Grid Connected PV- Wind - Battery Based NPC with Multi Input Transformer Coupled Bi directional DC – DC Converter for Home Appliances

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***ABSTRACT*—a new control strategy for an efficient multi-input transformer-coupled bidirectional dc–dc converter for power flow management in a grid-connected hybrid photovoltaic (PV)–wind-battery-based system is presented in this paper. A transformer-coupled boost half-bridge converter is used to harness power from wind, while a bidirectional buck– boost converter is used to harness power from PV along with battery charging/discharging control. A single phase NPC Inverter is used for feeding ac loads and interaction with the grid. The proposed system aims to satisfy the load demand, manage the power flow from different sources, inject the surplus power into the grid, and charge the battery from the grid as and when required. Also, the proposed converter architecture has reduced number of power conversion stages with less component count and reduced losses compared with existing grid-connected hybrid systems. This improves the efficiency and the reliability of the system. Simulation results obtained using MATLAB/Simulink show the performance of the proposed control strategy for power flow management under various modes of operation.**

***Index Terms*— buck-boost converter, full-bridge bidirectional converter, hybrid system, MPPT, photovoltaic (PV), NPC inverter, WECS ,transformer-coupled boost dual-half-bridge bidirectional converter*.

I. INTRODUCTION

During recent years, the world is moving towards to the renewable energy sources due to the increase in fossil fuel prices, exhausting fossil fuel and the environmental problems caused by the use of conventional fuel sources. Among the renewable power generators, solar and wind are the most encouraging energy sources and are being increasingly used [1]. Wind power alone already provides a huge share of electricity in many areas. In the near future the electric

Grid will include a large number of small energy producers by the combination of renewable energy sources such as solar panels or wind generators to the grid. It is a challenge to supply stable and continuous power using these sources. This issue can be solved efficiently by integrating with energy storage elements.

To achieve the combination of multiple renewable sources, the traditional technique includes using committed single-input converters one for each source, which are associated to a common dc-bus [1]–[15]. However, these converters are not effectively utilized, due to the intermittent nature of the renewable sources. In addition, there are multiple power conversion stages which decrease the efficiency of the system.

In this paper, the sources and storage are interfaced at the dc-link through their devoted converters. Other contributions are made on their modeling characteristics and control systems for a stand-alone hybrid energy system in [9]–[15]. Dynamic performance of a stand-alone hybrid PV–wind system with battery storage is analyzed in [9]. In [14], a passivity/sliding mode control is presented which controls the operation of wind energy system to suppplement the solar energy generating system. Not many attempts are made to optimize the circuit con-figuration of these systems that could reduce the cost and increase the efficiency and reliability. In [16]–[19], integrated converters for PV and wind energy systems are presented.

An integrated four-port topology dependent on hybrid PV–wind system is proposed in [18]. However, despite simple topology, the control scheme used is complex. In [19], to feed the dc loads, a low capacity multiport converter for a hybrid system is presented. Hybrid PV–wind-based generation of electricity and its interface with the power grid are the important research areas. Chen et al. [20], [21] have proposed a multi-input hybrid PV–wind power generation system which has a buck/buck– boost-fused multi-input dc–dc converter and a full-bridge dc–ac inverter. This system is mainly focused on improving the dc-link voltage regulation. In the six-arm converter topology proposed in [22], the outputs of a PV array and wind generators are fed to a boost converter to match the dc-bus voltage.

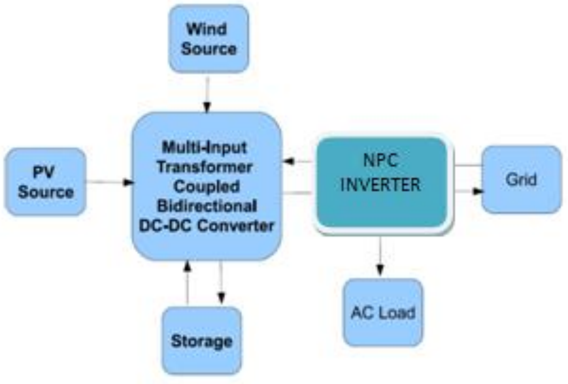
This paper focuses on system engineering, such as energy generation, system reliability, unit sizing, and cost analysis. The use of multi-input converter for hybrid power systems is attracting increasing attention because of reduced component count, enhanced power density, compactness, and centralized control. Because of these advantages, many topologies are pro-posed, and they can be classified into three groups, namely, nonisolated, fully isolated, and partially isolated multiport topologies.

All the power ports in nonisolated multiport topologies share a common ground. To derive the multiport dc–dc converters, a series or parallel configuration is employed in the input side [23]–[25]. Some components can be shared by each input port. However, a time-sharing control scheme couples each input port, and the flexibility of the energy delivery is limited. The series or parallel configuration can be extended at the output to derive multiport dc–dc converters. However, the power components cannot be shared. All the topologies in nonisolated multiport are mostly combinations of the basic topology units, such as the buck, the boost, the buck–boost, or the bidirectional buck/boost topology unit. These time-sharing-based multiport topologies promise low cost and simple execution. However, a common limitation is that power from multiple inputs cannot be simultaneously transferred to the load. Furthermore, matching wide voltage ranges will be difficult in these circuits.

The magnetic coupling approach is used to derive a multi-port converter where the multi winding transformer is employed to combine each terminal. In fully isolated multi-port dc–dc converters, the half-bridge, full-bridge, and hybrid-structure-based multiport dc–dc converters with a magnetic coupling solution can be derived for various applications, power, voltage, and current levels. The snubber capacitors and transformer leakage inductance are employed to accomplish soft-switching by adjusting the phase-shift angle. However, the circuit layout is complex, and the only sharing component is the multiwinding transformer. Therefore, the disadvantage of time-sharing control to couple input port is overcome. Here, among multiple inputs, each input has its own power components which increase the component count. In addition, the design of multiwinding transformer is an involved process.

In order to address the above-mentioned limitations, partially isolated multiport topologies are becoming increasingly attractive. In these topologies, some power ports share a common ground, and these power ports are isolated from the remaining for matching port voltage levels.

A trimodal half-bridge topology is basically a modified version of the half-bridge topology with a free-wheeling circuit branch consisting of a diode and a switch across the primary winding of the transformer. The magnetizing inductance of the transformer is used to store energy and to interface the sources/storage devices. A decoupled-controlled triport dc–dc converter for multiple energy interfaces has enhanced power density and the circuit structure is simplified. However, it can interface only one renewable source and energy storage element. Furthermore, the pulsewidth modulation plus phase-shift control strategy is introduced to provide two control freedoms and achieve the decoupled voltage regulation within a specific operating range.



v

Fig. 1. Grid-connected hybrid PV–wind-battery-based system for household applications

All the state of the art on converter topologies presented so far can accommodate only one renewable source and one energy storage element. Whereas the proposed topology is capable of interfacing two renewable sources and an energy storage element. Hence, it is more reliable, as two different types of renewable sources, such as PV and wind, are used either individually or simultaneously without an increase in the component count compared with the existing state-of-the-art topologies.

The proposed system has two renewable power sources, load, grid, and battery. Hence, a power flow management system is essential to balance the power flow among all these sources. The main objectives of this system are as follows.

1) To explore a multi objective control scheme for optimal charging of the battery using multiple sources.

2) Supplying uninterruptible power to loads.

3) Ensuring the evacuation of surplus power from the renewable sources to the grid, and charging the battery from the grid as and when required.

The grid-connected hybrid PV–wind-battery-based system for home appliances is shown in Fig. 1, which can work either in stand-alone or in grid-connected modes. This system is suitable for home appliances, where a low-cost, simple and compact topology capable of autonomous operation is desirable. The core of the proposed system is the multi-input transformer-coupled bidirectional dc–dc converter that interconnects various power sources and the storage element. Furthermore, a control scheme for effective power flow management to provide uninterrupted power supply to the loads while injecting excess power into the grid is proposed. Thus, the proposed configuration and control scheme provide an elegant integration of PV and wind energy source. It has the following advantages.

1) The maximum power point (MPP) tracking of both the sources, battery charging control, and bidirectional power flow is accomplished with six controllable switches.

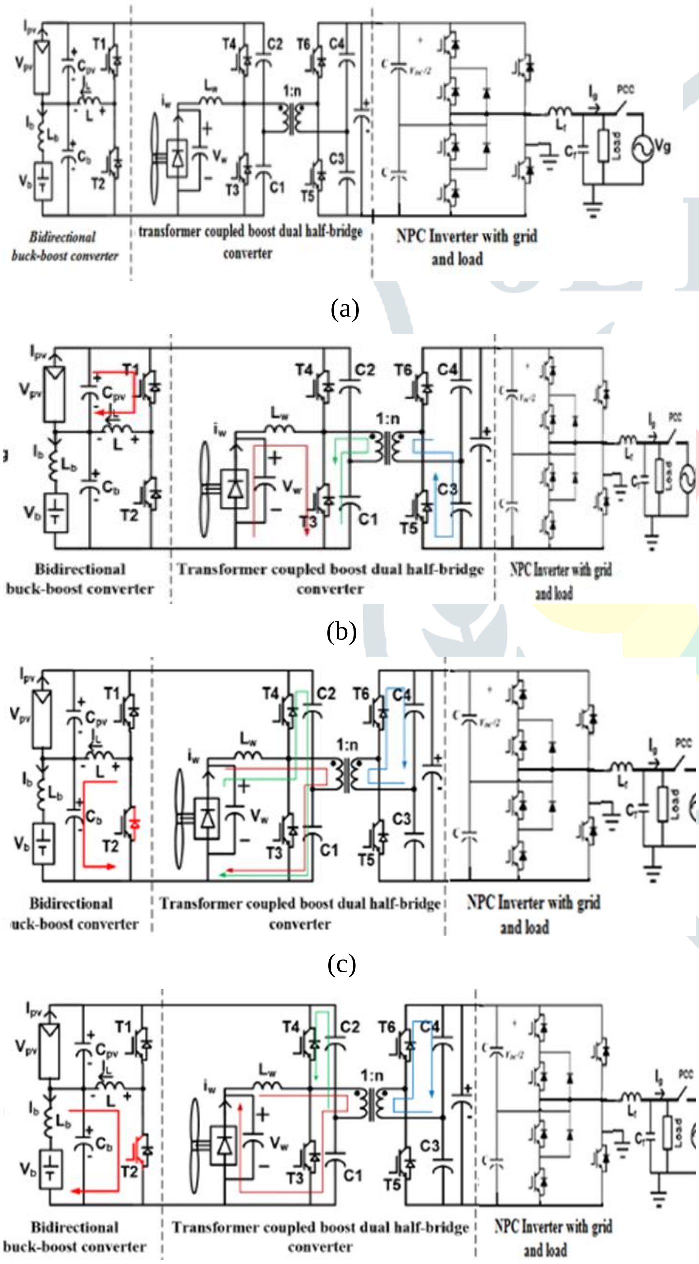
2) The voltage boosting ability is accomplished by connecting PV and battery in series which is additionally improved by a high-frequency step-up transformer.

3) The improved utilization factor of the power converter, since the utilization of dedicated converters for ensuring MPP operation of both the sources is eliminated.

4) Galvanic isolation between the input sources and the load.

5) The proposed controller can operate in various modes of a grid-connected scheme, ensuring proper operating mode selection and smooth transition between various possible operating modes.

6) Enhancement in the battery charging efficiency as a single converter is present in the battery-charging path from the PV source.



(a)

(b)

(c)

(d)

Fig. 2. Operating modes of the proposed multi-input transformer-coupled bidirectional dc–dc converter. (a) Proposed converter configuration. (b) Operation when switch T3 is turned ON. (c) Operation when switch T4 is ON, charging the capacitor bank. (d) Operation when switch is T 4 ON, capacitor C2 discharging.

The fundamental philosophy and preliminary study of a compact and low-cost multi-input transformer-coupled dc–dc converter capable of interfacing multiple sources for a stand-alone application. In this paper, the integration of renewable sources to the grid, detailed analysis, exhaustive simulation, and experimental studies have now been included.

II. CONVERTER CONFIGURATION

The proposed converter consists of a transformer-coupled boost dual-half-bridge bidirectional converter fused with a bidirectional buck–boost converter and a single-phase full-bridge inverter. The proposed converter has decreased number of power conversion stages with less component count and high efficiency compared with the existing grid-connected schemes. The topology is simple and needs only six power switches. The schematic of the converter is shown in Fig. 2(a). The boost dual-half-bridge converter has two dc-links on both the sides of the high-frequency transformer. Controlling the voltage of one of the dc-links ensures controlling the voltage of the other. This makes the control strategy simple. Moreover, additional converters can be integrated with any one of the two dc-links. A bidirectional buck–boost dc–dc converter is integrated with the primary side dc-link, and a single-phase full-bridge bidirectional converter is connected to the dc-link of the secondary side.

The input of the half-bridge converter is framed by interfacing the PV array in series with the battery, thereby incorporating an inherent boosting stage for the scheme. The boosting capability is further enhanced by a high-frequency step-up transformer. The transformer also ensures galvanic isolation to the load from the sources and the battery. A bidirectional buck–boost converter is used to harness power from PV along with battery charging/discharging control. The unique feature of this converter is that MPP tracking, battery charge control, and voltage boosting are accomplished through a single converter. A transformer-coupled boost half-bridge converter is used for harnessing power from wind, and a single-phase full-bridge bidirectional converter is used for feeding ac loads and interaction with the grid. The proposed

$$V_{dc} = V_{C3} + V_{C4} = k\,\frac{V_w}{(1-E_w)} \qquad (1)$$

Therefore, the output voltage of the secondary side dc-link is a function of the duty cycle of the primary side converter and turns ratio of transformer.

In the proposed configuration, as shown in Fig. 2(a), a bidirectional buck–boost converter is used for MPP tracking of PV array and battery charging/discharging control. Furthermore, this bidirectional buck–boost converter charges/discharges the capacitor bank $C1$–$C2$ of the transformer-coupled half-bridge boost converter based on the load demand. The half-bridge boost converter extracts energy from the wind source to the capacitor bank $C1$–$C2$. During battery-charging mode, when switch $T\,1$ is ON, the energy is stored in the inductor L. When switch $T\,1$ is turned OFF and $T\,2$ is turned ON, energy stored in L is transferred to the battery. If the battery discharging current is more than the PV current, inductor current becomes negative. Here, the stored energy in the inductor increases when $T\,2$ is turned ON and decreases when $T\,1$ is turned ON. It can be proved that $V_b = \left(\frac{E}{1-E}\right) V_{pv}$. The output voltage of the transformer-coupled boost half-bridge converter is given by

$$V_{dc} = k(V_{C1} + V_{C2}) = k\left(V_b + V_{pv}\right) = \frac{kV_w}{(1-E_w)} \qquad (2)$$

This voltage is k times of primary side dc-link voltage. The primary side dc-link voltage can be controlled by Half-bridge boost converter or by bidirectional buck-boost converter. The relationship between the average value of inductor, PV, and battery current over a switching cycle is given by $I_L = I_b + I_{pv}$. It is evident that I_b and I_{pv} can be controlled by controlling I_L. Therefore, the MPP operation is assured by controlling I_L while maintaining a proper battery charge level. I_L is used as inner loop control parameter for faster dynamic response while for outer loop, capacitor voltage across PV source is used for ensuring MPP voltage. An incremental conductance method is used for MPP tracking (MPPT).

A. Limitations and Design Issues

The output voltage $V_{dc}$of the transformer-coupled boost dual half-bridge converter depends on the MPP voltage of PV array V_{pvmpp}, the battery voltage V_b,and the transformer turns ratio k". Since the environmental conditions influence PV array voltage and the battery voltage depends on its charge level, the output dc-link voltage V_{dc} is also influenced by the same. However, the PV array voltage exhibits narrow variation in voltage range with wide variation in environmental conditions. On the other hand, the battery voltage is generally stiff and it remains within a limited range over its entire charge–discharge cycle. Furthermore, the state of charge limits the operating range of the batteries used in a stand-alone scheme to avoid overcharge or discharge. Therefore, with proper selection of n, PV array, and battery voltage, the output dc-link voltage V_{dc} can be kept within an allowable range, though not controllable. However, when there is no PV power, by controlling the PV capacitor voltage, the output dc-link voltage V_{dc} can be controlled.

III. POWER FLOW MANAGEMENT

A grid-connected hybrid PV–wind-battery-based system consisting of four power sources (grid, PV, wind source, and battery), and three power sinks (grid, battery, and load) requires a control scheme for power flow management to balance the power flow among these sources.

The control philosophy for power flow management of the multisource system is developed based on the power balance principle. In the stand-alone case, PV and wind source generate their corresponding MPP power, and load takes the required power. In this case, the power balance is achieved by charging the battery until it reaches its maximum charging current limit Ib max. Upon reaching this limit, to ensure power balance, one of the sources or both have to deviate from their MPP power based on the load demand. In the grid-connected system, both the sources always operate at their MPP. In the absence of both the sources, the power is drawn from the grid to charge the battery as and when required. The equation for the power balance of the system is given by

$$V_{pv}I_{pv} + V_wI_w = V_bI_b + V_gI_g \qquad (3)$$

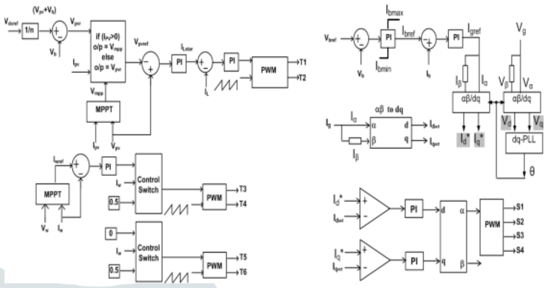


Fig. 3. Proposed control scheme for power flow management of a grid-connected hybrid PV–wind-battery-based system.

The peak value of the output voltage for a single-phase full-bridge inverter is

$$V = s_aV_{dc} \qquad (4)$$

and the dc-link voltage is

$$V_{dc} = k\left(V_{pv} + V_b\right) \qquad (5)$$

Hence, substituting for V_{dc} in (4) gives

$$V_g = \frac{1}{\sqrt{2}} s_a k\left(V_{pv} + V_b\right) \qquad (6)$$

In the boost half-bridge converter

$$V_w = (1 - E_w)\left(V_{pv} + V_b\right) \qquad (7)$$

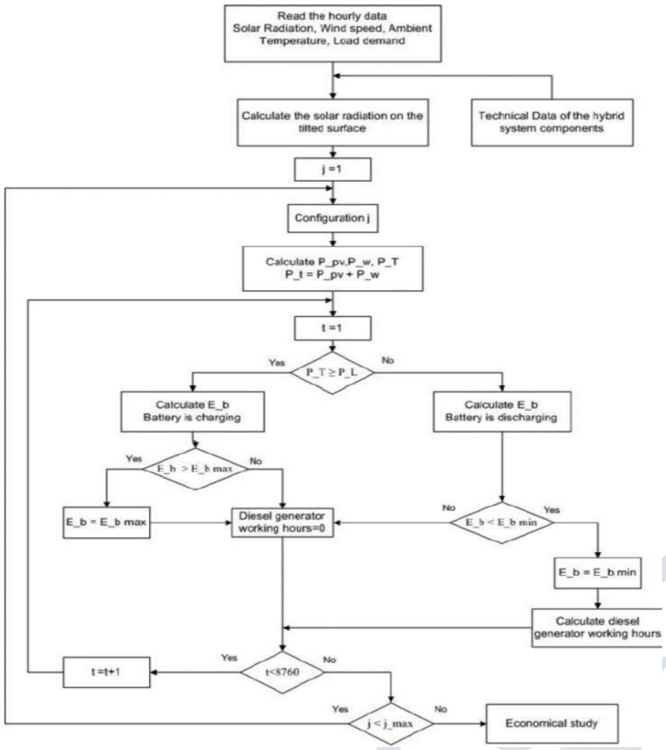
Now, substituting Vw and Vg in (3)

$$V_{pv}I_{pv} + \left(V_{pv} + V_b\right)(1 - E_w)I_w$$

$$= V_bI_b + \frac{1}{\sqrt{2}} s_a k\left(V_{pv} + V_b\right)I_g \qquad (8)$$

After simplification

$$I_b = I_{pv}\left(\frac{1 - E_{pv}}{E_{pv}}\right) + I_w\left(\frac{1 - E_w}{E_{pv}}\right) - I_g\left(\frac{s_a k}{\sqrt{2}E_{pv}}\right) \qquad (9)$$



From (9), it is evident that if there is a change in power extracted from either PV or wind source, the battery current can be regulated by controlling the grid current I_g. Hence, the control of a single-phase full-bridge bidirectional converter depends on the availability of grid, power from PV and wind sources, and battery charge status. Its control strategy is shown in Fig. 3. To ensure the supply of uninterrupted power to critical loads, priority is given to charge the batteries. After reaching the maximum battery charging current limit I_b max, the surplus power from renewable sources is fed to the grid. In the absence of these sources, battery is charged from the grid.

From (9), it is evident that if there is a change in power extracted from either PV or wind source, the battery current can be regulated by controlling the grid current Ig. Hence, the control of a single-phase full-bridge bidirectional converter depends on the availability of grid, power from PV and wind sources, and battery charge status. Its control strategy is shown in Fig. 3. To ensure the supply of uninterrupted power to critical loads, priority is given to charge the batteries. After reach-ing the maximum battery charging current limit Ib max, the surplus power from renewable sources is fed to charge from the the grid. In the absence of these sources, battery is grid.

TABLE I: SIMULATION PARAMETERS

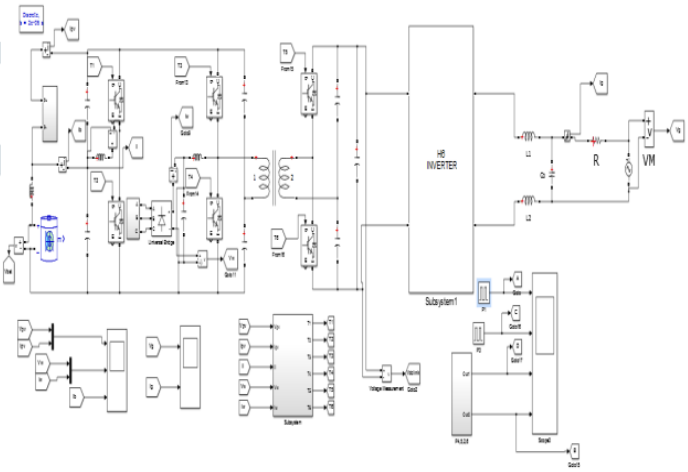
Parameter	Value
Solar PV power	525 W (I_{mpp} = 14.8 A) (V_{mpp} = 35.4 V)
Wind power	300 W (I_{mpp} = 8 A) (V_{mpp} = 37.5 V)
Switching frequency	15 kHz
Transformer turns ratio	5.5
Inductor-half bridge boost converter, L_w	500 μH
Inductor-bidirectional converter L	3000 μH
Primary side capacitors C1-C2	500μF
secondary side capacitors C3-C4	500μF
Secondary side capacitor for the entire dc-link	2000 μF
Battery capacity & voltage	400 Ah, 36 V

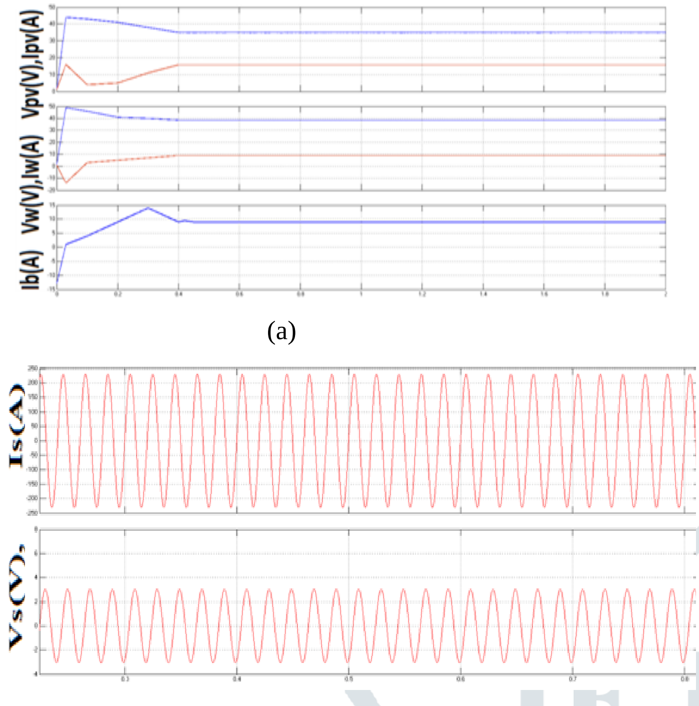
IV. MATLAB/SIMULATION RESULTS

Detailed simulation studies are carried out on the MATLAB/Simulink platform, and the results obtained for various operating conditions are presented in this section. The values of parameters used in the model for simulation are listed in Table I.

The steady-state response of the system during the MPPT mode of operation is shown in Fig. 4. The values for source-1 (PV source) is set at 35.4 V (V_{mpp}) and 14.8 A (Impp), and for source-2 (wind source) is set at 37.5 V (V_{mpp}) and 8 A (Impp). It can be seen that V_{pv} and I_{pv} of source-1, and V_w and I_w of source-2 attain set values required for MPP operation. The battery charged with the constant magnitude of current, and the remaining power is fed to the grid.

The system response for step changes in the source-1 insolation level while operating in the MPPT mode is shown in Fig. 5. Until 2 s, both the sources are operating at MPPT and charging the battery with constant current and the remaining power is fed to the grid. At instant 2 s, the source-1 insolation level is increased. As a result, the source-1 power increases, and both the sources continue to operate at MPPT.





(a)

(b)

Fig. 4. Steady-state operation in the MPPT mode (a) Simulink Model (b) Output Results

Though the source-1 power has increased, the battery is still charged with the same magnitude of current, and power balance is achieved by increasing the power supplied to the grid. At instant 4 s, the insolation of source-1 is brought to the same level as before 2 s. The power supplied by source-1 decreases. Battery continues to get charged at the same magnitude of current, and power injected into the grid decreases. The same results are obtained for step changes in the source-2 wind speed level. These results are shown in Fig. 6.

The response of the system in the absence of source-1 is shown in Fig. 7. Until time 2 s, both the sources are generating the power by operating at their corresponding MPPT and charging the battery at constant magnitude of current, and the remaining power is being fed to the grid. At 2 s, source-1 is disconnected from the system. The charging current of the battery remains constant, while the injected power to the grid reduces.

At instant 4 s, source-1 is brought back into the system. There is no change in the charging rate of the battery. The additional power is fed to the grid. The same results are obtained in the absence of source-2. These results are shown in Fig. 8. Fig. 9 shows the results in the absence of both PV and wind power, battery is charged from the grid.

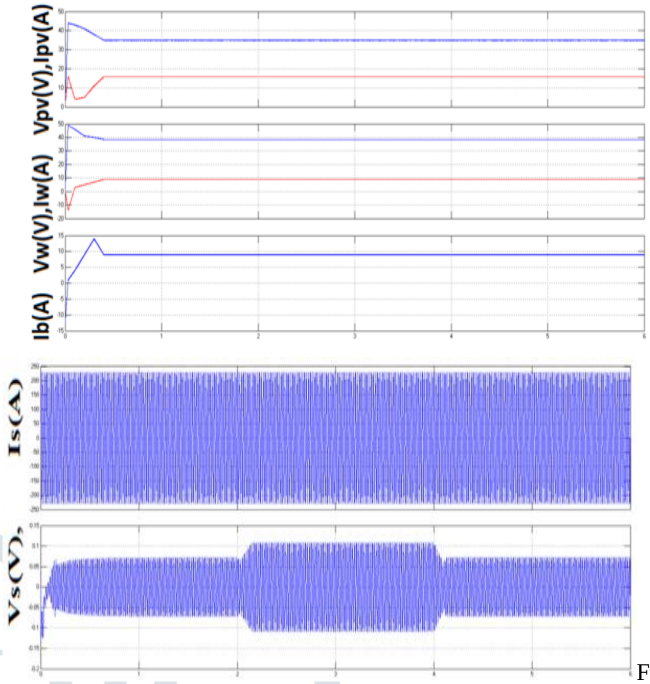


Fig. 5. Response of the system for changes in an insolation level of source-1 (PV source) during operation in the MPPT mode.

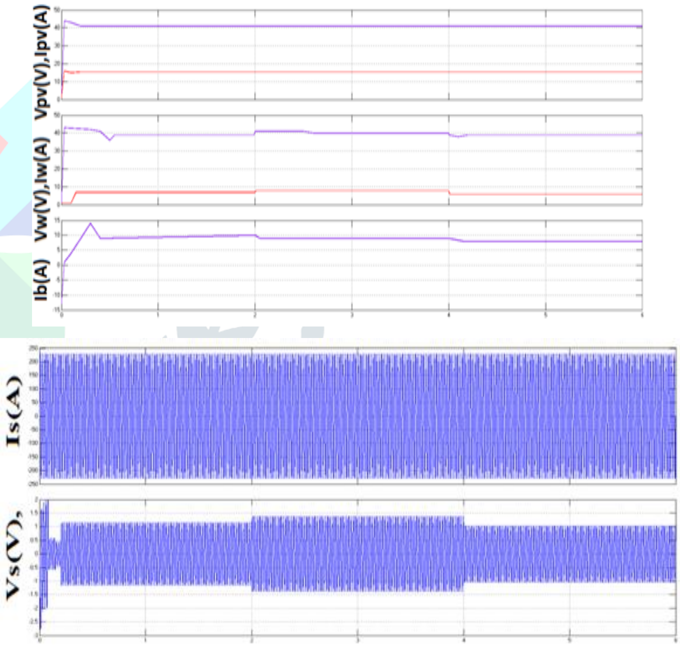
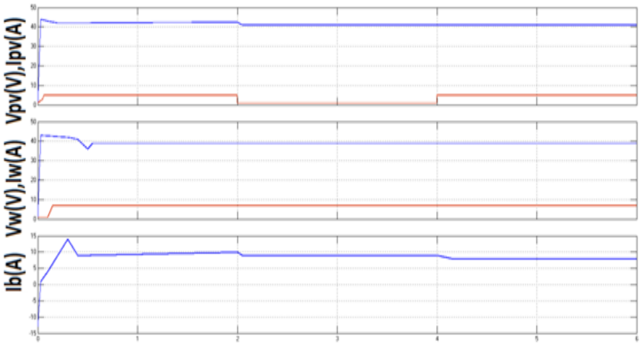


Fig. 6. Response of the system for changes in wind speed level of source-2 (wind source) during operation in the MPPT mode.



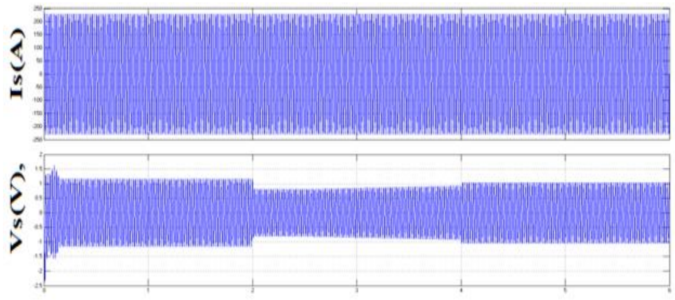


Fig. 7. Response of the system in the absence of source-1 (PV source), while source-2 continues to operate at MPPT.

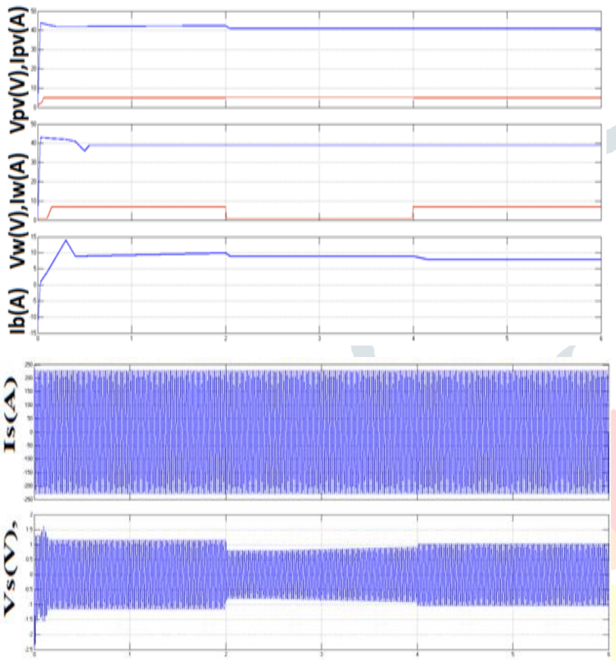


Fig. 8. Response of the system in the absence of source-2 (wind source), while source-1 continues to operate at MPPT.

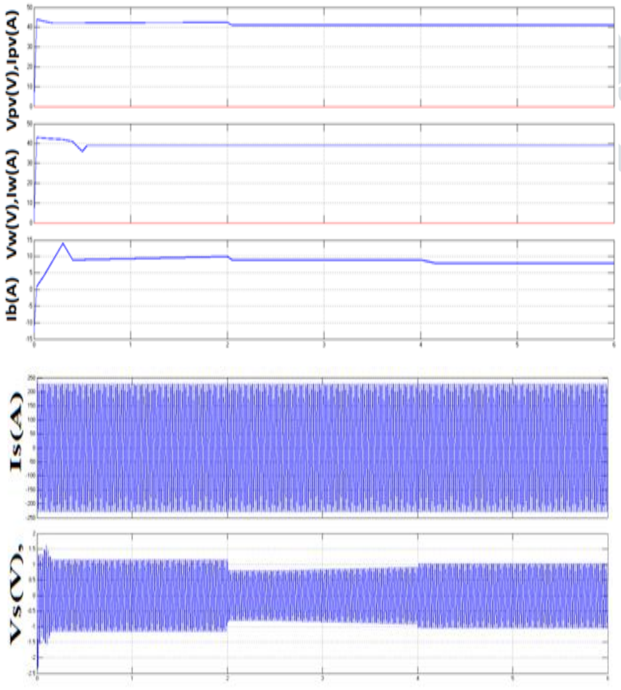


Fig. 9. Response of the system in the absence of both the sources and charging the battery from the grid.

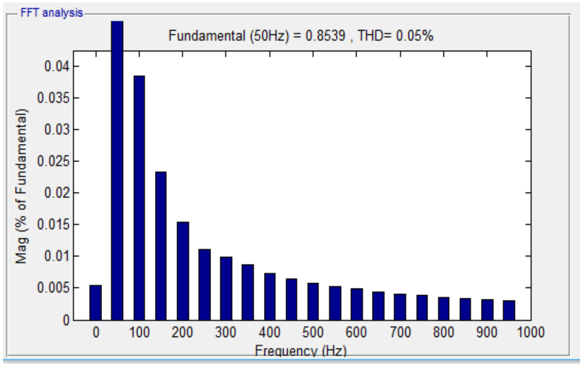


Fig .10 . THD Values of the Grid Current in %

V CONCLUSION

A grid-connected hybrid PV–wind-battery-based power evacuation scheme for household application is proposed. The proposed hybrid system provides an elegant integration of PV and wind source to extract maximum energy from the two sources. It is realized by a novel multi-input transformer coupled bidirectional dc–dc converter followed by a conventional full-bridge inverter. A versatile control strategy which achieves a better utilization of PV, wind power, battery capacities without effecting life of battery, and power flow management in a grid-connected hybrid PV–wind-battery-based system feeding ac loads is presented. Detailed simulation studies are carried out to ascertain the viability of the scheme. The MATLAB simulation results obtained are in close agreement with simulations and are supportive in demonstrating the capability of the system to operate either in grid feeding or in stand-alone modes. The proposed configuration is capable of supplying uninterruptible power to ac loads, and ensures the evacuation of surplus PV and wind power into the grid.

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