A Novel Asymmetrical Single-Phase Multilevel Inverter Suitable for Hybrid Renewable Energy Sources

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Abstract: This paper introduces a novel asymmetrical single-phase multilevel inverter suitable for hybrid renewable energy sources. The proposed inverter consists of two isolated DC sources and six power semiconductor controlled switches. The suggested inverter is capable of generating seven level output when the input DC voltage is take in the ratio of 1:2. The higher magnitude DC source is fed from Photo Voltaic (PV) panels, where as the lower magnitude DC source is fed from Wind turbine (WT) driven permanent magnet DC (PMDC) generator. Both the renewable energy sources are connected to the inverter via two DC-DC boost converters connected in cascade (i.e. one for maximum power point tracking and another for DC-link voltage control). The proposed hybrid renewable energy source inverter is connected to single-phase grid via proper control systems. The complete system is simulated using MATLAB/SIMULINK and the results are presented in detail.

Key words: Asymmetrical Multilevel inverter · DC-DC boost converter · Photo-voltaic · Wind Turbine · Permanent magnet DC generator · Maximum power point tracking

INTRODUCTION

In recent years, Renewable Energy Sources (RES) are gaining more importance over the globe because of the exhausting nature of the conventional energy sources, rise in earth's temperature due to carbon dioxide emissions, ever increasing oil price, non availability of power supply in the rural areas etc [1-4]. The energy generated from RES depends upon the environmental conditions [5] (i.e. energy generated from solar energy conversion system depends upon the solar irradiation and energy generated from wind energy conversion system depends upon the wind speed), whereas the electrical grid requires constant voltage and frequency. Hence proper power electronic interface must be provided between the renewable energy and the grid for stable operation [6].

In order to connect RES to the grid, two stages of power conversion are used. First stage is to boost up the low voltage output of RES and to track its Maximum Power Point (MPP), where as the second stage is used to convert DC into AC signal as required by the grid [3]. To increase the efficiency of the grid connected renewable energy systems single stage boost inverters are proposed in the literature [1-4]. Single stage power conversion technique reduces the losses there by increases the efficiency, but it suffers from drawbacks like poor total harmonic distortion [THD] at the output voltage which eventually increases the filter size, thereby increasing the cost and size of the total system [5].

To improve the harmonic profile of the output voltage of the inverter Multilevel Inverters [MLI] are suggested in [1-6]. MLIs have nearly sinusoidal output voltage and current waveforms with improved harmonic profile, less stress in power electronic switches due to reduced voltages, lower switching losses when compared to conventional three level inverters, smaller filter size and reduced electromagnetic interference [5].

In recent years various MLIs are proposed in the literature. Among those commonly used types are diode-clamped MLI [7, 8], capacitor clamped MLI [8], cascaded

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H-bridge MLI [9-12] and modified H-bridge MLI [12-13]. MLIs are further classified into symmetrical and asymmetrical types. Asymmetrical MLIs (ASMLI) are capable of producing more levels for the given power electronic devices when compared with symmetrical MLIs (SMLI) [14].

This paper introduces a modified ASMLI topology suitable for renewable energy sources. The proposed inverter is capable of generating seven levels with two isolated DC sources and six power semiconductor controlled switches. The two isolated DC sources are of different in magnitudes of voltages with the ratio of 1:2. Among the six power semiconductor devices, two devices are bidirectional and four devices are unidirectional devices. The proposed inverter has many advantages like simple in structure, adaptable for integrating RES with the grid, lower THD and lesser number of semiconductor switches.

The remaining part of this paper is structured as follows. The operation and description of the modified ASMLI topology along with switching logic are detailed in Section II, the suggested ASMLI fed from RES along with proper control system are described in Section III, Section IV details the simulation results obtained from MATLAB/SIMULINK and the performance of the system is recapitulated at the conclusion.

Circuit Topology: The proposed topology consists of a two bidirectional switches added to the conventional H bridge inverter. The proposed topology has been derived from the topology proposed in [5]. The topology proposed in [6] has only one bidirectional switch which is capable of generating only five levels and is of symmetrical type. Whereas the topology proposed in [6] has two bidirectional switches which is capable of generating seven levels, but it has the problem of capacitor voltage balancing when fed to high power loads [8]. Further the MLI proposed in [10] is again of
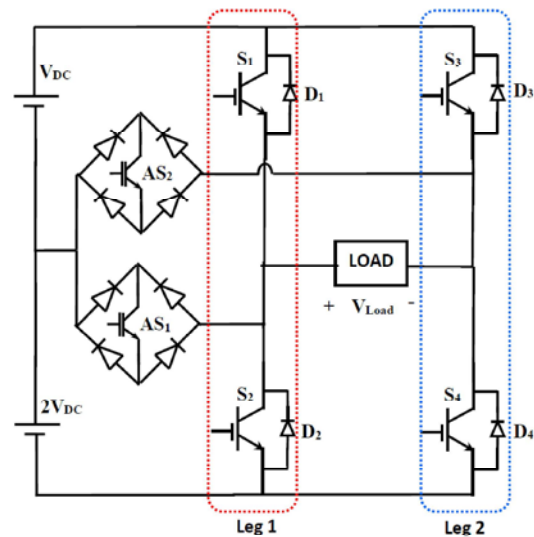

Fig. 1: Proposed Asymmetrical MLI Topology

symmetrical in nature. The asymmetrical MLI proposed in this paper requires only two bidirectional switches to generate seven levels further the problem of capacitor voltage balancing does not exist. Fig 1 shows circuit topology of the proposed asymmetrical MLI topology.

The proposed topology of ASMLI consists of two isolated DC sources with the ratio of 1: 2, six power semiconductor devices in which two devices are bidirectional (i.e. AS_1 and AS_2). The switch AS_1 is connected between the middle of the Leg 1 and to the middle of the two isolated DC sources, where as the switch AS_2 is connected between the middle of the leg 2 and to the middle of the DC sources. Fig 2 shows the modes of operation of the proposed inverter. In fig 2 the conducting paths are shown in dark black lines whereas the non-conducting paths are shown in the light grey colors. Table 1 shows the switching table of the proposed ASMLI, which is capable of generating seven levels. Further the proposed ASMLI is capable of generating higher levels if the basic blocks are connected in cascade.

Table 1: Switching logic of the Basic Block of the Proposed ASMLI

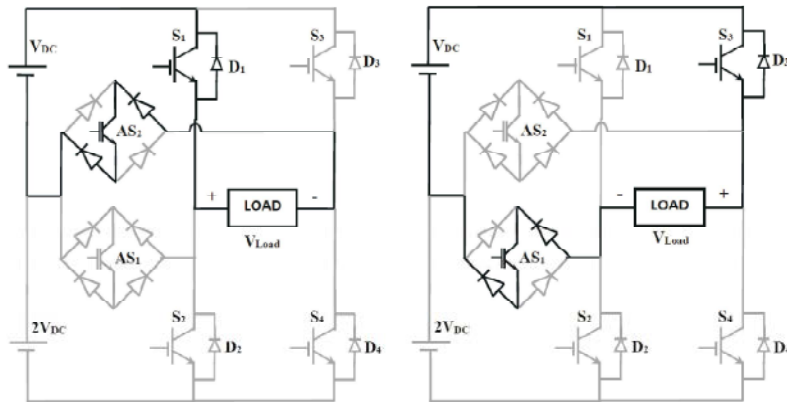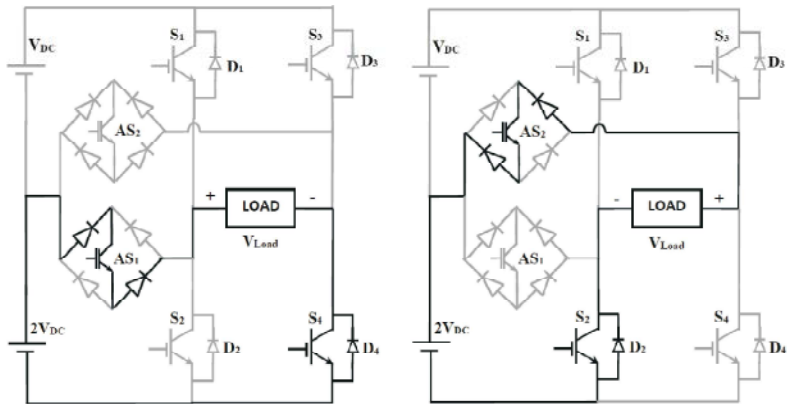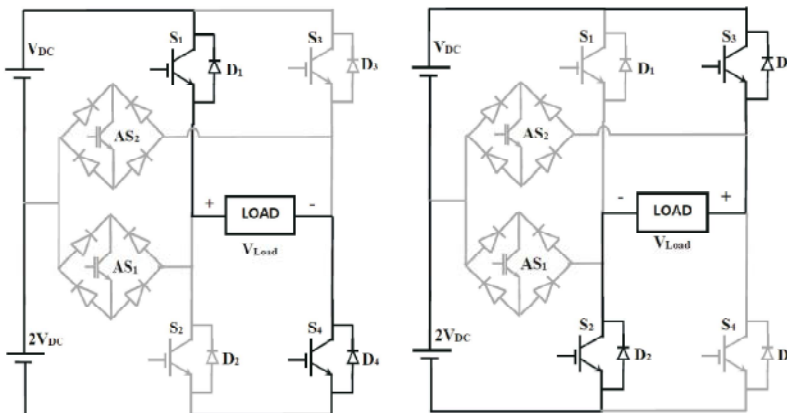| Sl.No	S_1	S_2	S_3	S_4	AS_1	AS_2	V_{Load}	Reference
1	ON	OFF	OFF	ON	OFF	OFF	$+3V_{DC}$	Fig 2(e)
2	OFF	OFF	OFF	ON	ON	OFF	$+2V_{DC}$	Fig 2(c)
3	ON	OFF	OFF	OFF	OFF	ON	$+V_{DC}$	Fig 2(a)
4	OFF	OFF	OFF	OFF	ON	ON	0	-
5	OFF	OFF	ON	OFF	ON	OFF	$-V_{DC}$	Fig 2(b)
6	OFF	ON	OFF	OFF	OFF	ON	$-2V_{DC}$	Fig 2(d)
7	OFF	ON	ON	OFF	OFF	OFF	$-3V_{DC}$	Fig 2(f)

Fig. 2(a)

Fig. 2(b)

Fig. 2(c)

Fig. 2(d)

Fig. 2(e)

Fig. 2(f)

Fig. 2: Modes of operation of the proposed ASMLI

(a)$V_{LOAD} = +V_{DC}$ (b) $V_{LOAD} = -V_{DC}$ (c) $V_{LOAD} = +2V_{DC}$ (d) $V_{LOAD} = -2V_{DC}$ (e) $V_{LOAD} = +3V_{DC}$ (f) $V_{LOAD} = -3V_{DC}$

In order to generate gating signals for the proposed inverter, six level shifted carrier waves are used as shown in figure 3. The logical diagram for generating the gating signals using the six level shifted carrier waves are shown in figure 4. From figure 4 it is very clear that the logic is very simple to implement and uses XOR, NOT and XNOR operations.
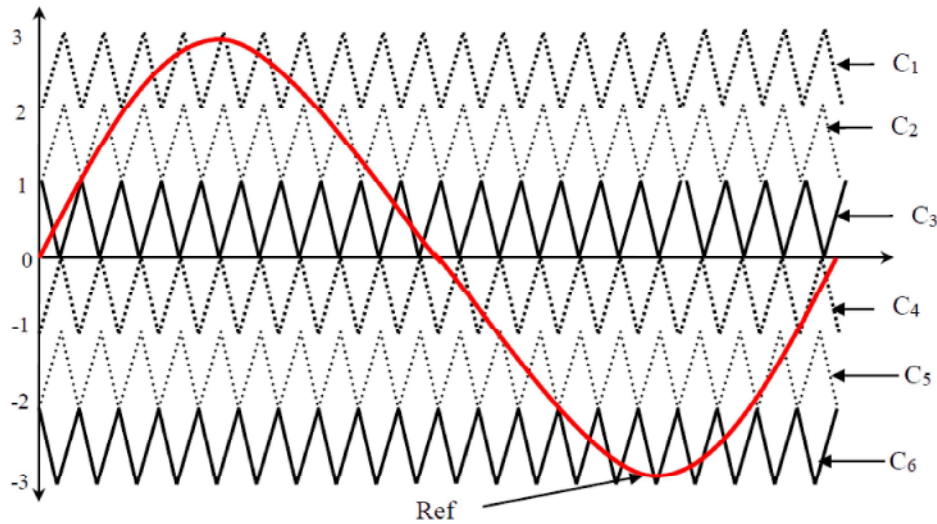
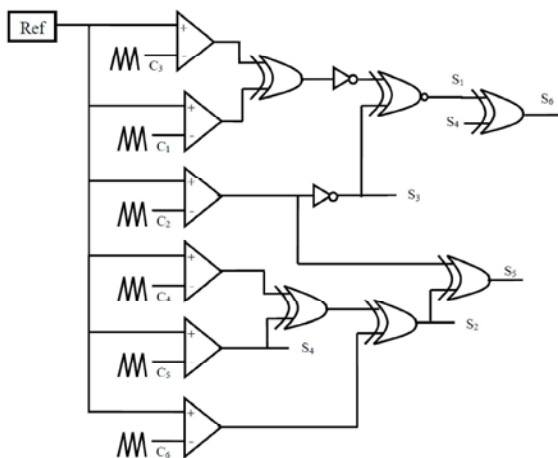Fig. 3: Carrier signals used for generating gating signals

Fig. 4: Logic diagram for geneating gating signals for the proposed inverter.

Proposed Inverter Fed from Renewable Energy Sources: The proposed inverter is a best fit for grid connected renewable energy applications. The figure 5 shows the proposed inverter fed from solar photovoltaic and wind turbine driven PMDC generator. The upper DC source is fed from Solar PV, where as the lower DC source is fed from WT driven PMDC generator. The operating point of solar PV module is decided by solar radiation, temperature of PV module and the resistance of the load. For a given cell temperature and solar radiation, there is an exclusive operating point of the PV array in its PV curve with maximum output power. Hence Maximum Power Point Tracking (MPPT) is essential in PV arrays in order to draw maximum power from it irrespective of the climatic and load conditions [11]. A similar situation exists in Wind

Turbine also [12]. Generally DC-DC boost converter is used next to PV module for two main reasons. Primary reason is to track the MPP and the secondary reason is to boost up the low output voltage of PV module to a higher level. Hence the DC-DC boost converter's duty cycle is dependent on the MPPT algorithm. Thus when the environmental conditions vary MPPT algorithm will change the duty cycle which in turn reduces or increases the output voltage of the boost converter. But the DC input voltage of the inverter should have a stiff value when it is connected to the grid. Hence two DC-DC boost converters are used in cascade, one is to track the MPP and the other is to maintain the DC-link voltage (i.e. input voltage of the inverter) to a stiff value. Similar option is used in the WT also.

Maximum Power Point Tracking: The PV and VI Characteristics of TATA BP 180W panel is shown in figure 6 for various irradiations and cell temperature. It is very clear from the figure 6 that the location of the maximum power point varies when the environmental condition varies (i.e. irradiation and module temperature). Similarly the wind power vs. turbine speed characteristics for various wind velocities is shown in figure 7. It can be observed from figure 7 if wind velocity varies MPP also varies. Hence MPPT is essential in the case of PV arrays and WT. The details of PV module and WT coupled PMDC machine is given in table 2. There is lot of MPPT algorithms proposed in the literature [1]-[8]. Among the various MPPT algorithms perturb and observe and Incremental conductance algorithms are most popular due to their simplicity and easy implementation [15].
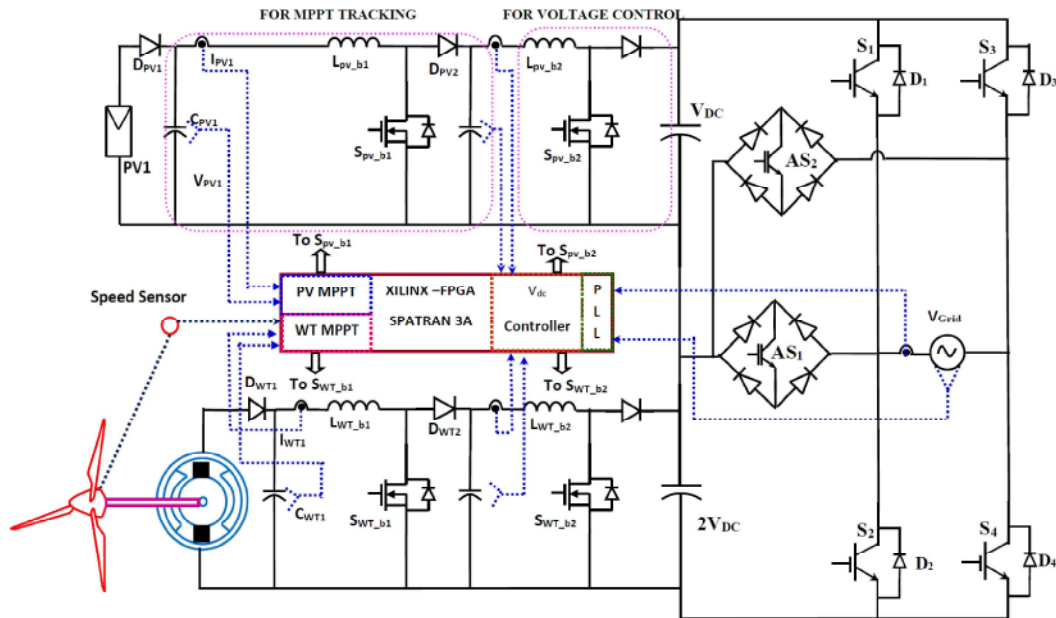
Fig. 5: System Configuration of the Proposed Inverter fed from PV arrays and WT driven PMDC Generator.

Table 2: PV Module, WT and PMDC parameters

------------------ PV Module ----------------		--------------- Wind Turbine --------------		-------------------- PMDC ----------------	
Power Output P_{MAX}	180W	Rated Power	1.8 kW	Rated power	1.1 kW
Voltage at P_{MAX} V_{MPP}	35.8V	Rated wind speed	10 m/s	Armature Voltage	37.2V
Current at P_{MAX} I_{MPP}	5.03A	Radius	1.525 m	Rated RPM	1000
Open Circuit Voltage	43.6V	Gear Ratio	5	Armature resistance	0.3Ω
Short Circuit Current	5.48A	Air density	1.08 m³/Kg	Armature inductance	0.06mH
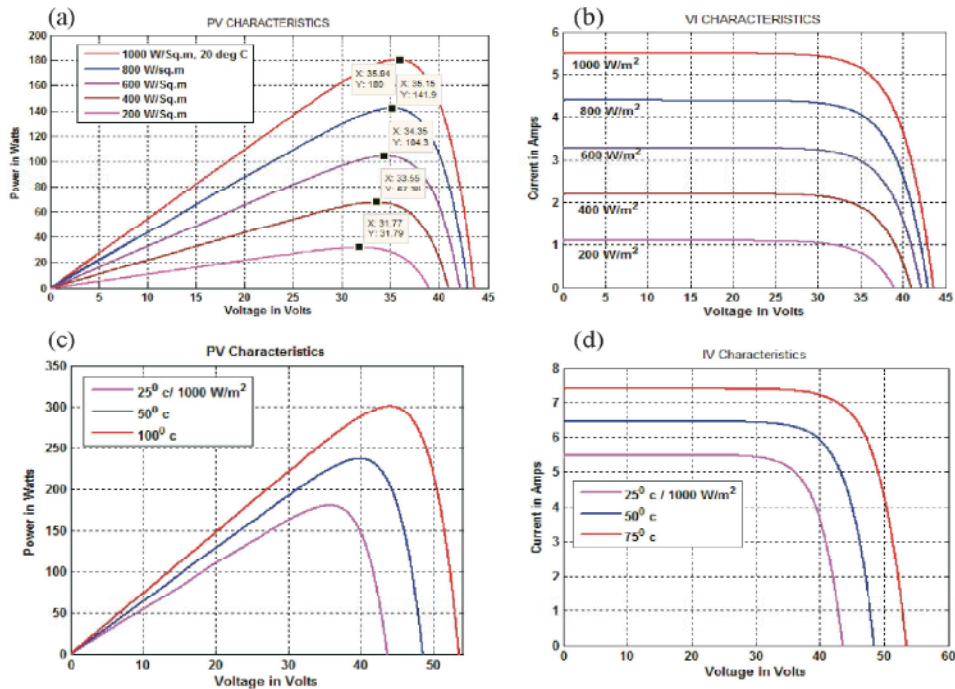
Fig. 6: (a) PV characteristics of PV array for constant temperature (25⁰C) (b) IV characteristics of PV array for constant temperature (25⁰C) (c) PV characteristics of PV array for constant irradiance (1000 W/m²) (d) IV characteristics of PV array for constant irradiance (1000 W/m²)

But these algorithms have draw back in selecting the incremental value of the control factor. When the incremental value is chosen very small, it gives poor dynamic performance and the algorithm becomes very slow. On the other hand when large value of chosen, the steady state error becomes very high [15]. Hence this paper proposes sliding mode based MPPT tracking for fast tracking with good dynamic and steady state performance.
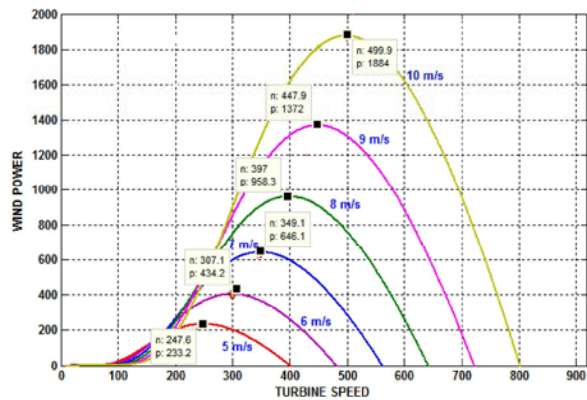

Fig. 7: Turbine Speed Vs Turbine Power for various wind velocities.

In sliding mode control sliding surface is determined by finding the MPP for various environmental conditions (i.e. irradiation, module temperature and wind velocity) through simulation. Once the MPP is determined for various environmental conditions, sliding surface equation is determined by using curve fitting toolbox in MATLAB/SIMULINK. The sliding surface equation for PV module and WT are shown in figure 8. When the result of sliding surface equation is greater than zero the boost converter switch is turned ON, on the other hand when it is less than zero it is turned OFF.

The sliding surface of PV module is given by

$$Y = 0.02499X^3 - 2.346X^2 + 73.82X - 778.1. \qquad (1)$$

Where Y is the PV module current and X is the PV module Voltage. Since the sliding surface equation is passing through the maximum power points, the result of the above equation should be zero to ensure MPP. Hence PV module current and voltage are sensed and equation (1) is calculated instantaneously. When the result of the above equation is greater than zero, the switch S_{pv_b1} (shown in figure 5) is turned ON, else it is turned OFF.
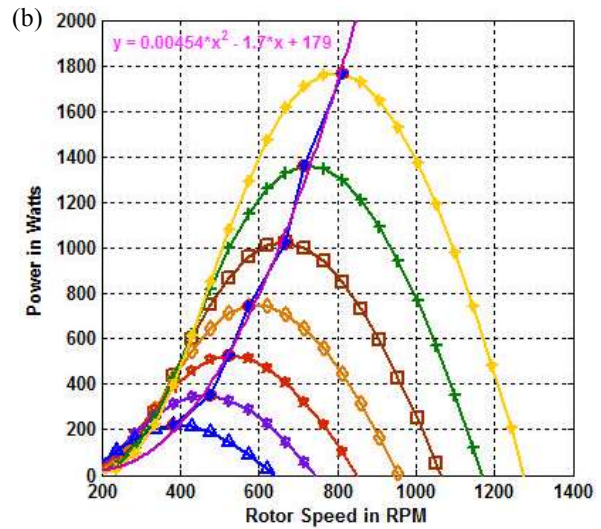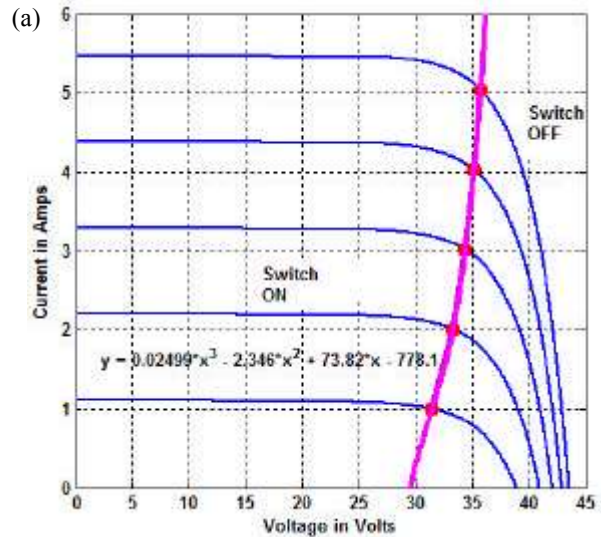
(a)

(b)

Fig. 8: (a) Sliding surface of PV module (b) Sliding surface of WT

In order to evaluate the proposed sliding mode algorithm, step change in the irradiance is given and the corresponding power output is measured and compared with actual MPP power as shown in figure 9. It is evident from figure 9 that the panel is generating 180 Watts when irradiance is 1000 W/m².

Similarly the sliding surface of WT is given by

$$Y = 0.00454X^2 - 1.7X + 179. \qquad (2)$$

Where Y is the power output of PMDC generator and X is the WT rotor speed. When the result of the above equation is greater than zero, the switch S_{WT_b1} (shown in
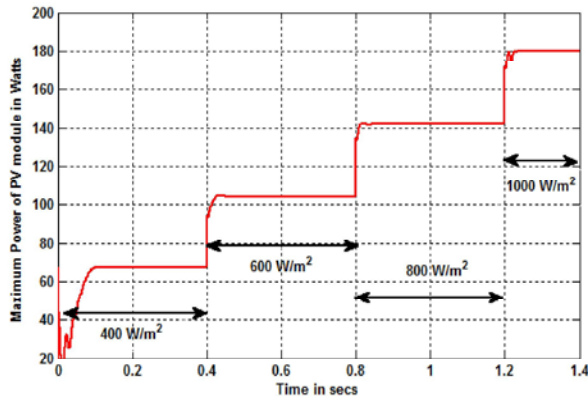
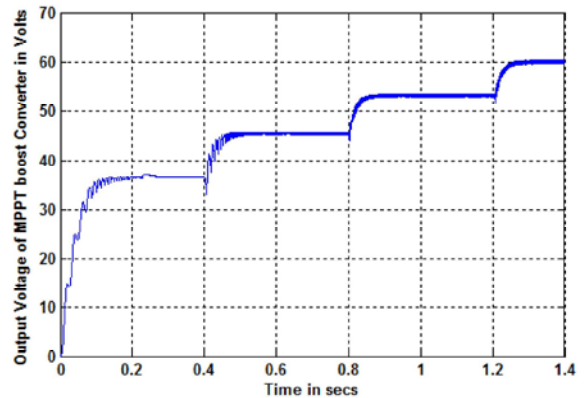Fig. 9: MPPT of PV module using Sliding Mode algorithm

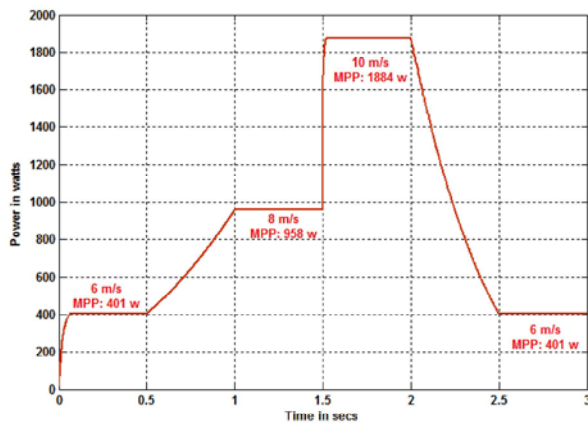Fig. 11: Output voltage of MPPT boost converter of PV module

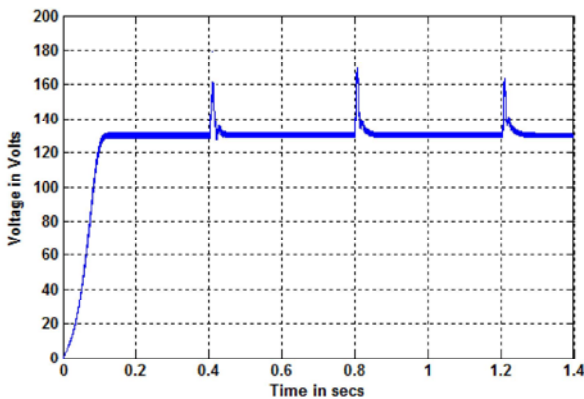Fig. 10: MPPT of Wind Turbine using Sliding Mode algorithm

Fig. 12: Output Voltage of Voltage Control Boost Converter of PV module.

figure 5) is turned ON, else it is turned OFF. In order to evaluate the proposed sliding mode algorithm, step change in the wind speed is given and the corresponding power output is measured and compared with actual MPP power as shown in figure 10.

By comparing figure 9 with data points of figure 6(a), it is very clear that steady state error is very minimum and also it has good dynamic response. Similar comparison can be made between Figure 10 and figure 7 to evaluate the performance of sliding mode control of WT.

Cascaded Boost Converters: Two boost converters are connected in cascade between the RES and the inverter DC sources as shown in figure 5. The output of the MPPT boost converter of PV module is shown in figure 11. Since the primary task of the MPPT boost converter is track the MPP, the output voltage of the MPPT boost converter also varies when there is a change in environmental conditions as shown in figure 11. But the DC link voltage of the inverter should be maintained constant for stable

grid integration. Hence another Boost converter is connected in cascade with MPPT boost converter. The main purpose of the second boost converter is to maintain constant voltage in the DC link. Figure 12 shows the output voltage obtained from the second boost converter, which remains constant at 130 volt.

Similarly the output voltage of MPPT boost converter of WT also varies when there is a variation in the wind speed. Hence the Voltage control boost converter is connected in cascaded to have stiff voltage at the DC link of the inverter. Figure 13 shows the output voltage of voltage control boost converter of WT. It is evident from figure 13 that the output voltage of WT voltage control boost converter is 260 volts.

Grid Integration: The proposed inverter fed from renewable energy sources is connected to grid through control components as shown in figure 5. The control block diagram of the grid integration is shown in the figure 14.
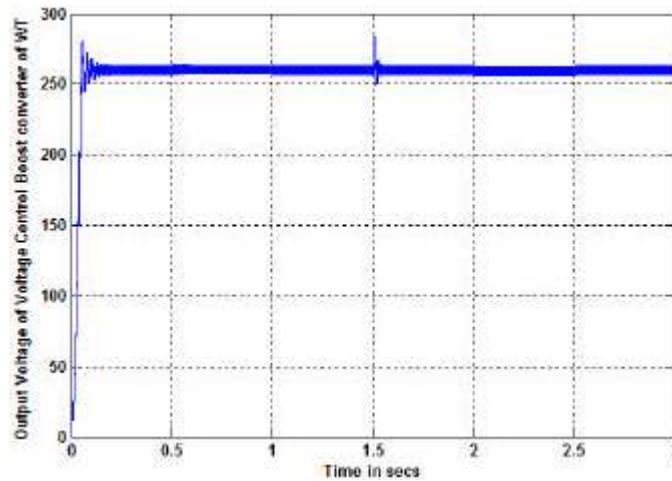
Fig. 13: Output Voltage of Voltage Control Boost Converter of WT.
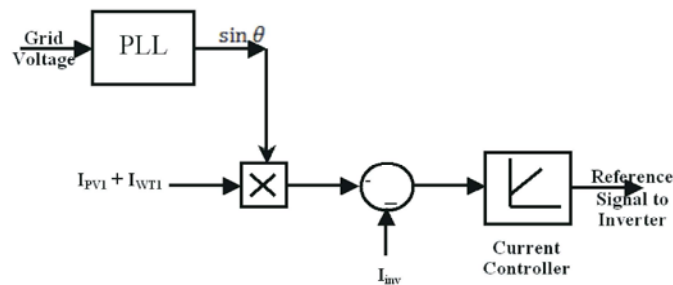

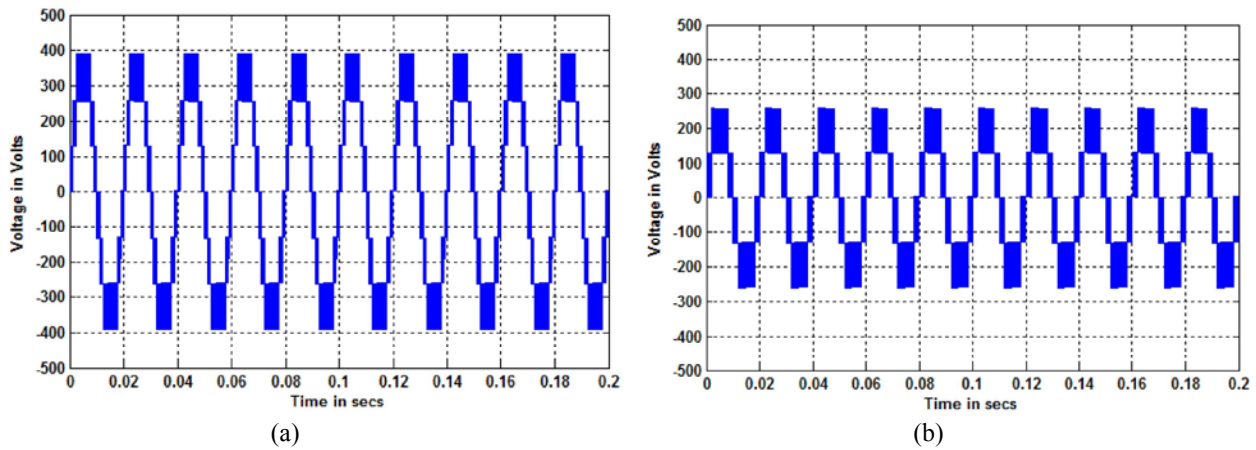Fig. 14: Control Block diagram of Grid Integration

Fig. 15: (a) Output voltage of proposed inverter when the modulation index is 0.95 (Seven levels)
(b)Output voltage of proposed inverter when the modulation index is 0.6 (Five levels)

The upper DC link of the proposed inverter (figure 5) is set to 130 volts where as the lower DC link voltage is set to 260 volts. The output voltage of the proposed inverter with seven levels is shown in figure 15(a) for modulation index of 0.95. When the modulation index is reduced to 0.6, the inverter is capable of generating only five levels which is shown in figure 15 (b). Figure 16 shows the capability of the proposed inverter when there is sudden change in the grid voltage (i.e. Grid Disturbance). It can be seen in the figure 16 that when the grid voltage falls the inverter modulation index is adjusted itself so that the inverter voltage also reduces[13-15].
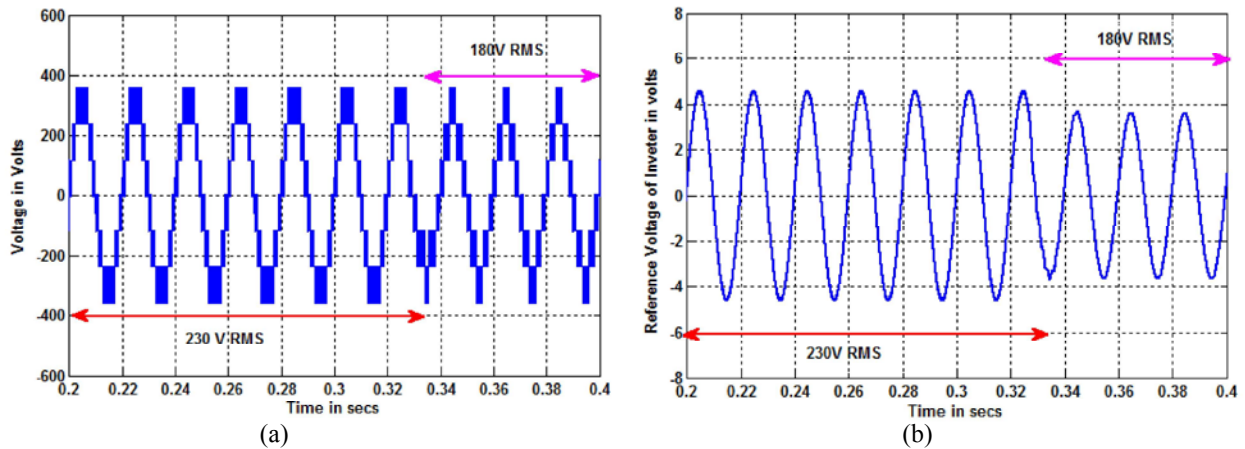
Fig. 16: (a) Output Voltage of the proposed inverter due to grid disturbance
(b)Reference waveform of the inverter due to grid disturbance.
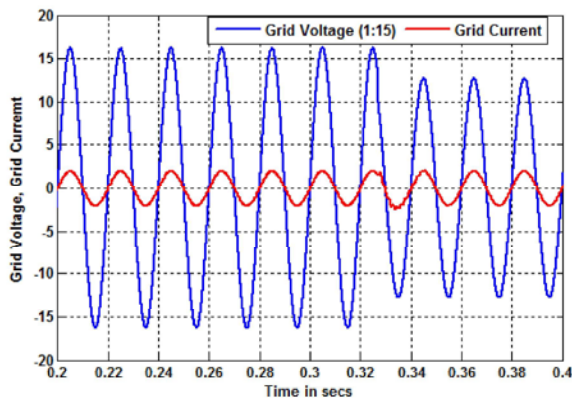
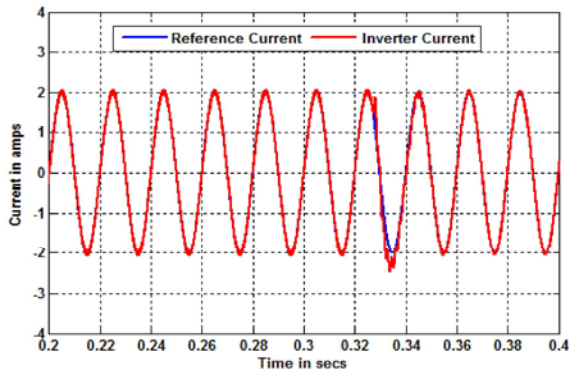

Fig. 17: Grid Voltage and Grid Current

Fig. 18: Reference and inverter current.

Figure 17 shows the grid voltage and grid current waveform during the time of grid disturbance. It is very clear from figure 17 that the grid voltage and grid current are in phase and the power factor is almost unity. It can be seen from figure 18 that the reference current from MPPT controllers and the inverter current are one over the other and tracks very perfectly.

CONCLUSION

In this paper a novel asymmetrical multilevel inverter is proposed. The operation of the proposed inverter is discussed, simulated in MATLAB/SIMULINK environment and the results are presented. The proposed inverter is fed from renewable energy sources through two boost converter connected in cascade one for tracking the MPP and another for voltage control. Further the proposed inverter is connected to the single phase grid through proper control structure. The complete system is simulated and the results are presented.

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