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Flying Capacitor Multilevel Inverter Implemented in UPQC by using P-q Theory for Enhancement of Power Quality in Utility System

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Abstract: This paper proposes a novel control strategy for a unified power quality conditioner integrated with a 7-level flying capacitor multilevel inverter to compensate the power quality problems in distribution system. Power quality problems have been increasing due to the wide use of nonlinear loads, which cause harmonic currents in networks and consequently distort the voltage and current at the point of common coupling. This distorted voltage and current harmfully affects the other loads connected at the PCC. To avoid this problem and protect loads from distortions, the harmonic components of the voltage and current must be fully compensated. UPQC is an efficient custom power device for enhancing the electric power quality at distribution levels, which is a combination of series and shunt active power filters sharing a common dc-link capacitor. In this paper the realization of shunt active power filter is carried out using a three-phase seven level flying capacitor multilevel inverter and the series active power filter is realized using a three-phase voltage source inverter. The flying capacitor multilevel inverter offers several advantages like, good power factor control due to the effect of large amount of storage capacitors, reduced harmonic current and different voltage levels etc. The control of shunt connected FCMLI is achieved by a control strategy known as p-q theory. The performance of the proposed system is analyzed through simulations with MATLAB SIMULINK software.

Key words: Flying Capacitor Multilevel Inverter (FCMLI) · Unified Power Quality Conditioner (UPQC) · Active Power Filter (APF) · Point of Common Coupling (PCC)

INTRODUCTION

It has been always a challenge to maintain the quality of electric power within the acceptable limits. In general, poor power quality may result into increased power losses, abnormal and undesirable behaviour of equipments, interference with nearby communication lines and so forth [1-4]. The widespread use of power electronic based systems has further burden on power system by generating harmonics and also all non-linear loads draw highly distorted currents from the utility system. The increasing use of non-linear loads, accompanied by an increase in associated problems concerns both electrical utilities and utility customer alike [5-9].

To improve the power quality, series and shunt active power filters are preferred. There are two types of filters, one is passive filters and another one is active filters [10]. The passive filters are L and C components are connected, which is simplicity and cost effective etc. The passive filters have few drawback like resonance problems, filter for every frequency and bulky [11]. UPQC is one of the major custom power devices, capable of mitigating the effect of non-linear loads at the load end or at the Point of Common Coupling (PCC). UPQC can compensate almost all power quality problems such as; voltage harmonics, voltage unbalance, voltage flickers, voltage sags, voltage swells, Current harmonics, current unbalance, etc [12].

The proposed system of three-phase UPQC integrated with flying capacitor multilevel inverter is implemented by using p-q theory based control [13-15]. Multi-level inverters have many advantages over conventional two-level inverters such as high-power, high voltage capacity, low switching losses and low cost [16].

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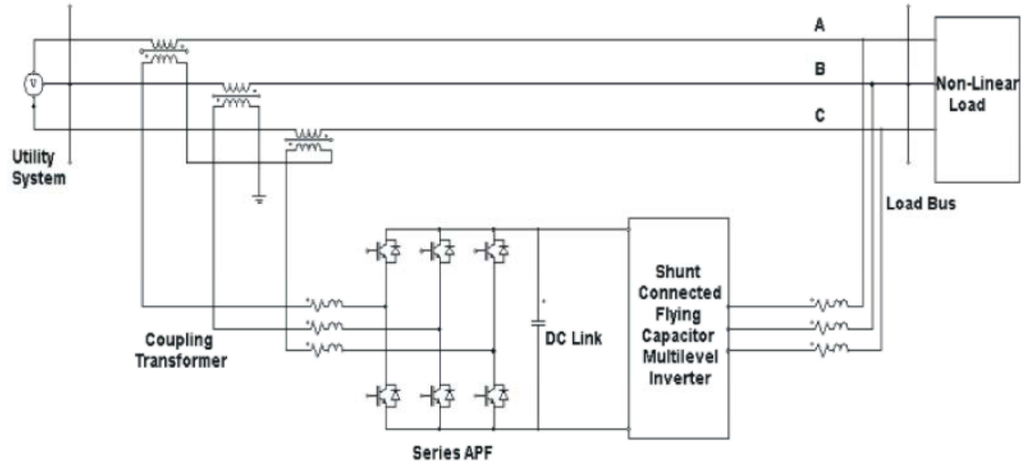

Fig. 1: Integrated FCMLI in three phase UPQC system

In case of N-level, the multi-level inverters can increase the power (N -1) times than that of conventional two-level inverter by using the series connection of power semiconductor devices [17-19]. Comparing with conventional two-level inverter system under the condition of the same power rating, multi-level inverters have the advantages that harmonic components of line-to-line voltage, switching frequency of device and EMI component could be significantly decreased [20].

Flying Capacitor Multilevel Inverter Integrated with UPQC: A UPQC consists of series and shunt connected inverters for the compensation of both voltage and current. Three phase UPQC has series transformer in order to connect the inverters in series with the line as a controlled voltage source. Figure 1 shows three phase distribution system connected with Flying Capacitor Multilevel Inverter integrated with UPQC.

In series APF Inverter injects a voltage in series with the line which feeds the polluting load through a transformer. The injected voltage will be mostly harmonics with a small amount of sinusoidal component which is in-phase with the current flowing in the line. The small sinusoidal in-phase (with line current) component in the injected voltage results in the right amount of active power flow into the Inverter to compensate for the losses within the series APF and to maintain the D.C side capacitor voltage constant. Obviously the D.C voltage control loop will decide the amount of this in-phase component. Series active power filter compensate the distortion caused by non-linear load.

The flying capacitor multilevel inverter (FCMLI) is a multiple voltage level inverter topology intended for high-power and high-voltage operations at low distortion. It uses capacitors, called flying capacitors, to clamp the voltage across the power semiconductor devices. The active filter uses power electronic switching to generate harmonic currents that cancel the harmonic currents from a non-linear load. In this configuration, the FCMLI is connected in parallel with the load being compensated. Therefore the configuration is often referred to as an active parallel or shunt filter. Figure 2. illustrates the general view of One Phase Leg of a 7-Level flying capacitor multilevel inverter. This inverter uses dc capacitors as the supply and can switch at a high frequency to generate a signal that will cancel the harmonics from the non-linear load.

Single leg of a seven-level inverter consists of SA1 to SA6 and S’A1 to S’A6 power semiconductor device (e.g. GTO, IGBT) and an anti-parallel diode. The Voltages of capacitor VC, Vc1, Vc2, Vc3, Vc4 and Vc5 are Vdc, 5/6 Vdc, 2/3 Vdc, Vdc/2, Vdc/3 and Vdc/6 respectively. The possible switch combinations are given in Table 1, which is synthesizing the output voltage of phase-a, Van, with respect to the neutral point n. The main dc capacitor C is the energy storage element, while capacitors CA1, CA2, CA3, CA4 and CA5 are the flying capacitors that provide the multilevel voltage ability to the converter. The pairs of the switches (SA1, S’A1), (SA2, S’A2), (SA3, S’A3), (SA4, S’A4), (SA5, S’A5) and (SA6, S’A6) are closed in complementary manner, like SA1 is ON, S’A1 is OFF and vice-versa. For any initial state of clamping voltage, the inverter output three phase voltages is given by:

$$V_{an} = S_{a1}\left(V_c - V_{ca1}\right) + S_{a2}\left(V_{ca1} - V_{ca2}\right) + S_{a3}\left(V_{ca2} - V_{ca3}\right)$$
$$+S_{a4}\left(V_{ca3} - V_{ca4}\right) + S_{a5}\left(V_{ca4} - V_{ca5}\right) + S_{a5}V_{ca5} - \frac{V_c}{2} \quad (1)$$

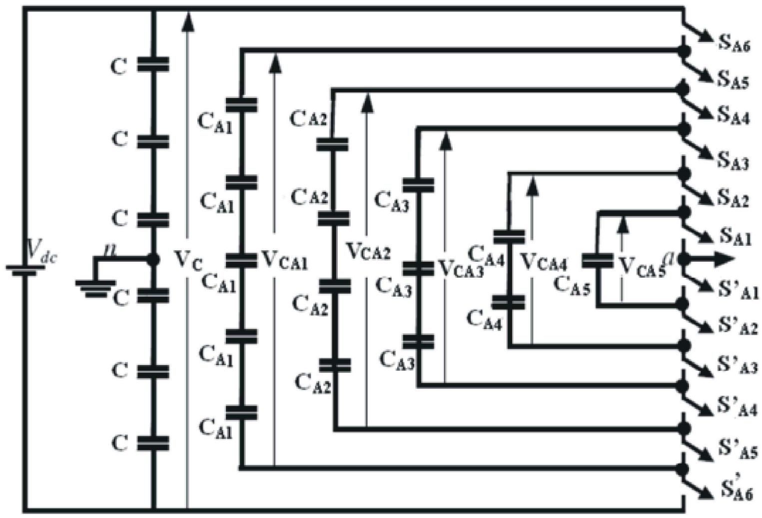

Fig. 2: Single leg of a seven-level inverter

Table 1: Switching Scheme of Single Leg Seven-Level FCMLI

SA6	SA5	SA4	SA3	SA2	SA1	Van
ON	ON	ON	ON	ON	ON	Vdc/2
ON	ON	ON	ON	ON	OFF	Vdc/3
ON	ON	ON	ON	OFF	ON	
ON	ON	ON	OFF	ON	ON	
ON	ON	OFF	ON	ON	ON	
ON	OFF	ON	ON	ON	ON	
OFF	ON	ON	ON	ON	ON	
OFF	OFF	ON	ON	ON	ON	Vdc/6
OFF	ON	OFF	ON	ON	ON	
OFF	ON	ON	OFF	ON	ON	
OFF	ON	ON	ON	OFF	ON	
OFF	ON	ON	ON	ON	OFF	
OFF	ON	ON	ON	OFF	OFF	0
OFF	OFF	ON	ON	ON	OFF	
OFF	OFF	OFF	ON	ON	ON	
ON	OFF	OFF	OFF	ON	ON	
ON	ON	ON	OFF	OFF	OFF	
ON	OFF	OFF	OFF	OFF	ON	-Vdc/6
ON	OFF	OFF	OFF	ON	OFF	
ON	OFF	OFF	ON	OFF	OFF	
ON	OFF	ON	OFF	OFF	OFF	
ON	ON	OFF	OFF	OFF	OFF	
ON	OFF	OFF	OFF	OFF	OFF	-Vdc/3
OFF	ON	OFF	OFF	OFF	OFF	
OFF	OFF	ON	OFF	OFF	OFF	
OFF	OFF	OFF	ON	OFF	OFF	
OFF	OFF	OFF	OFF	ON	OFF	
OFF	OFF	OFF	OFF	OFF	ON	
OFF	OFF	OFF	OFF	OFF	OFF	-Vdc/2

$$V_{bn} = S_{b1}\left(V_c - V_{cb1}\right) + S_{b2}\left(V_{cb1} - V_{cb2}\right) + S_{b3}\left(V_{cb2} - V_{cb3}\right) + S_{b4}\left(V_{cb3} - V_{cb4}\right) + S_{b5}\left(V_{cb4} - V_{cb5}\right) + S_{b5}V_{cb5} - \frac{V_c}{2} \quad (2)$$

$$V_{cn} = S_{c1}\left(V_c - V_{cc1}\right) + S_{c2}\left(V_{cc1} - V_{cc2}\right) + S_{c3}\left(V_{cc2} - V_{cc3}\right) + S_{c4}\left(V_{cc3} - V_{cc4}\right) + S_{cc5}\left(V_{cc4} - V_{cc5}\right) + S_{c5}V_{cc5} - \frac{V_c}{2} \quad (3)$$

The main dc-link capacitor voltage is Vdc and the innermost clamping capacitor voltage is:

$$\frac{V_{dc}}{n-1} \quad (4)$$

The voltage of the next innermost clamping capacitor will be:

$$\frac{V_{dc}}{n-1} + \frac{V_{dc}}{n-1} = \frac{2V_{dc}}{n-1} \quad (5)$$

Each next clamping capacitor will have the voltage increment of $\frac{V_{dc}}{n-1}$ from its immediate inner one. The voltage levels and the arrangements of the flying capacitor in the FCMLI structure assure the voltage stress across each main device is same. It is equal to $\frac{V_{dc}}{n-1}$ for an n- level inverter.

Design Of Upqc Controllers

Controller for Series Active Filter: The control algorithm for series APF is based on PLL reference control scheme. The reference load voltage signals extracted for series APF are used instead of actual load voltage. The reference voltage signals for phase a, b, c can be represented as:

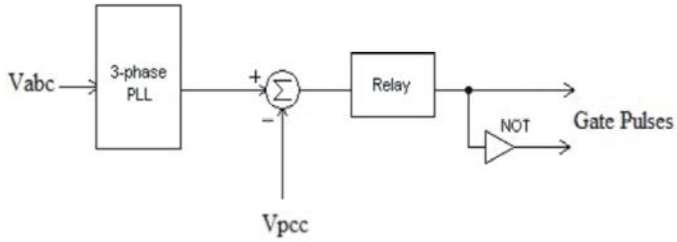

Fig. 3: PLL reference control

$$\begin{bmatrix} Vl_a \\ Vl_b \\ Vl_c \end{bmatrix} = \begin{bmatrix} Vl\sin\omega t \\ Vl\sin(\omega t-120) \\ Vl\sin(\omega t+120) \end{bmatrix} \quad (6)$$

A PLL is used to generate the reference voltages and also synchronize on a set of variable frequency, three-phase sinusoidal signals. These reference voltage signals are then compared with the voltage at the point of common coupling (PCC).The resulting signal is used to generate the gate pulses for series active filter. The block diagram representation of PLL reference control is shown in Figure 3.

P-q Theory for Shunt Connected FCMLI: The control strategy for shunt APF (p-q theory) is based on Clarke's theory of $\alpha\beta0$ transformation. According to this theory, a single phase system can be defined as a pseudo two-phase system by giving $\pi/2$ lead or $\pi/2$ lag, which is each phase voltage and current of the original three phase systems. This resultant two phase systems can be represented in α-β coordinates, thus the active and reactive currents are calculated from these α-β components and are applied as reference signal for the shunt connected FCMLI.

The p-q control is based on the $\alpha\beta0$ transformation [Clarke (1943)], which consists in a real matrix to transform three-phase voltages and currents into the $\alpha\beta0$ stationary reference frame. The Clarke's Transform of phase voltages to α and β coordinates has the form:

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

It is assumed that line voltages (Va, Vb, Vc) are referenced to an artificial zero, i.e., Va + Vb + Vc = 0. At such a condition, the Clarke's Transform of phase voltages can be simplified to the form.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{3}}{2} & 0 \\ \frac{1}{\sqrt{2}} & \sqrt{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \end{bmatrix} \quad (8)$$

Similarly, in three-wire systems Ia+Ib+Ic = 0, thus, the Clarke's Transform of the line currents has the form:

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{3}}{2} & 0 \\ \frac{1}{\sqrt{2}} & \sqrt{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \end{bmatrix} \quad (9)$$

With voltages and currents transformed to the α and β co-ordinates, the instantaneous active (real) power is defined, according to p-q theory.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (10)$$

that is, real power,

$$p = V_\alpha I_\alpha + V_\beta I_\beta \quad (11)$$

and reactive power,

$$q = V_\alpha I_\beta + V_\beta I_\alpha \quad (12)$$

where $p = p_{dc} + p_{ac}$ (13)

and $q = q_{dc} + q_{ac}$ (14)

In (13) and (14), pdc and qdc represent the dc components that are responsible for fundamental active and reactive powers, whereas pac and qac represent the ac components that are responsible for harmonic powers. The active and reactive powers are calculated by summing instantaneous fundamental active and reactive power demands of all the three phases.

$$p = p_{dc(a)} + p_{dc(b)} + p_{dc(c)} \quad (15)$$

$$q = q_{dc(a)} + q_{dc(b)} + q_{dc(c)} \quad (16)$$

With these two, p and q, instantaneous powers, instantaneous active and reactive currents are defined. The instantaneous active current, ip, is defined in the α and β coordinates as;

$$I_{\alpha p} = \frac{V_\alpha}{V_{\alpha^2} + V_{\beta^2}} p \quad (17)$$

and $$I_{\beta p} = \frac{V_\beta}{V_{\alpha^2} + V_{\beta^2}} p \quad (18)$$

The instantaneous reactive current, iq, in the α and β co-ordinates is defined as;

$$I_{\alpha p} = \frac{-V_\beta}{V_{\alpha^2} + V_{\beta^2}} q \quad (19)$$

and $$I_{\beta p} = \frac{V_\alpha}{V_{\alpha^2} + V_{\beta^2}} q \quad (20)$$

Respective compensating α, β current are:

$$I_{c\alpha} = I_{\alpha p} + I_{\alpha q} \quad (21)$$

$$I_{c\beta} = I_{\beta p} + I_{\beta q} \quad (22)$$

Line currents can be obtained from currents in α and β coordinates with the inverse Clarke's Transform:

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{c\alpha} \\ I_{c\beta} \end{bmatrix} \quad (23)$$

Then compare with the current at the point of common coupling. That resulting current is taken as the reference signal for the modulation scheme of seven-level FCMLI. Figure 4 reveals the block diagram of p-q control for reference current signal.

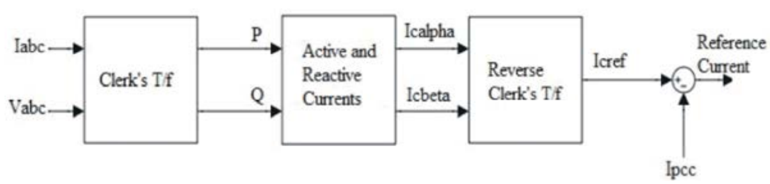

Fig. 4: P-q control

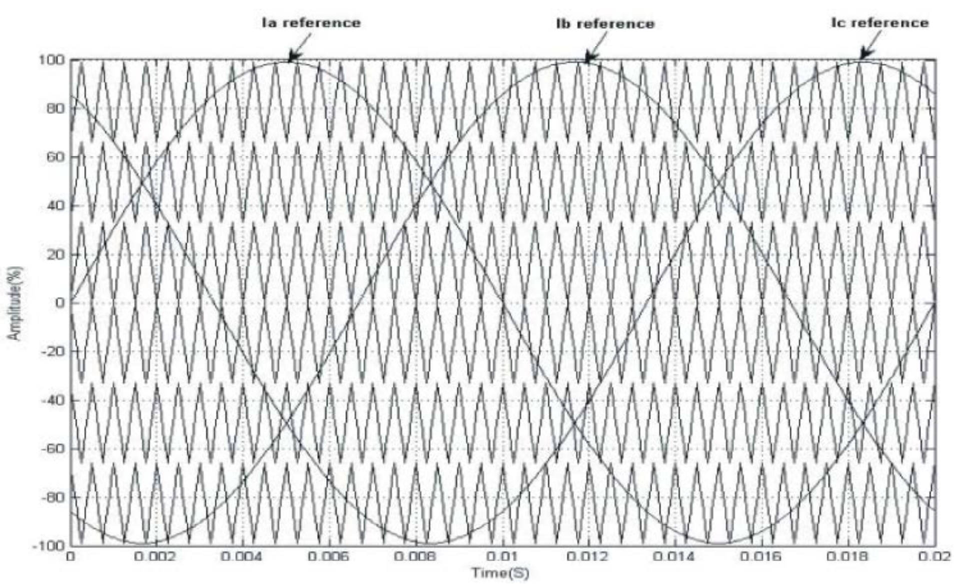

Fig. 5: Modulation scheme of seven-level FCMLI

FCMLI Modulation Scheme: The seven-level flying capacitor multilevel inverter requires a modulating signal and six carrier waves for each phase, which is shown Figure 5. In modulation scheme the reference signal of Ia, Ib, Ic are displaced from each other by 120°, All the carriers wave has same frequency fc and the same amplitude Ac, while the modulating signal has a frequency of fm and amplitude of Am.

The carrier and reference waves are compared and the output of the comparator defines the output voltage waveform. The modulating signal varies from 0% to 100%, which is varied based on the error signal. The amplitudes of the 6 carrier waves vary from 0% to 33.3% and 33.3% to 66.6%, 66.6% to 100%. Whenever the modulating signal is greater than carrier waves it produces the sinusoidal pulse width modulation, which is applied to FCMLI. The outputs of each comparator for each phase are combined to produce the corresponding decision signals for the switches to synthesize the output voltage of that phase. This signal resembles with the output voltage waveform of the inverter and decides the voltage level, which is to be generated at a particular instant.

RESULTS AND DISCUSSION

The UPQC should maintain the system voltage at a desired value and free from distortion with the help of seven-level FCMLI. The series active power filter injects the required compensating voltages through series transformer, making the system voltage free from distortion and at a desired level. The shunt connected FCMLI effectively compensates the current flowing toward the transformer. The proposed system have been simulated and Compensation of unbalanced voltage and current, Power factor correction, Harmonic compensation, Recovery from fault conditions are analyzed.

Without Compensator for Non-Linear Load and Three Phase Fault: In distribution systems, harmonics also occur due to normal electric current waveform distortion by non-linear loads. Without UPQC the distorted wave forms of voltage, current and power factor are shown in Figure 6-8, which created due to the effects of non linear load and three phase faults. With non-linear loads, the third harmonic on all three phases is exactly in phase and adds, rather than cancels, thus creating current and heat on the neutral conductor. Left un-treated, harmonic loads can reduce the distribution capacity and degrade the quality of the power of public utility power systems and result in equipment malfunctions such as communication errors and data loss and also the three phase faults cause sudden dips and variation in the normal waveforms.

FCMLI Integrated UPQC with Non-Linear Load and Three Phase Fault: The unbalanced and distorted waveforms are appeared due to power electronic load and system fault. The FCMLI Integrated UPQC injects the three phase voltage and current as shown in Figure 9 and Figure 10, which maintains the sinusoidal voltage and current as shown in Figure 11 and Figure 12. The series injected voltage is used to compensate the voltage related problems on the system and current compensation is done by UPQC integrated with FCMLI with p-q Control.

In an electric power system, a load with low power factor draws more current than a load with a high power factor for the same amount of useful power transferred. The higher currents increase the energy lost in the distribution system and require larger wires and other equipment. A high power factor is generally desirable in a transmission system to reduce transmission losses and improve voltage regulation at the load. It is often desirable to adjust the power factor of a system to near 1.0.UPQC is one of the effective custom power devices, which improves the power factor and also the combined effect of capacitors in FCMLI helps to improve the total system power factor which is shown in Figure 13.

Non-linear load draws harmonic currents, there for the system may get distorted. The dynamic behaviour of industrial loads such as rolling mills, arc furnaces, traction loads and large fluctuating single-phase loads draw wildly fluctuating amounts of reactive power from the supply systems. These loads cause unbalance on the system and leads to wide fluctuations in the supply voltage and effects like incandescent light flicker and malfunctioning computer equipments etc.

The FFT analysis of the PID and Fuzzy based system and proposed p-q theory based FCMLI-UPQC Systems are shown in below figures. In PID based UPQC, Utility voltage and current are distorted with a THD of 0.34% and 5.34% respectively. In FLC based, Utility voltage and current are distorted with a THD of 0.33% and 0.76% respectively. The compensated utility voltage and current in p-q theory based FCMLI-UPQC System a profile shown in Figure 16 & 19 has a THD of 0.29% and 0.17% respectively. The proposed system of p-q theory based FCMLI integrated UPQC System should maintain the system voltage and current at a desired value and free from distortion. The percentages of THD in source voltage and source current comparison are shown in Figure 20 and Figure 21.

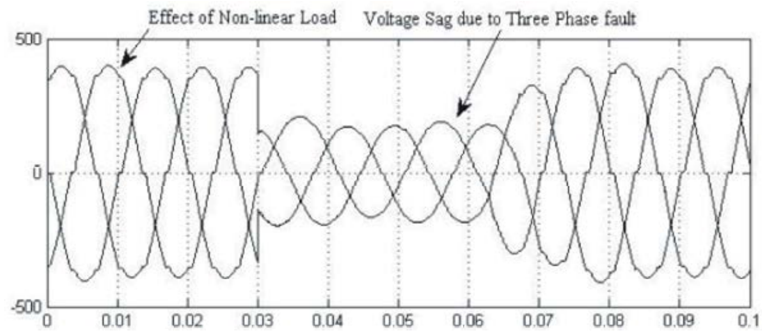

Fig. 6: Without compensator system voltage

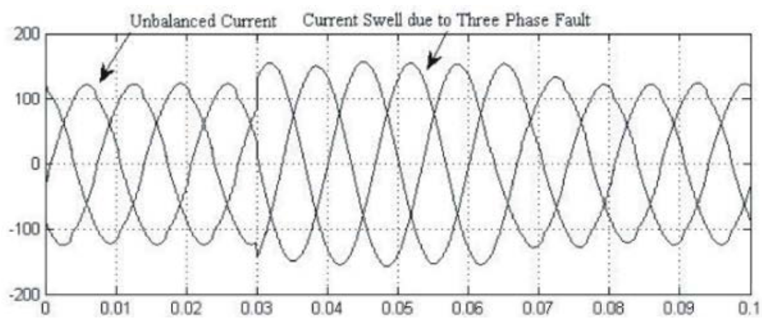

Fig. 7: Without compensator system current

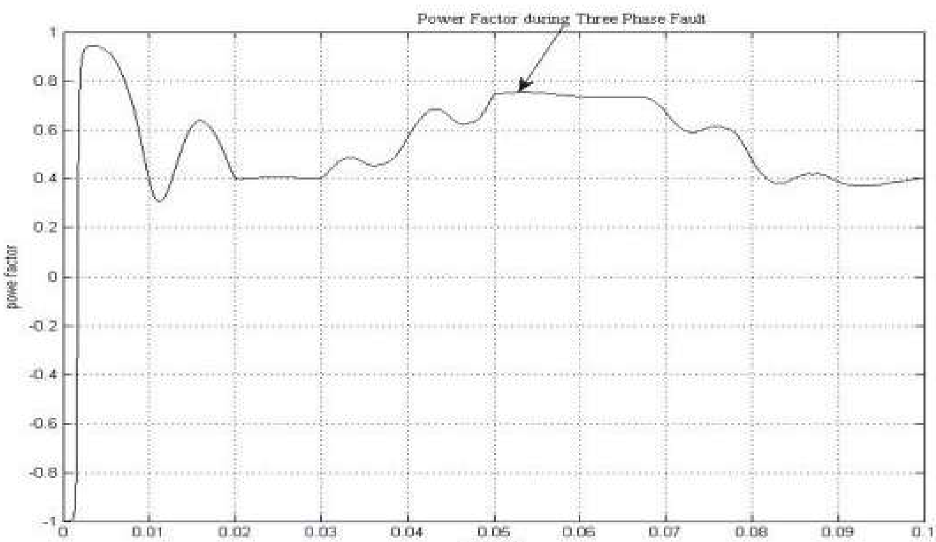

Fig. 8: Without compensator system Power factor

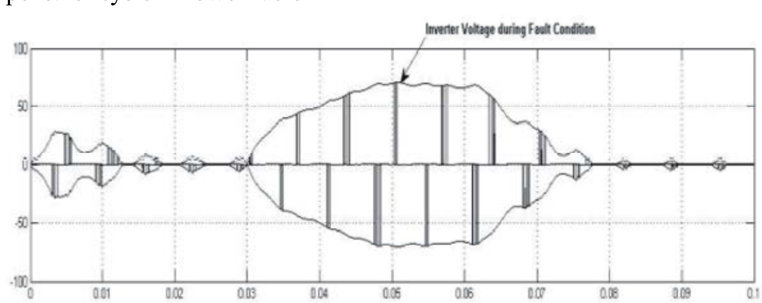

Fig. 9: Inverter injected voltage

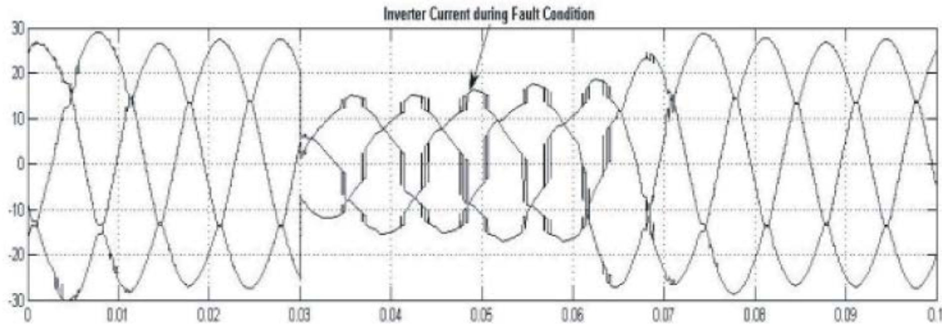

Fig. 10: Inverter current during fault condition

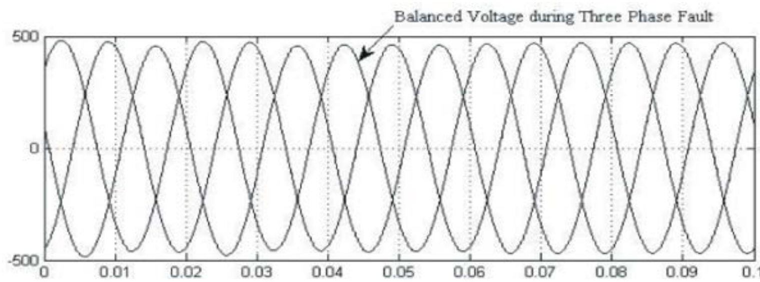

Fig. 11: Balanced source voltage

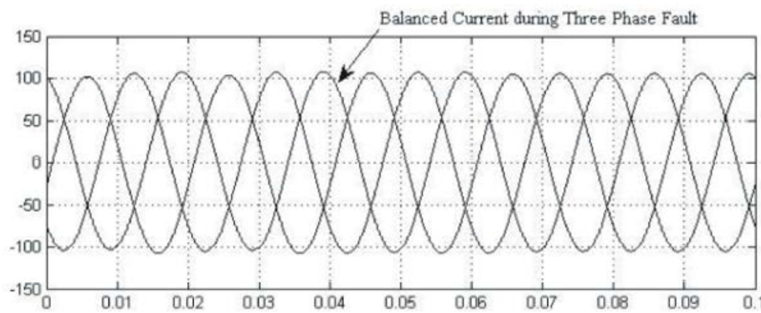

Fig. 12: Balanced Source Current

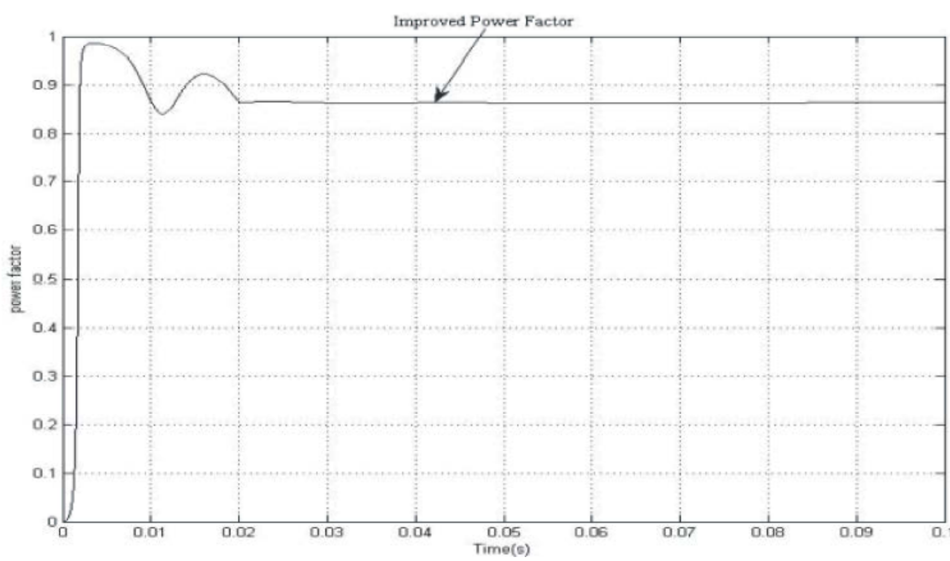

Fig. 13: Improved system power factor

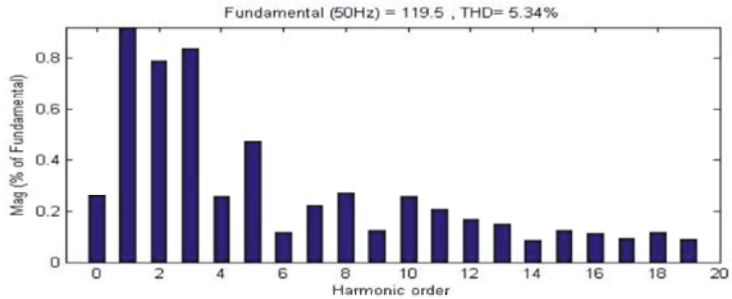

Fig. 14: Source current THD using UPQC and PID

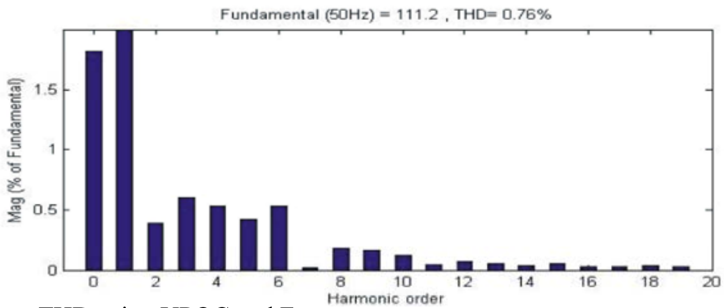

Fig. 15: Source current THD using UPQC and Fuzzy

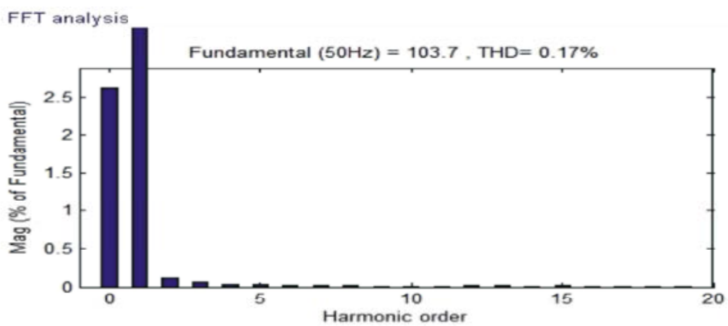

Fig. 16: Source current THD using p-q controlled FCMLI integrated UPQC

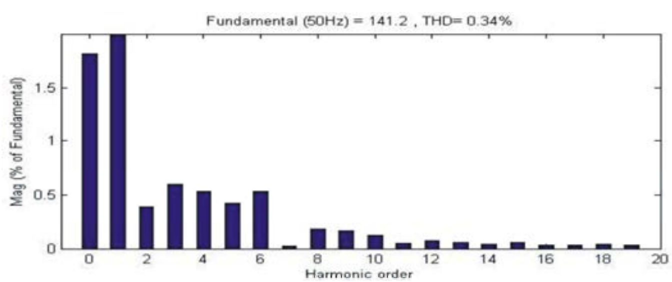

Fig. 17: Source voltage THD using UPQC and PID

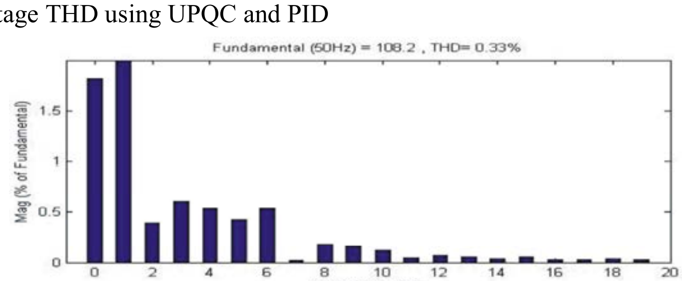

Fig. 18: Source voltage THD using UPQC and Fuzzy

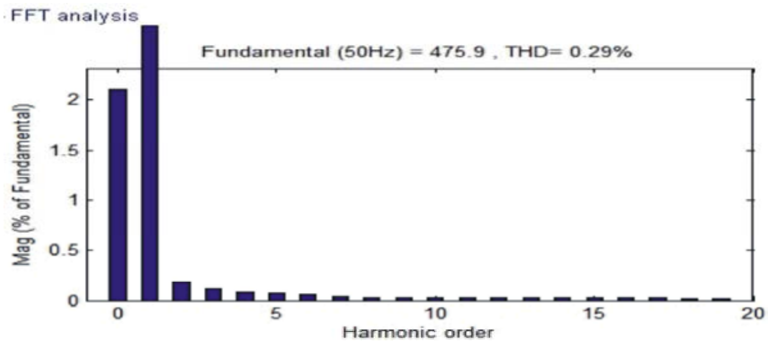

Fig. 19: Source voltage THD using p-q controlled FCMLI integrated UPQC

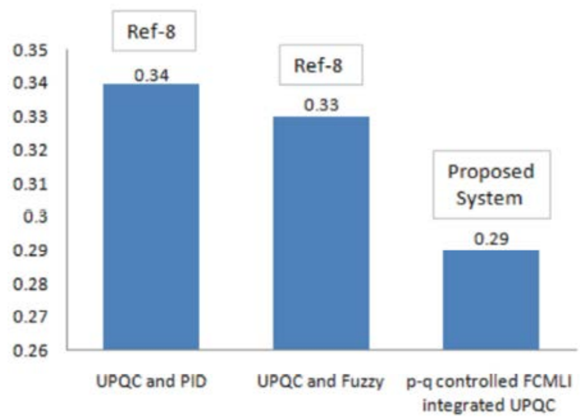

Fig. 20: THD Comparison of source voltage

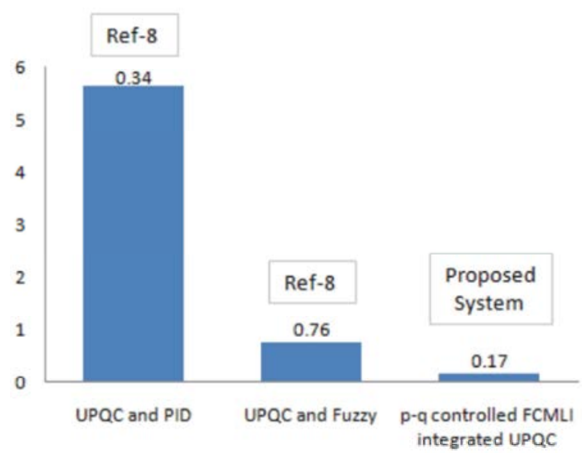

Fig. 21: THD Comparison of source current

CONCLUSION

The FCMLI integrated UPQC corrects the voltage and current fluctuations and prevents the harmonic load currents entering in to the power system. The UPQC is tested under non-linear load condition and three phase to ground fault condition, it is seen that UPQC is capable of maintaining voltage and current in permissible limit. Shunt active filters allow the compensation of current harmonics and unbalance, together with power factor correction. The flying capacitor multilevel inverter with seven-level having lower harmonics and better power factor when compared to other inverters. The proposed seven-level FCMLI integrated with UPQC provide low switching losses, reduced harmonics, improved power factor, good stability and better power quality. The proposed system absorbs almost all the power quality problems and reduced the total harmonic distortion in an efficient and simple way.

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