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A Hysteresis Current Controller for PV-Wind Hybrid Source Fed STATCOM System Using Cascaded Multilevel Inverters

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Abstract – This paper elucidates a hysteresis current controller for enhancing the performance of static synchronous compensator (STATCOM) using cascaded H-bridge multilevel inverter. Due to the rising power demand and growing conventional generation costs a new alternative in renewable energy source is gaining popularity and recognition. A five level single phase cascaded multilevel inverter with two separated dc sources, which is energized by photovoltaic - wind hybrid energy source. The voltages across the each dc source is balanced and standardized by the proposed hysteresis current controller. The performance of STATCOM is analyzed by connecting with grid connected system, under the steady state & dynamic state. To reduce the Total Harmonic Distortion (THD) and to improve the output voltage, closed loop hysteresis current control is achieved using PLL and PI controller. The performance of the proposed system is scrutinized through various simulation results using matlab/simulink and hardware results are also verified with simulation results.

Keywords: PV-Wind Hybrid system, Cascaded Multilevel Inverter (CMI), Static Synchronous Compensator (STATCOM), Hysteresis Current Control (HCC), Grid connected system

1. Introduction

Flexible AC Transmission systems are rising in the most recent years to reduce the power quality problems and improve power transfer capabilities. The power quality issues like unbalanced voltage levels, harmonics level, power factor, steady state and transient state problems are remedied by using FACTS controllers like STATCOM, UPFC, IPFC & TCSC [1]. Also voltage variations are occurred, because of power factor variations and the power swing oscillation. And to meet the increase in power demand we have to switch over to renewable energy sources [2].

Sustainably energy cannot be relied on fossil fuel sources to meet the energy demands in the long run and the vacuum fashioned by them will eventually has to be filled by alternating energy sources [3]. Natural sources like wind, solar provide clean energy available in plenty. Oil & gas prices keep fluctuating whereas the running and maintenance cost of the renewable systems is zero, so the cost of electricity generate can be assumed stable for a time period. These DPGS (Distributed power generation systems) can be installed close to load which reduces the transmission losses incurred in the conventional transmission and distribution system [4].

The concept of multilevel inverter was proposed in 1975 by nabae [5]. Multilevel inverters are mostly used in high power and medium voltage applications. However, the basic concept used in multilevel inverter to achieve high power, a series of power semiconductor switches with many low voltage dc sources is used to produce staircase output voltage levels [6]. Fuel cells, batteries, capacitors, PV cell, Wind energy and other renewable sources can be used as multiple DC sources for multilevel inverters. The rating of the power semiconductor devices are designed upon the dc supply voltage ratings [7]. Based on multilevel inverters the following factors can be attained like harmonics reduction, nearly sinusoidal output (stair case waveform), electromagnetic interference problems, common mode voltage and voltage balancing [8].

Among various multilevel topologies, cascaded H-bridge inverter topology become more admired in high power AC supplies and adjustable speed drives applications [9]. The cascaded multilevel inverter contains H-bridge (single leg bridge shape) and it may contain m-phases [10]. The level of inverter depends on the number of bridges and power semiconductor switches connected in the system, where each bridge circuit has separate dc sources. The main disadvantages of cascaded multilevel inverter are the voltage unbalance. The PWM control scheme requires more number of power semiconductor switches compared to other topologies [11].

The anticipated pulse width modulation techniques for multilevel converters are sinusoidal pulse width modulation (SPWM), Hysteresis control, maximum boost control, Space Vector Pulse Width Modulation (SVPWM) and selective harmonic elimination [12]. A new hysteresis reactive current algorithm is used to control the cascaded inverter, which increases the total harmonic distortion and solve the problems in synchronization between inverter and

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grid system. [13, 14].

In this proposed system, PV-Wind Hybrid source fed STATCOM system using Cascaded Multilevel Inverters provides better reduction of total harmonic distortion as per the IEEE standard. The improved output voltage and better current control by using a hysteresis current control technique is proposed. The power quality issues are voltage unbalance and synchronization remedy by connecting STATCOM with grid system and reactive load. The system is excited from PV-Wind hybrid energy sources and closed loop control is implemented to meet the power demand in the system.

2. PV – Wind Hybrid Energy Source

2.1 PV-source

A PV cell or an array converts the solar energy into electricity by photovoltaic effect, which takes place when incident radiation energy is greater than the threshold junction voltage of the semiconductor device [15]. The electrons attract this energy and comprise current if a circuit is congested. Since the output of a single cell is of the order of a few mill amperes, several such cells are attached to form PV arrays. Series connection of arrays increases voltage and parallel connection increase the current [16]. A simple model of a PV cell is a current source is parallel with a diode.

2.2 MPPT method (Incremental Conductance)

Incremental conductance MPPT method uses two voltage and current sensors to sense the output voltage and current of PV panels. Using this method the maximum power can be tracked from the PV array at every instant of time. The MMP the slope of the PV array curve should be zero. The flowchart for incremental conductance - MPPT algorithm is shown in Fig. 1.

$$(\frac{dP}{dV})_{MPP} = \frac{d(VI)}{dV} \quad (1)$$

$$I + \frac{VdI}{dV_{MPP}} = 0 \quad (2)$$

$$\frac{dI}{dV_{MPP}} = -\frac{I}{V} \quad (3)$$

The sensors are used to sense the voltage and current values of generated maximum power, where the generated power depends on the solar radiations and temperature of the sun. Implementation of this system is simpler than other methods like fuzzy logic method, fractional short circuit current, fractional open circuit voltage, neural network and hill clamping method [17]. The tracking of maximum power using incremental conductance method is shown in Fig. 2.

2.3 Wind system

Wind flows due to pressure dissimilarity twisted by non uniform heating of surface air by sun.When the wind speed is high sufficient (>5m/s) or low but stable for a long period of time, wind turbines can economically be installed in those places. Kinetic energy of the wind is used to turn out mechanical rotation of the turbine rotor, owing to the wind speed, the turbine blades experience rotational torque which causes rotation and the axial drive which should be withstood by the structure.

The amount of mechanical energy output of the tubine depends on the wind speed and the pressure plunge as the wind passes through the rotor thereby losing its kinetic energy [18].

In this representation of WECS, the wind turbine is connected to a PMSG (Permanent Magnet Synchronous Generator) through a common shaft which spawn torque for the generator depending upon wind speed. Due to

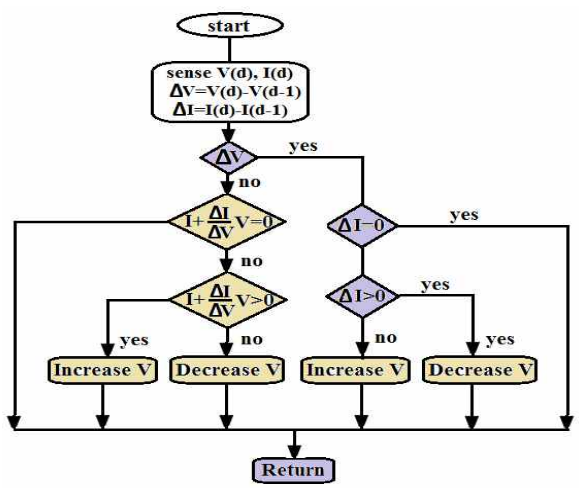


Fig. 1. Flowchart for incremental conductance - MPPT algorithm

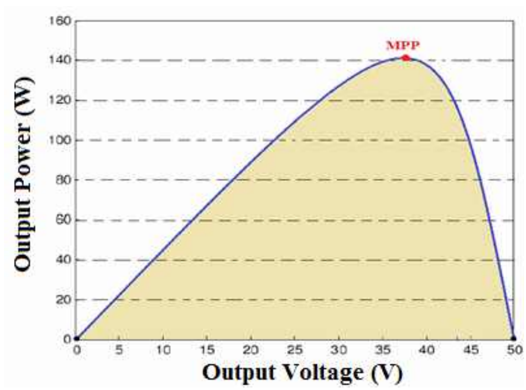


Fig. 2. PV panel characteristics showing MPP using Incremental Conductance method

enhancement in the magnetising capabilities and also their easy accessibility, Permanent magnets are the viable choice as the rotor for the generator [19]. Losses are minimised as well since there is no excitation current, hence no excitation losses.The need for the gearbox can be abolished if the number of poles of the machines are sufficiently large [20]. But the PMSG output contains several harmonics which can destabilize not only the performance of the inverter but also expose the safety of the sensitive equipment if the harmonic level is not controlled. For these reasons we use a diode rectifier which converts the ac voltage of the PMSG into dc. The diode rectifier used is the common three phase full wave ac-dc converter using diode bridge [21]. The dc output of PV and the rectified PMSG output is coupled together and the cumulative voltage is fed to the single phase cascaded multilevel inverter.

3. STATCOM using Cascaded Multilevel Inverters

The STATCOM model is constructed using single phase five level cascaded multilevel inverter. When the number of levels in multilevel inverter system increases, the quantity of power electronic switching devices and other equipments are also increased enormously and the construction of the inverter also becoming more complex. A convoluted controller with a proper related switching gate drive circuit is needed to manage and coordinate the switching devices and voltage level. The numbers of voltage sources in the system used are substantial when the number of levels increased, which mainly effect voltage imbalance among various the voltage sources placed in the system that may results in overvoltage occur in one or more of the switches. However, the condition can be remedied by using voltage clamping circuit or voltage control circuit. Most of the research works concerning multilevel inverters concentrate on the modulation techniques used for the control of the power switching devices.

For an alternative multilevel Inverter system with less power devices is very known as cascaded H bridge multilevel Inverter (CMI) and the system is based on the series connection of H-bridges with separate DC sources. The Fig. 3 shows the single phase cascaded H-bridge multilevel inverter, the output terminals of the H bridges are connected in series, the DC sources must be isolated from each other. Due to this property, CMIs have also been projected to be used with fuel cells or photovoltaic arrays in order to achieve higher levels with reduced total harmonic distortion.

The resulting AC output voltage is synthesized by the addition of the voltages generated by different H bridge cells. The single phase H-bridge generates five voltage levels as $+V_{dc}/2$, $+V_{dc}/4$, 0, $-V_{dc}/4$, $-V_{dc}/2$ by connecting the DC source to the AC output by different arrangement of eight switches, S_1, S_2, S_3, and S_4. The CMI utilizes two

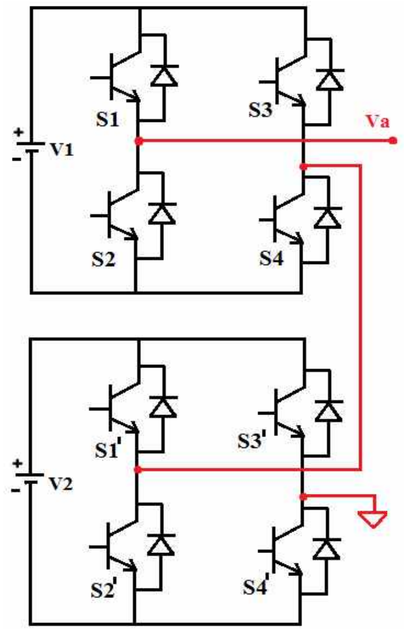


Fig. 3. Single phase five level cascaded H-bridge inverter

separate DC sources per phase and generates an output voltage with five levels. To obtain $+V_{dc}$, S_1 and S_4 switches are turned on, whereas $-V_{dc}$ level can be obtained by turning the S_2 and S_3 switches or S_3 and S_4 switches.

If t is assumed as the number of modules connected in series, p is the number of output levels in each phase as shown in Eq. (4). The switching states of a CMI can be determined by using equation (5) is,

$$p = 2(t+1) \tag{4}$$

$$SW = 3 * p \tag{5}$$

CMIs have been earlier planned for static VAR compensators and motor drives, but the topology has been prepared for interface with renewable energy sources due to the use of separate DC sources. Numerous studies have been performed on CHB-MLIs for connecting renewable energy sources with AC grid and power factor correction.

The block diagram of STATCOM using cascaded MLI and its proposed control scheme is shown in Fig. 4. In the cascaded multilevel inverter acquires energy from the PV-Wind hybrid energy sources. The PV array maximum power is tracked by using incremental conductance MPPT algorithm, which is added with wind energy system voltage through 3-phase rectifier circuit. The CMI output is synchronized with grid connected system using split inductor instead of using transformer, which avoids the leakage current problem and reduces the cost of the system. The split inductor L_1 and L_2 are used to convert staircase output into pure sinusoidal waveform to synchronise with any ac load. The reactive load is connected across the grid system to increase power demand of the proposed system. The cascaded multilevel inverter is controlled by using

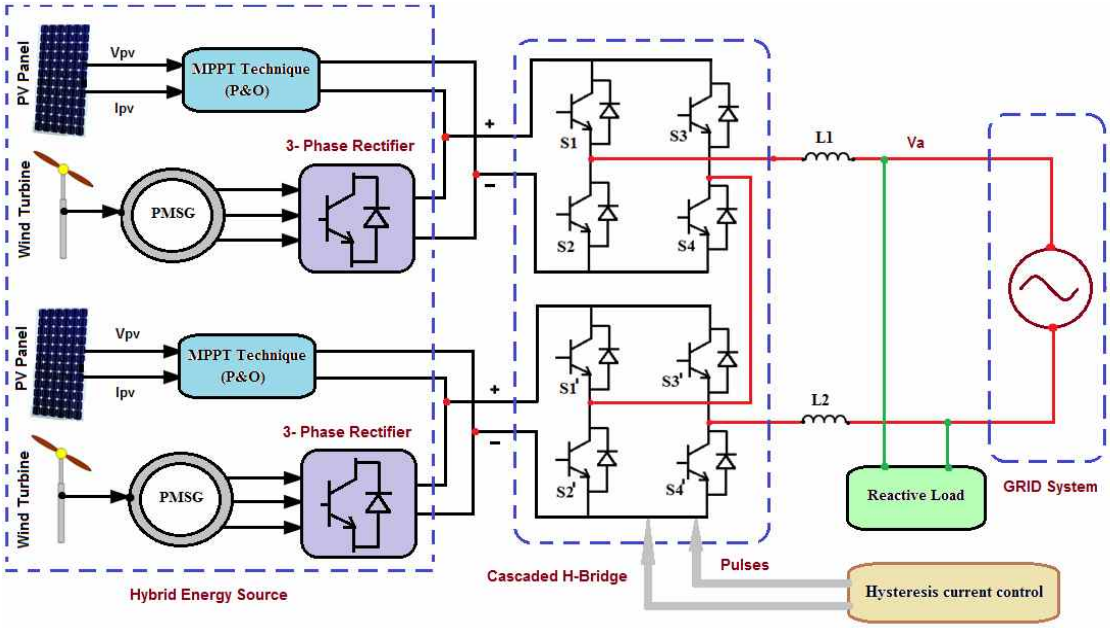


Fig. 4. Block diagram of STATCOM with proposed control scheme

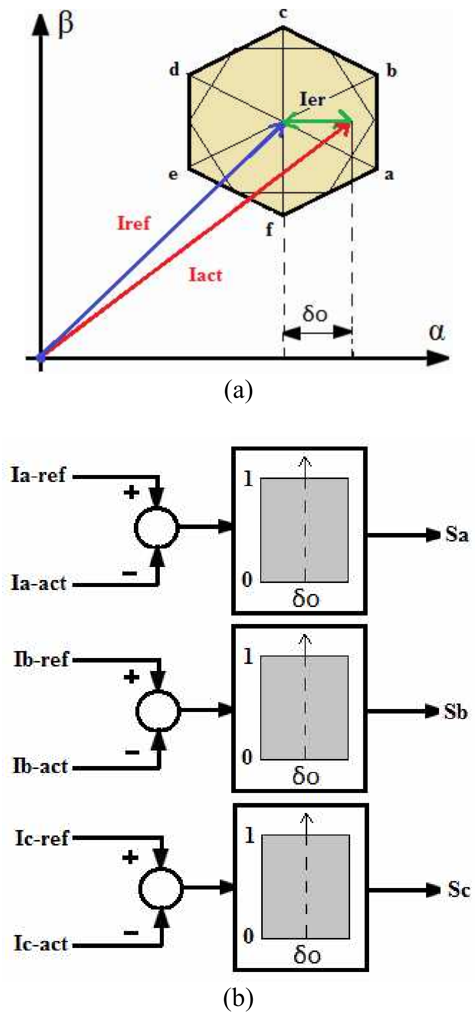


Fig. 5. HCC system (a) schematic hysteresis vector diagram (b) Error current calculation system

enhanced hysteresis current control algorithm.

4. Hysteresis Current Control Algorithm

The hysteresis current control depends on the magnitude of error for an 'n' inverter can be linked with number of bands around the reference vectors. Based on the error current value the hysteresis band h and h_1 will be decided, the output voltage level of the proposed system depends on the variation of hysteresis band. The error is decided by the difference between the actual current measured from the system and reference current value. The hysteresis current control schematic diagram and error current calculation is shown in Fig. 5(a) and Fig. 5(b). The HCC control is applied for single phase five level CMI inverter to obtain the output voltage levels are $+V_{dc}/2$, $+V_{dc}/4$, 0, $-V_{dc}/4$, $-V_{dc}/2$. The voltage injection with the proposed the inverter is operated with R-L load, which expressed in the following eqn. (6) and the Fig. 6. Shows the output voltage changes based on error current variation using hysteresis current control for cascaded multilevel inverter.

$$V_{inv} = R_i + L\frac{di}{dt} + V_b \tag{6}$$

The Fig. 7 shows the output voltage generation for proposed five level CMI inverter system for variation of error current value. When it attains the point p, the voltage level is $-V_{dc}/4$. Then it reaches the point, the voltage reaches the maximum in negative range. Similarly, the positive range of output voltage is obtained, when the error current variation occurs from point *s* to *z*. At point *w* the output voltage of the proposed system reaches maximum in

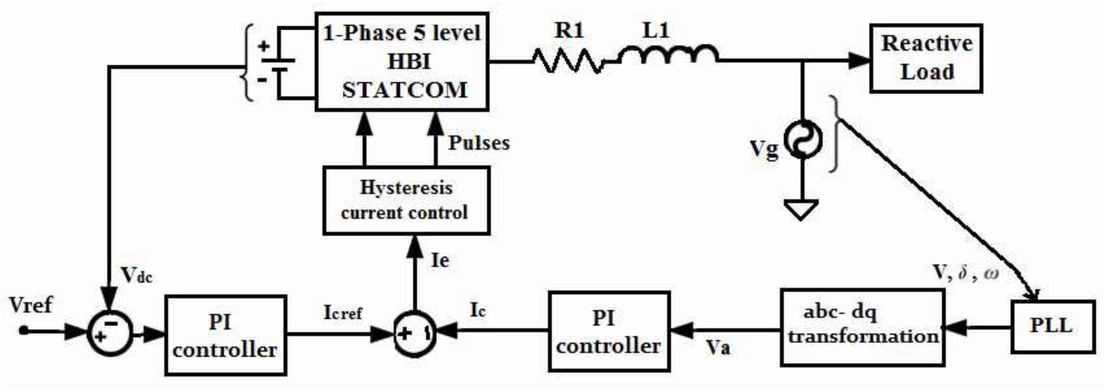


Fig. 6. block diagram for closed loop operation of proposed system

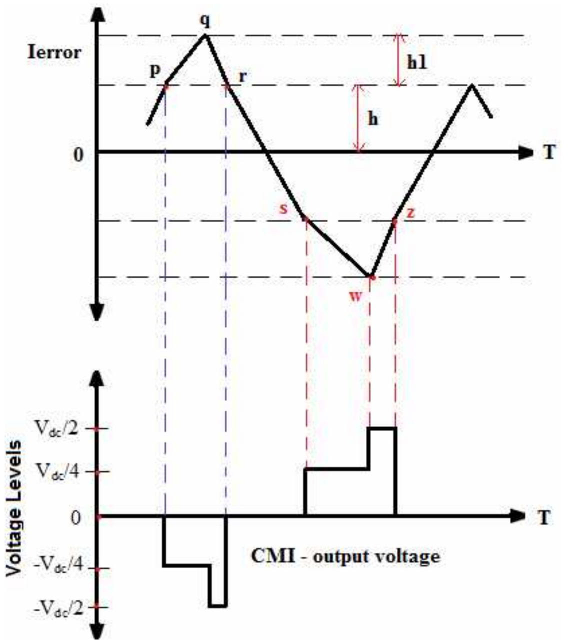


Fig. 7. HCC for cascaded multilevel inverter

positive side. The following eqns (7), (8) & (9) represents the error current value for three phase ac currents.

$$I_{a\_error} = I_{a\_ref} - I_{a\_act} \tag{7}$$

$$I_{b\_error} = I_{b\_ref} - I_{b\_act} \tag{8}$$

$$I_{c\_error} = I_{c\_ref} - I_{c\_act} \tag{9}$$

4.1 Control strategy for proposed system

The proposed system shown in Fig. 6, which increases the output voltage and enhance current control with minimized THD. Initially the reference voltage is compared with actual voltage of the system, which is measured from the STATCOM scheme.

After the comparison, error voltage parameter is converted to reference current parameter by using PI controller.

Actual current parameter of the system is produced from grid voltage by using PI controller used in the grid side. And synchronization of voltage and current parameters are controlled by using PLL and abc-dq transformation. Finally hysteresis current control receives the error current value by comparing actual and reference current generated from the proposed system. And by varying the hysteresis band value from 0.1 to 0.95, which improves the output voltage and current of proposed with minimized THD value.

5. Simulation Results and discussion

The projected system presented here is to focus on improving the power quality injected to the grid. It is simulated using *Matlab R2016a*. The PMSG ac voltage is converted to dc with help of 3-phase rectifier, which is added with the dc output of the PV array has variations of solar irradiation of $300W/m^2$ to $1200W/m^2$ and temperature of (0-40) degree. For synchronizing the inverter stepped output with the grid parameters, split inductors are used with *4mH*.

Closed loop current control is applied in which the inverter side three phase current is measured and abc-dq transformation is applied using park's transformation equation. Reference current value from the hybrid source is added and using dq- abc transformation this three phase reference current is added to the system using hysteresis current control. The PV array dc output voltage of 80 V and current with 6A is shown in Fig. 8. The Fig. 9 shows the rectified dc output voltage using 3-phase rectifier.

Another input source of the proposed system is wind energy PMSG system, which generates ac output voltage of 150V is shown in Fig. 9, which added with PV array voltage. The HCC based switching pulses for S_1 & S_2 of the cascaded H-bridge inverter are shown in Fig. 12

The proposed work improves the output voltage by the hysteresis controller by the varying the hysteresis band from 0.1 to 0.95 is shown in fig.11. In that fig.11a&b shows output voltage of proposed system with hysteresis

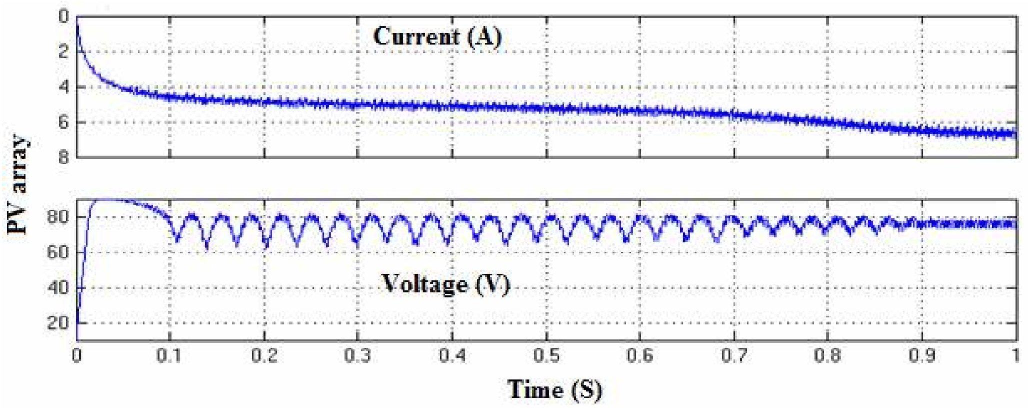


Fig. 8. PV array – output current and voltage

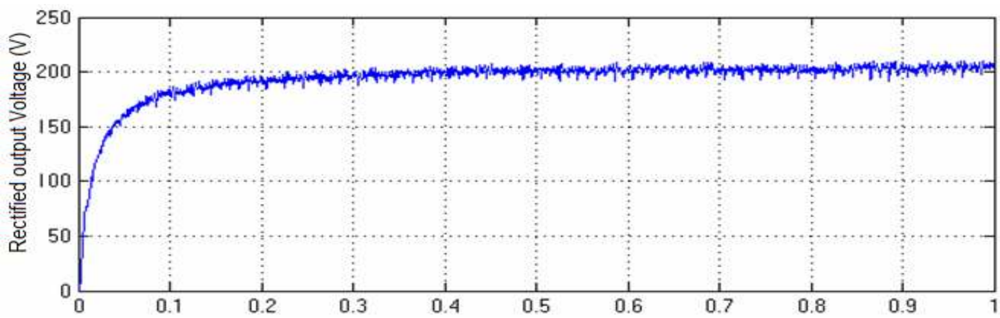


Fig. 9. Rectified dc voltage using 3-phase rectifier

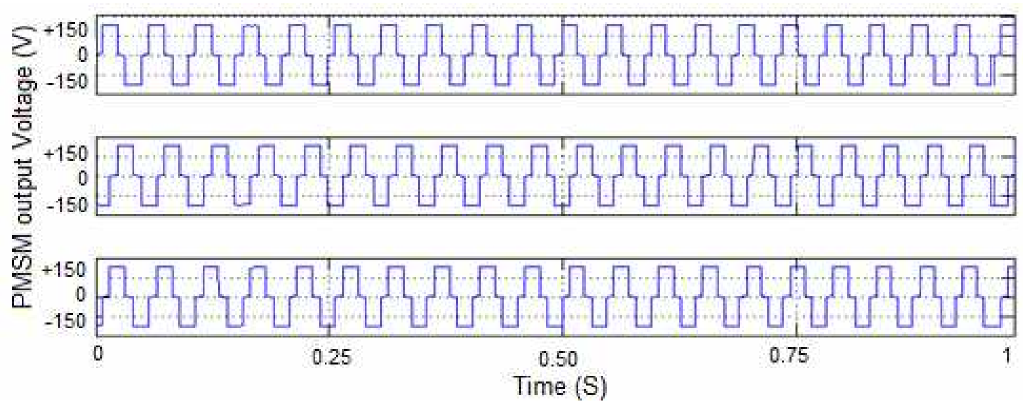


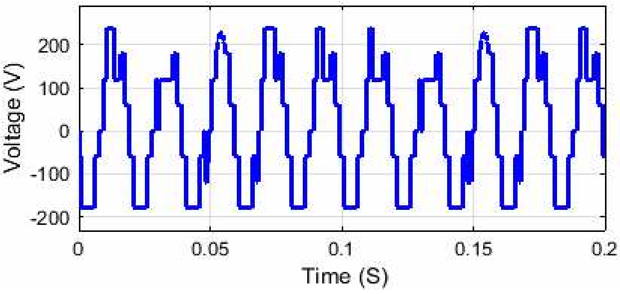
Fig.10. Wind energy - PMSG output voltage

band of 0.1 and 0.4 respectively and fig.11c shows output voltage of 245.4V with hysteresis band of 0.95, which improves the output voltage compared to other hysteresis band values.

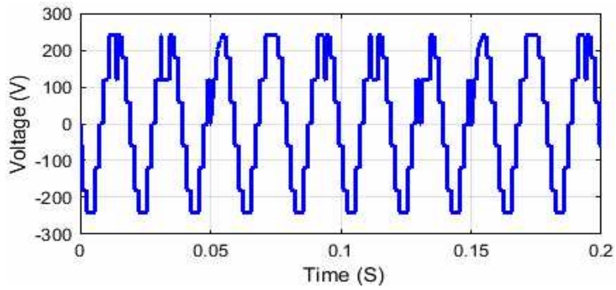
The Fig. 13 shows the controlled current of split inductor L_1 and L_2. The PLL and split inductor is used to synchronize the stepped inverter output with grid system. In Fig. 14(a) and (b) shows synchronization between grid voltage and current for sinusoidal pulse width modulation and hysteresis current control respectively. THD analysis of the proposed system for output voltage with 2.54% and for current with 4.30% is shown in Fig. 15(a) and (b) respectively.

6. Experimental results and discussion

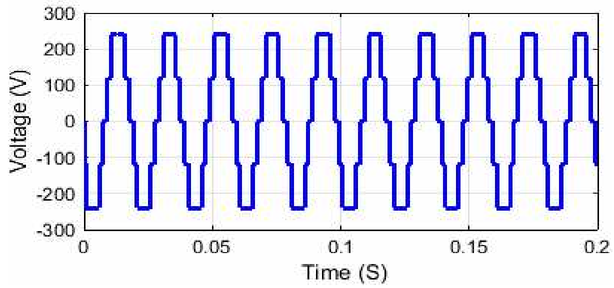
To authenticate the simulation results of the proposed system, the experimental setup for hysteresis current controlled for PV-Wind Hybrid source fed STATCOM system using five level cascaded inverter was designed and tested. PMSG-wind energy system ac voltage of 150V is converted to 148V dc using 3-phase bride rectifier and it is added with PV system voltage of 80V, which is feed to



(a)



(b)



(c)

Fig. 11. Single phase H-bridge inverter voltage with Hysteresis Band variation: (a) HB=0.1, (b) HB= 0.4 (c)

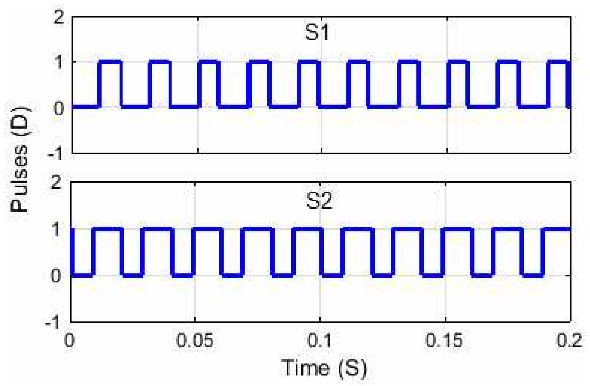


Fig. 12. Switching pulses for leg 1 & 2 of H-bridge inverter

cascaded h-bridge inverter.

The stepped output of 238.4 V is obtained at the inverter side and the THD is shown in Fig.16. With help of split inductors a sinusoidal voltage of 235.4V is obtained, which is synchronized with single phase grid connected system.

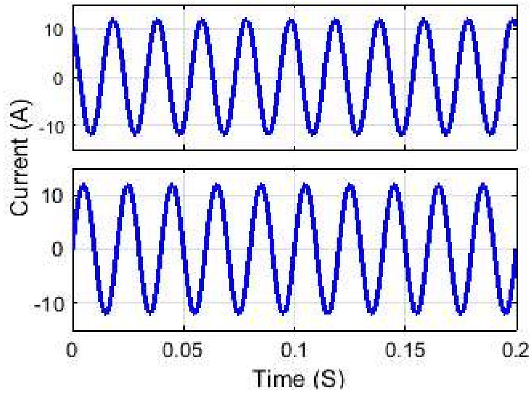
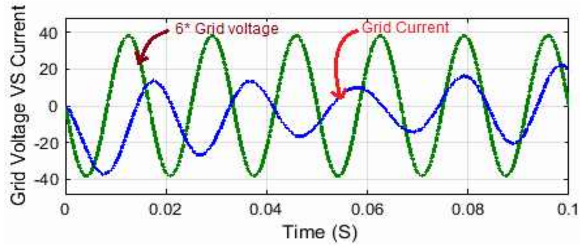
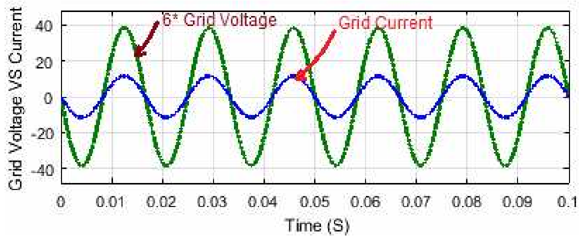


Fig. 13. Split inductor current waveform Id & Iq



(a)



(b)

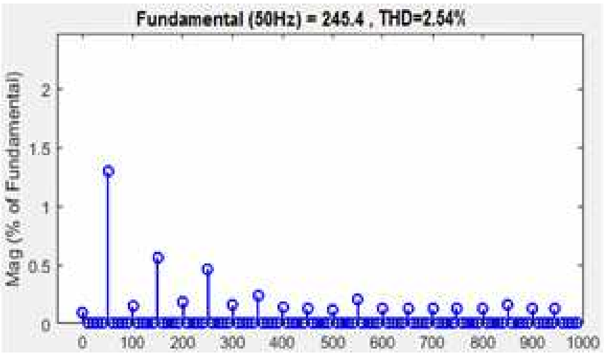
Fig. 14. Grid current / Voltage synchronization: (a) SPWM (b) Hysteresis current control

The sinusoidal ac voltage obtained using split inductor with THD analysis is shown in Fig. 17. In Fig. 18 shows the output current of grid system with split inductor.

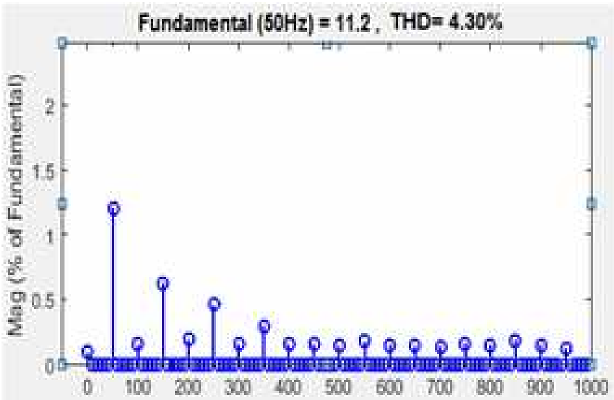
IRF840 MOSFET switches were used for the Inverter legs, which also minimizes switching loss compared to conventional inverter and output waveforms were obtained using Digital Storage Oscilloscope (DSO). Hysteresis current control is implemented using DSPIC30F micro-controller. The experimental setup of the proposed system is shown in Fig. 19. Table 1 shows THD comparison for various inverter topologies with HCC algorithm at hysteresis band of 0.95. The Fig. 20 shows comparison of output voltage for various inverter topologies.

7. Conclusion

A hysteresis current controller algorithm suitable for STATCOM with single phase five level cascaded H-bridge inverter was proposed. The performance of the proposed



(a)



(b)

Fig. 15. THD analysis: (a) output voltage (b) output current

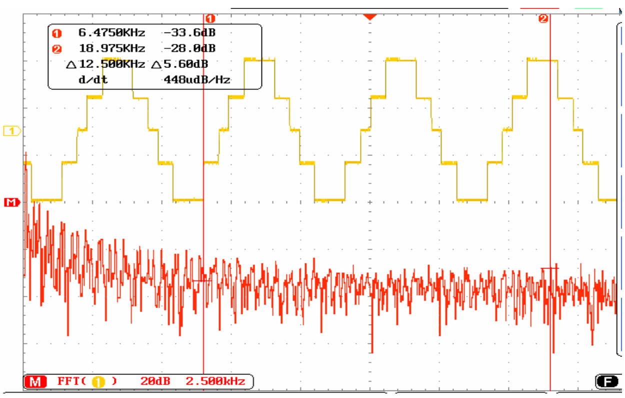


Fig. 16. H-bridge inverter output voltage at 0.95 (Hysteresis Band) and THD analysis

system was investigated through matlab/simulink and experimental setup. The hysteresis current controller is established to attain the improved output voltage, better current control & reduced THD. Hence, this controller is used to reduce the voltage stress on the each power semiconductor switches and produce nearly sinusoidal output waveform. The proposed system is energized by hybrid energy (PV-Wind) source and PLL and split inductor are used to achieve synchronization between inverter and grid. From this proposed system the following results are obtained, Improved output voltage and better

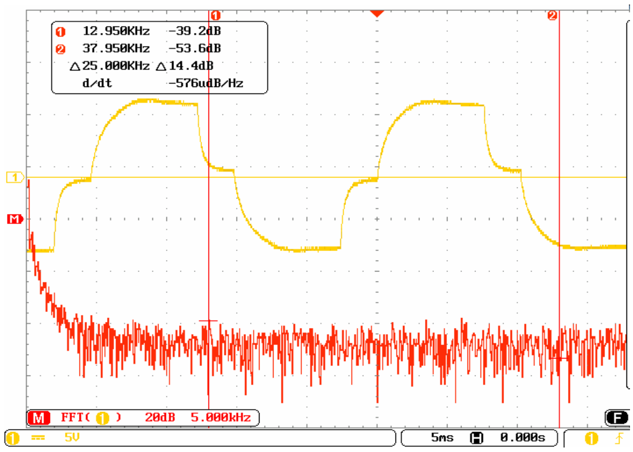


Fig. 17. Split inductor based output voltage and THD analysis

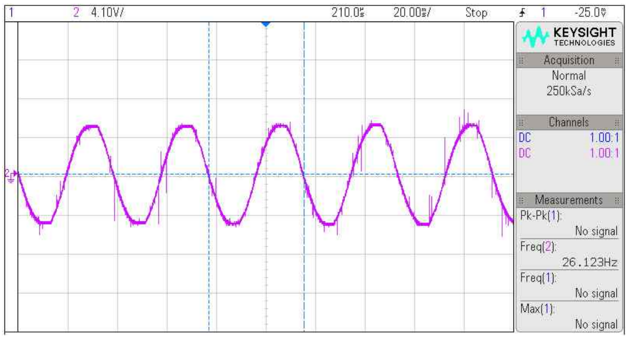


Fig. 18. Output current waveform of inverter with split inductor

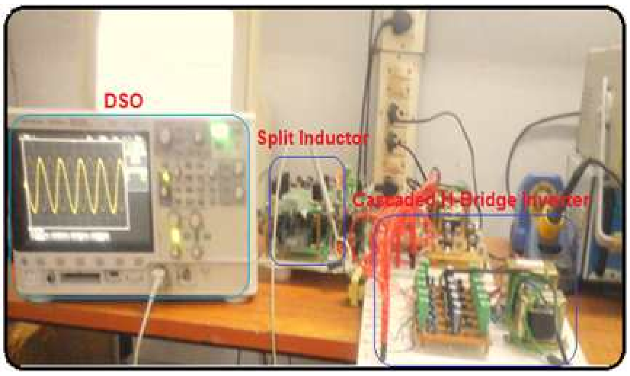


Fig. 19. Experimental setup of proposed system

Table 1. THD comparison for various inverter topologies with HCC algorithm at 0.95 (hysteresis band)

Number of level (n)	Voltage THD comparison for various inverter topologies (%)			
	Proposed system	Diode clamped	Flying capacitor	Conventional VSI with Reduced switches
3	2.54	4.20	4.43	8.42
5	2.86	6.40	4.64	12.4
7	3.10	8.89	8.88	14.85

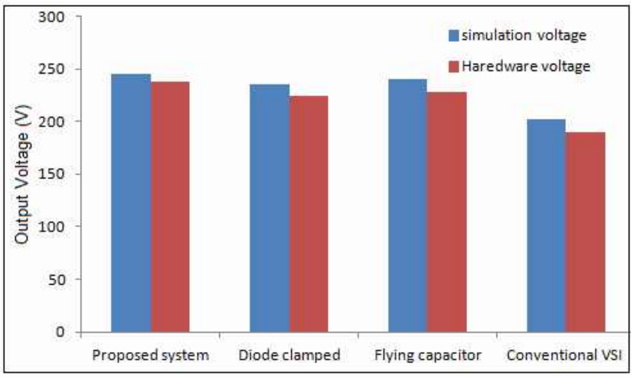


Fig. 20. Comparison of output voltage for various inverter topologies

current controlled with minimized THD of 2.54% and 4.30% respectively, which is attained with hysteresis band of 0.95.

Implemented closed loop control improves power demand of the system and voltage stress on the each switches are reduced using hysteresis current controller.

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