Unified Power Quality Conditioner for Enhancement of Power Quality and Hybrid Power Generation Injection to Grid

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ABSTRACT
Power quality problems have become more complex at all level of power system. The power electronic based power conditioning devices can be the effective solution to improve the quality of power supplied to the distributed system. UPQC is custom power device, designed to compensate both source current and load voltage imperfections. In this paper the design of combined operation of unified power quality conditioner and a hybrid power generation is proposed. The proposed system is composed of series and shunt inverters, PV array and WECS connected to DC link which is able to compensate the voltage sag, swell, harmonics and voltage interruption. The proposed system is able to inject the active power to grid in addition to its ability in improvement of power quality in distribution system. The performance of the proposed UPQC system is validated through simulations using MATLAB/SIMULINK.

Keywords **– Power quality (PQ), Photovoltaic Array (PV), Series Active Filter (SEF), Shunt Active Filter (SAF), Unified Power Quality conditioner (UPQC), Wind Energy Conversion System (WECS).**

I. INTRODUCTION
The integration of renewable energy into existing power system presents technical challenges and that requires consideration of voltage regulation, stability, power quality problems [14]. The power quality is an essential customer focused measure and it's greatly affected by the operation of a distribution and transmission network. Nowadays, generation of electricity from renewable sources has improved very much. Since most renewable energy sources are intermittent in nature, it is a challenging task to integrate a significant portion of renewable energy resources into the power grid infrastructure. Traditional electricity grid was designed to transmit and distribute electricity generated by large conventional power plants. The electricity flow mainly takes place in one direction from the centralized plants to consumers. In contrast to large power plants, renewable energy plants have less capacity, and are installed in a more distributed manner at different locations. The integration of distributed renewable energy generators has great impacts on the operation of the grid and calls for new grid infrastructure. UPQC was widely studied by many researchers as an eventual method to improve power quality in distribution system.

The quality of the electrical power is affected by many factors like harmonic contamination, due to non-linear loads, such as large converters, rectifiers, voltage and current flickering due to arc in arc furnaces, sag and swell due to the switching of the loads etc. One of the many solutions is the use of a combined system of shunt and series active filters like unified power quality conditioner a new member of the custom power family. This device combines a shunt active filter together with a series active filter in a back to back configuration, to simultaneously compensate the supply voltage and the load current or to mitigate any type of voltage and current fluctuations and power factor correction in a power distribution network. UPQC is able to compensate current harmonics reactive power, voltage distortions and control load flow but cannot compensate voltage interruption because of not having sources. The interest in renewable energy has been increasing rapidly because renewable energy might play an important role in the future power system. A small distributed generation (DG) should be interconnected with the power system in order to maintain the frequency and voltage. Several studies proposed on the interconnection system for distributed generation with the power system through the inverter because the inverter gives versatile functions in proving the ability of distributed generation. The attention to distributed generating sources is increasing day by day. The reason is their important roll they will likely play in the future of power systems. Recently, several studies are accomplished in the field of connecting DG to grid using power electronic converters [9]. Here grid interface shunt inverters are considered more where the reason is low sensitiveness of DG to grid parameters and DG power transferring facility using this approach. Although DG needs more controls to reduce the problems like grid power quality and reliability. PV and WECS distributed generation sources which provides a part of human required energy now a day and will provide in the future. The greatest share of this kind of energy in the future will be its usage in interconnected system.

II. PROPOSED SYSTEM
The quality of the power leads to a direct economic impact on utilities, their customers, and suppliers. Custom power devices including power electronic interface can be the effective solution for increasing power quality problems because they can provide fast response and flexible compensation. In this paper UPQC and hybrid power generation combined system has been presented as shown in Fig. 1. The advantage of proposed combined system is voltage interruption compensation and active power injection to grid in addition to the mentioned abilities. Also this proposed system has higher efficiency and functioning ability in compare with other common PVs and WECS also cause reduction in system total cost. In this strategy both load voltage and source current sensing is required for

compensate current harmonics and source voltage interruption simultaneously.

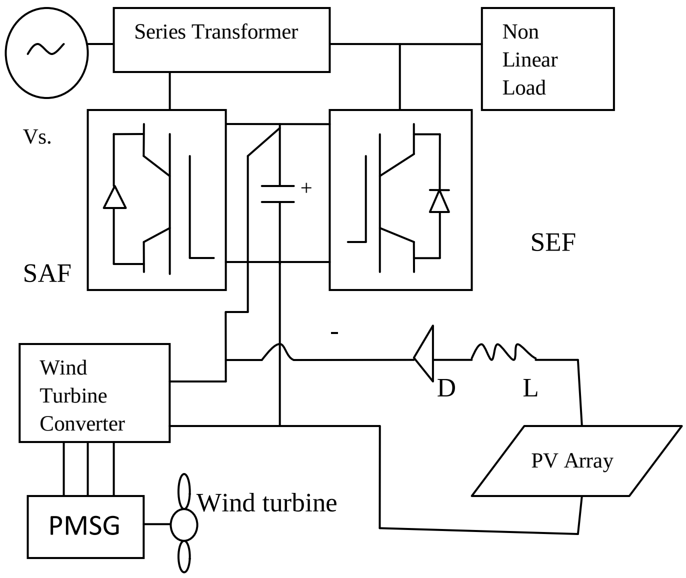

Fig. 1: configuration of proposed system

Normally, UPQC has two voltage source inverters in three phase four wire or three phase three wire configuration. One inverter is called series inverter is connected through transformers between the source and the common connection point. The other inverter called shunt inverter is connected in parallel with the common connection point through transformers. The series inverter operates as voltage source, while the shunt inverter operates as a current source.

UPQC has compensation capabilities for the harmonic current, reactive power compensation, the voltage disturbances, and the power flow control. But UPQC has no capability in compensating the voltage interruption because there is no energy storage. This paper proposes a new configuration of UPQC that has DG connected to the dc link through the rectifier. The UPQC can compensate the voltage interruption in the source, while the DG supplies power to the source and load or load only. There are two operating modes in the proposed system. One is called the interconnected mode, in which the DG provides power to the source and the load. The other is called islanding mode, in which the distributed generation provides power to the load within its power rating.

III. HYBRID SYSTEM MODELING

The Stand-alone hybrid generation systems are usually used to supply isolated areas or locations interconnected to a weak grid. They combine several generation modules, typically assimilating different renewable energy sources. The application of these hybrid topologies reduces the probability of energy supply shortage and, with the incorporation of energy storage; it allows to eliminate the background diesel generator (which is commonly required in generation systems based on a single renewable energy source). In this context, many electrical generation hybrid system frequently combine solar and wind energy sources (taking advantage of their complementary nature) with a lead-acid battery bank (to overcome periods of scarce generation). The topology of the hybrid system under consideration in this paper is depicted in Fig. 2.The wind generation module is constituted by a windmill, permanent-magnet synchronous generator (PMSG), a rectifier, and a dc/dc converter to interface the generator with the dc bus. The converter commands the voltage on the PMSG terminals, indirectly controlling the operation point of the wind turbine and, consequently, its power generation. The solar module comprises several PV panels connected to the dc bus via a dc/dc converter. Similar to the wind subsystem, the converter controls the operation point of the PV panels. The dc bus collects the energy generated by both modules and delivers it to the load if necessary.

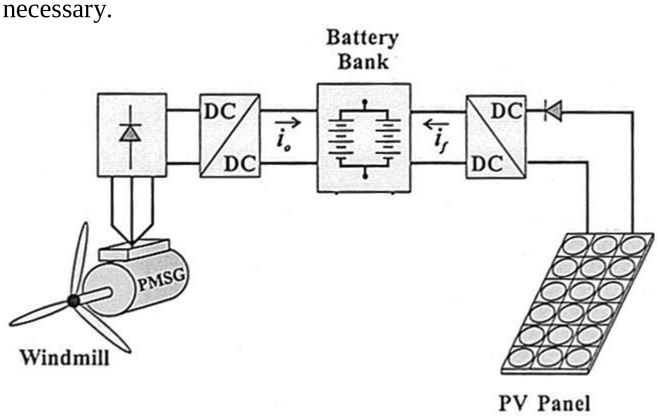

Fig. 2: Hybrid Generation system

The wind turbine of the stand-alone hybrid system already presented in Fig. 2 [11], drives a multi-polar PMSG whose terminal voltage equations can be described by the following matrix expression

$$V_{abc} = R_{sabc}\, i_{abc} + S\emptyset_{m\,abc} \tag{1}$$

Where Rs is the stator phase winding resistance matrix, ϕm is the matrix of flux linked by the stator windings, and is the Laplace operator. Expressing this model in a rotor reference frame, (1) can be written as

$$V_q = -R_s i_q - L_q S i_q - \omega_e L_q i_d + \omega_e \emptyset_m \tag{2}$$

$$V_d = -R_s i_d - L_d S i_d - \omega_e L_d i_q \tag{3}$$

and the electromagnetic torque is given by

$$T_e = \frac{3P\,(\emptyset_m i_q + (L_d - L_q) i_q i_d}{4} \tag{4}$$

Where L_q and L_d are the stator inductances in the d-q axes, ω_e=P ωm/2 is the electrical angular speed, and the number of poles. As it is shown in Fig. 2, the PMSG is linked to the dc bus through a diode bridge rectifier and a dc/dc converter. This configuration presents to the PMSG terminals a pure active power load whose value can be modified through the duty cycle (δ) of the converter. All controls of the hybrid distributed generation are conducted by the inverter control, not only in normal state but also in case of occurring of disturbances such as sags or swells; the wind generator performs only a role of maintaining the dc-link voltage in constant set point. Moreover, when any even happen in the distribution system, the PMSG supplies power required from the local load through the shunt inverter.

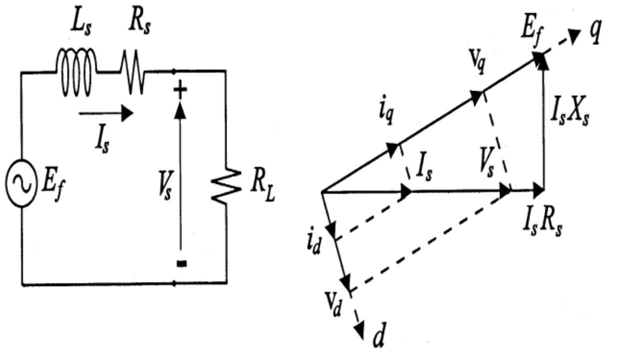

Fig. 3: Phase circuit and phasor diagram of the PMSG.

Fig. 3 shows a simple per phase equivalent circuit of the PMSG working under this condition and its corresponding phasor diagram. Vs and Is are the line voltage and current in the PMSG terminals, respectively, E_f corresponds to the emf in the stator windings and Xs is the synchronous reactance. From this last figure, using simple mathematical relationships, (2) and (3) can be expressed in terms of the terminal PMSG voltage, as

$$\frac{V_s i_q}{\sqrt{i_q^2+i_d^2}} = -R_s i_q - L_q S i_q - \omega_e L_q i_d + \omega_e \emptyset_m \quad (5)$$

$$\frac{V_s i_d}{\sqrt{i_q^2+i_d^2}} = -R_s i_d - L_d S i_d - \omega_e L_d i_q \quad (6)$$

Then, assuming a full bridge topology for the dc/dc converter, the relationship between the voltage on the dc bus terminals (V_b) and V_s can be described by the following expression:

$$V_s = \frac{\pi V_b U_x}{3\sqrt{3}} \quad (7)$$

where U_x is a simple function of the dc/dc converter duty cycle δ , given for this configuration by U_x = Ktr/δ, with Ktr the winding ratio of the transformer included in the dc/dc converter. Thus, replacing (7) in (6) and operating, the latter can be rewritten as

$$i_q = -\frac{R_s}{L} i_q - \omega_e i_d + \frac{\omega_e \emptyset_m}{L} - \frac{\pi V_b i_q U_x}{3L\sqrt{3(i_q^2+i_d^2)}} \quad (8)$$

$$i_d = -\frac{R_s}{L} i_d - \omega_e i_q - \frac{\pi V_b i_d U_x}{3L\sqrt{3(i_q^2+i_d^2)}} \quad (9)$$

Assuming an ideal static conversion, the current injected by the wind subsystem in the dc bus can be readily determined equating the input and output power of the dc/dc converter. As it was previously said, this paper deals with the regulation of the output power of the system by focusing in the control of the wind subsystem. The control design of the photovoltaic subsystem is not under consideration here, so its operation is represented by a variable but measurable current i_f injected in the dc bus. Similarly, assuming an ideal voltage inverter, the load demand can be referred to the dc side as a measurable output current i_L Therefore, the current across the battery bank can be written as

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$$i_o = \frac{\pi\sqrt{i_q^2+i_d^2 U_x}}{2\sqrt{3}} \quad (10)$$

$$i_b = \frac{\pi\sqrt{i_q^2+i_d^2 U_x}}{2\sqrt{3}} + i_f - i_L \quad (11)$$

where i_F and i_L are measurable currents, and thus, assumed to be known currents. To complete the dynamic model of the system, it is necessary to outline the mechanical dynamic equation of the wind subsystem. Neglecting the friction term, this equation is given by (12)

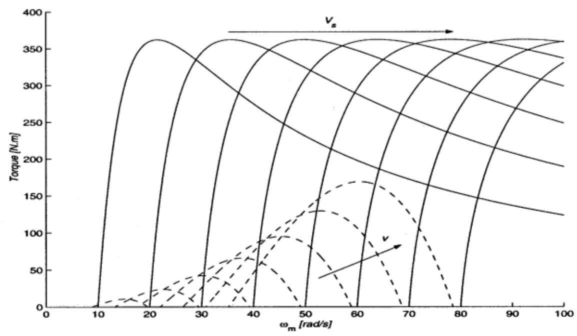

Fig. 4: Turbine and PMSG torque-shaft speed.

$$\dot{\omega}_e = \frac{P(T_t - T_e)}{2J} \quad (12)$$

where is the inertia of the rotating system and T_t is the turbine torque. Thus, replacing (4) in (12) and considering that in radial flux PMSGs it holds L_d=L_q=L_s =L, (12) can be rewritten as

$$\dot{\omega}_e = \frac{P\left(\frac{T\emptyset_t - 3\emptyset_m i_q}{4}\right)}{2J} \quad (13)$$

Therefore, considering (8), (11), and (13), and modeling the battery bank as a voltage source E_b connected in series with a resistance R_b and a capacitance C_b , a complete nonlinear dynamical model of the hybrid system may be written as

$$i_q = -\frac{R_s}{L} i_q - \omega_e i_d + \frac{\omega_e \emptyset_m}{L} - \frac{\pi V_b i_q U_x}{3L\sqrt{3(i_q^2+i_d^2)}} \quad (14)$$

$$i_d = -\frac{R_s}{L} i_d - \omega_e i_q - \frac{\pi V_b i_d U_x}{3L\sqrt{3(i_q^2+i_d^2)}} \quad (15)$$

$$\dot{\omega}_e = \frac{P}{2J}\left(T_t - \frac{3}{2}\frac{P}{2}\emptyset_m i_q\right) \quad (16)$$

$$\dot{V}_c = \frac{1}{C_b}\left(\frac{\pi}{2\sqrt{3}}\sqrt{i_q^2 + i_d^2 U_x} + i_f - i_L\right) \quad (17)$$

where V_c is the voltage in the capacitor C_b , and the voltage on the dc bus terminals is given by (18)

$$V_b = E_b + V_c + \left(\frac{\pi}{2\sqrt{3}}\sqrt{i_q^2 + i_d^2 U_x} + i_f - i_L\right) R_b \quad (18)$$

Fig. 4 shows in the torque shaft speed plane, the turbine torque (Tt) developed by a horizontal shaft turbine parameterized in terms of the wind speed (dashed line) and the generator torque (Te) curves parameterized in function of Vs in solid line. It is interesting to note that for a given constant voltage in the PMSG terminals, there exists a minimum shaft speed below which the wind subsystem cannot generate.

$$\omega_{elim} = \frac{V_s}{\varnothing_m} = \frac{\pi V_b U_x}{3\sqrt{3\varnothing_m}} \quad (19)$$

This lower limit arises naturally from the analysis of the phasor diagram depicted in Fig. 3, since it cannot be built for speeds that induce E_f smaller than V_s . Its expression is obtained in through the steady state analysis of a similar topology, and can be written for the electrical angular speed as given in above equation.

IV. CONTROL STRATEGY FOR UPQC

The control strategy is basically the way to generate reference signals for both shunt and series APF of UPQC. The compensation effectiveness of the UPQC depends on its ability to follow with a minimum error and time delay to calculate the reference signals to compensate the distortions, unbalanced voltages or currents or any other undesirable condition. In the following section an approach based on Unit Vector Templates Generation is explained to extract the reference voltage and current signals for series and shunt active power filters respectively. As for the shunt active filter of the UPQC it is represented by $(Vdc/2)U_2$ with Ish as the first order low-pass interfacing filter and rsh as the losses of the shunt VSI. $(Vdc/2)U_2$ represents the switched voltage across the shunt VSI output of the UPQC. The injection current of the shunt active filter is denoted by Iing both U_1 and U_2 take the value of either -1 or 1 depending on the switching signal of the hysteresis control. The instantaneous current of the nonlinear load iL is expanded into 3 terms.

$$U_a = \sin(\omega t)$$

$$U_b = \sin(\omega t - 120) \quad (20)$$

$$U_c = \sin(\omega t + 120)$$

The first term $i_L Jp$ is the load Reference currents and voltages are generated using Phase Locked Loop (PLL).The control strategy is based on the extraction of Unit Vector Templates from the distorted input supply. These templates will be then equivalent to pure sinusoidal signal with unity (p.u.) amplitude [8]. Multiplying the peak amplitude of fundamental input voltage with unit vector templates of equation (20) gives the reference load voltage signals.

$$V_{abc}^* = V_m . U_{abc} \quad (21)$$

The error generated is then taken to a hysteresis controller to generate the required gate signals for series APF. The unit vector template can be applied for shunt APF to compensate the harmonic current generated by non-linear load. The extractions of three phase voltage reference signals are based on unit vector template generation. A phase Locked Loop (PLL) is used to extract the pure sinusoidal signal at fundamental frequency. The PLL gives signal in terms of sine and cosine functions. Here only sine terms are considered. As we know the supply voltage peak amplitude in advance, we can generate the unity supply voltage signals. To get the unity terminal voltage vector the terminal voltage are sensed and multiplied by a inverse of peak amplitude of fundamental terminal voltage. These unity voltage vectors are then taken into PLL. Thus the output of PLL is equal to the unity terminal voltage at fundamental frequency only. With proper phase angle shifting the unit vector templates for three phase are generated. We also know the desired load voltage level at load voltage, V_L , with unit vector templates, gives the reference load voltage signals for series APF. The overall reference signal generation for series APF is shown in Fig. 5.

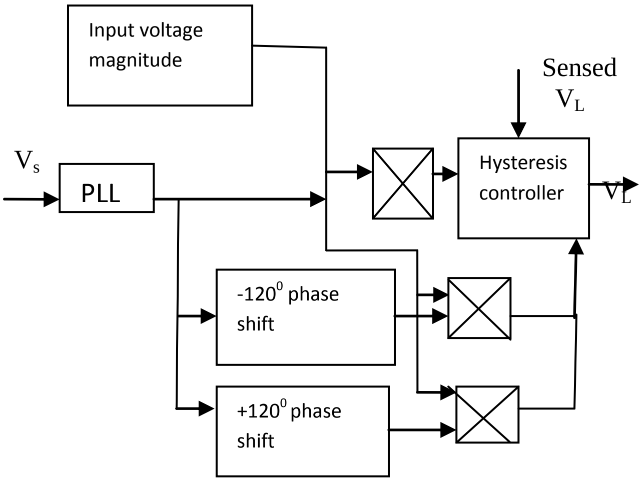

Fig. 5: Reference voltage signal generation for series APF

The shunt APF is used to compensate for current harmonics as well as to maintain the dc link voltage at constant level. To achieve the above mentioned task the dc link voltage is sensed and compared with the reference dc link voltage. A PI controller then processes the error. The output signal from PI controller is multiplied with unit vector templates of equation (1) giving reference source current signals. The source current must be equal to this reference signal. In order to follow this reference current signal, the 3-phase source currents are sensed and compared with reference current signals. The error generated is then processed by a hysteresis current controller with suitable band, generating gating signals for shunt APF. The UPQC uses two back-to-back connected three phase voltage source inverters sharing a common dc bus. The hysteresis controller is used here to control the switching of the both voltage source inverters. UPQC consists of series compensator and shunt compensator. The shunt compensator is controlled by a PWM current control algorithm, while the series converter is controlled by a PWM voltage control algorithm. The effectiveness of an active power filter depends basically on the design characteristics of the current controller, the method implemented to generate the reference current signal template and gating signal generation used. The control scheme of shunt active filter must calculate the current reference waveform for each phase of the inverter, maintain the dc voltage as constant and generate the inverter gating signals.

4.1 REFERENCE CURRENT SIGNAL GENERATION

The unit vector templates can also be applied for shunt APF to compensate current harmonics currents generated by non-linear load. The shunt APF is used for compensate current harmonics as well as to maintain the dc link voltage at constant level. To achieve the aforementioned task the dc link voltage is sensed and compared with the reference dc link voltage. The error is then processed by a PI controller. The output of the PI controller then will be the peak amplitude of fundamental input current which must be drawn from the supply in order to maintain dc kink voltage at constant level and to supply losses associated with UPQC. This peak amplitude is then multiplied with unit vector templates giving reference current signals for shunt APF as shown in Fig. 5. For static shunt compensator the instantaneous current of the nonlinear load iL is expanded into 3 terms. The first term iLJp is the load functions sent from PLL (Phase Locked Loop) in accordance with equation. (22)

$$I_{Ldqo} = T_{abc}^{dqo} i_{Labc} \tag{22}$$

By this transform, the fundamental positive sequence components are transformed into dc Quantities in d and q axes, which can easily be extracted by low-pass, filter (LPF). The switching loss can cause the dc link capacitor voltage to decrease. Other disturbances such as unbalances and sudden variations of loads can also cause this voltage to fluctuate. In order to avoid this, a PI controller is used the input of the PI controller is the error between the actual capacitor voltage and the desired value, its output then added to the reference current component in the d-axis to form a new. All harmonic components are transformed into ac quantities with a fundamental frequency shift.

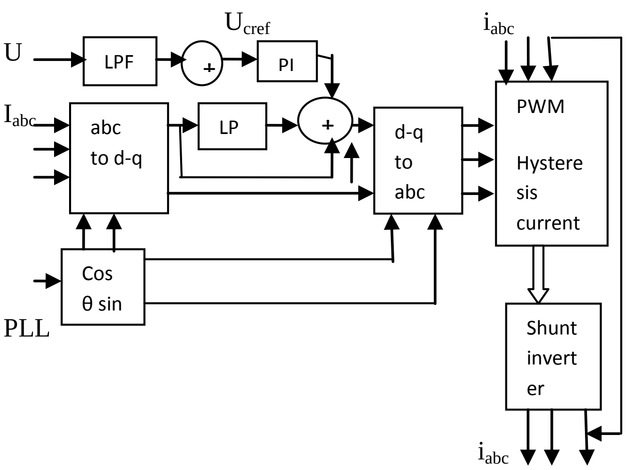

Fig. 6: Control of shunt converter for UPQC

$$I_{Lq} = \tilde{i}_{Lq} + \bar{\bar{i}}_{Lq} \tag{23}$$

Since $i_L = i_j + i_c$ (24)

In static series compensator the system side voltage may contain negative-zero-sequence as well as harmonics components which need to be eliminated by the series compensator. The control of the series compensator is shown in Figure.5. The system voltages are detected then transformed into synchronous dq-0 reference frame using equation (6).

$$U_{sdqo} = T_{abc}^{dqo} U_{sabc} = U_{sLi} + U_{sLn} + U_{sLo} + U_{sh} \tag{25}$$

4.2 GATING SIGNAL GENERATION

After extracting the reference voltage and current signals for series and shunt APF, the next step is to force the inverters to follow these reference signals. This can be done by switching the inverter IGBTs in a proper manner. To have the required gating signals, the modulation technique is used. Here the hysteresis band control technique based on PWM strategy is considered for both APF.

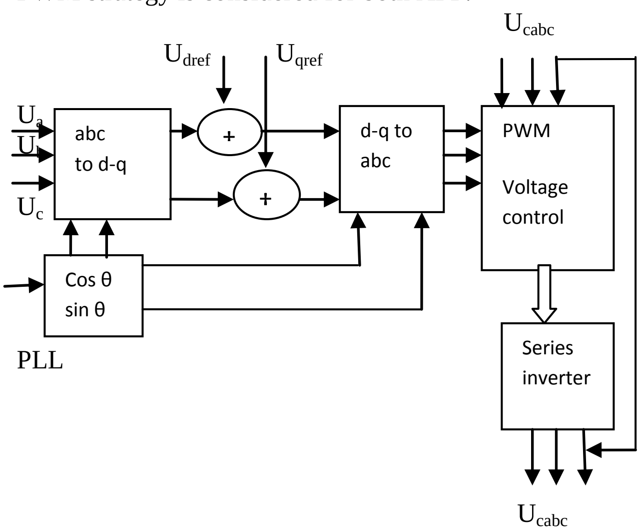

Fig. 7: Control of series converter for UPQC

The generated current reference signal s and the voltage signals for shunt and series APF are compared with actual sensed source current and the actual sensed load voltage respectively. The Hysteresis controller gives the switching instant whenever the error exceeds the hysteresis band.

V. SIMULATION RESULT

This study analyses the feasibility of protecting sensitive loads from power quality problems (voltage sags, flicker, harmonic current compensation, etc.) with compensation being performed at the distribution voltage. To verify the operating performance of the proposed unified power quality conditioner with hybrid power generation in a three phase electrical system, a phase locked loop extraction circuit with hysteresis controlled UPQC is simulated using MATLAB software. Fig. 8 show that the simulation diagram for unified power quality conditioner with hybrid (Photovoltaic's and Wind energy conversion system) power generation. The harmonic current injected by the non linear load appears at the source side giving the distorted source current waveform. Fig. 9 shows the waveform of distorted supply voltage before compensation. It consists of fundamental frequency as well as the harmonic content due to the non-linear load.

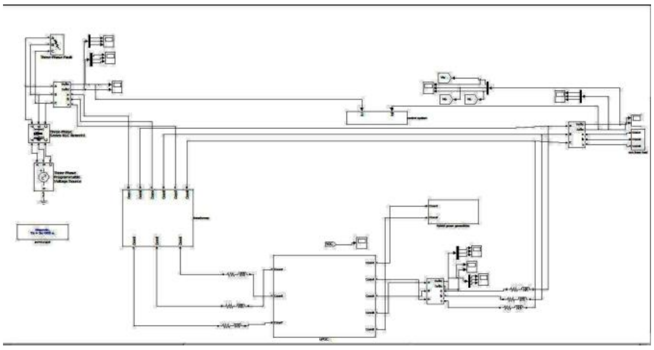

Fig. 8: Simulation diagram for UPQC with hybrid power

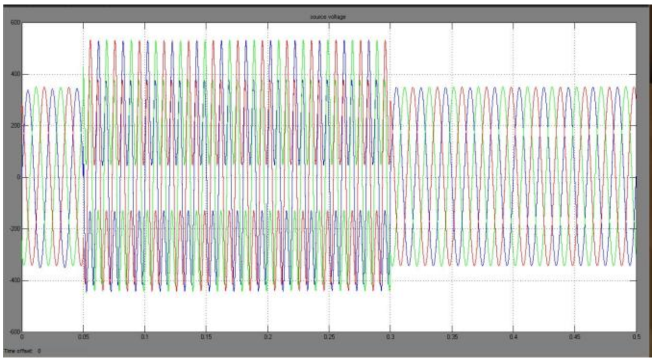

Fig. 9: Distorted source voltage

Fig. 10 shows the waveform of supply voltage interruption before compensation.

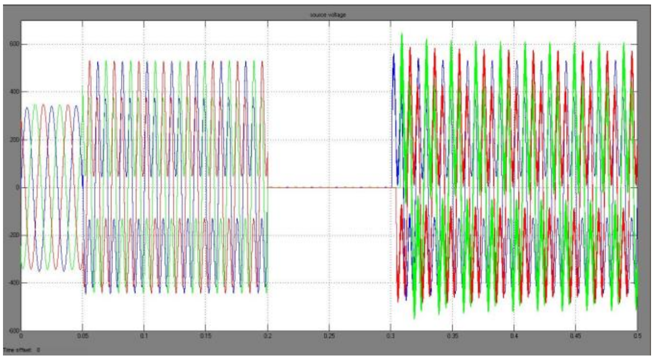

Fig. 10: Source voltage interruption

The main advantage of proposed method is to compensate deep voltage interruption. The interruption voltage present in the supply voltage is eliminated by interconnecting hybrid power generation into unified power quality conditioner through capacitor. The purpose of using this combined system is to reduce the harmonics effectively. The power factor also improved by using the combined system. The proposed model for the UPQC is to compensate input voltage harmonics and current harmonics caused by non linear load. The load current in both case is found to be content of all odd harmonic providing a total harmonic distortion. The hybrid power generation system proposed in this paper has the functions of improving power quality, blocking reverse power, and ensuring the continuity of electricity supply.

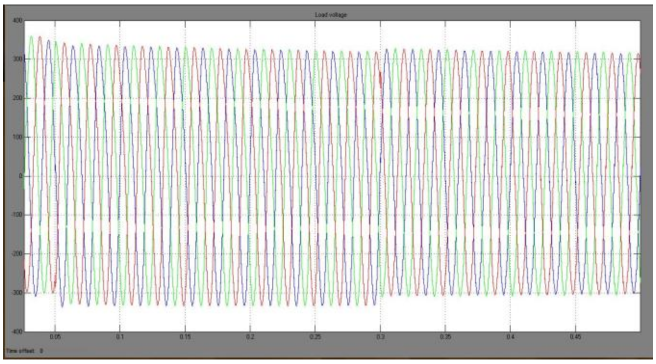

Fig. 11: Compensated load voltage

Fig. 11 shows the waveform of Load voltage after compensation. The waveform is more sinusoidal when compared with Fig. 8 and Fig. 9.

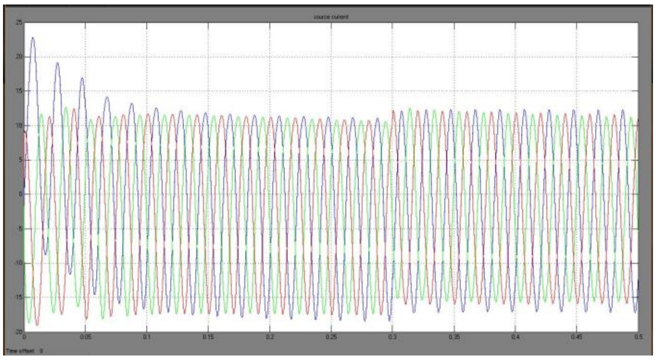

Fig. 12: Distorted source current

Fig. 12 shows the waveform of distorted source current before compensation. It consists of fundamental current as well as the harmonic current due to the non-linear load

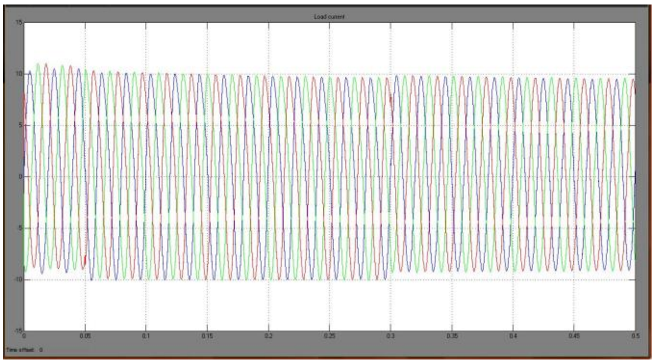

Fig. 13: Compensated load current

The Fast Fourier Transform (FFT) analysis of supply current after compensation the Total Harmonic Distortion of the supply current is reduced to 0.16% from 23.44%. Fig. 13 shows the waveform of Load voltage after compensation. PI controller used to eliminate error between the filter current and the harmonic current. The purpose of controller is tuned to reduce the particular harmonics. The harmonic current present in the supply current is eliminated by using the shunt compensation device. The distortion present in the supply current is reduced when compared Fig. 12.

VI. Conclusion

In this paper, the results of analyzing combined operation of UPQC and hybrid power generation is explained. The proposed system is composed of series and shunt inverters, PV array and wind energy conversion system which can compensate the voltage sag, swell, interruption, and reactive power and harmonics in both islanding and interconnected modes. The advantage of proposed system is reducing the expense of hybrid power generation connection to grid because of applying UPQC shunt inverter and also is the ability of compensating the voltage interruption using UPQC because of connecting distributed generation to DC link. The proposed system can improve the power quality at the point of installation on power distribution system or industrial power systems.

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