



A HYBRID DIESEL-WIND-PV-BASED ENERGY GENERATION SYSTEM WITH BRUSHLESS GENERATORS

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Abstract

This paper presents an experimental implementation of a standalone micro grid topology based on a single voltage source converter (VSC) and brushless generators. The micro grid system is energised with different renewable energy sources namely wind and solar PV array. However, a diesel generator (DG) set and a battery energy storage system (BESS) are also used to maintain the reliability of the system. The proposed topology has the advantage of reduced switching devices and simple control. The implemented topology has DG set as an ac source. The wind generator and the solar PV array are dc sources which are connected to the dc link of the VSC. The BESS is also used at the dc link to facilitate the instantaneous power balance under dynamic conditions. Along with the system integration, the VSC also has the capability to mitigate the power quality problems such as harmonic currents, load balancing, and voltage regulation. A wide variety of test results are presented to demonstrate all the features of the proposed system.

Key Words: Brushless generator, composite observer, power quality, standalone micro grid, voltage regulation, voltage source converter (VSC).

1 INTRODUCTION

There are many locations in the world where the small localities are developed far away from the well-developed societies. It is technically and economically difficult to setup a transmission system to make electricity available there due to the cost incurred, the problems related to grounding of the transmission tower at hilly areas and Right of Way problems due to forests in between. However, on the other hand, these areas have abundance of natural resources like solar energy, wind, hydro, etc. Due to the uncertain nature of all these renewable energy sources, a small self-sustaining supply system cannot be established which can supply the loads continuously. To make the system self-sustaining, some reliable sources are required. Therefore, generally a diesel generator (DG) is used at these sites. To account for randomness of the natural resources, a full rating DG is a costly option. Some energy storage device can be employed there, which reduces the DG rating and considerable fuel consumption.

As described earlier, since the system is setup at a remote area, the brushless generators [1] are used to avoid the maintenance as much as possible. The proposed topology in this paper includes solar PV array and wind energy as natural resources. A substantial literature is available for different topologies, control, operational aspects, power electronics of the wind, and solar PV systems [2][5]. Authors have proposed many topologies, control algorithms and operation strategies for the micro grid system with many energy sources. Like doubly fed induction generators are used for the wind- and diesel-based system [6], where the controller is optimizing the fuel consumption and regulating the voltage and frequency of the system with maximum available power extraction from wind. Different operating strategies to include wind power in a diesel-based system to save fuel and to reduce the overall cost of the system are proposed in [7] and [8]. A time frame-based control algorithm is proposed in [9] for a wind-diesel system with an energy storage. In this paper, authors have proposed an energy

storage system to account for wind randomness and fuel cost. A standalone hybrid wind-solar system with an engine generator and a battery is proposed in [10], where the operational aspects and topology are described. The proposed topology has six VSCs to integrate the complete system. With the given load profile of an area for whole day, size and scheduling of the generator are performed to maximize the generator efficiency. Similarly to reduce the battery size and to increase efficiency of the system, an ultra capacitor is used with the battery to exchange power during dynamics and the battery is used to supply under sustained load generator power mismatch. Along with these different topologies and control strategies, other studies are also reported in the literature. Simulation studies are carried out for a micro grid system with many sources and energy storage devices with different controllers to regulate the frequency of the system [15]. Different generators are used with the diesel engine and the studies are performed with diesel, PV, and diesel- PV mixed generation. where wind energy conversion system reliability is obtained taking into consideration the wind fluctuations and component failure. Moreover, the reliability analysis of the complete system is also performed by taking diesel, wind, and battery.

The control of a permanent magnet synchronous generator (PMSG) based wind energy conversion system (WECS) connected to an inverter with battery acting as a grid is presented in [18]. The power generated by WECS is used to control the SOC of battery. In most of the systems, described in the literature, variable speed wind energy conversion system operates to extract the maximum power from the wind. Wind energy is free energy at the operation stage, so it is beneficial to extract the maximum power and to increase the efficiency and the utilization of WECS. It needs initial capital cost, but the fuel is free. There are many topologies and algorithms reported for MPPT in WECS and solar PV system. As in [19][21], different methods for MPPT in WECS are proposed like algorithm similar to hill climbing, the mechanical sensor less MPPT algorithm with the current controlled inverter, and the mechanical sensor less MPPT algorithm with a boost converter. Basic MPPT algorithms for solar PV system. These are perturbed and observe algorithm and incremental conductance-based algorithm.

Moreover, a control algorithm is required to control the VSC

connected for its operation as voltage and frequency controller, mitigating power quality problems and integrating the dc sources with ac sources. Many basic control algorithms are reported in the literature.

This paper deals with an implementation of a reduced converter topology of a diesel-wind-solar PV-based standalone micro grid system with the BESS. These generators are synchronous reluctance generator (SyRG) and permanent magnet brushless dc generator (PMBLDCG). Both these generators are brushless in construction. The wind and solar PV systems are always operated at their maximum power point using boost converters and the DG is operated within a specified power range to optimize the efficiency of the DG. A VSC is used to integrate the DC sources with the AC sources with the bidirectional power flow capability and the power quality improvement capability. A mechanical sensor less MPPT algorithm is used for WECS and an incremental conductance based MPPT algorithm is used for solar PV system.

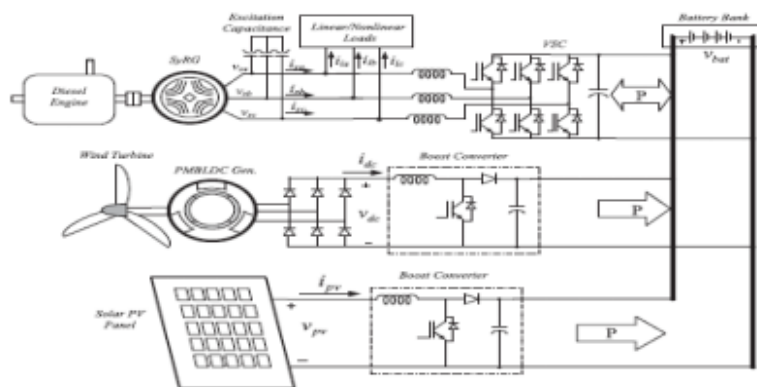


Fig:1. Proposed single VSC and the brushless generation-based standalone micro grid system.

2 STANDALONE MICROGRID TOPOLOGY

The proposed system is a diesel-wind-solar PV based standalone micro grid with the battery energy storage to feed the local loads. The complete system topology is shown in Fig. 1. A SyRG is used as a DG and a PMBLDCG as a wind generator. These generators are selected purposefully due to the following reasons. Both these generators are brushless generators that reduce the maintenance cost relative to the brushed ones. For a DG, SyRG is used rather than a conventional synchronous generator, so the need of a speed governor and AVR is eliminated yet the voltage and frequency of the system are regulated using VSC. The PMBLDC generator is driven by a wind turbine. As shown in Fig. 1, the WECS is connected at the dc link of the VSC through a diode rectifier and a boost converter. PMBLDCG is best suited for an uncontrolled rectification due to trapezoidal back EMF. If the winding currents are also made quasi-square wave, then a low-ripple torque is produced and the machine operates smoothly. This feature is not there with PMSG as the EMF generated is sinusoidal, so the quasi-square wave currents produce a fluctuating torque. Moreover, the energy density of the PMBLDC machine is high which makes it small in size, hence good option for pole mounting application. The proposed topology also includes solar PV system, which is also connected to the dc link of the VSC for power transfer to the ac side where loads are present. As discussed earlier, to maintain the power balance and reliability of the supply, the battery energy storage device is required. Hence, a battery bank is also installed at the dc link of the VSC.

3 CONTROL STRATEGY FOR PROPOSED STANDALONE MICROGRID SYSTEM

The proposed system topology has many sources, so an operational strategy is developed to optimize the fuel efficiency and to maximize the extraction of free energy available. The DG is the only ac source

in the system, so the system and the load end frequency is related to the operation of the DG only.

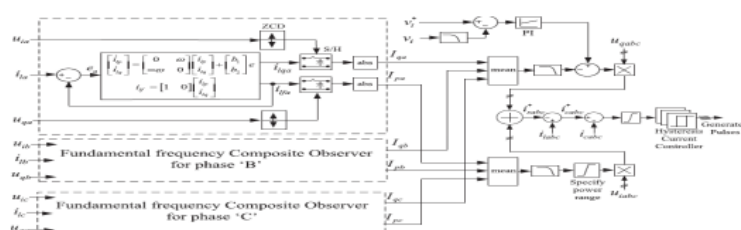


Fig. 2 Control strategy for VSC.

A constant frequency of the system means the constant speed of the generator (as the generator is SyRG). It is stated in [29] that with fixed speed operation of the diesel engine, the fuel consumption does not vary much from its value at full load, thus making the diesel engine fuel efficiency poor at lighter loads. The diesel engines operate at reasonable good efficiency between 80-100% loading. Here, the control strategy is developed for the DG to operate it always within a specified loading range as shown in Fig. 2. The DG with rating as full load rating is not required as there are renewable energy resources and the battery energy storage device is available.

The WECS consists of a PMBLDC generator, three-phase diode bridge rectifier (DBR) and a boost converter. An inductor is used after the DBR to make the dc current almost constant which reflects as quasi-square waveform of current on the ac side which is beneficial for the operation of PMBLDCG as discussed earlier. The operation of the WECS is simplified by eliminating the need of any mechanical sensor for MPPT. An MPPT algorithm is used which requires only sensing of v_{dc} and i_{dc} . This MPPT algorithm is the same as perturb and observe, which is used for maximum power extraction in solar PV system.

A. Voltage and Frequency Control of DG

Any distorted signal like voltage or current can be decomposed into the dc and different frequencies sinusoidal signals as defined by Fourier series. All these frequency components can be estimated online using composite observers. However the control algorithm

for this system requires only fundamental frequency component estimation. So a composite observer is used to extract the fundamental frequency component of the load currents. The basic structure of a composite observer is described here. It creates a specified frequency in-phase and quadrature-phase components of the input signal. The state space representation of one unit of composite observer is shown as $\dot{X}_n = \Omega_n X_n + B_n e$; $y_n = C_n^T X_n$; where n = harmonic order

$$\dot{X}_n = [\dot{x}_{1n} \quad \dot{x}_{2n}]^T, X_n = [x_{1n} \quad x_{2n}]^T$$

$$\Omega_n = \begin{bmatrix} 0 & n\omega \\ -n\omega & 0 \end{bmatrix}, B_n = \begin{bmatrix} b_{1n} \\ b_{2n} \end{bmatrix}, C_n = \begin{bmatrix} 1 \\ 0 \end{bmatrix}. \quad (1)$$

$$e = y - \sum_{n=1}^N y_n$$

N = number of harmonics considered

As described in (1), with a composite observer having many units present for different harmonics, each unit tends to extract the particular harmonic component for which it is tuned. Thus, combination of all these components converges towards the actual signal. So in this type of system, the error e eventually becomes zero. However, with the proposed scheme, only unit corresponding to the fundamental frequency is used, which extracts only fundamental frequency component. The in-phase component of load current is obtained as output of the system and the quadrature-phase is obtained as the internal state of the system.

The characteristic of a unit of the composite observer corresponding to $\omega = 250$ rad/s can be derived as

$$\dot{X} = \Omega X + B e \quad (2a)$$

$$X(s) = (sI - \Omega)^{-1} B E(s) \quad (2b)$$

$$X(s) = \frac{1}{s^2 + \omega^2} \begin{bmatrix} s & -\omega \\ \omega & s \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} E(s) \quad (2c)$$

$$\text{As } y = C^T X, \text{ and } C^T = [1 \quad 0] \quad (3a)$$

$$\frac{Y(s)}{E(s)} = \frac{s b_1 - \omega b_2}{s^2 + \omega^2}. \quad (3b)$$

The transfer function of (3b) is similar to a peak filter and with the selected value of b_1 and b_2 , the quality can be adjusted. Using these in-phase and quadrature-phase components of load currents, the active and reactive power components of the load currents are estimated as shown in Fig. 2. For generation of reference source currents, in-phase and quadrature-phase unit vectors of PCC voltage are required. Their calculation is described in [25]. The control algorithm for the VSC to act as voltage and frequency controller is shown in Fig. 2. VSC maintains the active power output of the generator thereby regulating the frequency indirectly and it provides reactive power required to maintain the voltage.

B. Mechanical Sensor less-Based MPPT Algorithm for WECS

The wind energy is free energy as there is no fuel cost, so WECS is operated to extract the maximum available power from the wind. An MPPT algorithm is used to perform this task. To simplify the control and to make it cost effective, an MPPT algorithm is used which does not require measurement of any of wind speed, rotor speed, or turbine speed [21]. Hence, mechanical speed sensor is eliminated by virtue of the proposed system configuration and control algorithm. A perturb and observe-based MPPT algorithm is used to control the boost converter which extracts the maximum power from the wind generator. The mathematical formulation for MPPT algorithm is described as

$$(\Delta i_{dc} > 0 \ \& \ \Delta p_{dc} > 0) \ OR \ (\Delta i_{dc} < 0 \ \& \ \Delta p_{dc} < 0)$$

$$\text{if } i_{ref} = i_{dc} + \delta$$

$$(\Delta i_{dc} > 0 \ \& \ \Delta p_{dc} < 0) \ OR \ (\Delta i_{dc} < 0 \ \& \ \Delta p_{dc} > 0)$$

$$\text{If } i_{ref} = i_{dc} - \delta \dots\dots\dots(4)$$

where $p_{dc} = v_{dc}.i_{dc}$ and δ is a small value. The i_{ref} and i_{dc} are reference and sensed inductor current of the boost converter. The current is perturbed by a small value (δ) and the power output is observed for the change. In case, the power increases, the next perturbation is kept in the same direction to force the system toward MPP. However, in case the power decreases, the direction of perturbation is changed to pull back the system toward the MPP.

The duty cycle is used to generate pulse width modulation pulses as shown in Fig. 3.

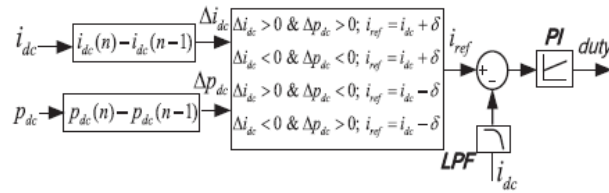


Fig. 3. Control system for WECS.

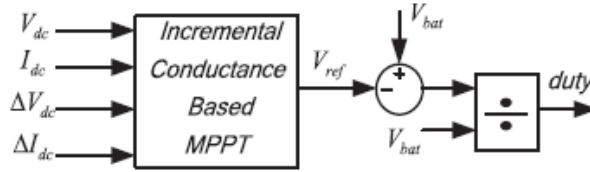


Fig. 4. Control system for solar PV system.

C. Incremental Conductance-Based MPPT Algorithm for Solar PV System

The maximum power available from a solar PV array is extracted using an incremental conductance-based algorithm [23]. This MPPT algorithm gives the reference voltage of the PV array at which it should be operated to provide maximum power output. The reference duty ratio for the boost converter switch is estimated using reference PV array voltage and the known battery voltage. The corresponding gate pulse for the boost converter switch is generated as shown in Fig. 4.

D. Charge Discharge Control of Battery Storage

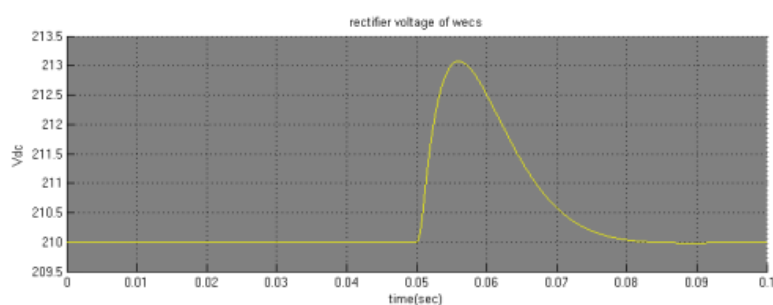
As the focus of the paper is on the hybrid generation system, the battery charge discharge control is not considered much. But this section is dedicated to provide some idea behind power flows in the topology and how battery status can be monitored and controlled. It can be seen that other than battery, all the other currents/powers are measured. So it would not be difficult to estimate the battery current and take actions accordingly. If some situation arises where

the charge discharge has to be exactly monitored, a current sensor can be installed in the system to measure the battery current. The battery voltage is already being measured and these can be used to determine the state of charge and other parameters to control charge discharge.

4 SIMULATION RESULTS AND DISCUSSION

A. Steady State and Dynamic Performance of Simulation-Based Verification of MPPT Algorithm for WECS

As described earlier, the complete system is simulated using MATLAB/SIMULINK and from simulation results the MPPT of WECS is verified. The pitch angle is taken as fixed and the base wind speed as 10 m/s. The corresponding performance of the MPPT algorithm under variable wind operation is shown in Fig.5. The results with constant wind speed are shown in Fig.5 until $t=4$ s. The wind speed is changed from 10 to 12 m/s at $t = 4$ s. The dynamic behaviour of the system is demonstrated during such variation in wind speed. From these results, it is seen that with an increase in the wind speed, the power output of the WECS increases and also it can be seen that the PMBLDCG current has also increased.



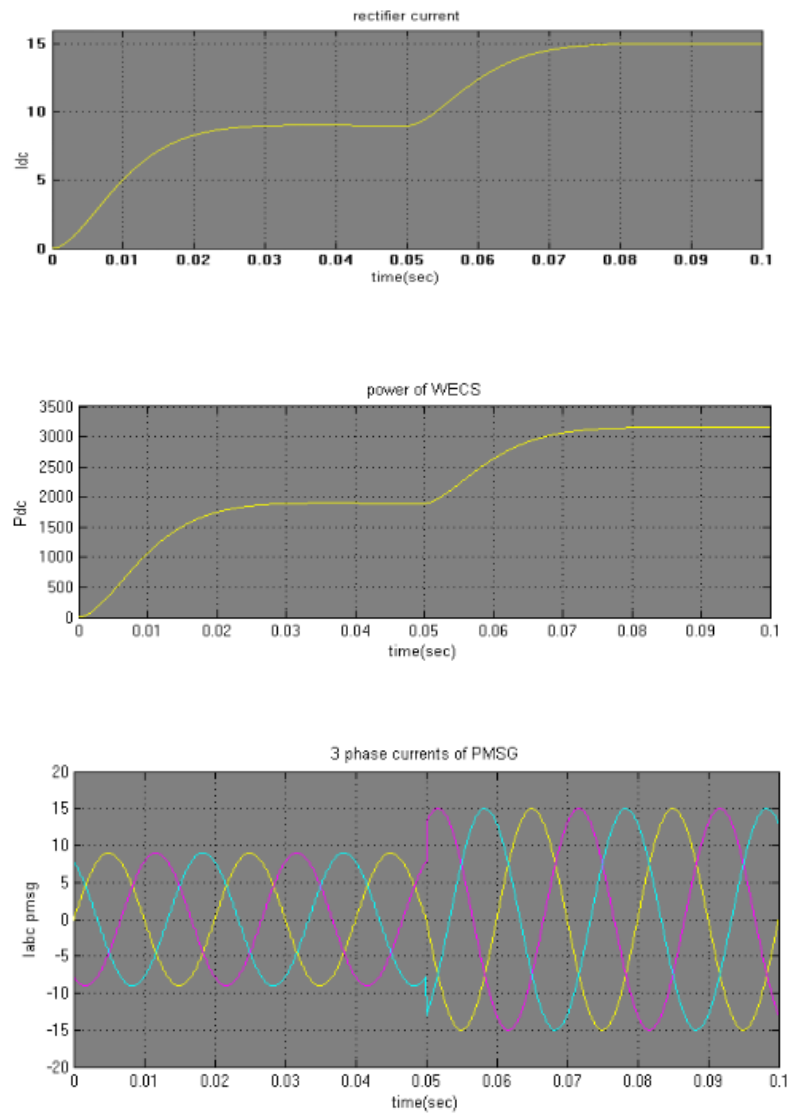
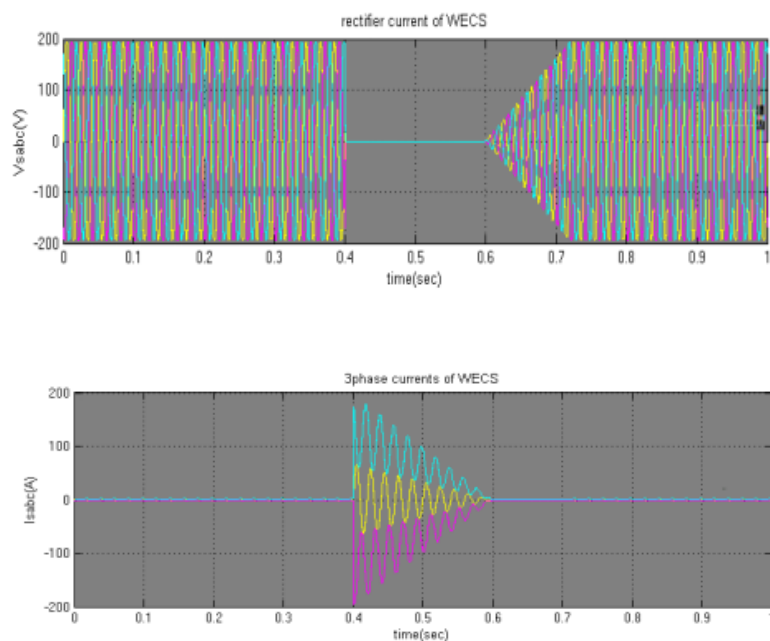


Fig:5. Performance of WECS under varying wind speed.

D. System Performance Under Faulted Condition

This section provides a brief understanding of how the system will

behave under some fault conditions. The fault situations are created and analyzed using simulation tool. First case is taken where the fault is created at the ac bus. Current through the converter is controlled within the control algorithm. As the currents are non sinusoidal, a hard current limit is used to protect the devices and the system. If the switching devices have their own protection system (like desaturation for IGBTs), then an indirect current control can be used, which requires only source currents. But those protections are latchable (shutdown the system), so it is better to limit the current without disrupting the operation. That is why a direct current control incorporating compensator currents is used. The results are shown in Fig.6.



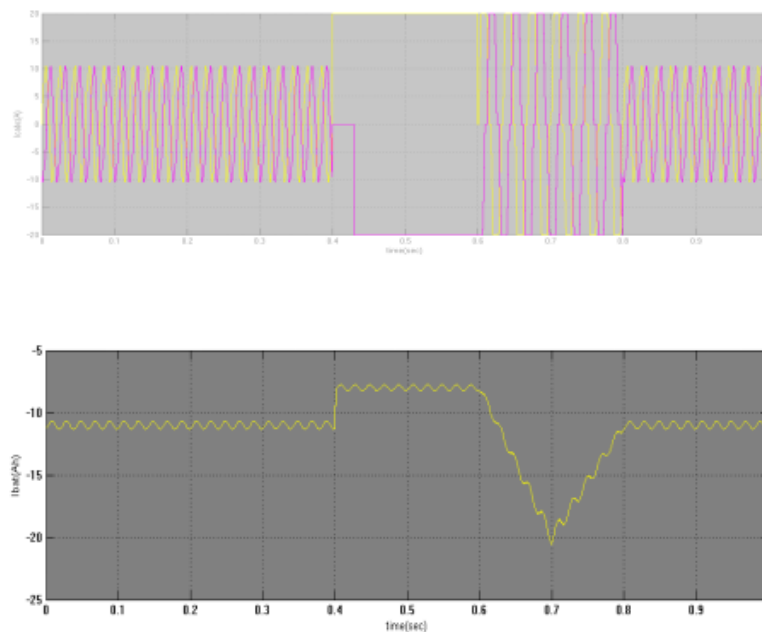


Fig.6. System performance under faulted condition.

As shown in Fig.8, the reactive power support to the generator is mostly provided by the converter and with the fault on the ac line, the reactive power diverts to the low-impedance fault path and the generators voltage collapses. But as soon as the fault is cleared, the generator picks up again. Another advantage of this system is that it is a machine-based system and hence the generator majorly contributes to the fault current, which has a large short circuit rating compared to the semiconductor devices. Moreover, the fault current in such cases is large, which makes the protection system design easier. Other case could be fault at the dc bus, which is catastrophic in every case of energy storage. In that case, the battery will be protected by the fuse or MCB and the system has to shut down. Or in some cases, the storage can be isolated and the load can be fed by generator, but that can be achieved only by observing the load conditions and maintaining power balance, e.g., shedding load in case of overload. In that case, the converter can act as a shunt compensator to provide reactive power support.

5 CONCLUSION

The proposed micro grid topology with a single voltage source converter and brushless generators has been implemented under various operating conditions. An integrated operation of control algorithms is also tested for systems voltage and frequency control, mitigation of power quality issues, power balance in the whole system under various disturbances ranging from large load variation to renewable energy supply uncertainty. Some idea of battery charge/discharge control and fault analysis is also discussed. Test results have confirmed the suitability of this topology for rural/isolated areas as the topology is simple and cost effective.

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