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Multi-Input Transformer Coupled Bidirectional DC-DC Converter Based Grid-Connected PV-Wind-Battery for Induction motor Drive applications

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Abstract: *Renewable energy sources have become a popular alternative electrical energy source where power generation in conventional ways is not practical. In the last few years the photovoltaic and wind power generation have been increased significantly. In this study, we proposed a hybrid energy system which combines both solar panel and wind turbine generator as an alternative for conventional source of electrical energy like thermal and hydro power generation. A simple control technique which is also cost effective has been proposed to track the operating point at which maximum power can be coerced from the PV system and wind turbine generator system under continuously changing environmental conditions. The wind and solar PV system are connected to the common load through Bidirectional DC-DC converter. The converter is designed to drive a induction motor directly from photovoltaic (PV) energy source and a wind generation. The modeling and simulation of hybrid system along with the Induction Motor drive is implemented and results verified by using MATLAB/SIMULINK.*

Keywords—Hybrid system, solar photovoltaic, wind energy, transformer coupled boost dual-half-bridge bidirectional converter, bidirectional buck-boost converter, maximum power point tracking, full bridge bidirectional converter, battery charge control.

1 INTRODUCTION

In recent days, the number of applications which require more than one power source is increasing. Distributed generating systems or micro-grid systems normally use more than one power source or more than one kind of energy source. Also, to increase the utilization of renewable energy sources, diversified energy source combination is recommended. The combination of more power sources and diversified power sources make it possible to obtain higher availability in a power system. A parallel connection of converters has been used to integrate more than one input energy source in a power system. However, a MIC [1]-[4] can generally have the following advantages compare to a combination of several individual converters like cost reduction, compactness, more expandability and greater manageability. MICs are being used in aerospace, electric and hybrid vehicles, sustainable energy sources and micro grid applications. India has tremendous energy requirements and increasing intricacy in meeting those needs through conventional means of power generating system. Consumption of electricity has been rising at fastest rates in the world owing to growing population and economic development. Our economy has been put forth to increasing challenges since energy supply is struggling to meet the demand and there are energy shortages almost many places in the country. Such continual lack of energy and unreliable supplies warn our economic growth.

Renewable Energy Sources (RES) [5] such as solar and wind, produce power intermittently according to the weather conditions rather than to the power demanded. Energy Storage Systems may be used to mitigate the intermittent generation from RES and to increase the quality of power supply. This makes it difficult to integrate the power generated from these RES into the electric network. One major benefit with the use of renewable sources is that as it is renewable and so will never run out. Their fuel being obtained from natural and readily available resources reduces the operation cost and maintenance. Even more significantly, renewable energy produces little or no waste products such as carbon dioxide or other chemical pollutants, so has negligible impact on the environment. Human activity is overfilling our atmosphere with carbon dioxide and other global warming emissions, which trap heat, steadily drive up earth's temperature, and create harmful impacts on our health, surroundings and climate.

Electricity production is majorly generated by coal-fired power plants which emits global warming gases. The air and water pollutants emitted by coal and natural gas plants are avoided by using RES.

Hence, Solar and Wind energy [6]- [9] sources are considered as the input sources for MIC.

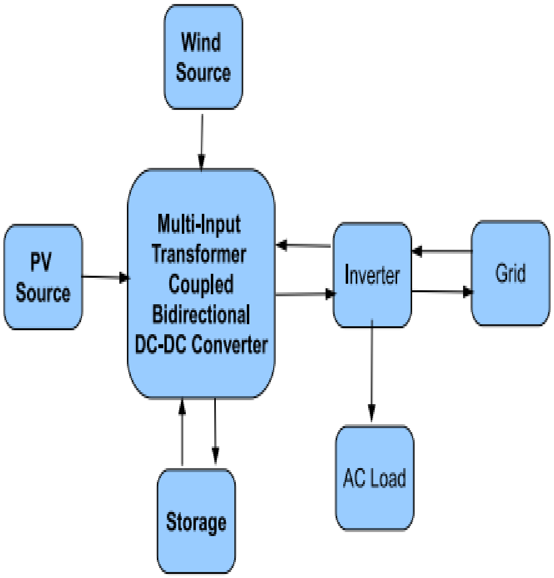


Fig 1. Grid-connected hybrid PV-wind-battery based system for household applications.

The use of multi-input converter (MIC) for hybrid power systems is attracting increasing attention because of reduced component count, enhanced power density, compactness and centralized control. Due to these advantages, many topologies are proposed and they can be classified into three groups, non-isolated, fully-isolated and partially-isolated multi-port topologies.

All the power ports in non-isolated multi-port topologies share a common ground. To derive the multi-port dc-dc converters, a series or parallel configuration is employed in the input side [23] - [27]. 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 multi-port dc-dc converters [28]. However, the power components cannot be shared. All the topologies in non-isolated multi-port are mostly combinations of basic topology units, such as the buck, the boost, the buck-boost or the bidirectional buck/boost topology unit. These timesharing based multi-port topologies promise low-cost and easy implementation. However, a common limitation is that power from multiple inputs cannot be transferred simultaneously to the load. Further, matching wide voltage ranges will be difficult in these circuits. This made the researchers to prefer isolated multi-port converters compared to non-isolated multi-port dc-dc converters.

The magnetic coupling approach is used to derive a multiport converter [29] - [32], where the multi-winding transformer is employed to combine each terminal. In fully isolated multiport dc-dc converters, the half-bridge, full-bridge, and hybrid structure based multi-port dc-dc converters with a magnetic coupling solution can be derived for different applications, power, voltage, and current levels. The snubber capacitors and transformer leakage inductance are employed to achieve soft switching by adjusting the phase-shift angle. However, the circuit layout is complex and the only sharing component is the multi-winding transformer. So, the disadvantage of timesharing control to couple input port is overcome. Here, among multiple inputs, each input has its own power components which increase the component count. Also, the design of multi-winding transformer is an involved process.

In order to address the above limitations, partially isolated multi-port topologies [33] - [39] 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 tri-modal half-bridge topology is proposed by Al-Atrash et al. in [33]and [34]. This topology is essentially 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. Wuhua Li et.al. [37] - [38], have proposed a decoupled controlled tri-port dc-dc converter for multiple energy interface. The power density is improved and circuit structure is simplified. However, it can interface only one renewable source and energy storage element. Further, the pulse width modulation plus phase-shift control strategy is introduced to provide two control freedoms and achieve the decoupled voltage regulation within a certain operating range.

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 like PV and wind are used either individually or simultaneously without increase in the component count compared to 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:

- To explore a multi-objective control scheme for optimal charging of the battery using multiple sources.
- Supplying un-interruptible power to loads.
- Ensuring evacuation of surplus power from renewable sources to the grid, and charging the battery from grid as and when required.

The grid-connected hybrid PV-wind-battery based system for household applications is shown in Fig. 1, which can work either in stand-alone or grid connected mode. This system is suitable for household applications, 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. Further, 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:

- MPP tracking of both the sources, battery charging control and bidirectional power flow are accomplished with six controllable switches.
- The voltage boosting capability is accomplished by connecting PV and battery in series which is further enhanced by a high frequency step-up transformer.
- Improved utilization factor of the power converter, since the use of dedicated converters for ensuring MPP operation of both the sources is eliminated.
- Galvanic isolation between input sources and the load.
- The proposed controller can operate in different modes of a grid-connected scheme ensuring proper operating mode selection and smooth transition between different possible operating modes.
- Enhancement in the battery charging efficiency as a single converter is present in the battery charging path from the PV source.

The basic 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 is presented.

2 PROPOSED CONVERTER CONFIGURATION

The proposed converter consists of a transformer coupled boost dual-half-bridge bidirectional converter fused with bidirectional buck-boost converter and a single-phase full-bridge inverter. The proposed converter has reduced number of power conversion stages with less component count and high efficiency compared to the existing grid-connected schemes. The topology is simple and needs only six power switches. The schematic diagram of the converter is depicted in Fig.3.2(a).The boost dual-half-bridge converter has two dc-links on both 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 single-phase full bridge bidirectional converter is connected to the dc-link ofthe secondary side.

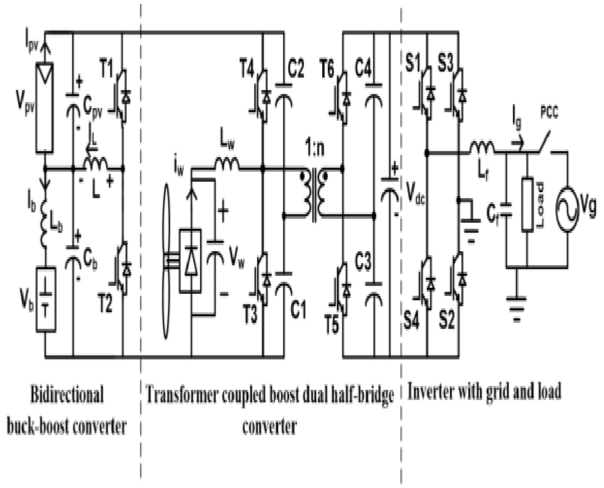
The input of the half-bridge converter is formed by connecting the PV array in series with the battery, thereby incorporating an inherent boosting stage for the scheme. The boosting capability is further enhanced by a high frequency step-up transformer. The transformer also ensures galvanic isolation tothe load from the sources and the battery. 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. 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 grid. The proposed converter has reduced number of power conversion stages with less component count and high efficiency compared to the existing grid-connected converters.

The power flow from wind source is controlled through a unidirectional boost half-bridge converter. For obtaining MPP effectively, smooth variation in source current is required which can be obtained using an inductor. In the proposed topology, an inductor is placed in series with the wind source which ensures continuous current and thus this inductor current can be used for maintaining MPP current. When switch T_3 is ON, the current flowing through the source inductor increases. The capacitor C1 discharges through the transformer primary and switch T_3 as shown in Fig.3.2(b). In secondary side capacitorC3 charges through transformer secondary and anti-parallel diode of switch T_5. When switch T_3 is turned OFF and $T_4$is turned ON, initially the inductor current flows through anti parallel diode of switch T_4 and through the capacitor bank. The path of current is shown in Fig.3.2(c). During this interval, the current flowing through diode decreases and that flowing through transformer primary increases. When current flowing through the inductor becomes equal to that flowing through transformer primary, the diode turns OFF. Since, T_4 is gated ON during this time, the capacitor C_2 now discharges through switch T_4 and transformer primary. During the ON time ofT_4, anti-parallel diode of switch T_6 conducts to charge the capacitor C_4. The path of current flow is shown in Fig.2.2(d).During the ON time of T_3, the primary voltage VP = −VC_1.The secondary voltage $V_S = nV_p = -nV_{C1} = -V_{C3}$, or$VC_3$ = nVC_1 and voltage across primary inductor Lw is Vw. When T_3 is turned OFF and T_4 turned ON, the primary voltage VP = VC_2. Secondary voltage $V_S = nV_P = nV_{C2} = V_{C4}$ and voltage across primary inductor $L_w$is $V_w - (V_{C1} + V_{C2})$.It can be proved that$(V_{C1} + V_{C2}) = \frac{V_w}{(1-D_w)}$. The capacitor voltages are considered constant in steady state and they settle at$V_{C3} = nV_{C1}, V_{C4} = nV_{C2}$. Hence the output voltage is given by

$$V_{dc} = V_{C3} + V_{C4} = n\frac{V_w}{(1 - D_w)} \tag{1}$$

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.3.2(a), a bidirectional buck-boost converter is used for MPP tracking of PV array and battery charging/discharging control. Further, this bidirectional buck-boost converter charges/discharges the capacitor bank C1-C2 of 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.



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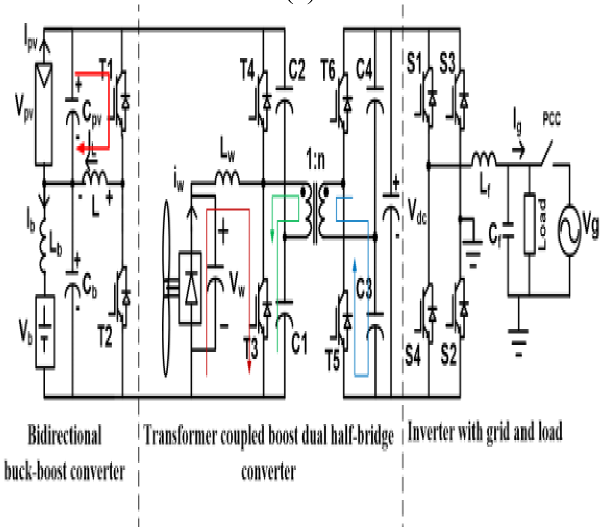

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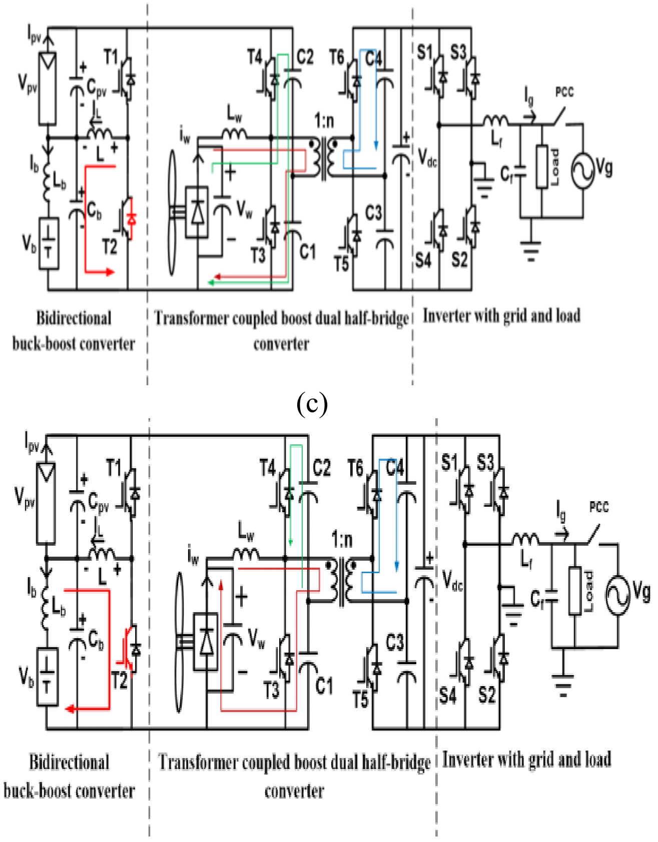


(c)

(d)

Fig.2Operating modes of 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 ON, charging the capacitor bank. (d) Operation when switch T4 ON, capacitor C2 discharging.

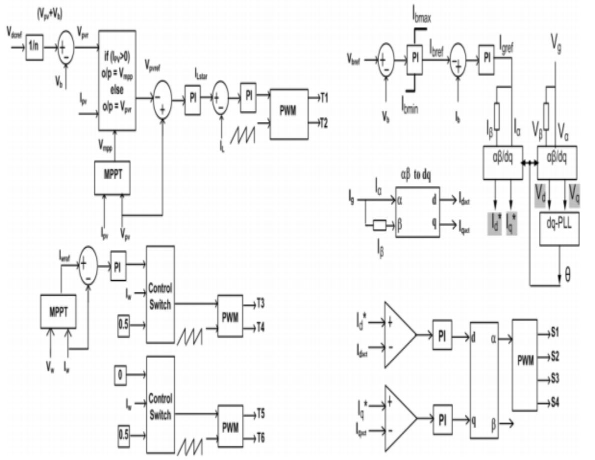


Fig. 3. Proposed control scheme for power flow management of a grid-connected hybrid PV-wind-battery based system.

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 $V_b = \frac{D}{1-D}V_{pv}$. The output voltage of the transformer coupled boost half-bridge converter is given by,

$$V_{dc} = n(V_{C1}+V_{C2}) = n(V_b+V_{pv}) = \frac{nV_w}{(1-D_w)} \qquad (2)$$

This voltage is n 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 IL = Ib + Ipv. It is evident that, Ib and Ipv can be controlled by controlling IL. Therefore, the MPP operation is assured by controlling IL,while maintaining proper battery charge level. IL is used asinner loop control parameter for faster dynamic response while for outer loop, capacitor voltage across PV source is used forensuring MPP voltage. An incremental conductance method is used for MPPT.

(i) Limitations and Design issues

The output voltage Vdc of transformer coupled boost dual half-bridge converter, depends on MPP voltage of PV arrayVP V mpp, the battery voltage Vb and the transformer turns ratio n. Since the environmental conditions influence PV array voltage and the battery voltage depends on its charge level, the output dc-link voltage Vdc 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. Further, the SOC 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 Vdc 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 Vdc can be controlled.

(3) Proposed Control Scheme for 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 thematic-source 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 Ibmax. 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:

$$V_{pv}I_{pv} + V_wI_w = V_bI_b + V_gI_g \tag{3}$$

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

$$\hat{v} = m_aV_{dc} \tag{4}$$

and the dc-link voltage is,

$$V_{dc} = n(V_{pv} + V_b). \tag{5}$$

Hence, by substituting for Vdc in (3.4), gives,

$$V_g = \frac{1}{\sqrt{2}}m_an(V_{pv} + V_b) \tag{6}$$

In the boost half-bridge converter,

$$V_w = (1 - D_w)(V_{pv} + V_b) \tag{7}$$

Now substituting Vw and Vg in (3.3),

$$V_{pv}I_{pv} + (V_{pv} + V_b)(1 - D_w)I_w = V_bI_b + \frac{1}{\sqrt{2}}m_an(V_{pv} + V_b)I_g \tag{8}$$

After simplification,

$$I_b = I_{pv}\left(\frac{1 - D_{pv}}{D_{pv}}\right) + I_w\left(\frac{1 - D_w}{D_{pv}}\right) - I_g\left(\frac{m_an}{\sqrt{2}D_{pv}}\right) \tag{9}$$

From the above equation 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 availability of grid, power from PV and wind sources and battery charge status. Its control strategy is illustrated using Fig.3.3. 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 Ibmax, the surplus power from renewable sources is fed tothe grid. In the absence of these sources, battery is charged from the grid.

III. INDUCTION MOTOR

An asynchronous motor type of an induction motor is an AC electric motor in which the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding. An induction motor can therefore be made without electrical connections to the rotor as are found in universal, DC and synchronous motors. An asynchronous motor's rotor can be either wound type or squirrel-cage type.

Three-phase squirrel-cage asynchronous motors are widely used in industrial drives because they are rugged, reliable and economical. Single-phase induction motors are used extensively for smaller loads, such as household appliances like fans. Although traditionally used in fixed-speed service, induction motors are increasingly being used with variable-frequency drives (VFDs) in variable-speed service. VFDs offer especially important energy savings opportunities for existing and prospective induction motors in variable-torque centrifugal fan, pump and compressor load applications. Squirrel cage induction motors are very widely used in both fixed-speed and variable-frequency drive (VFD) applications. Variable voltage and variable frequency drives are also used in variable-speed service.

In both induction and synchronous motors, the AC power supplied to the motor's stator creates a magnetic field that rotates in time with the AC oscillations. Whereas a synchronous motor's rotor turns at the same rate as the stator field, an induction motor's rotor rotates at a slower speed than the stator field. The induction motor stator's magnetic field is therefore changing or rotating relative to the rotor. This induces an opposing current in the induction motor's rotor, in effect the motor's secondary winding, when the latter is short-circuited or closed through external impedance. The rotating magnetic flux induces currents in the windings of the rotor; in a manner similar to currents induced in a transformer's secondary winding(s). The currents in the rotor windings in turn create magnetic fields in the rotor that react against the stator field. Due to Lenz's Law, the direction of the magnetic field created will be such as to oppose the change in current through the rotor windings. The cause of induced current in the rotor windings is the rotating stator magnetic field, so to oppose the change in rotor-winding currents the rotor will start to rotate in the direction of the rotating stator magnetic field. The rotor accelerates until the magnitude of induced rotor current and torque balances the applied load. Since rotation at synchronous speed would result in no induced rotor current, an induction motor always operates slower than synchronous speed. The difference, or "slip," between actual and synchronous speed varies from about 0.5 to 5.0% for standard Design B torque curve induction motors. The induction machine's essential character is that it is created solely by induction instead of being separately excited as in synchronous or DC machines or being self-magnetized as in permanent magnet motors.

For rotor currents to be induced the speed of the physical rotor must be lower than that of the stator's rotating magnetic field (n_s); otherwise the magnetic field would not be moving relative to the rotor conductors and no currents would be induced. As the speed of the rotor drops below synchronous speed, the rotation rate of the magnetic field in the rotor increases, inducing more current in the windings and creating more torque. The ratio between the rotation rate of the magnetic field induced in the rotor and the rotation rate of the stator's rotating field is called slip. Under load, the speed drops and the slip increases enough to create sufficient torque to turn the load. For this reason, induction motors are sometimes referred to as asynchronous motors. An induction motor can be used as an induction generator, or it can be unrolled to form a linear induction motor which can directly generate linear motion.

Synchronous Speed:

The rotational speed of the rotating magnetic field is called as synchronous speed.

$$Ns = \frac{120 \times f}{P} \quad (RPM) \tag{10}$$

Where, f = frequency of the supply
P = number of poles

Slip:

Rotor tries to catch up the synchronous speed of the stator field, and hence it rotates. But in practice, rotor never succeeds in catching up. If rotor catches up the stator speed, there won't be any relative speed between the stator flux and the rotor, hence no induced rotor current and no torque production to maintain the rotation. However, this won't stop the motor, the rotor will slow down due to lost of torque, and the torque will again be exerted due to relative speed. That is why the rotor rotates at speed which is always less the synchronous speed.
The difference between the synchronous speed (Ns) and actual speed (N) of the rotor is called as slip.

$$\%\ \text{slip} \quad s = \frac{Ns - N}{Ns} \times 100 \tag{11}$$

Advantages:

- Less component count and reduced losses.
- Reduced number of power conversion stages.
- Inject surplus power into the grid and charge the battery from grid as and when required.

Applications:

- Household Application.

IV. MATLAB/SIMULINK RESULTS

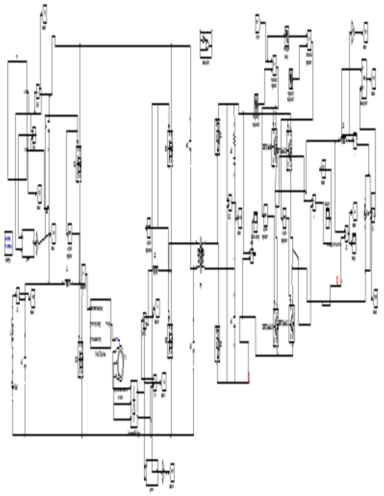
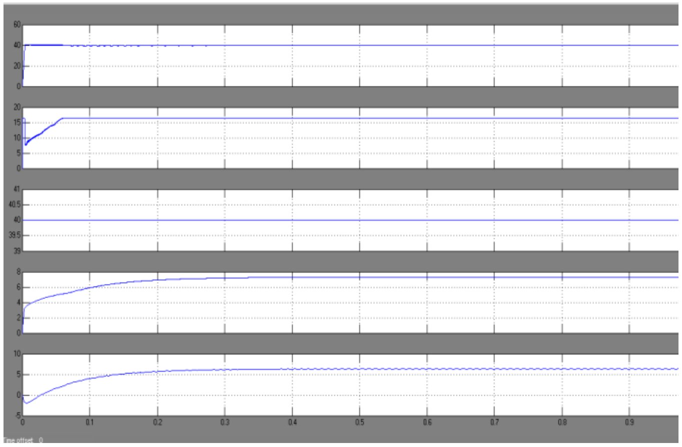


Fig 4 Steady state operation in MPPT mode.



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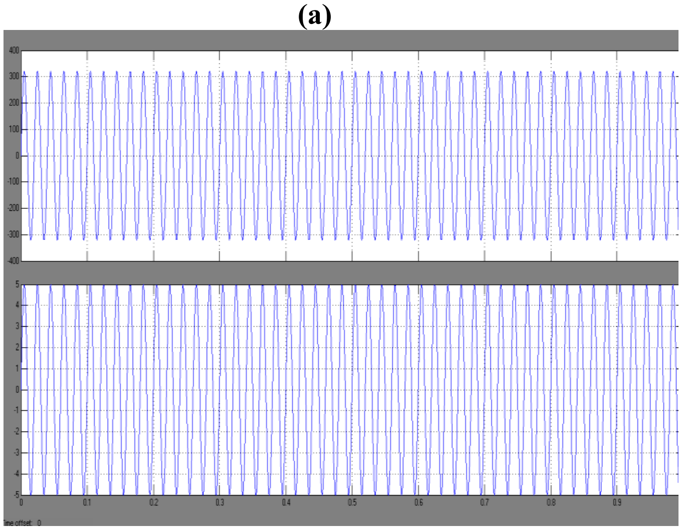

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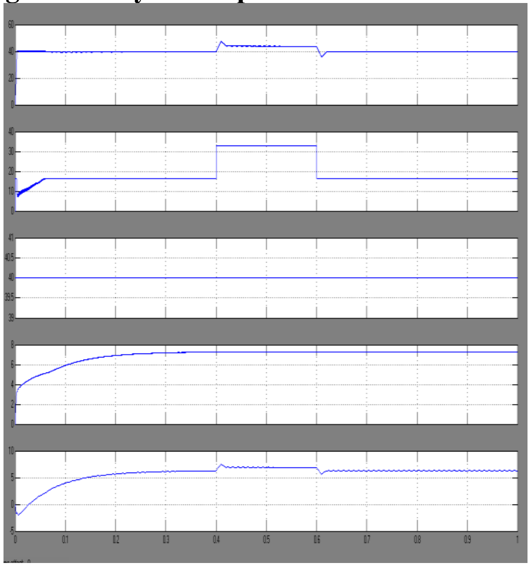
Fig. 5. Steady state operation in MPPT mode.



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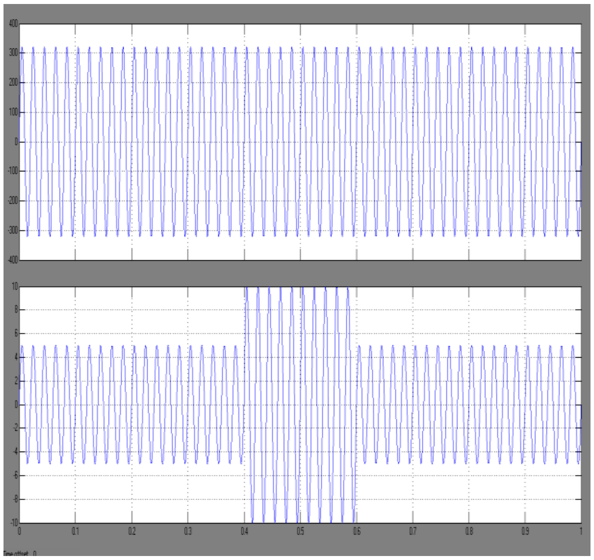

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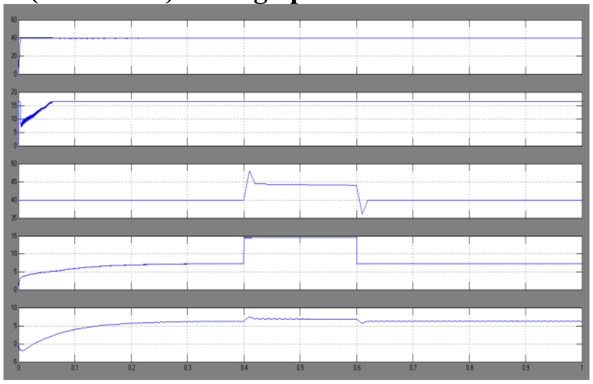
Fig. 6. Response of the system for changes in insolation level of source-1 (PV source) during operation in MPPT mode.



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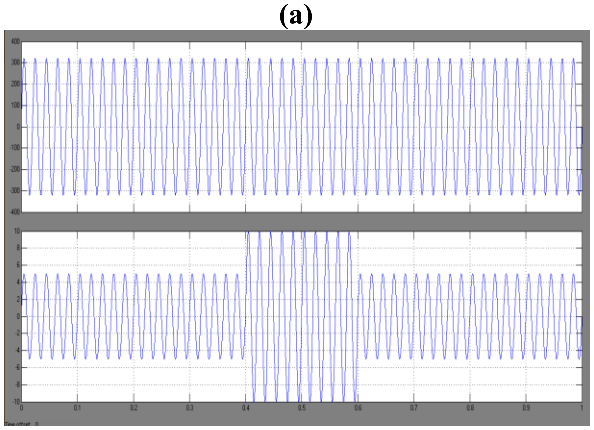

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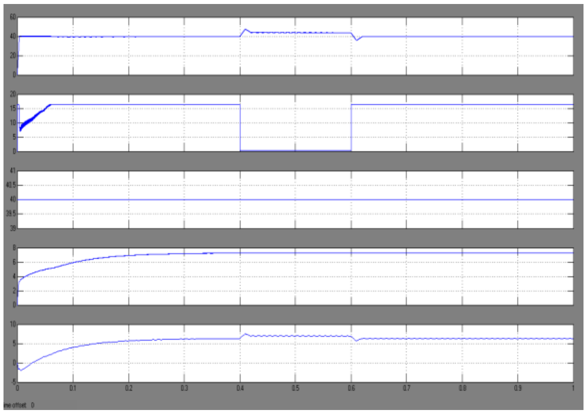
Fig. 7. Response of the system for changes in wind speed level of source-2 (wind source) during operation in MPPT mode.



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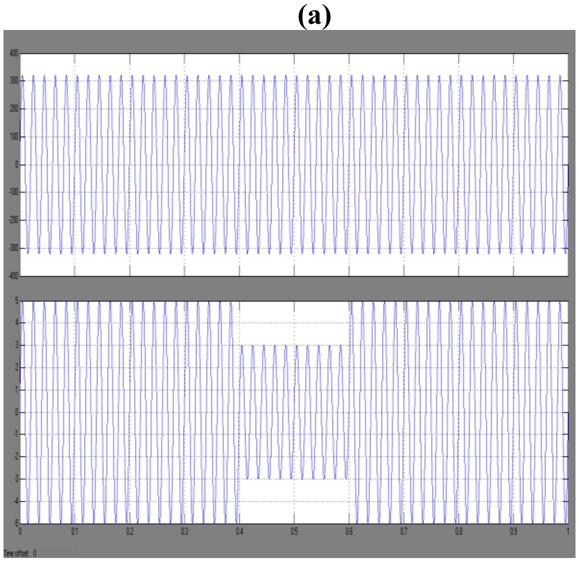

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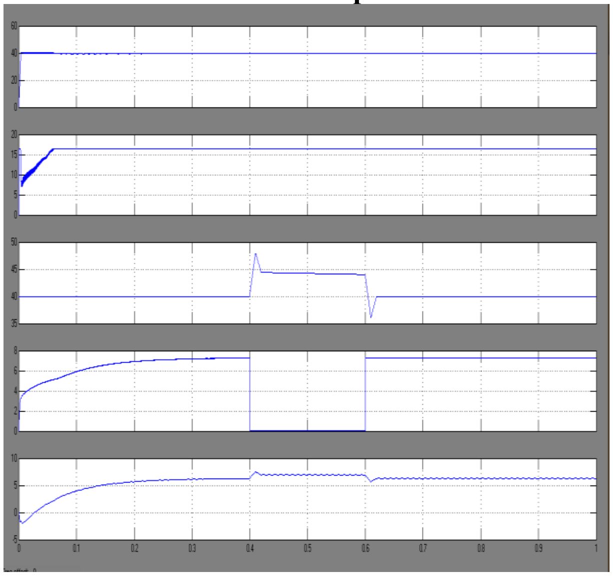
Fig. 8. Response of the system in the absence of source-1 (PV source) while source-2 continues to operate at MPPT.



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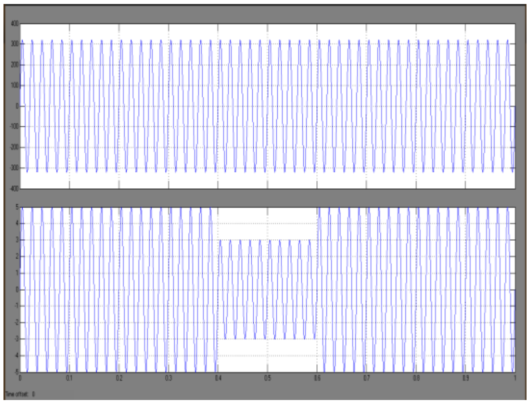
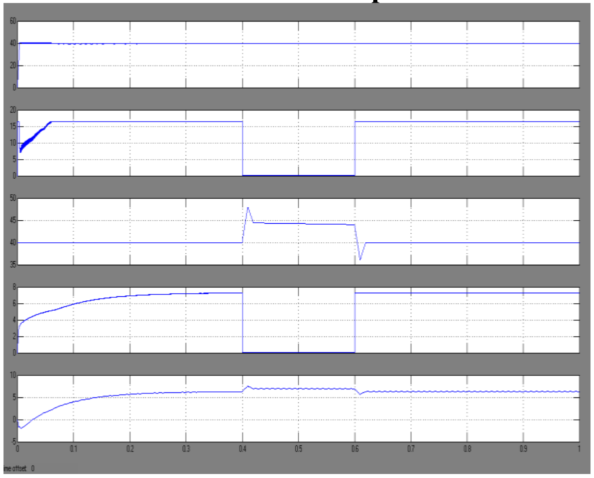


(b)

Fig. 9. Response of the system in the absence of source-2 (wind source) while source-1 continues to operate at MPPT.



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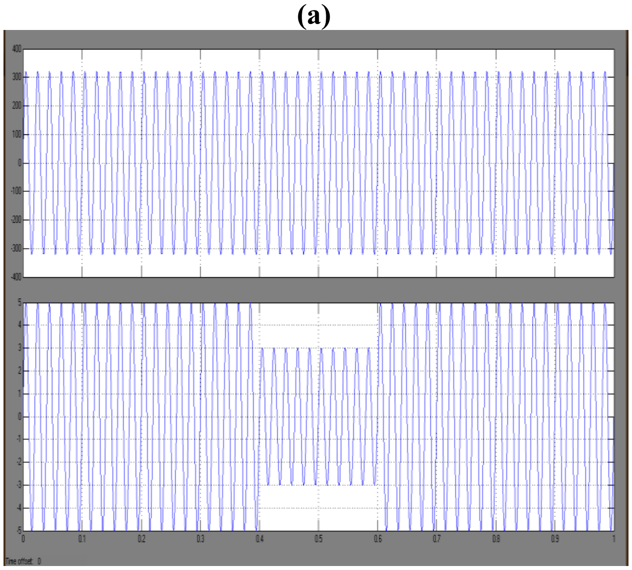

(b)

Fig. 10. Response of the system in the absence of both the sources and charging the battery from grid.

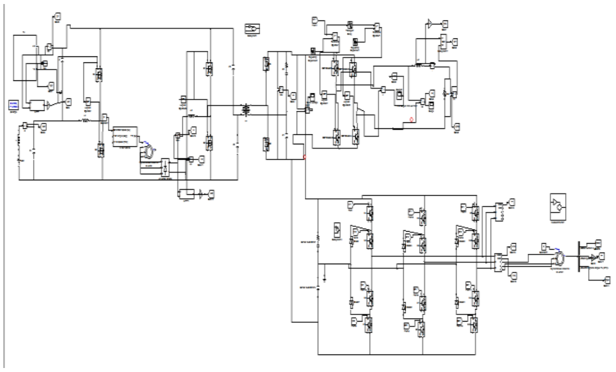

Fig.11 Simulink model connected with Induction motor drive

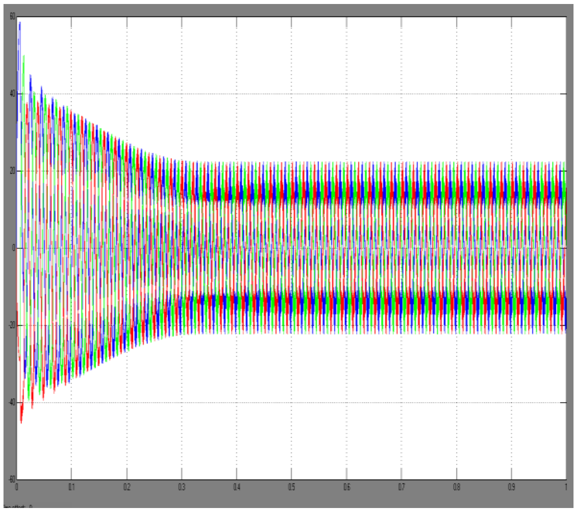

Fig.9 Stator current

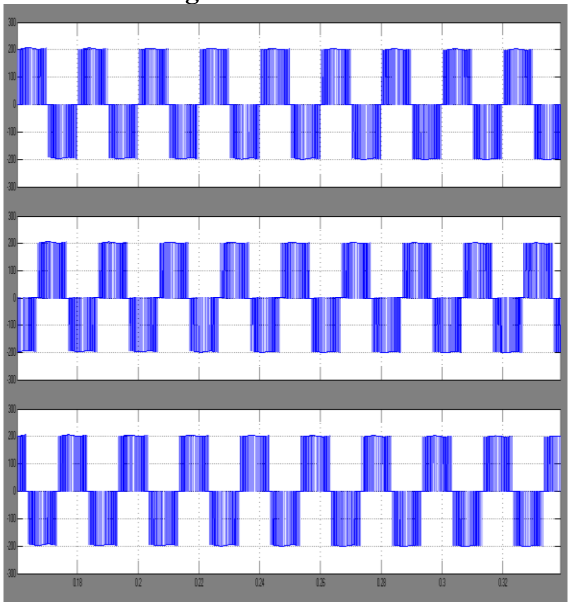

Fig phase voltage of the induction motor

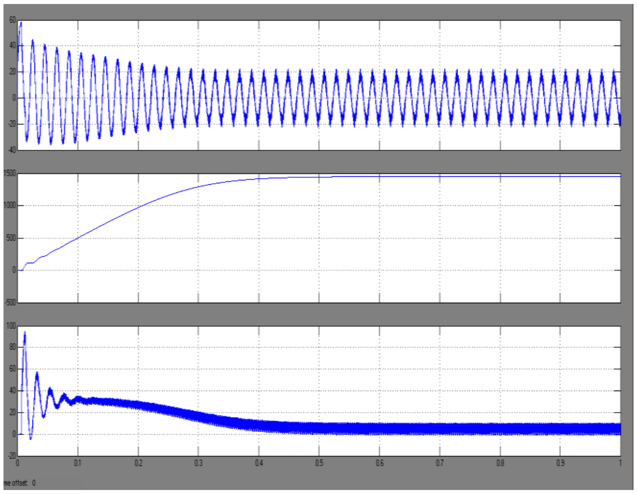

Fig.11 speed & Torque characteristics of the induction motor.

(5) Conclusion

A new topology of the A grid-connected hybrid PV-wind-battery based power evacuation scheme for household application was introduced for induction motor drive applications. 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 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 proposed circuit is applied to Induction Motor Drive to check the performance of entire system. Simulation results are shown.

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