Multi Level Inverter Based STATCOM for Grid Connected Wind Energy Conversion System

G.Muni Reddy*‡, T.Gowri Manohar**

*Research Scholar, Department of Electrical and Electronics Engineering, S.V University, Tirupati, Andhra Pradesh, India.

** Professor, Department of Electrical and Electronics Engineering, S.V University, Tirupati, Andhra Pradesh, India.

(munireddyg@gmail.com, tgmanohar1973@rediffmail.com)

‡ Corresponding Author; G.Muni Reddy, Research Scholar, Department of Electrical and Electronics Engineering, S.V University, Tirupati-517502, Andhra Pradesh, India, Tel: +919032258962, Email: munireddyg@gmail.com

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Abstract- The sustainable energy resources, like wind energy, for electrical energy generation is augmented due to environmental problems and the scarcity of conventional energy sources, leading to integration of large number of wind generators in to grid. Integration of large scale of wind generators in to grid presents challenges such as voltage stability, reactive power management, frequency control, grid stability and power quality. In this proposed scheme, Multi Level Inverter based Static Compensator with a battery energy storage system employs Hysteresis Current Controller to diminish the effects of power quality issues. The proposed scheme for the grid connected wind energy conversion system is simulated using MATLAB/SIMULINK. The efficacy of the proposed control scheme is, it takes care of the reactive power requirement of the load and the induction generator, thus improving the source side power factor and also there will be a discernible reduction in the Total Harmonic Distortion. Using Multi Level inverter based STATCOM, lower source current distortions and lower switching frequency shall be obtained, when compared to conventional two level inverter based STATCOM.

Keywords- Wind Energy Conversion System (WECS); Static Synchronous Compensator (STATCOM); Hysteresis Current Control (HCC); Multi Level Inverter (MLI), Three Level Inverter (TLI); Battery Energy Storage System (BESS); Total Harmonic Distortion (THD)

1. Introduction

Rising apprehension for rising cost of energy, environmental impacts due to the use of fossil fuels, fast diminution of fossil fuels reserves and it is indispensable to reduce green house gas emissions encouraged the development of the renewable energy. Of all the renewable energy sources, wind power has undergone colossal development in recent years because wind power is pollution free and cost effective [1-2]. In recent years, there is an enormous increase in the installed capacity of wind power throughout the world. As an example, in European Union (EU), there is an increase in the installed capacity from 12.9 GW in 2000, which was 2.4 % of EU's electricity demand, to 128.8 GW in 2014, 10.2% of EU's electricity demand. An estimated capacity of 147 GW of renewable energy capacity addition is made in 2015, which is the world's largest addition in a year. Out of this installed capacity, wind energy is at the top position with capacity addition of 63 GW in 2015 [3-4].

An Induction Generator (IG) requires reactive power support and it is most commonly employed in a Wind Turbine (WT) to engender electricity. The reactive power adjustment is indispensable to sustain rated voltage in the power system. Normally, power system mainly consists of traditional power plants where alternators are directly connected to the grid. The attributes of WTs, mainly coupled with IGs, are diverse from the traditional alternators, affecting power system grid. Therefore, new regulations are forced by transmission companies to make certain that all necessary measures required for grid stability are taken care, when WTs are incorporated into the grid. Present day's research is to utilize Flexible AC Transmission Systems (FACTS) devices for improving performance of the grid connected WECS, taking into consideration of grid codes and grid stability [5].

With the integration of WECS in to the grid the power quality shall be affected. One of the simple methods of running a WECS is to connect the grid system directly with the IG. The IG has the advantages of cost effectiveness and proposed control scheme for MLI based STATCOM shall take care of reactive power requirement, to sustain unity power factor (UPF) at source side and shall effectively mitigate the harmonics in the system, thus reducing the THD to prescribed level.

The proposed MLI based STATCOM with HCC for grid connected WECS for power quality improvement has the following objectives.

- To maintain UPF at the source side even with the presence of WECS with IG and non linear RL load.
- To cancel the harmonics injected by non linear load and thus to improve the power quality of the system.
- To provide reactive power support to IG and Load.
- To achieve quick dynamic response with smaller switching frequencies.

2. Wind Energy Conversion System

WECS transform the kinetic energy (KE) of the wind into electrical energy or to some other form. The WT extracts the KE of the wind and produces rotating torque and the generator utilizing this torque produces electrical energy, which is fed in to the grid. WTs are of two types: vertical axis and the horizontal axis. Contemporary WTs mostly utilize the horizontal axis arrangement having two or three blades, which operate either down-wind or up-wind.

A WT shall be designed to operate for a fixed speed or variable speed. More energy is produced by variable speed WTs in comparison to fixed speed WTs; nevertheless, they require power electronic converters to facilitate a constant frequency and constant voltage electrical energy output. Gears mechanism is engaged for matching the high speed 3-Φ AC generators with the low speed WT. Generators utilized for WTs shall be of the types: alternators, permanent magnet synchronous generators (PMSG) and IGs of two types: the squirrel cage and wound rotor. Reliability and low cost made PMSG and squirrel cage IGs popular in small and medium sized WTs. In this paper, constant speed with pitch control WT is employed. The IG is employed in this paper because of its simple and rugged construction, economical, no need of separate excitation circuit, and has inherent safety for short circuit [6].

The total power available in the wind is given by the equation,

$$P_w = \frac{1}{2}\rho A v_w^3 \tag{1}$$

Where A is the exposed area in m^2, ρ is the density of the air in kg/m^3, v_w is the wind speed in m/s. For recovering total KE of wind, wind velocity shall be reduced to zero, which causes no air flow through the wind turbine. Thus it excerpts a portion of power in wind, given by the equation

$$P_m = C_p P_w \tag{2}$$

robustness. However, an IG takes lagging currents for magnetization, forces the source to supply the required reactive power. Thus the source has the additional burden of supplying reactive power to load as well as to IG. The

Where Cp is called power coefficient of the WT. The wind is converted to mechanical power with an efficiency C_p, and transmitted mechanically to the generator with efficiency η_m, and further converted to electricity with an efficiency η_g. The electrical power output is then [7]

$$P_e = c_p \eta_m \eta_g P_w \tag{3}$$

3. Static Synchronous Compensator

All the power electronic circuits with internal control to produce var output relative to an input reference are known as static var generators. Recently, for reactive power control, the Voltage Source Inverter (VSI) based Static VAR compensators have been used, which are known as advanced static VAR compensator or Static Synchronous Compensator [8]. The capacitor serves as DC source voltage for STATCOM and as the capacitor can stock up only a negligible charge, STATCOM can supply a very negligible active power. The STATCOM works as a VSI, but instead of connecting to a passive load as in traditional VSI, connected to grid. The phase angle and the magnitude of the output voltage are the two control parameters of STATCOM that provide control of voltage and reactive power. Just like rotating synchronous machines, the reactive power transfer between the STATCOM and the grid shall be managed by changing the magnitude of the output voltage of VSI. If the magnitude of the output voltage of VSI is augmented to a voltage greater than that of grid, the VSI generates reactive power just like a capacitor, otherwise VSI consumes reactive power just like an inductor and the reactive power transfer is nil for the same voltages of grid and VSI. Thus by continuously changing voltage magnitude, the reactive power from VSI can be adjusted incessantly form positive to negative [8-9]. When compared to other ideology for reactive power compensation, the STATCOM offers several benefits as discussed in [10-11].

3.1 Battery Energy Storage System (BESS)– STATCOM

Traditional STATCOM, lacking the energy storage capability, shall be regulated in only inductive and capacitive modes; whereas STATCOM with BESS shall be regulated in extra two modes with charging and discharging capabilities. As there is no energy storage device, traditional STATCOM has negligible capacity of active power transfer. In WECS, due to discontinuous property of wind, the real power produced is fluctuating in nature, causing the reactive power fluctuations of WECS, leading to low frequency oscillations in the grid. These oscillations shall be reduced effectively by either active power or reactive power injection/absorption in to the grid. But the approach of active power injection/absorption for damping oscillations is more efficient. Hence, compared to traditional STATCOM, STATCOM+BESS shall be employed for the above discussed problem. STATCOM-BESS also stores excess energy generated from WECS. STATCOM- BESS also reduces the value of DC link capacitor [12].

4. Configuration of Grid Connected WECS

The connection diagram of grid connected WECS is shown in Fig. 1, which consists of IG based WT, non linear RL load and BESS –STATCOM connected to grid at Point of Common Coupling (PCC). The current supplied by BESS-STATCOM shall cancel the IG's and load's reactive current part and harmonics injected by the load and thus facilitate to obtain UPF and THD within the standards specified.

The main block diagram of grid connected WECS with the HCC scheme is shown in Fig. 2. The inputs to the proposed control scheme are source voltage, source current, DC link capacitor voltage, V_{dc}, and V_{dcref}. The grid voltages, V_{sa}, V_{sb}, V_{sc}, are sensed for the purpose of synchronization with grid. The source currents are to be measured for the purpose of comparing with the reference values in the control block so as to switch the STATCOM to maintain the source current waveform as per the reference. The STATCOM - BESS has desired control scheme to vary the output of STATCOM so as to maintain the power quality of the grid system within the specified norms.

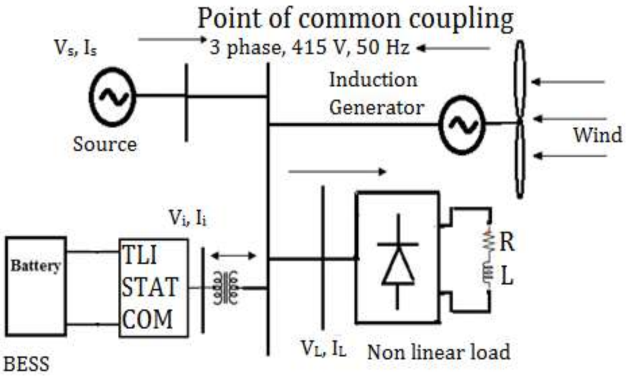

Fig.1 Grid connected system

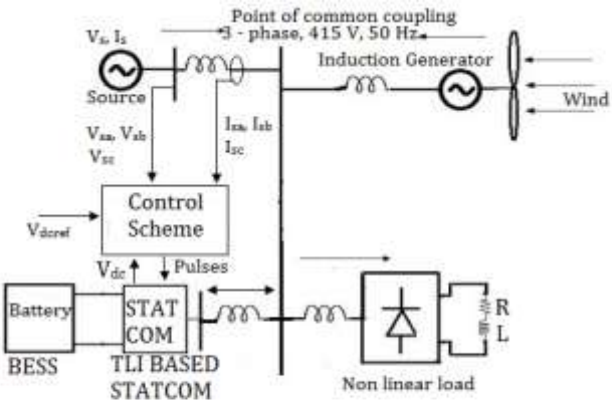

Fig.2 Grid connected system with control scheme

In this paper a three level diode clamped inverter based STATCOM is employed. The advantages of Multi Level Inverter (MLI) when compared to conventional two level inverters (CTLI) are: [13]

- Output voltages with small THD and lower dv/dt stress, leads to reduced electromagnetic compatibility problems.
- Small source current distortions.
- Lower switching frequency

At this point, it is worth to know the disadvantages of higher switching frequency.

- Increase of switching losses in IGBT, increased copper and core losses in inductors.
- Requirement of more sophisticated devices, improved reactive elements and more costly heat management and this leads to increased cost of components.
- Electromagnetic Interference qualification is more complex; printed circuit board layout and management of heat produced require special interest and thus increases complexity of design.
- Current carrying capability of IGBT degenerate more rapidly as frequency increases [14-15].

To validate the above discussed advantages of TLI over CTLI, a comparative analysis of the test system shown in Fig.1 is also performed with CTLI based STATCOM.

5. Control Scheme

The unit template or PI controller based control algorithm is employed for controlling the TLI based STATCOM. This is a simple control algorithm and can be implemented easily [16]. Figure 3 shows the proposed control algorithm of STATCOM for maintaining the prescribed power quality norms. In this control strategy, 3-Φ voltages are detected at PCC, which are fed to a filter to obtain distortion less phase voltages, V_{sa}, V_{sb}, and V_{sc} . Using these voltages, the amplitude of the PCC voltage, V_{sp}, is calculated as:

$$V_{sp}=\{\tfrac{2}{3}(V_{sa}^2+V_{sb}^2+V_{sc}^2)\}^{1/2} \tag{4}$$

Now, using Eq. (4), the in-phase unit templates K_{sa}, K_{sb}, K_{sc} are obtained

$$K_{sa}=\frac{V_{sa}}{V_{sp}};\ K_{sb}=\frac{V_{sb}}{V_{sp}};\ K_{sc}=\frac{V_{sc}}{V_{sp}} \tag{5}$$

The self-supporting DC bus is implemented using a PI controller and the detected voltage, V_{dc}, and reference voltage V_{dcref}. The amplitude of reference supply currents, I^*_{spp}, is provided by the PI controller for calculating in phase reference supply currents i_{sa}^{ref}, i_{sb}^{ref}, and i_{sc}^{ref}.

$$i_{sa}^{ref}=I^*_{spp}.K_{sa};\ i_{sb}^{ref}=I^*_{spp}.K_{sb};\ i_{sc}^{ref}=I^*_{spp}.K_{sc} \tag{6}$$

Thus, for obtaining the fundamental UPF supply currents, the calculated in-phase reference supply currents as described above shall become the reference supply currents [16].

5.1 Hysteresis Current Controller

The reference currents are obtained from the Eq. (6) and the actual currents are detected by current sensors, both are subtracted for obtaining a current error, which is fed to a HCC. Thus the HCC provides ON/OFF switching signals for

IGBT of STATCOM to force the actual current to follow the reference current. [17-18]

The switching signals generation in MATLAB/ SIMULINK for phase 'A' of TLI based STATCOM is shown in Fig. 4. In the similar way switching signals for other phases can be generated. A relay is used to implement the hysteresis region in MATLAB/ SIMULINK. Here I_{saref} and I_{sa} are reference and actual currents respectively for phase 'A'. The hysteresis current controller shall switch the IGBTs of TLI based STATCOM so as to force the actual phase currents to follow the reference currents and thus obtaining the actual current in phase with voltage and THD of source current within the prescribed limit. The hysteresis current controller always maintains the source current between the boundaries of hysteresis region, which is taken as 0.1, and gives correct switching signals for STATCOM operation to force the source current to be sinusoidal in nature.

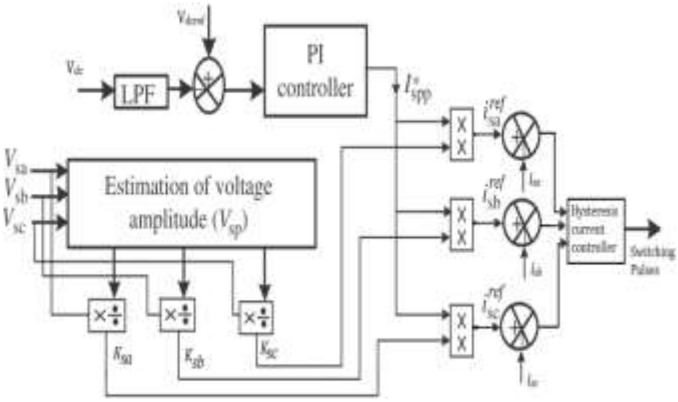

Fig. 3 Block diagram of the control system

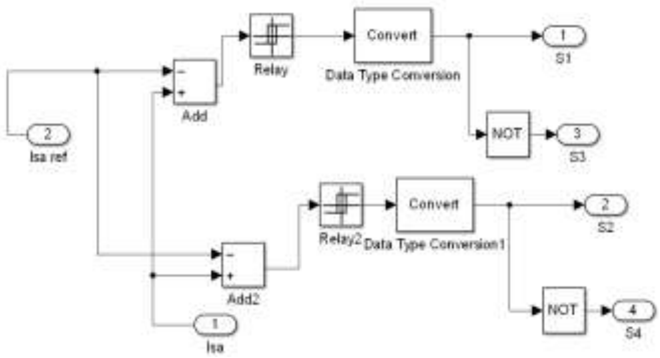

Fig. 4 Switching signals generation for phase A

6. Results and Discussion

The grid connected system shown in Fig.1 is simulated using MATLAB/SIMULINK with the system specifications as shown in Table 1. The power quality of the source current in the grid is influenced by nonlinear load and wind generator, which injects harmonics in to the source current waveform. The STATCOM injected current into the grid shall purge the distortions caused by the non-linear load and wind generator. In this paper, at first the system is simulated without the STATCOM and its controller. Later the same system is simulated with the CTLI based STATCOM having HCC and then with the TLI based STATCOM having HCC to compare the performance.

Table 1. System specifications

S.No	System parameters	Specifications
1.	Grid Voltage	3-Φ, 415V, 50Hz
2.	Induction generator	3.5KVA, 415V, 50Hz, P=4, Speed=1440 rpm, R_r=0.1Ω, R_s=0.15Ω, L_s=L_r=0.06H
3.	Line Inductance	0.05mH
4.	Inverter	DC Link Voltage=800V, DC Link Capacitance=100µF
5.	Load	Non-Linear Load with R=15 ohm and L= 20mH

6.1 *System performance without STATCOM and its Controller*

The system is simulated without the STATCOM and its controller and the waveforms are shown in Fig. 5. From Fig. 5a, it is obvious that the load current, due to non linear load, is highly distorted and this load current also injected the harmonics in to source current causing the source current waveform also distorted, as shown in Fig. 5b. Figure 5c shows the waveform of inverter current, which is zero, as the STATCOM is inoperative. From the Fig. 6, it is obvious that the source current waveform is highly distorted as the THD is 26.06%, which is not acceptable as per the standard norms. From Fig. 7 it is apparent that the power factor is lagging due to reactive power requirement of non linear load and the IG.

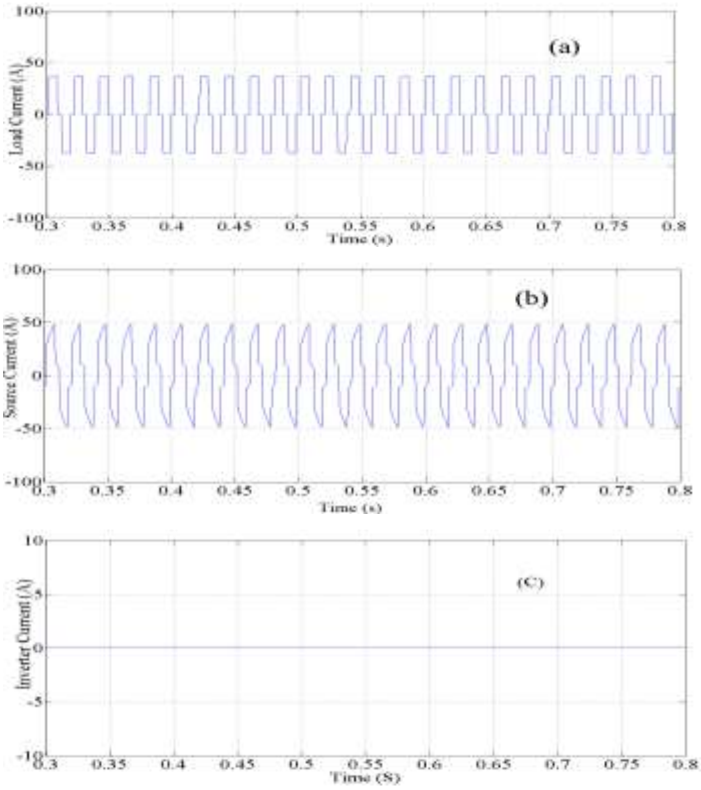

Fig.5 (a) Load Current (b) Source Current (c) Inverter Injected Current, Without STATCOM

6.2 System performance with CTLI based STATCOM with HCC

The system is simulated with the CTLI based STATCOM and its HCC and the waveforms are shown in Fig. 8. From the Fig. 8a, it is lucid that the load current is highly distorted, which causes source current waveform also distorted. But the injected current into the grid from

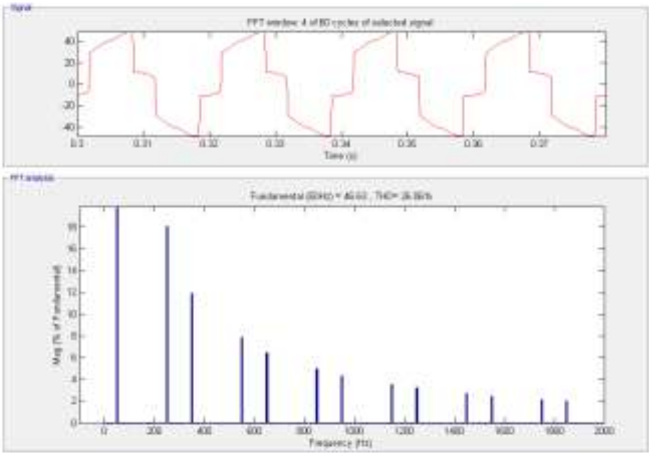

Fig. 6 FFT analysis of Source current waveform without STATCOM

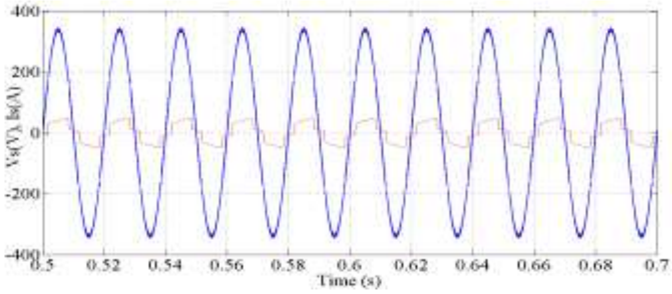

Fig. 7 Supply voltage & supply current at PCC without STATCOM

STATCOM shall nullify the distortion. Figure 8b shows the source current waveform, which is sinusoidal in nature due to cancellation of harmonics by the STATCOM injected current in to grid, as shown in Fig. 8c. From the Fig. 9, it is obvious that the source current waveform is nearly pure sinusoidal as the THD is only 3.24%, which is acceptable as per the standard norms. There is a drastic improvement in THD of source current from 26.06% to 3.24%. From Fig. 10, it is understandable that the power factor is unity even with the presence of non linear RL load and the IG. This clearly indicates that the STATCOM is providing the required reactive power support in the grid and thus relieving the source from supplying reactive power.

6.3 System performance with TLI Based STATCOM with HCC

Now the grid connected system shown in Fig.1 is simulated with the TLI based STATCOM and its HCC. From the Fig. 12a, it is clear that the load current is highly distorted. The injected current into the grid from STATCOM will cancel out the distortion caused by the nonlinear load. Figure 12b shows the source current waveform, which is sinusoidal in nature due to cancellation of harmonics by the STATCOM injected current in to grid, as shown in Fig. 12c. From the Fig. 13, it is obvious that the source current waveform is almost pure sinusoidal as the THD is only 2.02%, which is adequate as per the standard norms. There is a drastic improvement in THD of source current from 26.06% to 2.02%. From Fig. 14, it is comprehensible that the power factor is unity even with the presence of non linear RL load and the induction generator. This clearly indicates that the proposed TLI based STATCOM with the HCC is providing the required reactive power support in the grid and thus relieving the source from supplying reactive power.

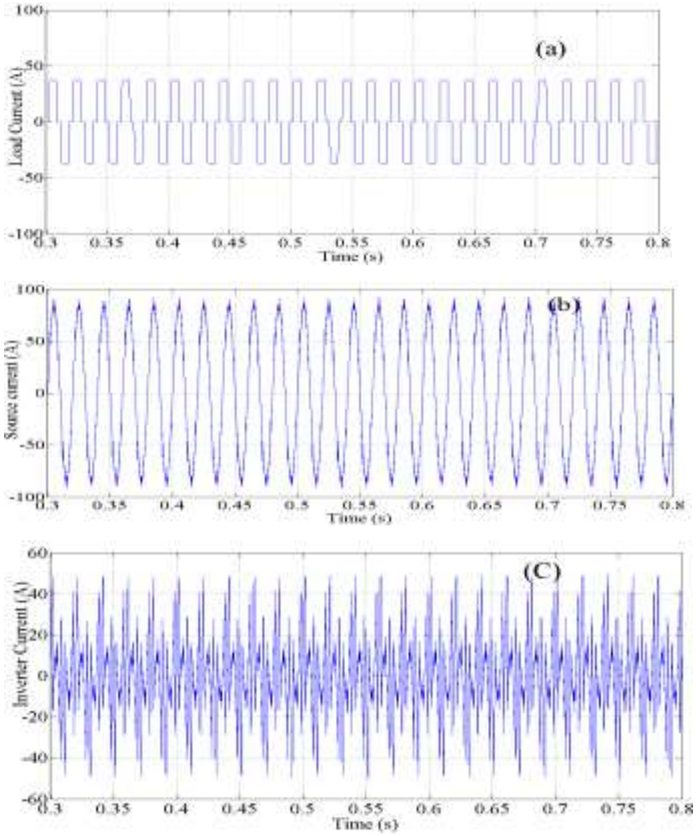

Fig. 8 (a) Load Current (b) Source Current (c) Inverter Injected Current, for CTLI based STATCOM with HCC

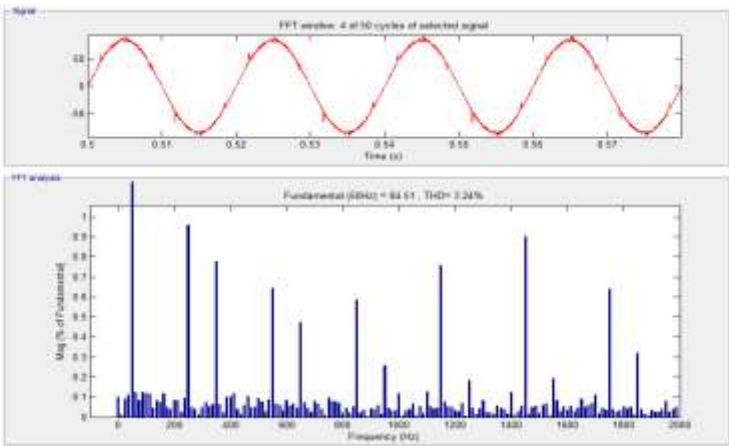

Fig. 9 FFT analysis of Source current waveform with CTLI based STATCOM with HCC

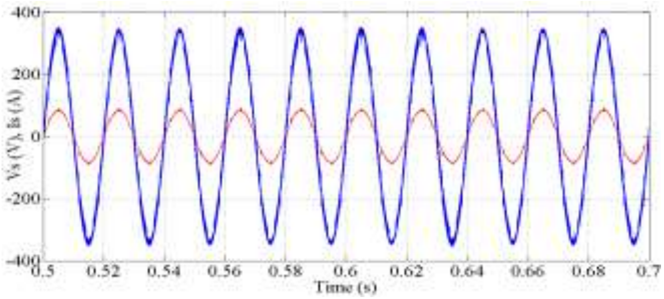

Fig. 10 Supply voltage & supply current at PCC with CTLI based STATCOM with HCC

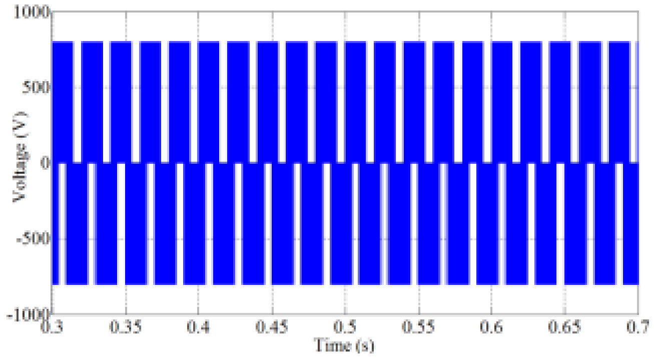

Fig. 11 Output Voltage of CTLI based STATCOM

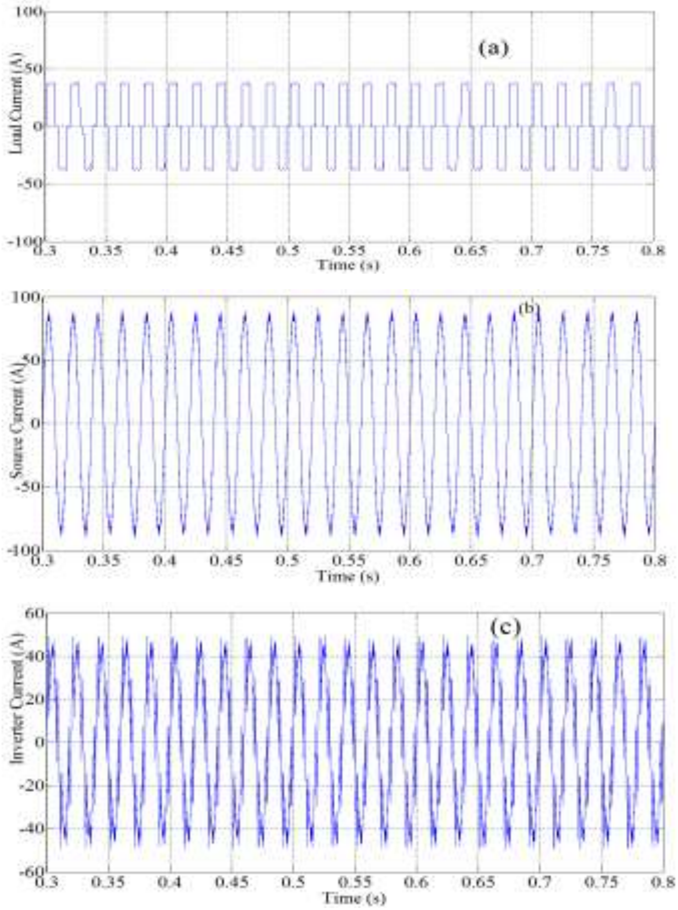

Fig. 12 (a) Load Current (b) Source Current (c) Inverter Injected Current, for the TLI based STATCOM with HCC

6.4 Comparison of switching frequency of CTLI based STATCOM and TLI based STATCOM

For the comparison of switching frequency of the CTLI based STATCOM and the TLI based STATCOM, the switching frequency of the IGBT in the upper position of phase A is plotted as shown in Fig. 16. From the Fig. 16, the frequency variation for CTLI based STATCOM is from 100 KHz to 518 Hz and that for the TLI based STATCOM is from 50 KHz to 343.6 Hz. For the TLI based STATCOM, as discussed in section 4, the switching frequency is lower. The disadvantages of higher switching frequency are also discussed in section 4.

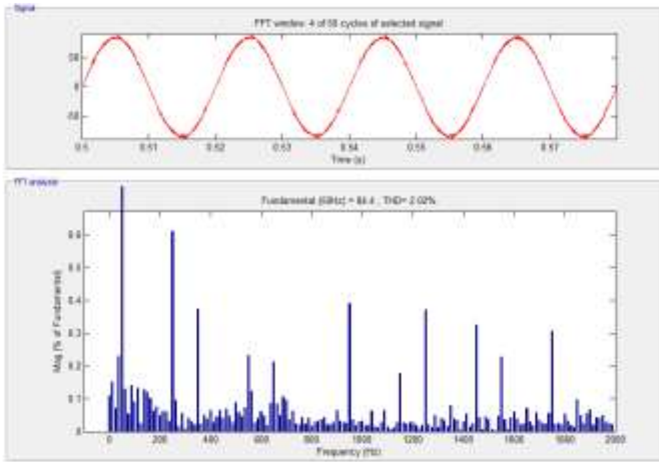

Fig. 13 FFT analysis of Source current waveform of TLI based STATCOM with HCC

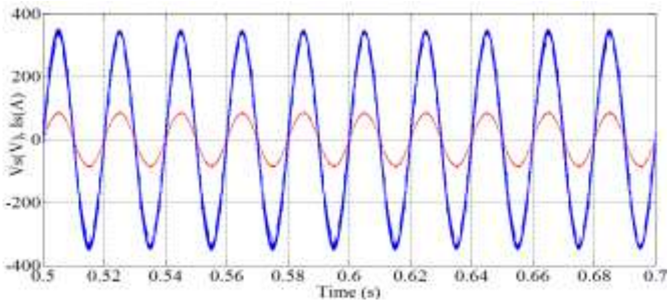

Fig. 14 Supply voltage & supply current at PCC with the TLI based STATCOM with HCC

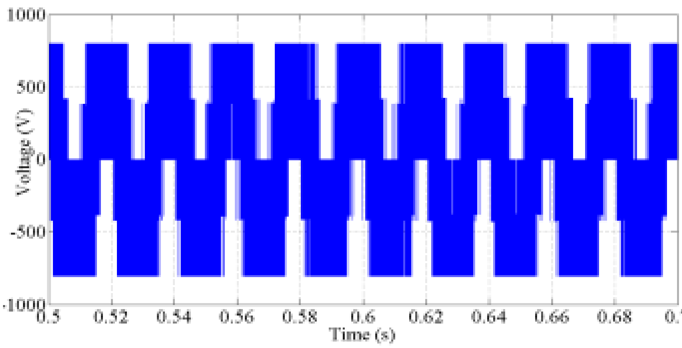

Fig. 15 Output Voltage of TLI based STATCOM

6.5 Performance of CTLI based STATCOM and TLI based STATCOM under dynamic load variations

The performance of the CTLI based STATCOM and TLI based STATCOM under dynamic conditions is also studied by applying step change in load at 0.5 s. Figure 17 shows the waveforms of source current and load current with step change in load. It is clearly seen from the waveforms that source current is also increased to supply the increased load current, when there is no STATCOM. Figure 17c shows the waveforms of source current with step change in load with the CTLI based STATCOM, where as Fig. 17d shows the waveforms of source current with step change in load with the TLI based STATCOM. For both the controllers, it is

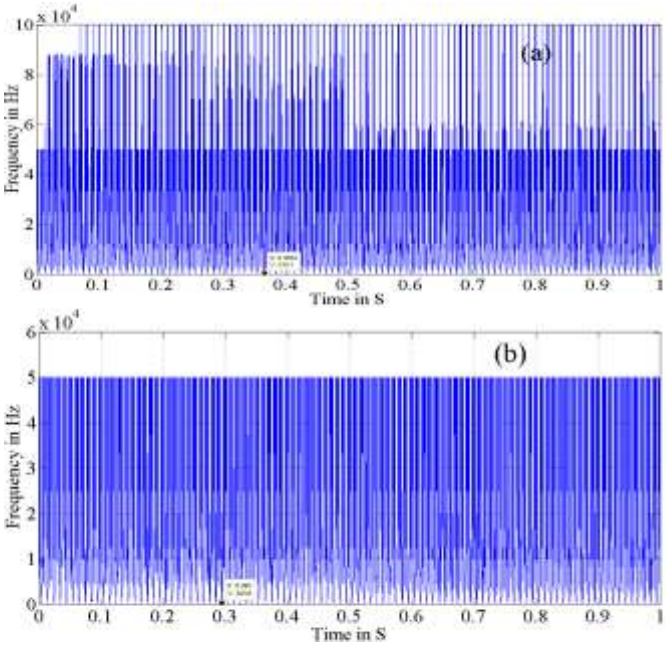

Fig. 16 Switching frequency (a) CTLI based STATCOM (b) TLI based STATCOM

clearly seen from the waveforms that the additional load demand is met by STATCOM compensator. Both the controllers of the STATCOM can effectively regulate the available real power from source by facilitating the real power transfer from the batteries to the load. Table 2 indicates the comparison of the performance of the system without STATCOM and with CTLI based STATCOM and TLI based STATCOM.

Table 2. Comparison of performance of the system

S. N	Without STATCOM	With CTLI based STATCOM	With TLI based STATCOM
1.	Source and load currents are highly distorted	Source current is sinusoidal even though the load current is highly distorted	Source current is sinusoidal even though the load current is highly distorted
2.	THD of source current is 26.06 %	THD of source current is 3.24 %	THD of source current is 2.02 %
3.	Source supplies the reactive power hence supply power factor is lagging	STATCOM mitigates the reactive power demand hence supply power factor is maintained at Unity	STATCOM mitigates the reactive power demand hence supply power factor is maintained at Unity
4.	Poor dynamic performance	Good dynamic performance	Good dynamic performance
5.	-	Higher switching frequency	Lower switching frequency

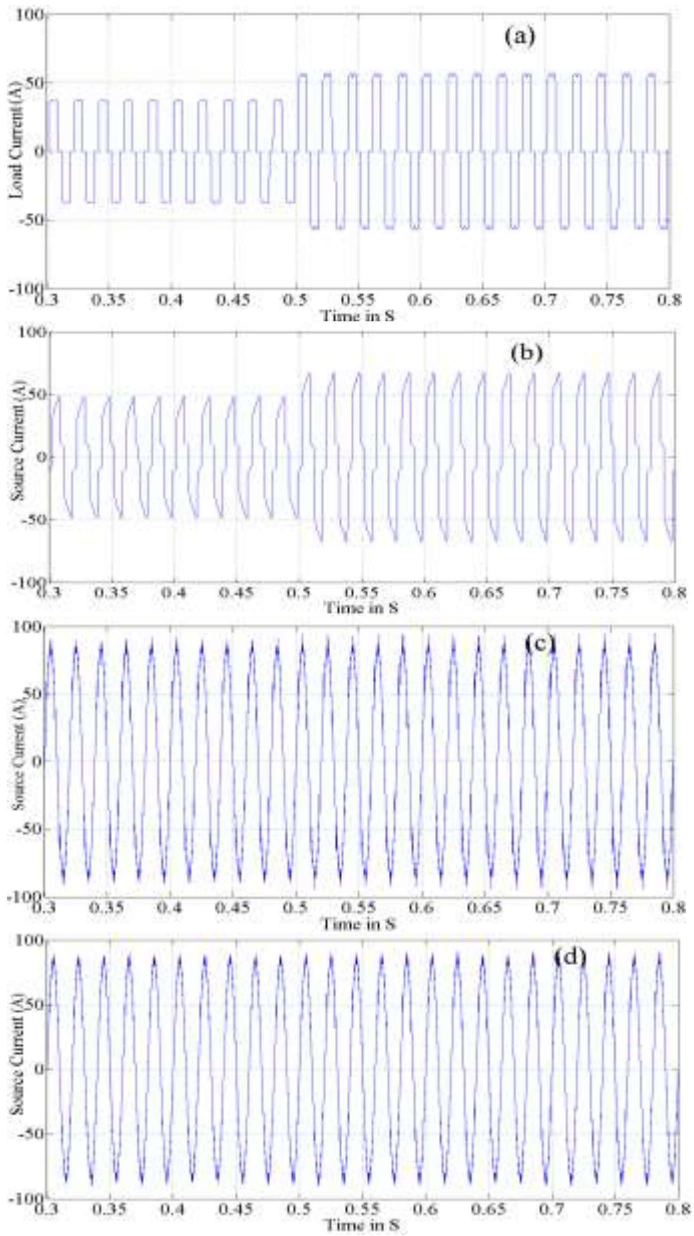

Fig. 17 (a) Load current (b) source current without STATCOM (c) Source current with CTLI based STATCOM (d) Source current with TLI based STATCOM during dynamic load changes

7. Conclusion

This paper presents the TLI based STATCOM with HCC for power quality enhancement in grid coupled with WECS and non linear load. The proposed control system for the STATCOM-BESS is simulated in MATLAB/SIMULINK. The proposed TLI based STATCOM has the potential of canceling out the harmonics injected by the non linear load in to the power system. It has been found clearly that the power quality has been enhanced by reducing the THD of source current waveform from 26.06% to 2.04%. The proposed TLI based STATCOM and its controller also maintains the power factor of the source as unity and thus provides the reactive power required for the wind generator and non linear load in the grid system, thus relieves the source from supplying reactive power. Thus by maintaining the UPF at the PCC of the grid, the proposed TLI based STATCOM controller improves the transmission line's utilization factor. The proposed TLI based STATCOM controller has shown to have stupendous dynamic performance also. The proposed TLI based STATCOM controller has shown to have the ability to compensate the sudden load demand in the system by regulating the available real power from source. The STATCOM controller is shown to facilitate the real power transfer from the batteries to the load and thus smoothing the source power fluctuations. In comparison with CTLI based STATCOM, TLI based STATCOM has shown to have lower THD in source current and also lower frequency, operating at 50% lower frequency, leading to various benefits like less switching losses, decreased cost of components, decreased complexity of design and increased current carrying capability. The grid connected WECS with TLI based STATCOM has shown the stupendous performance by gratifying the power quality norms as per the IEC standard.

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