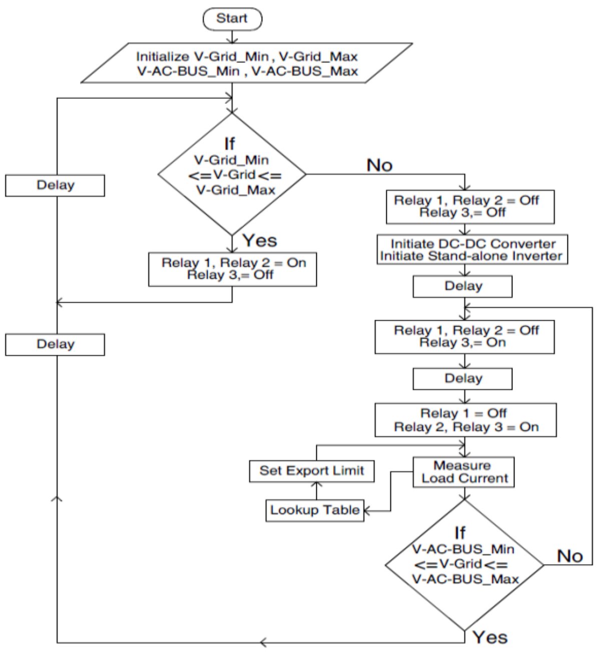


Fig. 10. Flow chart implemented for the proposed grid outage mitigation unit

- During this time, the loads also get disconnected from the AC bus (PCC) by relay 2 for about 5-10 seconds, as shown in Fig. 12. As observed in the figure, the grid-tied solar inverter goes into grid-checking mode again for a period around 60-65 seconds. During this period of 165th-225th second, the load power demand is satisfied by the grid power.
- Once the grid-tied inverter is ready to deliver solar PV power into the AC bus (PCC), the load gets reconnected to the AC bus (PCC) through relay 2. In the case of low PV power due to low irradiance level, the balance power is supplied by the utility grid in order to meet the required load demand.

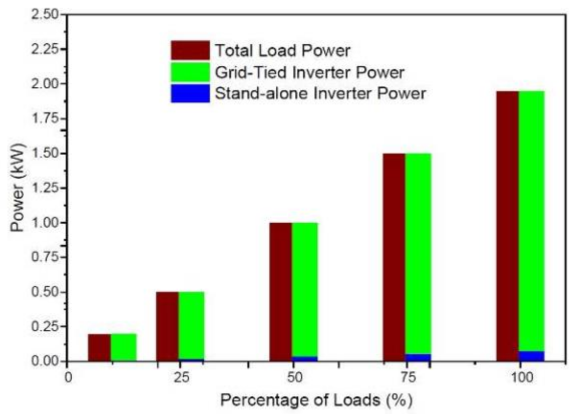


Fig. 11. A case study of power-sharing between two inverters

Figure 13 shows the validation of a practical case of around 2 hours duration. Here the energy outage mitigation is demonstrated from 9.05 hours to 11.05 hours of grid outage Shown in Fig. 13, the grid voltage falls from 230V to 0V) during daytime while having adequate solar irradiance. It is observed that the load demand of around 800W is met by the optimized scheduling and power-sharing of the grid-tied and the stand-alone inverter.

As shown in Fig. 13, the available PV power is utilized even during the grid outage period for an instance of two hours to satisfy the load demand without the use of energy storage systems. Practical solar PV power generation data is used (9 A.M to 11:10 A.M) to validate the proposed grid outage mitigation topology.

Figure 14 demonstrates a case study for driving a constant load under cloudy days and grid outage conditions. An equivalent insolation profile is set by a solar PV array simulator with a time interval of 1 sec. In this case, the insolation profile for a period of 300 sec. is observed for validation of the proposed solution. It is seen from Fig. 14 that at the 120th second, the solar insolation is lower than 300W/m^2, which is not capable of driving the 800W load, and also, there is no grid present at the AC bus shown in Figure 14.

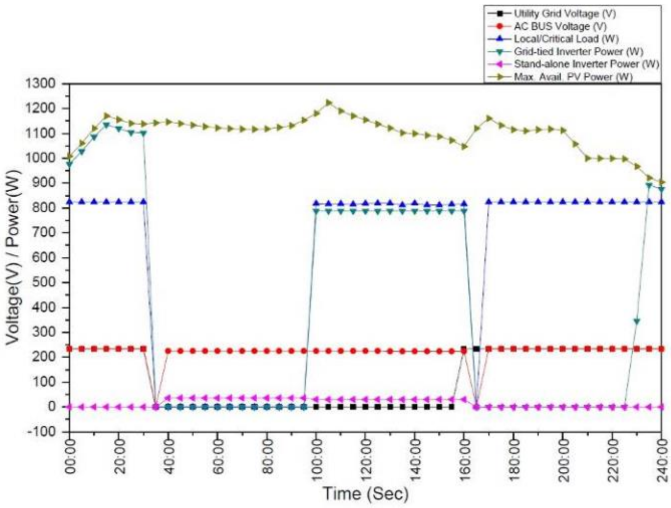


Fig. 12. Energy outage mitigation and load demand matching during daytime grid outage

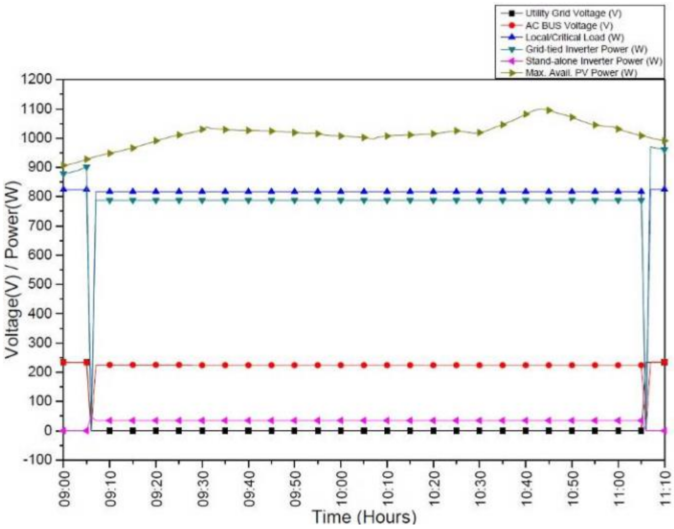


Fig. 13. Energy outage mitigation and load demand matching during a daytime grid outage (longer time for around 2 hours)

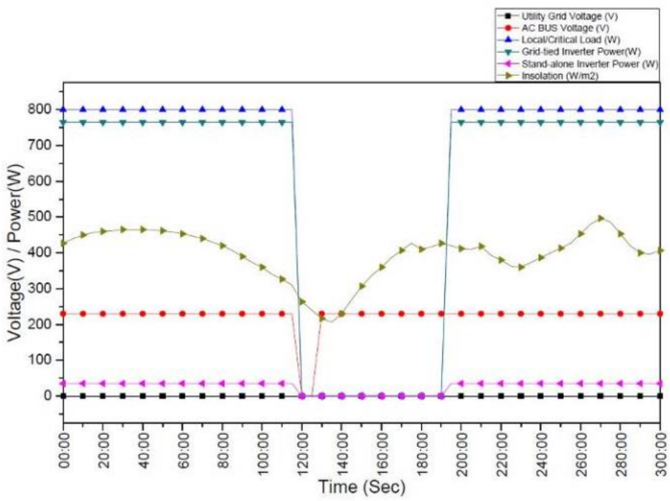


Fig. 14. Energy outage mitigation and load demand matching during a cloudy daytime grid outage

Because of that, the AC bus voltage sags below the under-voltage threshold of the grid-tied inverter, and it goes to the islanding mode. Therefore, at this stage, the local/critical load totally depends on the stand-alone inverter. But in this case, the stand-alone inverter can drive up to 150W load; therefore, the stand-alone inverter goes to shut down mode due to overload conditions. The DC-DC converter that interfaces the stand-alone inverter remains active due to the availability of solar power. After a cycle of checking with the help of voltage sensors at different nodes, the central controller activates the stand-alone inverter that energizes the AC bus again. At 125^{th} sec. Relay 3 shown in Fig. 1 connected the AC bus, and the AC bus gets re-energized. The grid-tied inverter and the local/critical load are connected via relay 2 shown in Fig. 1 at 190^{th} sec. to satisfy the demand during that period.

Grid outage frequently occurs during the daytime especially in the semi-urban and rural power distribution system, due to various reasons. An uninterruptible power supply (UPS) is required to mitigate the unreliability which occurs due to the grid outage; still, it is a costly solution and has a limitation in its capacity to meet the required power demand. However, those systems can meet the capability of redundancy in catering to the growing energy demand. In this case, a topology is proposed to mitigate the effects of the conventional grid outage in the daytime using the novel approach of parallel operation of inverters and load balancing.

In this case, a stand-alone inverter acts as a reference to the grid-tied inverter, which injects significant solar power into the reference AC bus to satisfy the local load demand during the daytime grid outage period.

4.4 Cost Analysis

A cost comparison between the proposed solution and the existing hybrid inverter solution has been done and presented in (Tables 2a and 2b). In case of satisfying the load demand during daytime grid outage for two hours using the existing hybrid inverter topology, the required battery capacity is 24V/100Ah considering battery DC-DC efficiency (around 80%) and the inverter efficiency (approximately 90%). In the proposed grid outage mitigation solution, the use of a battery pack and associated electronic circuitry has been replaced by a small capacity stand-alone inverter of capacity around 5% of that of the grid-tied inverter, thereby reducing the system's overall cost.

It has been observed from the case study that for the 2kW solar PV system operation under a daytime grid outage scenario, the cost involved in the proposed solution comes out to be around 60% less than that of the existing hybrid inverter-based grid outage mitigation solution. Therefore, the proposed solution claims to be cost-effective and attractive to solar PV plant owners, investors, and installers, and existing users also. The corresponding case-study results for grid outage mitigation and load demand management by the proposed solution have already been discussed in section 4.3 of this paper.

Table 2a. Cost of the proposed grid outage mitigation solution

Proposed grid outage mitigation unit	**Cost (INR)**
2kW Grid-Tied Inverter	18000
200VA Stand-alone Inverter	2100
10mH/5A (Iron Core) Line Reactor	550
Isolated Output (1kW/13.2VDC), Input (180V- 415VDC) DC-DC Converter	3250
Central Control Unit + Extra Protection	2850
Total cost	**26,750**

Table 2b. Cost of the existing hybrid inverter solution

Existing Hybrid Inverter for mitigation unit	**Cost (INR)**
2kW Solar hybrid Inverter unit	34,500
24V/ 100Ah battery pack (Pb-acid)	12,200
Total cost	**46,700**

Note: 1 INR ≈ 0.013 USD (as on date)

Conclusion

This work demonstrates a novel method to mitigate the loss of power supply probability in grid-tied solar PV power plants during the daytime grid outage. The key findings of this work are summarized as follows;

- In order to keep the grid-tied solar inverter operational even during the grid outage and to serve the local/critical AC loads, a low-capacity (up to 10% of the grid tied inverter capacity) stand-alone inverter is designed to provide the reference AC bus for the grid-tied solar inverter.
- The use of a battery storage-based hybrid inverter for daytime grid outage solution and the corresponding cost of BESS can be avoided by the proposed battery-less solution.
- An optimized scheduling algorithm has been developed in order to energize the grid-tied inverter and the stand-alone inverter considering the solar PV power generation and load demand in real-time to ensure seamless supply of power to the connected load.

The performance of the developed system has been validated with a practical 2kW grid-tied solar inverter and a small 200VA stand-alone inverter under constant load demand and daytime grid outage over a period of time. It is to be noticed that with the increasing power demand, the power shared by grid-tied inverter also gets increased, whereas the stand-alone inverter power-sharing can be kept limited to a small value. This power-sharing example gives a clear decision that a small stand-alone inverter can be used to maintain the virtual AC bus to ensure the operation of the grid-tied inverter even during the grid outage condition in the daytime for grid-connected solar power plants. From the practical case study, it has been observed in this work that for a 2kW scale grid-connected PV system operation, the cost involved in the proposed grid outage mitigation solution comes out to be around 60% less than that of the existing hybrid inverter-based solution. The proposed grid outage mitigation method is a generalized one and thus can be very useful for scalable grid-connected solar PV power plants, especially in the rural areas having emergency loads to be catered during the day-time grid-outage scenario.

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