

Enhancing the LVRT Capability and Mitigation of Power Quality Issues Using UPQC of a Grid Connected Wind Conversion System

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Abstract

In this paper unified power quality conditioner has been used to enhance low voltage ride through capability of grid connected wind conversion system taking doubly fed induction generator (DFIG). Unified Power quality conditioner (UPQC) device is a combination of series active filter and shunt active filter. This custom power device is mainly used to mitigate power quality issues which are an essential factor today because of wide application of power electronics devices. UPQC is capable to deal with voltage and current imperfection simultaneously. It is installed in the system mainly to improve the power quality i.e. Voltage sag/swell, Harmonics, reactive power compensation etc. at point of common coupling. System is modeled in MATLAB/SIMULINK and results shows utilization of UPQC for the enhancement of LVRT of a DFIG wind system according to Grid code. When fault occurs in the system, it will create voltage dip and series compensator of UPQC injects during this time to prevent disconnection from grid and stay connected to contribute during fault. UPQC is also used for fast restoration of system steady state, power factor improvement, prevent rotor over current.

Keywords: Power Quality, Wind Turbine, UPQC, LVRT, FACTS Devices.

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1. Introduction

The wind energy has grown itself over past few decades and has become one of the most reliable and popular renewable power sources worldwide. This growth of wind conversion system has motivated to establish new grid code for wind conversion system. Now-a-days wind plants has become one of the major power supplier so during any grid disturbances disconnection of wind power plant is not affordable [1]. Disconnection of wind system will affect the system stability [2]. The performance analysis of DFIG wind turbine during fault is a trending research topic in power system. According to Indian grid code for wind conversion system the generator must exhibit fault ride through and contribute to network stability during fault [3].

In case of voltage dip due to fault irrespective of location of occurrence in the system it will increase the stator current in the stator winding of wind generator [4, 5]. Because of magnetic coupling between stator and rotor winding, current in rotor winding will also get increased [6]. This can lead to destruction of rotor side converter and can also damage the stator and rotor windings. In this paper enhancement of LVRT capability during fault and compensation of different power quality issues using UPQC is proposed. System with and without fault is simulated in MATLAB/SIMULINK to achieve the goal. In this script two different control schemes are used for series and shunt APF.

Section II introduces brief about LVRT and technical requirement during fault to satisfy grid code. Section III describes DFIG wind conversion system, Section IV discuss brief introduction of Unified power quality conditioner. Section V describes control strategy, in section VI system analysis done in MATLAB/SIMULINK

2. LVRT and Other Power Quality Issues

2.1. Low Voltage Ride through

Wind conversion system must satisfy Indian grid code before it gets permission to be connected with the grid. Objective of new wind firm connection is to avoid unacceptable effect to

the system or grid. Major requirement of grid codes for stable operation is low Voltage ride through capability during faulty and voltage sag condition [7]. The fault ride through characteristic is shown in Figure 1 and fault clearing time for various voltage limits given in table1.

According to modified grid rule wind conversion wind system required to remain connected for specific time duration before it is allowed to disconnect.

Where,

$V_f = 15\%$ Nominal system voltage.

$V_{pf} =$ Minimum Voltage for normal operation of the Wind turbine.

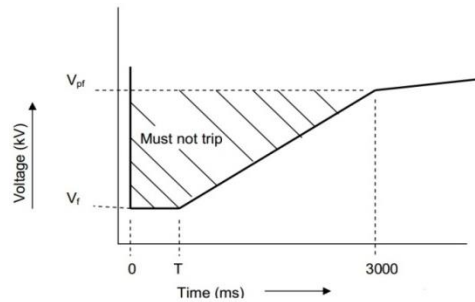


Figure 1. Fault ride through characteristic

Table 1. Fault clearing time and voltage Limit

Nominal Voltage(kV)	Fault Clearing Time, T(ms)	V_{pf} (kV)	V_f (kV)
400	100	360	60
220	160	200	33
132	160	120	19.8
110	160	96.25	16.5
66	300	60	9.9

Wind firm below 66 kV shall be capable of withstanding repeated faults as fault occurrence in this system is very frequent.

2.2. Different Power Quality Problems

Ultimate goal of the utilities is to supply their customer uninterrupted sinusoidal voltage with constant magnitude and frequency and unbalanced perfect sinusoidal current. But in present wide application of power electronic equipment results in serious impact on the nature of power supply [8]. Present day AC distribution system is facing power quality problems like Voltage unbalance, Harmonics, voltage flicker, sag, swell, Notches etc. But there are so many critical load connected across the distribution system like computers, Processors and power electronics based equipments which requires continuous supply. A small interruption due to voltage disturbance can lead to loss of money, product quality, time and services [9, 10]. So quality improvement of supplied voltage and current is also one of the main objectives.

3. DFIG Wind Conversion System

DFIG is widely used conversion topology to extract power. It is consisting of wind turbine, Gear box, doubly fed induction generator, grid side and rotor side converter [11]. The basic wind conversion system is given in Figure 2. Stator winding is directly connected to grid but rotor winding connected through back to back conversion circuit. A capacitor is connected between two converters as a dc voltage source. A coupling inverter L is used to connect grid side converter to grid and rotor side converter connected to grid through slip-ring and brushes [12]. The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings both. The control system generates the pitch angle command and the voltage command signals are

generated in order to control the power of the wind turbine, the DC bus voltage and the reactive power or the voltage at the grid terminals.

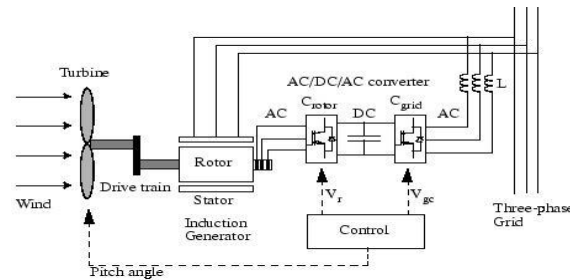


Figure 2. DFIG wind conversion System.

4. Unified Power Quality Conditioner (UPQC)

Unified power quality conditioner is considered as a one of the most powerful key to arising power quality problems. UPQC is a combination of shunt and series compensators, is proposed as a single solution for mitigating multiple PQ problems [13]. The basic block diagram model of UPQC is given in Figure 3. Shunt APF (active power filter) connected in parallel to point of common coupling and Series APF is connected in series through series transformer [14]. Shunt device is known as D-Statcom offers reactive power compensation along with load balancing, neutral current compensation, and elimination of harmonics to consumer load and series device is known as DVR offers voltage compensation between the supply and the consumer load, and restores the load voltage to its reference value [15, 16].

The shunt and series APF are controlled separately for power quality enhancement of voltage and current respectively. The instantaneous reactive power theory, synchronous reference frame theory, fuzzy control algorithm, instantaneous symmetrical component theory and neural network theory are some common control techniques.

The procedure for the calculation of dc capacitor voltage, ripple filter, and interfacing inductor are given in below.

4.1. DC Capacitor Voltage

DC link voltage define as:

$$V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} \tag{1}$$

m is modulation index, V_{LL} ac line voltage.

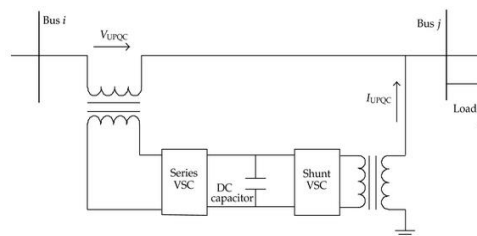


Figure 3. Block Diagram of UPQC

4.2. DC bus capacitor

The value of DC capacitor connected between back to back converter (C_{DC}) is calculated as:

$$\frac{1}{2} C_{dc} [V_{dc}^2 - V_{dc1}^2] = 3V(\alpha I)t \tag{2}$$

V_{dc} nominal dc voltage equal to reference dc voltage and V_{dc1} minimum voltage of dc, α overloading factor, V and I is phase voltage and current respectively, t is the by which dc voltage is to be recovered.

4.3. AC Inductor

L_f is inductance, *i_{cr(p-p)}* current ripple, *f_s* switching frequency, V_{dc} dc bus voltage. Above formula gives the value of the inductor. Ripple filter is used to eliminate noise from the injected voltage. It is a low pass filter with high switching frequency to cancel out high frequency noise.

$$L_f = \frac{\sqrt{3}mV_{dc}}{12\alpha f_s i_{cr(p-p)}} \tag{3}$$

5. UPQC Control Strategy

5.1. Control Strategy of Series APF

In this section control strategy used for series active filter is described. The control technique used to control Dynamic voltage restorer is called Unit Vector Template Generation (UVTG). Generation of reference voltage signal using this technique is shown in Figure 4.

The objective is to make the point of common coupling voltage perfectly sinusoidal, balanced and maintain at desired magnitude. In order to maintain distortion free voltage at PCC series active filter, have to inject opposite to the distortion and unbalance present in the system which will cancel out each other resulting a balanced and desired voltage magnitude at point of common coupling. The Series APF is designed to correct voltage sag of various magnitudes for various duration.

Three phase voltage waveform can be distorted or some power quality can be present at the point of common coupling. For the extraction of unit vector template signal three phase source voltage is sensed and multiplied with (1/V_m) where V_m is peak amplitude of fundamental voltage. The phase lock loop is used to achieve synchronization with supply voltage. The output of PLL generates two quadrature unit vectors which is in phase with sine and cosine. This output is used to compute the supply in phase which is 120° displaced three unit vector (U_a , U_b, U_c) using below equations.

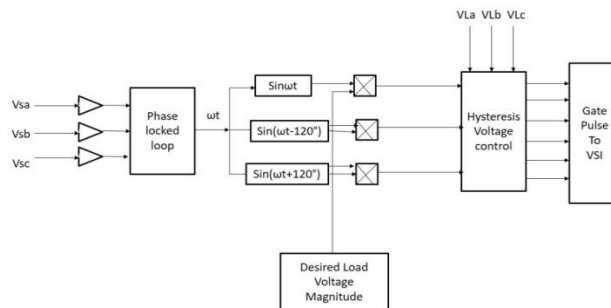


Figure 4. Control block diagram of series APF

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\sqrt{\frac{3}{2}} \\ -\frac{1}{2} & \sqrt{\frac{3}{2}} \end{bmatrix} * \begin{bmatrix} \sin\theta \\ \cos\theta \end{bmatrix} \tag{4}$$

The computed unit vectors using equation (4) is multiplied with desired peak value of the PCC (V_m), which is considered as a reference PCC voltage.

$$\begin{bmatrix} V_{La} \\ V_{Lb} \\ V_{Lc} \end{bmatrix} = V_m * \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \quad (5)$$

The reference voltage computed using control strategy is compared with sensed PCC voltage (V_{La}, V_{Lb}, V_{Lc}) which will generate error signal is fed to hysteresis controller. Output of hysteresis controller generates gate signal of the series inverter. Hysteresis band controller decides the pattern of switching and DVR injects voltage accordingly. Amount of Injected voltage can be calculated using following expression.

$$V_{injected} = V_{Load} - V_{Source} \quad (6)$$

$V_{injected}$ represents converter injected voltage, V_{Load} load voltage, V_{Source} Source Voltage.

5.2. Control Strategy of Shunt APF

The p-q theory or "The Generalized Theory of the Instantaneous Reactive power in a three phase is developed to control shunt APF. This control strategy is very efficient and flexible to design controllers for power conditioner based power electronics devices. This method offers to calculate real and reactive power required by load instantaneously. It is utilized to generate reference signal for the shunt APF, p-q theory consists of Clark's transformation of three phase voltage and current from a-b-c coordinate to α - β -0 coordinate followed by calculation of instantaneous power components. Instantaneous three phase voltage and load current is measured and converted to α - β -0 coordinate using following Equations (7) and (8).

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (8)$$

Instantaneous Real and reactive power in α - β -0 coordinate is calculated using Equation (9).

$$\begin{bmatrix} p_0 \\ P_s \\ q_s \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (9)$$

Instantaneous real power and imaginary power measured instantaneously and Equation (10) and (11) shows that real power and imaginary power is consist of average component and oscillating component.

$$P_s = P_{\text{Direct component of real Power}} + P_{\text{fluctuating component of real power}} \quad (10)$$

$$q_s = q_{\text{direct component of imaginary power}} + q_{\text{fluctuating component of imaginary power}} \quad (11)$$

P_{dc} = Direct component of real Power
 P_{ac} = Fluctuating component of real Power

The whole imaginary power and fluctuating component of real power is taken as power reference and current reference and using this compensating signal for reactive power, harmonics is generated. There will be no zero sequence power P_0 .

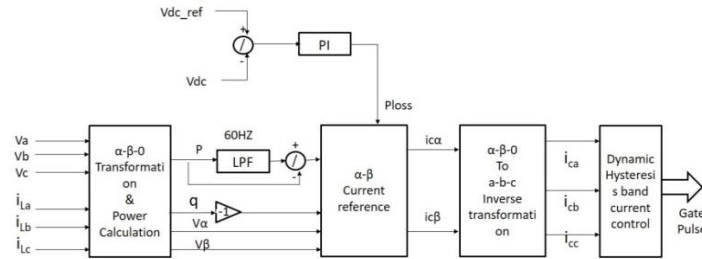


Figure 5. Control block diagram of Shunt APF

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \end{bmatrix} = \frac{1}{\sqrt{V_\alpha^2 + V_\beta^2}} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} -P_{ac} + P_{Loss} \\ -q_s \end{bmatrix} \quad (12)$$

The real power P_s is passed through a 5th order Butterworth low pass filter with frequency 60 Hz to separate direct component of real power from total real power. Output of low pass filter is subtracted again from total power P_s which gives fluctuating component of real power as output. The signal P_{loss} acquires from DC voltage regulator and it utilizes as average real power. It can also be specified as the instantaneous active power which corresponds to the resistive loss and the switching loss of the UPQC. The compensating currents (i_{ca}^* , i_{cb}^*) requires to meet the power demand by load. These compensating currents are in α - β coordinate which is converted into a-b-c coordinates using Equation (13).

$$\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{ca}^* \\ i_{cb}^* \end{bmatrix} \quad (13)$$

The control strategy explained in Figure 5 useful only when 3 phase system is ideal but inappropriate for non-ideal voltage system. $(V_\alpha^2 + V_\beta^2)$ value under non-ideal voltage system is not a constant value, so harmonics present in the system will be introduced in instantaneous real power and reactive power which results in generation of compensation current that will not be able to cancel out harmonics from the system. To overcome this problem sensed 3 phase voltage should be filtered first using Parks transformation passing through a 5th order filter with cutoff frequency 60 Hz using Equation (14).

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(\omega t) & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (14)$$

The filtered components again converted to α - β using Equation (15) to calculate reference current for Shunt APF.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} \quad (15)$$

Calculated reference current and sensed shunt APF current are compared and fed to hysteresis band controller to generate gating signal and the Figure 6 shows the simulink diagram of the hysteresis current controller.

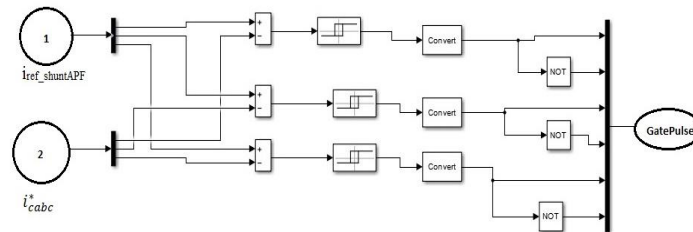


Figure 6. Hysteresis current controller modeled in Simulink

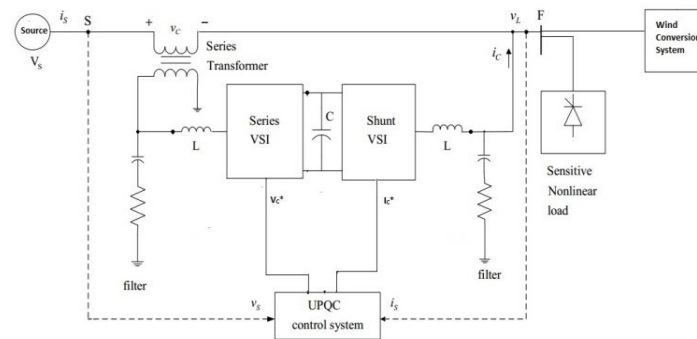


Figure 7. Proposed Block Diagram of UPQC connected WES

6. Simulation Results

In this section simulation studies using MATLAB/SIMULINK carried out to prove the effectiveness of proposed model shown in Figure 7 by enhancing LVRT capability during three phase to ground fault, reducing harmonics and voltage sag from the system making the system more stable. Here DFIG wind turbine is used of 9 MW is connected to point of common coupling through a step-up transformer of 575 kV/25 kV. To check the effectiveness during voltage sag and harmonics of the system heavy load and nonlinear load is connected at point of common coupling which is 25 kV. Unified power quality conditioner is connected to PCC to limit the fault current during system fault and maintaining voltage level to prevent disconnection of wind conversion system and also prove ability of UPQC in mitigating current harmonics and voltage sag.

Table 2. System Parameter

S.No.	Parameter	Rating
1.	Grid voltage	3 Phase, 25 kV, 60 Hz
2.	Wind generator	(1.5*6) MVA, 575 V, 60Hz, Wound Rotor Induction Generator.
3.	THD due to Non-linear load	30%
4.	Inverters	IGBT based, 3 arms, 6 Pulse, sample time 5micro sec. DC link capacitance=10000e-6
5.	PCC Voltage	25 kV
6.	Load	2 MW
7.	Injection Transformer Turns ratio	1:1

Case I. Three Phase to Ground Fault at Bus 25 kV:

A symmetrical fault happening at 0.1 s and clearing after 0.2 s is occurring near PCC 25 kV. The simulation results shown in Figure 8(a) and Figure 8(b) under three phase to ground fault condition, the amplitude of PCC voltage drop is more than 80% of its nominal voltage without UPQC support. In Figure 8(c) and 8(d) results shown with UPQC applied at PCC to restrict voltage drop during fault under allowable limit.

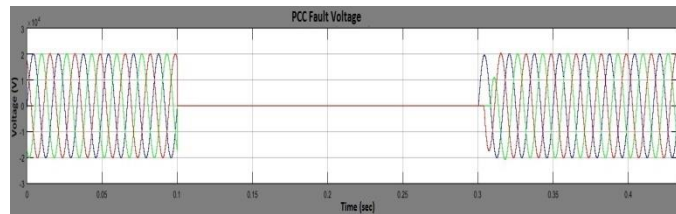


Figure 8(a). PCC voltage under fault condition

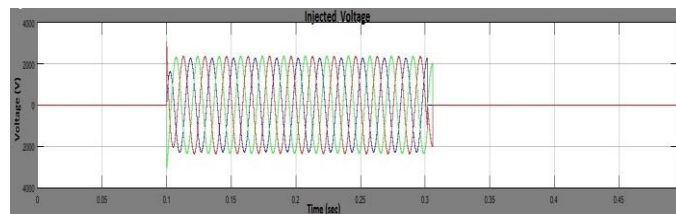


Figure 8(b). Fault current

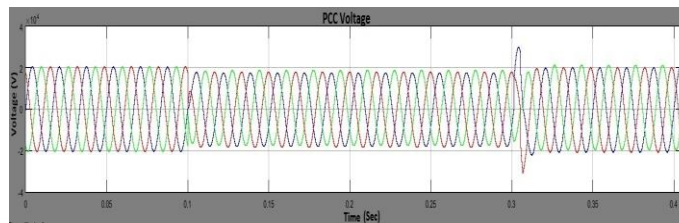


Figure 8(c). PCC Voltage with UPQC

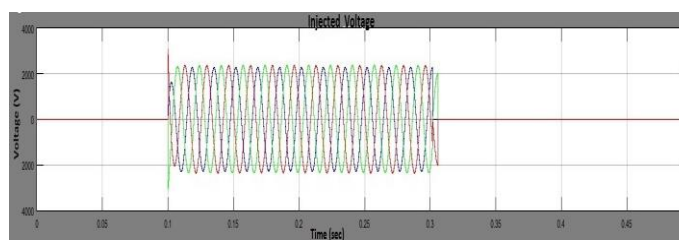


Figure 8(d) Injected Voltage

UPQC injects voltage in series to maintain desired voltage at PCC so that wind turbine stays connected during fault and contribute to system stability.

Case II. Current Harmonic Compensation:

Harmonics are introduced deliberately by connecting Non-linear load at Point of common coupling. In order to introduce non-linear load a three phase diode bridge with RL load is used. Current harmonics generated by non-linear load is compensated using UPQC. Shunt APF of UPQC add current in such a manner so that source current profile is balanced. Shunt APF also maintains the DC link voltage at a reference value.

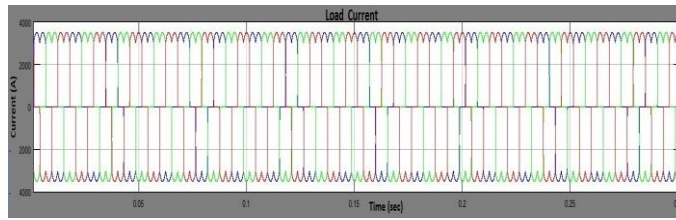


Figure 9. (a) Load Current with Non-Linear load

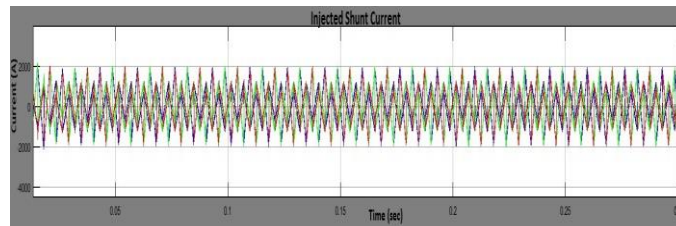


Figure 9. (b) Injected current by Shunt APF

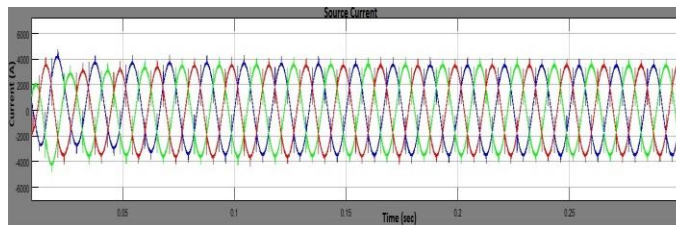


Figure 9(c). Source current with Shunt APF

Figure 9(a),9(b),9(c) shows load current drawn by non-linear load, injected current by Shunt APF and source current after implementing shunt compensation. THD analysis of source current without SAF is 30.05 % before compensation and THD should be limited under allowable limit according to IEEE standard for the proposed system. Shunt APF will inject current in opposite to harmonics present in the system which will cancel each other to obtain sinusoidal current waveform. THD analysis of source current with shunt APF is found 6.32% which is allowable for the proposed system.

6.3. Total Harmonic Distortion (THD) analysis

6.3.1. Load current THD analysis

Figure 9(d) shows THD of load current due to introduction of Non-linear load is 30.05%.

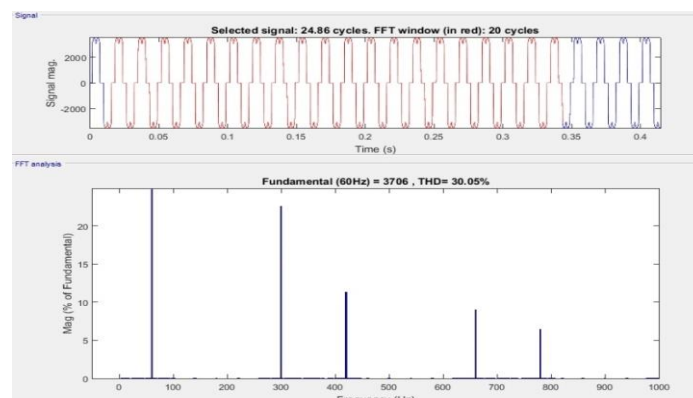


Figure 9(d). THD analysis of Load current

6.3.2. Source Current THD Analysis

THD analysis of source current is 6.32% after implementation of UPQC at point of common coupling shown in Figure 9(e). UPQC is able to maintain desired voltage at PCC during voltage sag but it requires active power supply so that voltage in phase can be injected. This power is drawn by shunt converter absorbing current more components from the system to keep the DC voltage at constant level. If a fixed level is not maintaining the voltage will drop to a very low value after few cycle of operation. Figure 9(f) shows the value of current drawn by shunt inverter.

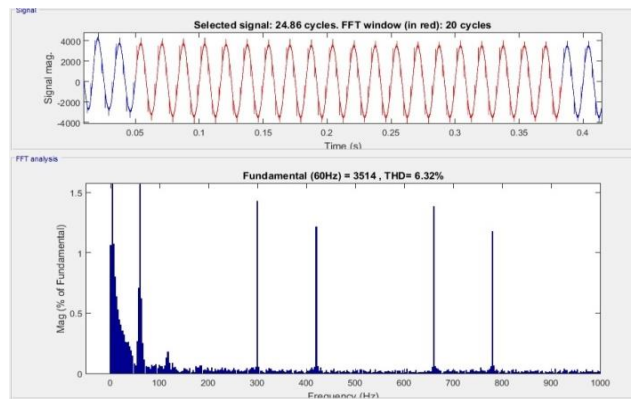


Figure 9 (e). THD analysis of source current

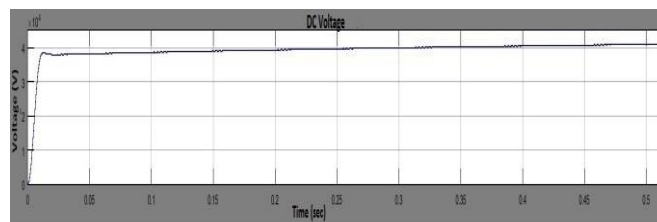


Figure 9(f). DC capacitance voltage

6.4. Voltage Sag Compensation

Here system condition during voltage sag is analyzed. Voltage sag of 50% is introduced at PCC at time 0.1 s for 0.2 s duration. Voltage is injected in series by series APF to achieve desired voltage magnitude at PCC. Figure 10(b) shows voltage level without compensation. Figure 10(c) shows PCC voltage after series compensation. 10(d) injected voltage by series APF through series transformer to restore missing voltage during sag.

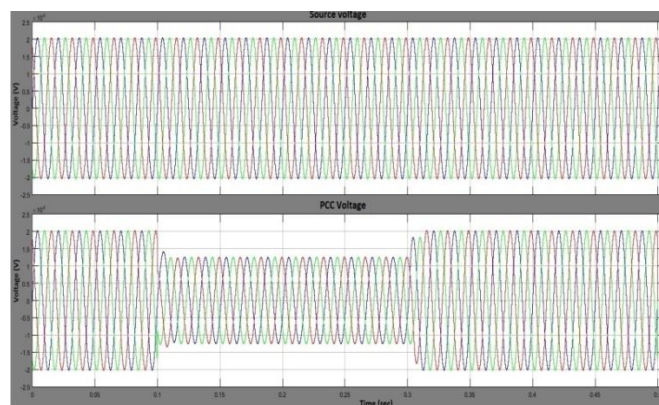


Figure 10. (a) Source voltage, (b) PCC Voltage

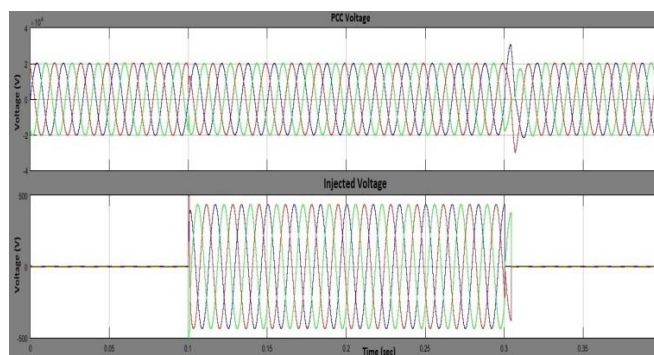


Figure 10(c). PCC voltage with compensation, (d) injected voltage by series APF
Active power, Reactive power and Terminal voltage of wind conversion system

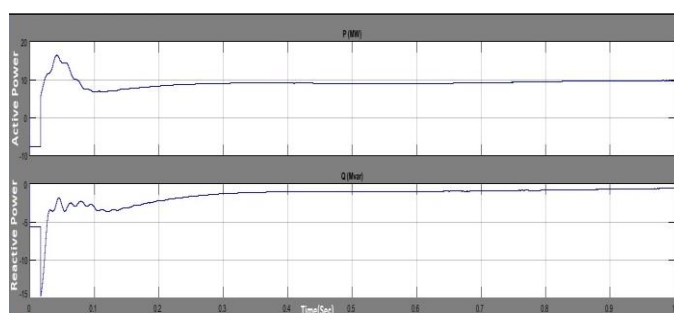


Figure 11. Wind Generator output

7. Conclusion

This paper analyses the effectiveness of unified power quality conditioner (UPQC) applied to a wind conversion system to improve the power quality and Low voltage ride through capability (LVRT). When fault, Non-linear load applied at PCC, UPQC maintains voltage level and harmonics within a safe allowable limit. In this proposed system, it has been demonstrated that during normal condition shunt APF keep the grid current at proper sinusoidal and balanced condition. During voltage sag series APF injects voltage in series to cover up the deficit voltage. By maintaining allowable voltage drops during three phase fault low voltage ride through can be achieved and disconnection of wind conversion system can be prevented. Besides UPQC provides protection from ground fault, fast recovery of system, improve power factor, prevent system from rotor over current and DC link over voltage.

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