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# POWER QUALITY IMPROVEMENT OF GRID CONNECTED WIND ENERGY SYSTEMS USING STATCOM-BATTERY ENERGY STORAGE SYSTEM

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## ABSTRACT
For the past few year renewable energy resources, without challenging environmental concerns has lead to significant increase in global power generation. Out of that wind energy is considered to be the most mature renewable energy source. However, the exploitation of wind energy is particularly challenging due to the stochastic nature of wind. This weak interconnection of wind generating source in the electrical network affects the power quality and reliability. FACTS technologies have already been used to enhance the controllability and power transfer capability of transmission system. Recently other important functions have been added such as harmonic elimination and dynamic voltage regulation, as a solution for power quality problems. In this paper FACTS device is used to enable smooth and proper integration of wind energy system to the grid is taken as the main objective. Furthermore, the detailed investigations using MATLAB/SIMULINK is explored in this paper for the enhancement of power quality using STATCOM, integrated with battery energy storage system. The STATCOM model is tested using a hardware setup.

**Keywords:** BESS, FACTS, hysteresis current control, power quality, statcom.

## INTRODUCTION
New energy source has become a focus for global economic growth and sustainable development with the depletion of resources and pollution of environment. This diverts researchers' attention towards renewable energy resources such as wind energy, solar energy, fuel cell, geothermal, biomass, and industrial waste heat [1,2]. Wind power is gaining momentum not only as a means to reduce the $CO_2$ emissions but also as an interesting economic alternative in areas with appropriate wind speeds [3]. The challenges the wind power introduce to the power system is related to the fluctuating nature of wind energy as well as the asynchronous generators that are introduced to the power system [4].

Asynchronous generators are connected to grid through the power converter and thus the power fluctuations caused by the variation in wind speed are absorbed and compensated by adjusting the generated frequency and the voltage to the grid [5]. The FACTS devices such as Static Var compensator (SVC), a combination of the thyristor-controlled reactors and fixed capacitors (FC-TCR) has made it possible to provide dynamic compensation of reactive power for power systems [6,7]. However, the effective reactive power that SVC can generate depends up on its terminal voltage. Thus due to voltage drop at the terminal bus the maximum reactive power output from SVC is always depressed than required, leading to controller saturation and prolonged response time.

STATCOM similar to SVC is a shunt connected device but it uses the Voltage Source Inverter (VSI) for dynamic reactive power generation and absorption rather than using capacitors and inductors [8]. VSI output voltage and current can be varied by properly controlling the modulation index. This means that dynamic exchange of reactive power flow control between STATCOM and transmission line is possible independent of terminal voltage variation. Another advantage is that STATCOM behaves analogously to synchronous condensers, except that STATCOMs have no mechanical inertia and are therefore capable of responding much more rapidly to changing system conditions and they do not contribute to short circuit currents.

The integration of Battery Energy Storage System (BESS) with STATCOM provides significant improvements in the performance over conventional STATCOM [9],[10]. The addition of energy storage allows the STATCOM to inject and/or absorb active and reactive power simultaneously. In this paper, STATCOM with BESS and its control are presented. The model is implemented in MATLAB/Simulink and computer simulation results are analyzed for transient stability.

## POWER QUALITY STANDARDS FOR WIND TURBINES
As stated the injection of wind power into grid will affect the power quality. As the power quality must be within certain limits to comply with the utility requirement, the effect should be assessed prior to installation of the turbine. The effects depend upon the electrical characteristics of wind turbine which are manufacturer specific rather than the site specific. International Electro technical Commission (IEC) seeing need of consistent and replicable documentation of power quality characteristics of wind turbine developed IEC 61400-21 and most large wind turbine manufacturer provided power quality characteristic data accordingly.

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According to IEC 61400-21 the relevant parameters for characterizing Power Quality of wind turbine are [1]

- Rated Real Power, Rated Reactive Power, Rated Apparent Power and Rated Current
- Maximum Permitted Power (10 minute average power)
- Maximum measured Power (60-second average power and 0.2 second average power)
- Reactive power (10 minute average value as a function of active power)
- Flicker coefficient as a function of network impedance phase angle and annual average wind speed
- Maximum number of specified switching operations of wind turbine with a 10 minute period and 2 hour period
- Flicker step factor and voltage change factor for specified operations of wind turbine
- Maximum harmonic current during continuous operation given as 10 minute average for each harmonic up to 50th

## STATCOM/BESS

Flexible AC Transmission Systems (FACTS) refers to a group of resources used to overcome certain limitations in the static and dynamic transmission capacity of electrical networks. The IEEE has given the definition for FACTS as “alternating current transmission systems incorporating power-electronics based and other static controllers to enhance controllability and power transfer capability” [7]. The main purpose of FACTS devices is to provide with necessary instantaneous inductive or capacitive reactive power as quickly as possible in accordance with network requirement, while also improving transmission quality and the efficiency of the power transmission system.

As the name indicates, Static Synchronous Compensator (STATCOM) is similar to the synchronous condenser in its operation; however it is an electronic device which has no inertia and is superior to the synchronous condenser as it provides better dynamics, a lower investment cost and lower operating and maintenance costs. A STATCOM can be seen as a voltage source behind a reactance. It provides reactive power generation as well as absorption purely by means of electronic processing of voltage and current waveforms in a Voltage Source Converter (VSC) [11].

One of the main disadvantages of a STATCOM (with no energy storage) is that it has limited degree of freedom and sustained action in which they can help the power grid. It has only two possible steady-state operating modes, namely inductive (lagging) and capacitive (leading). Even though STATCOM can control both the output voltage magnitude and phase angle, the independent adjustment in steady state is not possible due to the lack of significant active power capability of STATCOM. Typically, the output voltage of STATCOM is maintained in phase with the voltage at point of common coupling (PCC), which will ensure that only reactive power exchange takes place in between STATCOM and power system. However, owing to some losses present in the coupling transformer and the power electronic devices, the converter voltage will have small phase shift with respect to the PCC voltage. Thus in order to compensate these small losses, practically small amount of real power is drawn from the PCC to DC bus of VSI.

The STATCOM when integrated with an energy storage device such as battery bank, series of super capacitors or super conducting coils will provide more flexibility compared to traditional STATCOM [12]. Four steady-state operating modes are possible, such as inductive mode with DC charge and discharge, capacitive mode with DC charge and discharge. A battery connected to the STATCOM can be the best solution to maximize the power quality of Grid connected wind energy systems. The benefit of using a battery in parallel to the wind turbine is that it gives the chance to produce always as much power as possible and store the energy that cannot be injected to the grid. That is if there is an excess of wind generated power than the maximum power that can be injected into the power system, then the battery will act to absorb the extra surplus power and get charged. On other hand, the battery will provide the necessary power through discharge when required. In summary, the ability to independently control both active and reactive powers in STATCOM + BESS enhances the transient and dynamic stability, minimizes sub synchronous oscillations and improves voltage profile and power quality of the power system.

## SYSTEM DESCRIPTION

The proposed new control strategy for the power quality improvement of grid connected wind energy system is shown in Figure-1. This controller maintains the dc voltage constant under any load variations and also ensures the unity power factor and sinusoidal supply current irrespective of the variation in the load demand waveform and magnitude. The STATCOM with BESS is used to mitigate the power quality problems and enhancing the power transfer capability of the power system.

### Wind energy conversion system

It is not possible to extract all the kinetic energy of wind that is hitting the turbine blades, only a portion of K.E is captured by the turbine. The fundamental equation governing the mechanical power capture of the wind turbine rotor blades is given by

$$P_{mech} = C_p P_{wind} \tag{1}$$

But wind’s mechanical power may be defined as $P_{wind}$

$$P_{wind} = 1/2 \rho A V^3_{wind} \tag{2}$$

$$P_{mech} = 1/2 \rho A C_p V^3_{wind} \tag{3}$$

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$$\text{Tip speed ratio, } \lambda = \omega_{turbine}/V_{wind} \quad (4)$$

Where 'ρ' is the air density (kg/m3), A is the area swept by the rotor blades (m2), R is rotor radius of the turbine (m) and Vwind is the wind velocity (m/s). Cp is called the power coefficient or the rotor efficiency and is a function of tip speed ratio (λ) and pitch angle (θ) [13], [14].

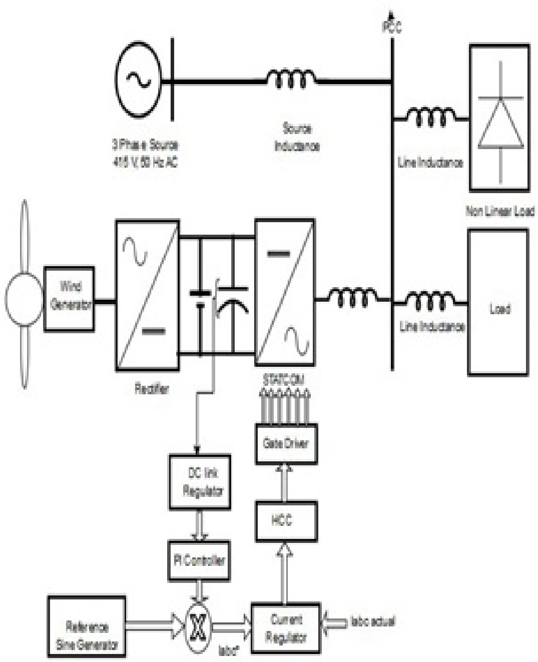


**Figure-1.** The proposed topology of the system.

**Control strategy**

The VSI inverter is operated in current control mode. The current controlled mode of inverter operation is represented as in Equations (5-8).

$$\frac{di_{ia}}{dt} = \frac{-R_{i*}\, i_{ia}}{Li} + \frac{Vsa - Via}{Li} \quad (5)$$

$$\frac{di_{ib}}{dt} = \frac{-R_{i*}\, i_{ib}}{Li} + \frac{Vsb - Vib}{Li} \quad (6)$$

$$\frac{di_{ic}}{dt} = \frac{-R_{i*}\, i_{ic}}{Li} + \frac{Vsc - Vic}{Li} \quad (7)$$

$$\frac{dV_{dc}}{dt} = \frac{(i_{ia}\, S_A + i_{ib}\, S_B + i_{ic}\, S_C)}{C} \quad (8)$$

Where Via, Vib, Vic are the inverter phase voltages and Vsa, Vsb, Vsc are the voltage at PCC and iia, iib, iic are the inverter current. The actual current is compared with the reference current isa*, isb*, isc* to generate and the produced error signal is given to hysteresis current controller which appropriates switching variable SA, SB, SC, for individual phases of the inverter [15].

**Hysteresis current controller (HCC)**

Hysteresis Current Control (HCC) technique is the most extensively used technique because of the simple implementation, outstanding stability, absence of any tracking error, quick transient response, inherent limited maximum current, and intrinsic robustness to load parameters variations [16],[17]. The current control technique is given in Figure-2.

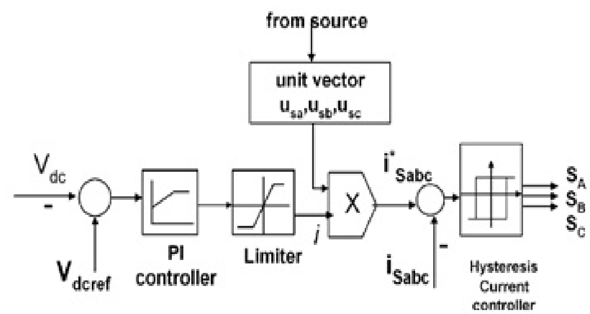


**Figure-2.** Current control.

In the HCC technique the error function is centred in a preset hysteresis band, i.e. with in upper and lower hysteresis band limits. When the error exceeds the upper or lower hysteresis limit the hysteresis controller makes an appropriate switching decision to control the error within the preset band and send these pulses to VSI to produce the reference current.

The switching function SA for phase 'a' is expressed as in Equation. (9).

$$\begin{aligned} isa &< (isa^* - HB) \rightarrow S_A = 0 \\ isa &> (isa^* - HB) \rightarrow S_A = 1 \end{aligned} \quad (9)$$

Where HB is current band of hysteresis controller. Similarly the switching function SB, SC can be derived for phases 'b' and 'c' respectively.

**BESS control**

The STATCOM based current controlled VSI injects the current into the grid in such a way that the source current is harmonic free and its phase-angle with respect to source voltage has a desired value. The injected current will cancel out the reactive part and harmonic part of the load and induction generator current. Thus source current is always maintained in phase with the source voltage, making the load appear to the source as a resistive circuit [11]. The magnitude of the reference current is regulated through the PI controller to compensate the dc voltage.

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**Grid synchronization**

The required source currents are controlled to be sinusoidal and in phase with the mains voltage in spite of the load characteristics. Therefore the reference current for the comparison must be derived from the source voltage. The instantaneous phase voltages of source (Vsa, Vsb, and Vsc) are considered close to sinusoidal [18-21] and their amplitude is computed as given in Equation. (10).

$$Vsm = \{\tfrac{2}{3}(Vsa^2 + Vsb^2 + Vsc^2)\}^{1/2} \quad (10)$$

The unity amplitude templates having instantaneous value in phase with instantaneous voltage (Vsa, Vsb, and Vsc), are derived as in Equation. (11).

$$Usa = Vsa/Vsm,\ Usb = Vsb/Vsm,\ Usc = Vsc/Vsm \quad (11)$$

The multiplication of these components with output of PI terminal voltage controller gives the reference source currents. This ensures that the grid current is controlled to be sinusoidal.

**RESULTS AND DISCUSSION**

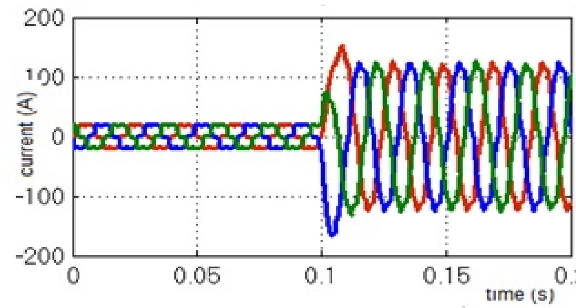
The proposed STATCOM with BESS is modelled and the transient performance is studied by simulating in MATLAB/ SIMULINK with the system parameters shown in Table-1.

**Table-1.** System parameters.

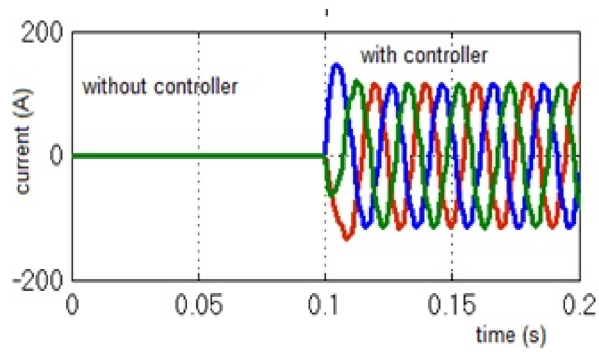
| S. No. | Parameter | Value |
|---|---|---|
| 1. | Source Voltage | 3-phase, 415Volt, 50 Hz |
| 2. | Battery Voltage | 700 Volt dc |
| 3. | Wind Generator (Induction Generator) | 275 kVA, 800 V, 50 Hz, P =4, Rs = 0.01 Ω, Rr = 0.015 Ω, Ls=0.06H, Lr=0.06H |
| 4. | DC Link Capacitance | 2800 uF |
| 5. | Load | 20 KW |

The SIMULINK model consist of VSI inverter based STATCOM, BESS, rectifier, wind energy system, source and critical load [22]. The hysteresis current control and BESS control are embedded into the simulation.

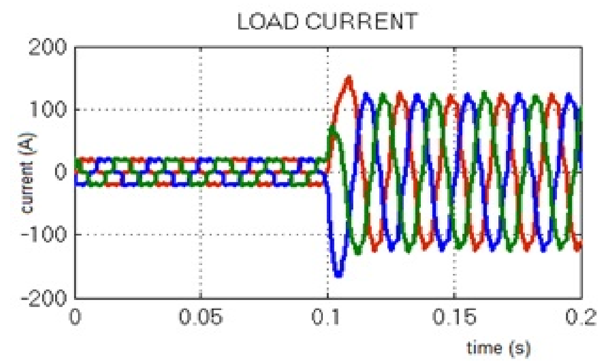
A nonlinear load consisting of diode bridge is used for simulating the system and performance of the system is observed for power quality improvement. The operation of the system without and with controller is as shown in Figure-3.




(a)




(b)

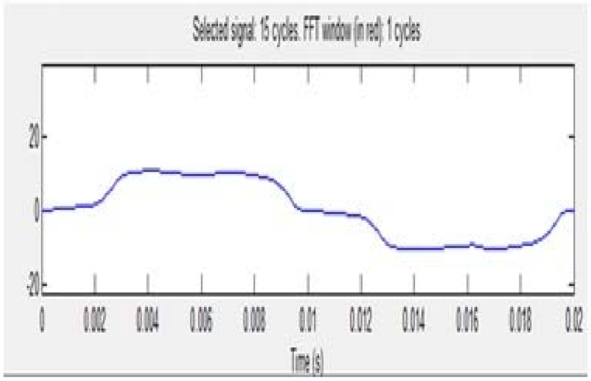



(c)

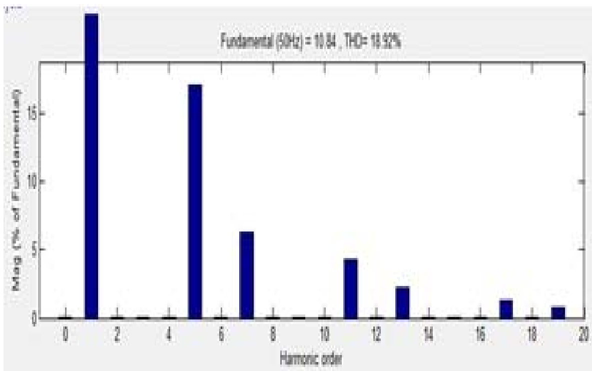
**Figure-3.** Operation of system with and without controller: a) Source current b) Inverter injected current and c) Load current.

The source current wave form is non sinusoidal without controller. The controller is switched on during 0.1s and the source current, inverter injected current and load waveform are observed. The source current waveform now become sinusoidal, indicating that the source current is harmonic free and STATCOM is able to compensate the reactive power requirement of the system.

THD analysis of source current with and without controller is shown in Figure-4. The THD is found to be 18.29% without the controller and is 2.72% with the controller and is within the IEC standard.



(a)



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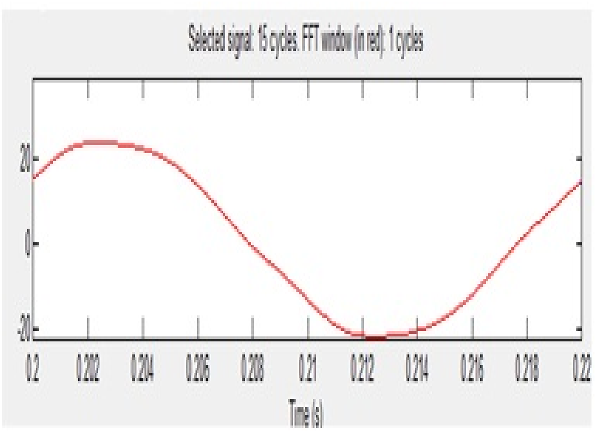
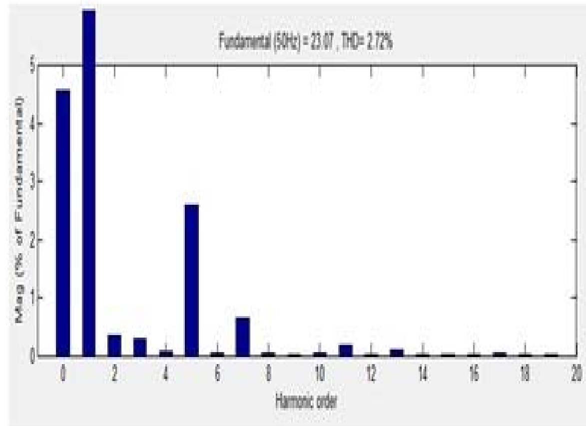


(c)



(d)

**Figure-4.** THD analysis of a) Source current without controller b) FFT of source current without controller c) Source current with controller and d) FFT of source current with controller.

The load connected to the system is inductive. The performance of controller shows that the controller is able to maintain the source current in phase with the voltage at the point of common coupling as shown in Figure-5.

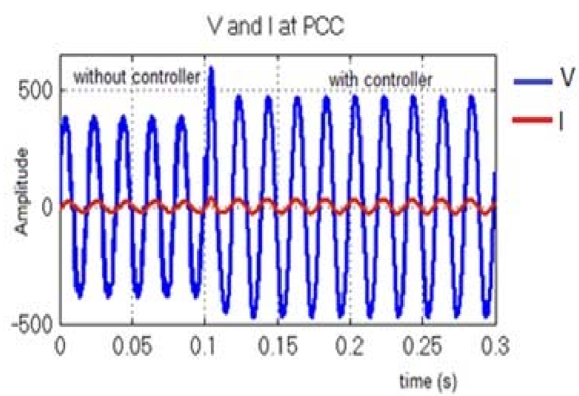



**Figure-5.** Voltage and current at the PCC.

The average active and reactive power flow of source, inverter and the load are monitored with and without controller at the PCC is shown in Figure-6. From Figure-6 it is clear that the STATCOM with controller is able to supply reactive power requirement of the load, thus load seems to the source as purely resistive and relives source from reactive power supply, thus improving the power quality of source.

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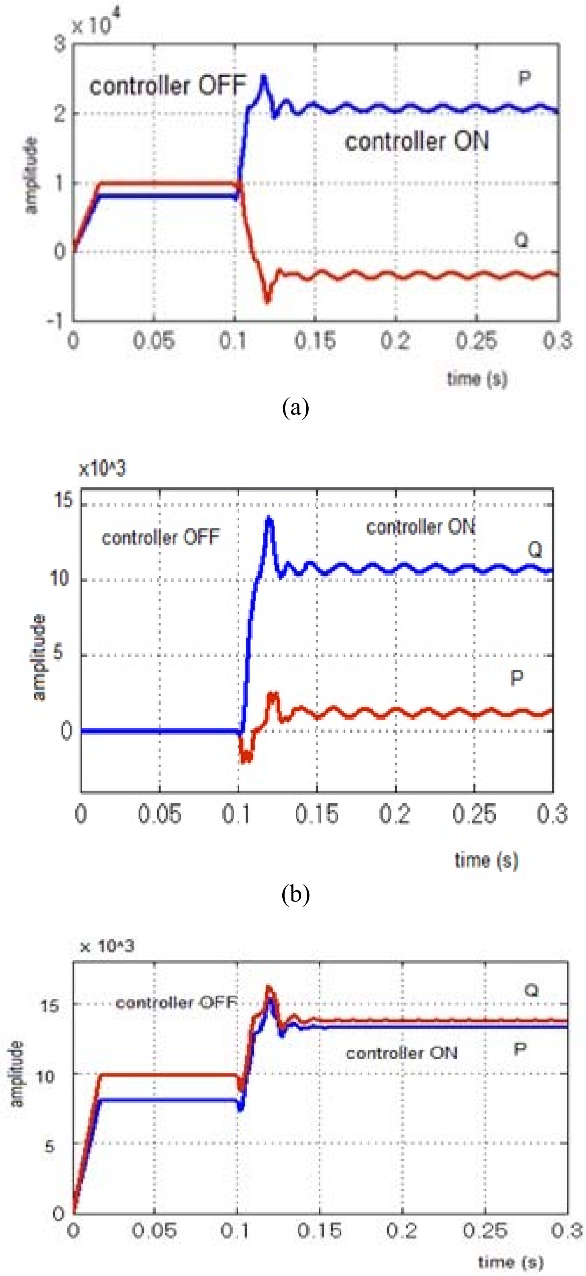


**Figure-6.** Real and reactive power: a) At source b) At inverter and c) At load.

Experimental setup consists of three phase inverter and its control circuit consisting of isolation and gate drive circuit. The control circuit section is composed of the MATLAB and dSPACE interface, optical isolation and the Gate driver circuit. The real time generation of SPWM pulse is being made using the MATLAB and dSPACE interface. The dSPACE output should be isolated from the power circuit for providing protection to the dSPACE kit. The IGBTs are voltage controlled devices and it requires a minimum gate threshold voltage of about 15 V higher than that of the emitter for establishing the rated collector to emitter conduction. This requirement makes it difficult to directly interface an IGBT to the dSPACE. Thus a driver circuit is to be provided for driving the gate at required voltage level for triggering the IGBTs. The TLP 250 ICs are capable of providing both the isolation and driver function is chosen for this project. For the high side device bootstrap circuitry is used to provide the floating supply to drive the IGBT. Experimental setup composed of MATLAB-dSPACE interface, isolation and gate driver circuit, and three phase inverter is shown in Figure-7.

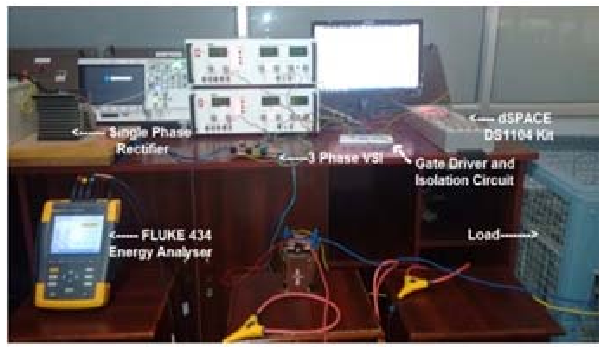


**Figure-7.** The complete experimental setup.

The IGBT IRG4BC30U is used as the switching device for the inverter. The Figure-8 shows the gate pulses for the three high side devices generated using the MATLAB-dSPACE interface.

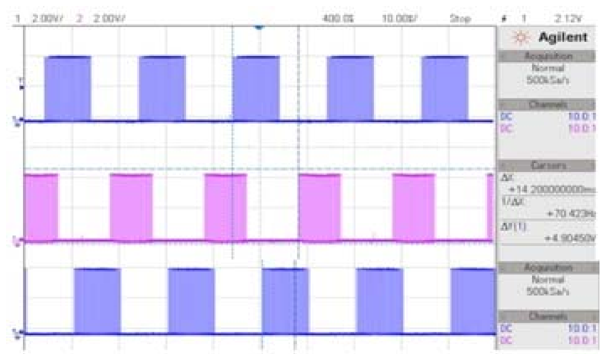


**Figure-8.** The high side pulses for IGBT's in three phase.

The dead band of 5μs provided between turn on and turn off is for avoiding the shoot through shown in Figure-9.

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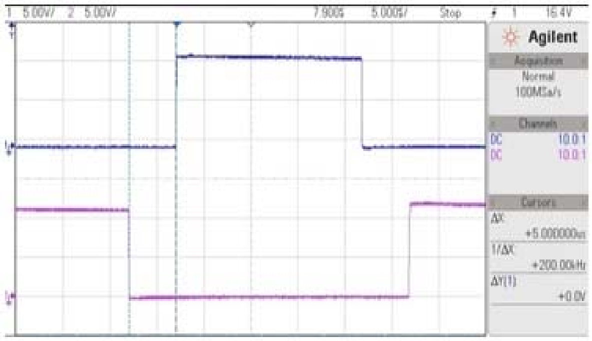


**Figure-9.** The dead band between non-inverting and inverting pulse.

The gate pulse generated by dSPACE has an amplitude of 4V and hence is not capable of driving the IGBT switches; hence TLP250 gate driver is used to amplify the voltage level of gate pulse and to provide the optical isolation. The output of the TLP250 is of 15V which can drive IGBT into conduction is shown in Figure-10.

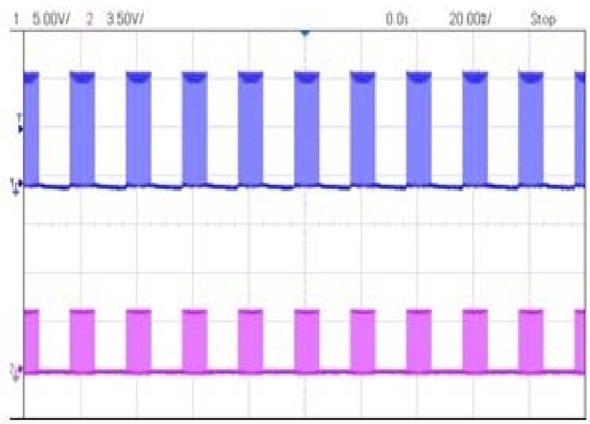

**Figure-10.** Input and output pulse of TLP250 gate driver.

The output obtained from the tree phase inverter when R load of 40 Ω is connected in star configuration is given in Figure-11.

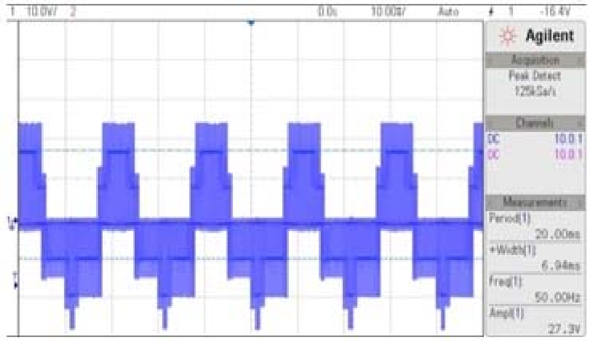


**Figure-11.** Output wave form of three phase inverter.

## CONCLUSIONS

This work presents a novel controller for an integrated STATCOM-Battery energy storage system for grid connected wind energy system. The control scheme focuses on eliminating the harmonics and maintaining unity power factor using VSI based STATCOM. The controller uses a very simple hysteresis current control technique to control the source current and a PI controller has been used to control the DC voltage along with the battery charging operation. The performance of the designed controller is evaluated and it is observed that the STATCOM with BESS, operated with specified controller, provides reactive power support, good harmonic mitigation as well as maintaining the source current in phase with the voltage. The STATCOM model is also tested using a scaled down hardware setup.

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