II. Power Quality Standards, Issues and Its Consequences

A. International Electro Technical Commission Guidelines

The guidelines are provided for measurement of power quality of wind turbine. The International standards are developed by the working group of Technical Committee-88 of the International Electro-technical Commission (IEC), IEC standard 61400-21, describes the procedure for determining the power quality characteristics of the wind turbine [4].

The standard norms are specified.

1) IEC 61400-21: Wind turbine generating system, part-21. Measurement and Assessment of power quality characteristic of grid connected wind turbine
2) IEC 61400-13: Wind Turbine—measuring procedure in determining the power behavior.
3) IEC 61400-3-7: Assessment of emission limit for fluctuating load IEC 61400-12: Wind Turbine performance.

The data sheet with electrical characteristic of wind turbine provides the base for the utility assessment regarding a grid connection.

B. Voltage Variation

The voltage variation issue results from the wind velocity and generator torque. The voltage variation is directly related to real and reactive power variations. The voltage variation is commonly classified as under:

- Voltage Sag/Voltage Dips.
- Voltage Swells.
- Short Interruptions.
- Long duration voltage variation.

The voltage flicker issue describes dynamic variations in the network caused by wind turbine or by varying loads. Thus the power fluctuation from wind turbine occurs during continuous operation. The amplitude of voltage fluctuation depends on grid strength, network impedance, and phase-angle and power factor of the wind turbines. It is defined as a fluctuation of voltage in a frequency 10–35 Hz. The IEC 61400-4-15 specifies a flicker meter that can be used to measure flicker directly.

C. Harmonics

The harmonic results due to the operation of power electronic converters. The harmonic voltage and current should be limited to the acceptable level at the point of wind turbine connection to the network. To ensure the harmonic voltage within limit, each source of harmonic current can allow only a limited contribution, as per the IEC-61400-36 guideline. The rapid switching gives a large reduction in lower order harmonic current compared to the line commutated converter, but the output current will have high frequency current and can be easily filter-out.

D. Wind Turbine Location in Power System

The way of connecting the wind generating system into the power system highly influences the power quality. Thus the operation and its influence on power system depend on the structure of the adjoining power network.

E. Self Excitation of Wind Turbine Generating System

The self excitation of wind turbine generating system (WTGS) with an asynchronous generator takes place after disconnection of wind turbine generating system (WTGS) with local load. The risk of self excitation arises especially when WTGS is equipped with compensating capacitor. The capacitor connected to induction generator provides reactive power compensation. However the voltage and frequency are determined by the balancing of the system. The disadvantages of self excitation are the safety aspect and balance between real and reactive power [5].

F. Consequences of the Issues

The voltage variation, flicker, harmonics causes the malfunction of equipments namely microprocessor based control system, programmable logic controller; adjustable speed drives, flickering of light and screen. It may leads to tripping of contractors, tripping of protection devices, stoppage of sensitive equipments like personal computer, programmable logic control system and may stop the process and even can damage of sensitive equipments. Thus it degrade the power quality in the grid.

III. Grid Coordination Rule

The American Wind Energy Association (AWEA) led the effort in the united state for adoption of the grid code for the interconnection of the wind plants to the utility system. The first grid code was focused on the distribution level, after the blackout in the United State in August 2003. The United State wind energy industry took a stand in developing its own grid code for contributing to a stable grid operation. The rules for realization of grid operation of wind generating system at the distribution network are defined as-per IEC-61400-21. The grid quality characteristics and limits are given for references that the customer and the utility grid may expect. According to Energy-Economic Law, the operator of transmission grid is responsible for the organization and operation of interconnected system [6].

1) Voltage Rise (u): The voltage rise at the point of common coupling can be approximated as a function of maximum apparent power $\mathrm{S}_{\max}$ of the turbine, the grid impedances R and X at the point of common coupling and the phase angle ϕ [7], given in (1)

$$\Delta u = S_{\max}(R\cos\phi - X\sin\phi)/U^2 \tag{1}$$

where Δu—voltage rise, $\mathrm{S}_{\max}$—max. apparent power, ϕ—phase difference, U—is the nominal voltage of grid. The Limiting voltage rise value is $< 2\%$

2) Voltage Dips (d): The voltage dips is due to start up of wind turbine and it causes a sudden reduction of voltage. It is the relative $\%$ voltage change due to switching operation of wind turbine. The decrease of nominal voltage change is given in (2).

$$d = K_u \frac{S_n}{S_K} \tag{2}$$

where d is relative voltage change, S_n rated apparent power, S_K short circuit apparent power, and K_u sudden voltage reduction factor. The acceptable voltage dips limiting value is $\leq 3\%$.

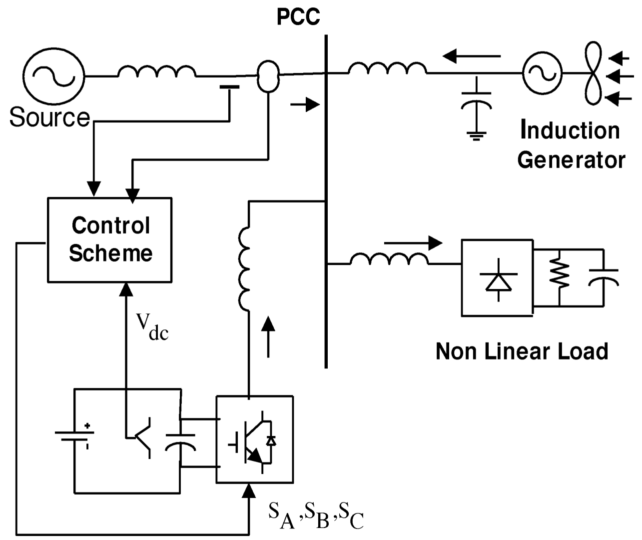

Fig. 2. System operational scheme in grid system.

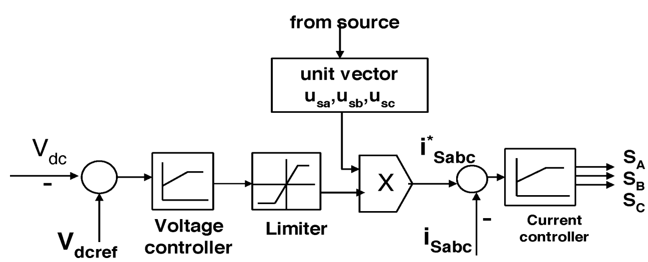

Fig. 3. Control system scheme.

strategy, so as to maintain the power quality norms in the grid system. The current control strategy is included in the control scheme that defines the functional operation of the STATCOM compensator in the power system. A single STATCOM using insulated gate bipolar transistor is proposed to have a reactive power support, to the induction generator and to the nonlinear load in the grid system. The main block diagram of the system operational scheme is shown in Fig. 2.

V. Control Scheme

The control scheme approach is based on injecting the currents into the grid using "bang-bang controller." The controller uses a hysteresis current controlled technique. Using such technique, the controller keeps the control system variable between boundaries of hysteresis area and gives correct switching signals for STATCOM operation.

The control system scheme for generating the switching signals to the STATCOM is shown in Fig. 3.

The control algorithm needs the measurements of several variables such as three-phase source current i_{Sabc}, DC voltage V_{dc}, inverter current i_{iabc} with the help of sensor. The current control block, receives an input of reference current i^*_{Sabc} and actual current i_{Sabc} are subtracted so as to activate the operation of STATCOM in current control mode [16]–[18].

A. Grid Synchronization

In three-phase balance system, the RMS voltage source amplitude is calculated at the sampling frequency from the source phase voltage (V_{sa}, V_{sb}, V_{sc}) and is expressed, as sample template *Vsm*, sampled peak voltage, as in (9).

$$V_{\mathrm{sm}} = \left\{\frac{2}{3}\left(V_{\mathrm{sa}}^2 + V_{\mathrm{sb}}^2 + V_{\mathrm{sc}}^2\right)\right\}^{1/2}. \quad (9)$$

The in-phase unit vectors are obtained from AC source—phase voltage and the RMS value of unit vector $\mathrm{u_{sa}}$, $\mathrm{u_{sb}}$, $\mathrm{u_{sc}}$ as shown in (10).

$$u_{\mathrm{sa}} = \frac{V_{\mathrm{Sa}}}{V_{\mathrm{sm}}}, \quad u_{\mathrm{sb}} = \frac{V_{\mathrm{Sb}}}{V_{\mathrm{sm}}}, \quad u_{\mathrm{sc}} = \frac{V_{\mathrm{Sc}}}{V_{\mathrm{sm}}}. \quad (10)$$

The in-phase generated reference currents are derived using in-phase unit voltage template as, in (11)

$$i^*_{\mathrm{Sa}} = I.u_{\mathrm{Sa}}, \quad i^*_{\mathrm{Sb}} = I.u_{\mathrm{Sb}}, \quad i^*_{\mathrm{Sc}} = I.u_{\mathrm{Sc}} \quad (11)$$

where I is proportional to magnitude of filtered source voltage for respective phases. This ensures that the source current is controlled to be sinusoidal. The unit vectors implement the important function in the grid connection for the synchronization for STATCOM. This method is simple, robust and favorable as compared with other methods [18].

B. Bang-Bang Current Controller

Bang-Bang current controller is implemented in the current control scheme. The reference current is generated as in (10) and actual current are detected by current sensors and are subtracted for obtaining a current error for a hysteresis based bang-bang controller. Thus the ON/OFF switching signals for IGBT of STATCOM are derived from hysteresis controller [19].

The switching function S_A for phase 'a' is expressed as (12).

$$\begin{aligned} i_{\mathrm{sa}} &< (i^*_{\mathrm{sa}} - HB) \rightarrow S_A = 0 \\ i_{\mathrm{sa}} &> (i^*_{\mathrm{sa}} - HB) \rightarrow S_A = 1 \end{aligned} \quad (12)$$

where HB is a hysteresis current-band, similarly the switching function S_B, S_C can be derived for phases "b" and "c".

VI. System Performance

The proposed control scheme is simulated using SIMULINK in power system block set. The system parameter for given system is given Table I.

The system performance of proposed system under dynamic condition is also presented.

A. Voltage Source Current Control—Inverter Operation

The three phase injected current into the grid from STATCOM will cancel out the distortion caused by the nonlinear load and wind generator. The IGBT based three-phase inverter is connected to grid through the transformer. The generation of switching signals from reference current is simulated within hysteresis band of 0.08. The choice of narrow hysteresis band switching in the system improves the current quality. The control signal of switching frequency within its operating band, as shown in Fig. 4.

The choice of the current band depends on the operating voltage and the interfacing transformer impedance. The compensated current for the nonlinear load and demanded reactive power is provided by the inverter. The real power transfer from

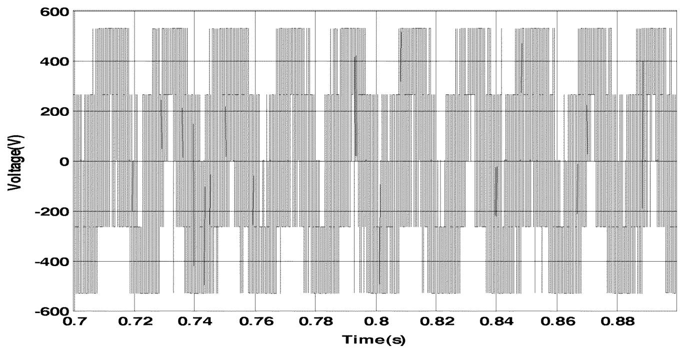

Fig. 8. STATCOM output voltage.

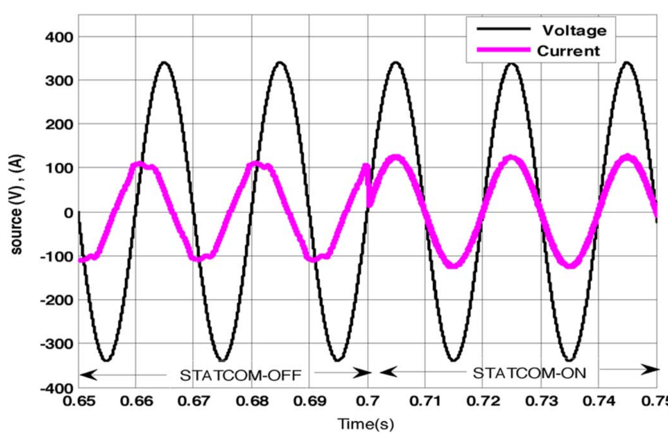

Fig. 9. Supply Voltage and Current at PCC.

C. Power Quality Improvement

It is observed that the source current on the grid is affected due to the effects of nonlinear load and wind generator, thus purity of waveform may be lost on both sides in the system. The inverter output voltage under STATCOM operation with load variation is shown in Fig. 8. The dynamic load does affect the inverter output voltage. The source current with and without STATCOM operation is shown in Fig. 9. This shows that the unity power factor is maintained for the source power when the STATCOM is in operation. The current waveform before and after the STATCOM operation is analyzed. The Fourier analysis of this waveform is expressed and the THD of this source current at PCC without STATCOM is 4.71%, as shown in Fig. 10.

The power quality improvement is observed at point of common coupling, when the controller is in ON condition. The STATCOM is placed in the operation at 0.7 s and source current waveform is shown in Fig. 11 with its FFT. It is shown that the THD has been improved considerably and within the norms of the standard.

The above tests with proposed scheme has not only power quality improvement feature but it also has sustain capability to support the load with the energy storage through the batteries.

VII. Conclusion

The paper presents the STATCOM-based control scheme for power quality improvement in grid connected wind generating system and with non linear load. The power quality issues and its consequences on the consumer and electric utility are presented. The operation of the control system developed for the STATCOM-BESS in MATLAB/SIMULINK for maintaining the power quality is simulated. It has a capability to cancel out the harmonic parts of the load current. It maintains the source voltage and current in-phase and support the reactive power demand for the wind generator and load at PCC in the grid system, thus it gives an opportunity to enhance the utilization factor of transmission line. The integrated wind generation and STATCOM with BESS have shown the outstanding performance. Thus the proposed scheme in the grid connected system fulfills the power quality norms as per the IEC standard 61400-21.

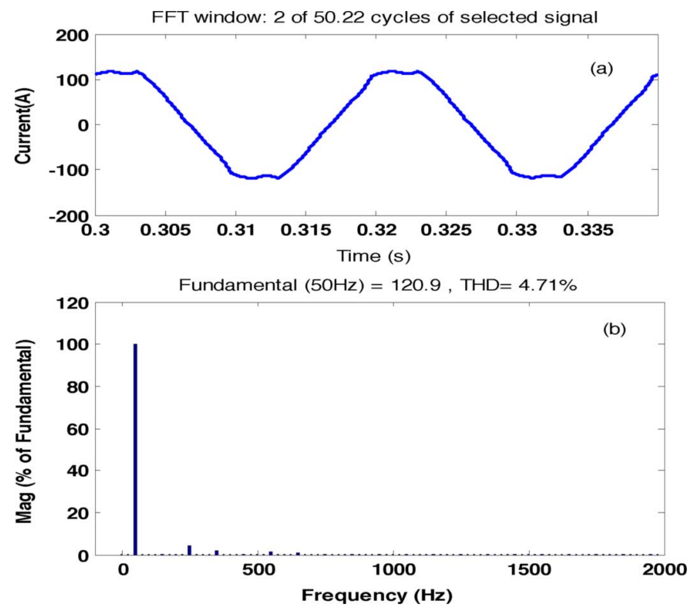

Fig. 10. (a) Source Current. (b) FFT of source current.

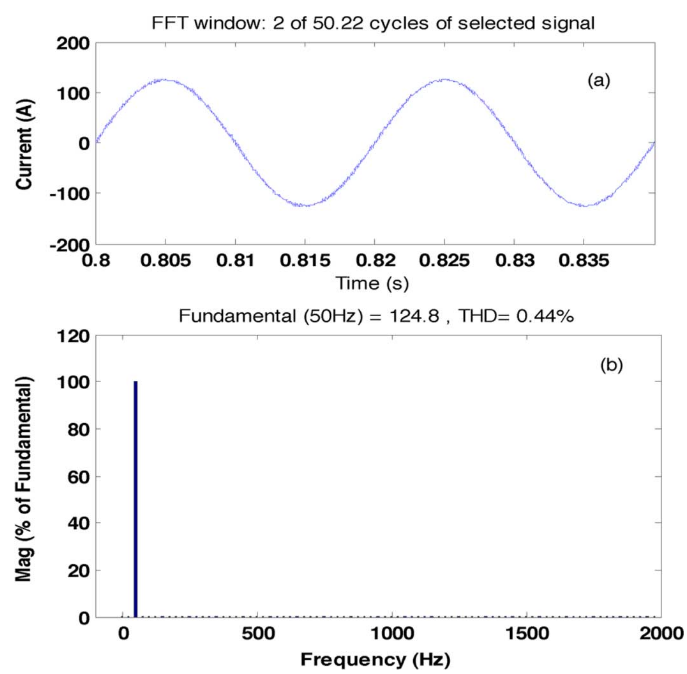

Fig. 11. (a) Source Current. (b) FFT of source current.