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# Comparative Performance of Supercapacitor and Fuel cell based UPQC

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*In this paper analysis comparative result of a supercapacitor based unified power quality conditioner comparing with a fuel cell based unified power quality conditioner. This work describes the unified power quality conditioner principles and power restoration for balanced or unbalanced voltage sag or swells in a distribution system. This method proposes a typical configuration of unified power quality conditioner that consists of a DC/DC converter supplied by a supercapacitor at the DC link. This analysis used for comparing how the THD will be improved and after injecting current and voltage to UPQC source current and source voltage are sinusoidal. This paper explains the comparative results of UPQC showing performance wise THD of supercapacitor and fuel cell, the harmonic distortion is reduced in fuel cell as compared to supercapacitor. The comparative studies analyse in both the cases fuel cell is better than supercapacitor in power quality parameters as THD and power factor etc. The result analysis shows the THD of supercapacitor and fuel cell, the harmonic distortion is quite reduced in fuel cell as compared to supercapacitor. The operation of the proposed system is modeled and simulated in MATLAB environment using Simulink and Simpower System toolboxes.*

Keywords*:* Fuel cell, power quality, supercapacitor, unified power quality conditioner.

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## 1. Introduction

The power quality problem is also due to the different faults conditions occurring on the power system network. These conditions cause voltage sag or swell in the system and malfunctioning of devices. The mitigation of these on the source and load sides is most important for improving the reliability as well as performance on the system. The Unified Power Quality Conditioner (UPQC) has a single topology that combines dynamic voltage restorer and distribution static compensator with a common DC link. These two are connected in a back to back configuration. Shunt active power filter compensates all current related distortions and series active power filter compensates all voltage related distortions. The compensation can be done effectively, if there is an effective DC link. The shunt compensator takes care of reactive power compensation, current harmonic compensation, load unbalance compensation and power factor improvement [1]. The series compensator acts for voltage harmonics, voltage sag or swells, flickering etc. with the harmonic isolation between load and supply [2]. The Supercapacitor Energy is used as a battery storage device across the DC link for short time duration.

The energy can be stored in the form of batteries, flywheels, compressed air, hydraulic systems and super conducting energy storage systems [3]. A configuration with distribution static compensator - supercapacitor energy storage system is used to enhance

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power system stability and quality [4]. Supercapacitors are also find applications in industrial drives such as traction [5], metro vehicles and hybrid electric vehicles [6]. The operation of both series active power filter and shunt active power filter are based on voltage source converter technique. The shunt active filter compensates the voltage interruption if it has the some energy storage or battery in the DC link [7]. The battery has a high storage capacity but unreliable and flywheels requires a lot of maintenance. The discharge rate is slower in batteries because of slower chemical process. As the future turned to higher rate of charging and discharging the energy which is possible with the supercapacitors. The supercapacitors stores less energy however, the power transfer capability is high compared to the conventional batteries. The rate of discharge of supercapacitor while compensation is fast and it takes only a small current for charging [3]. Use of supercapacitor is proposed in UPQC scheme as it is characterized by less weight, faster charge/discharge cycle time, higher power density, higher efficiency and almost maintenance free.

In paper [8] described the application of full bridge DC-DC converters in UPQC. Papers [9,10] and [11] concentrated only on voltage sag or swell utilizing the series inverter. UPQC can be utilized to solve power quality problems simultaneously [12,13] and [14]. The most important parameters and materials [15,16] and manufacturing process of a supercapacitor [17,18] and [19] include the capacitance(C), equivalent series resistance and equivalent parallel resistance which is also called leakage resistance [20]. Ultracapacitors having high power density can be used to complement the high energy density batteries to form an excellent hybrid energy storage system [19]. This paper suggests a new form of UPQC, DC/DC converter, fuel cell and energy storage system. A fuel cell is a device that directly converts the chemical energy of fuel to electric energy. Fuel cells are also used as power sources such as cars, trucks, buses, submarines and batteries for electronics such as laptops and smart phones as well as sources for uninterruptable power supplies. The operation of the proposed system is modeled and simulated in MATLAB environment using Simulink and Simpower System toolboxes. This paper is organized as: Section 2; describes the notations used throughout the paper, Section 3; describes the supercapacitor based UPQC, explains about schemes of series and shunt converters and supercapacitors. Section 4; deals with the description of the fuel cell based UPQC includes equivalent circuit diagram of fuel cell and principles. Section 5; presents the comparative study of UPQC based on supercapacitor and fuel cell. Section 6; presents the conclusion. Sections 7; presents the appendix.

## 2. Notation

The notations used throughout the paper listed below.

$V_L$ - Load voltage
Vs - Source voltage
$I_L$ - Load Current
Is - Source Current
$R_L$ - Load Resistance
$L_L$ - Load Inductance

$C_{dc}$ - DC Link Capacitance
$V_{dc}$ - DC Link Voltage
$R_s$ - Source Resistance
$L_s$ - Source Inductance
$L_{sh}$ - Shunt Inductance
Lse - Series Inductance
$i_f$ - Leakage current (A)
Vinj - Injected Voltage
Iinj- Injected Current
Iref - Reference Current
Vin - input voltage
Vcs - Voltage across stack capacitance
Vcr - Voltage across reformer capacitance
Rst - Stack resistance
Rrf -Reformer Resistance
$\tau r$ - Reformer time constant
$\tau s$ - stack time constant
THD - third harmonic distortion
Ubank_min - Minimum voltage across the bank
Ubank_max - Maximum voltage across the bank
Ns - No. of series supercapacitors required
Np - No. of parallel supercapacitors required
$\alpha$ - Charge transfer coefficient, Tafel equation (0<alpha<1)
$\Delta V$ - Over potential

## 3. Supercapacitor based UPQC

The block diagram representation for the proposed system is shown in Fig.1 Single phase UPQC connected to a power system feeding a combination of linear and non-linear loads. It consists of a two leg voltage controlled voltage source inverter used as a series active power filter and a two leg current controlled voltage source inverter used as a shunt active power filter. The DC link of both of these active filters is connected to a common DC link capacitor. Also capable of suppressing the harmonics in the source currents, load balancing and power factor correction. The series filter is connected between the supply and load terminals using a single phase transformer. The main aim of the series active power filter is to obtain harmonic isolation between the load and supply.

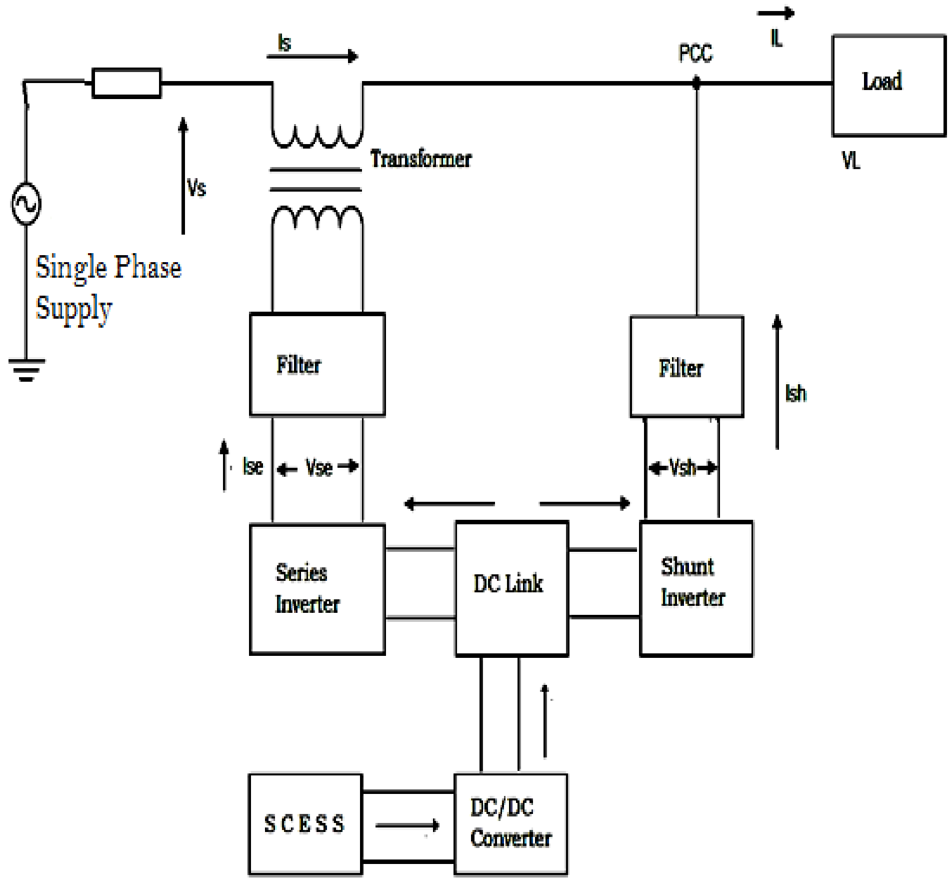



Fig.1 Block Diagram of the Proposed System

The voltage source inverters for both the series and shunt active power filters are implemented with IGBTs. The supercapacitor bank consists of number of series and parallel capacitors to increase the current as well as voltage at the DC link and the DC/DC converter is used to maintain constant voltage at the DC link irrespective of the voltage at the supercapacitor bank. It boosts the voltage level when sag appears in the line and consumes energy when there is a swell in the line. The voltage sag or swell can be effectively compensated using a dynamic voltage restorer, series active filter, UPQC, etc. The performance of a single-phase unified power quality conditioner is evaluated for the mitigation of customer-generated harmonics, total current harmonics, reactive power, voltage harmonics, and their combinations, depending on the requirements [21]. The series active power filter takes care about voltage related issues [22]. The shunt active power filter is used to absorb current harmonics to compensate for reactive power and to regulate the DC link voltage between both active power filters. The unified power quality conditioner has the capability of voltage imbalance compensation as well as voltage regulation and harmonic compensation at the consumer end [23, 24] and [25-26]. In this paper, the proposed synchronous reference frame based control method for the UPQC system with a DC/DC converter to control voltage at the supercapacitor end is used and the system performance is improved. In the proposed control method, load voltage, source voltage, source current are measured, evaluated also tested under unbalanced and distorted load conditions using MATLAB/Simulink software. The values of the circuit parameters and the loads under consideration in such a way that to compensate the problem are given in the appendix [27].

3.1. Control Scheme for Series Converter

The role of the proposed series converter is to eliminate harmonics and to provide reactive power requirement of the load so that ac source feeds only active component of unity power factor current. Since this series converter is connected in series with load, it improves the system efficiency. The proposed control strategy works by sensing the load voltage and compared with the reference voltage. Then the error is supplied to the controller for switching the inverter and to supply the required voltage by the series active power filter, thus making the voltage at point of common coupling a pure sinusoidal with a desired amplitude. Therefore, the sum of the supply voltage and the injected series voltage makes the desired load voltage. Fig.2 shows the block diagram of control scheme for the series active power filter system [22]. DC bus voltage, supply voltage and current are sensed to generate pulses for the series converter. AC source supplies fundamental active power of load current and a fundamental current to maintain the dc bus voltage to a constant value. The sensed dc bus voltage of the active power filter along with its reference value is processed in the proportional integral voltage control. The output of the proportional integral controller is taken as peak of source current. A unit vector in phase with the source voltage is derived using its sensed value. The peak source current is multiplied with the unit vector to generate a reference sinusoidal unity power factor source current. The reference source current and sensed source current are processed in hysteresis current controller to derive gate signals for the switches of the active power filter.

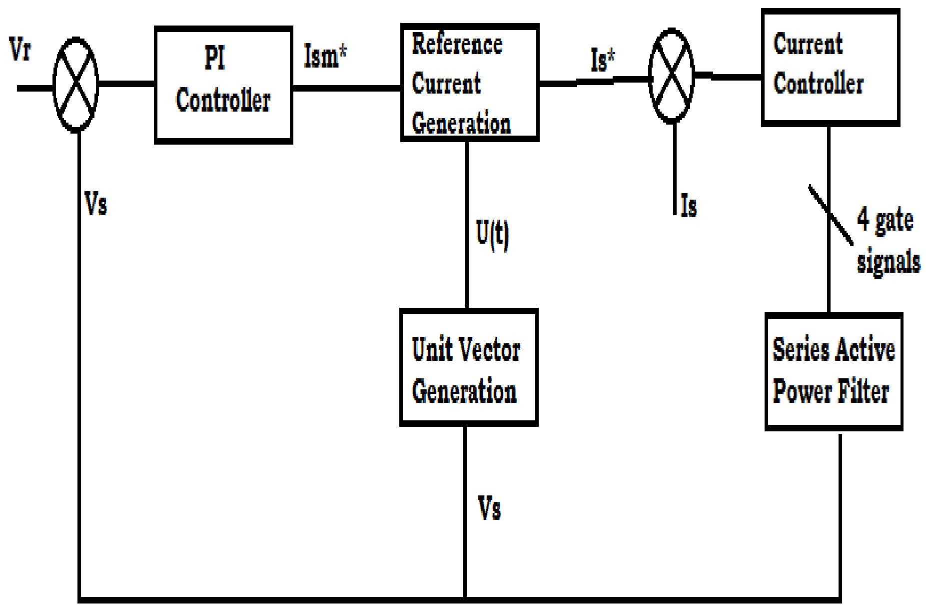



Fig.2 Control Scheme for Series Active Power Filter [22].

In response to these gate pulses, the active power filter impresses a pulse width modulation voltage to flow a current through filter inductor to meet the harmonic and reactive components of the load currents.

a. Control Scheme for Shunt Converter

The shunt active filter is a current controlled voltage source inverter, which is connected in parallel with the load. Hence, the utility needs to supply only the active part of the fundamental component of the load current. Control algorithm computes the reference for the compensation current to be injected by the shunt active filter. In the proposed control algorithm the sensed currents are compared with the reference currents in a hysteresis current controller to generate switching pulses for the shunt active power filter. The choice of the control algorithm therefore decides the accuracy and response time of the filter. The control strategy has an objective to guarantee balanced and sinusoidal source current at unity power factor. The hysteresis current control scheme decides the switching pattern of active filter in such a way to maintain the actual injected current of the filter to remain within a desired hysteresis band.

The switching logic is formulated as follows:

If $i_{inj}$< (iref – HB) S1, S2 ON & S3, S4 OFF

If $i_{inj}$> (iref + HB) S1, S2 OFF & S3, S4 ON

The switching frequency of the hysteresis current control method described above depends on how fast the current changes from upper limit to lower limit of the hysteresis band, or vice versa. Therefore the switching frequency does not remain constant throughout the switching operation, but varies along with the current waveform. Furthermore, the filter inductance value of the active filter is the main parameter determining the rate of change of active filter current.

3.2. Supercapacitor Energy Storage Systems

Usually supercapacitors are divided into two types: double-layer capacitors and electrochemical capacitors. Its capacitance is proportional to the specific surface areas of electrode material. The capacitors can work at high voltage without connecting many cells in series. The size of supercapacitor is determined from the size of load connected and the duration of voltage interruption. Therefore, total energy to be released during the voltage interruption is 30kJ. The maximum current flows through the supercapacitor bank, when it discharges the maximum power. The minimum voltage across the supercapacitor bank can be determined with the maximum discharge power and the current rating as the following [28].

$$\text{Ubank\_min} = \frac{20\ kw}{360\ A} = 55.5\text{V} \tag{1}$$

The lowest discharged voltage is determined to be 2.1V using the following [28].

$$\text{Uunit\_min} = \sqrt{\frac{3}{4}}\,\text{Uunit\_max} = 2.1\text{V} \tag{2}$$

Therefore, the lowest discharge voltage and the minimum unit voltage determine the number of units to be connected in series as the following [28].

$$Ns = \frac{Ubank\_min}{Uunit\_min} = \frac{55.5}{2.1} = 26.5 \qquad (3)$$

By using (2) and (3), bank design calculation can be determined as 28 units of supercapacitors.

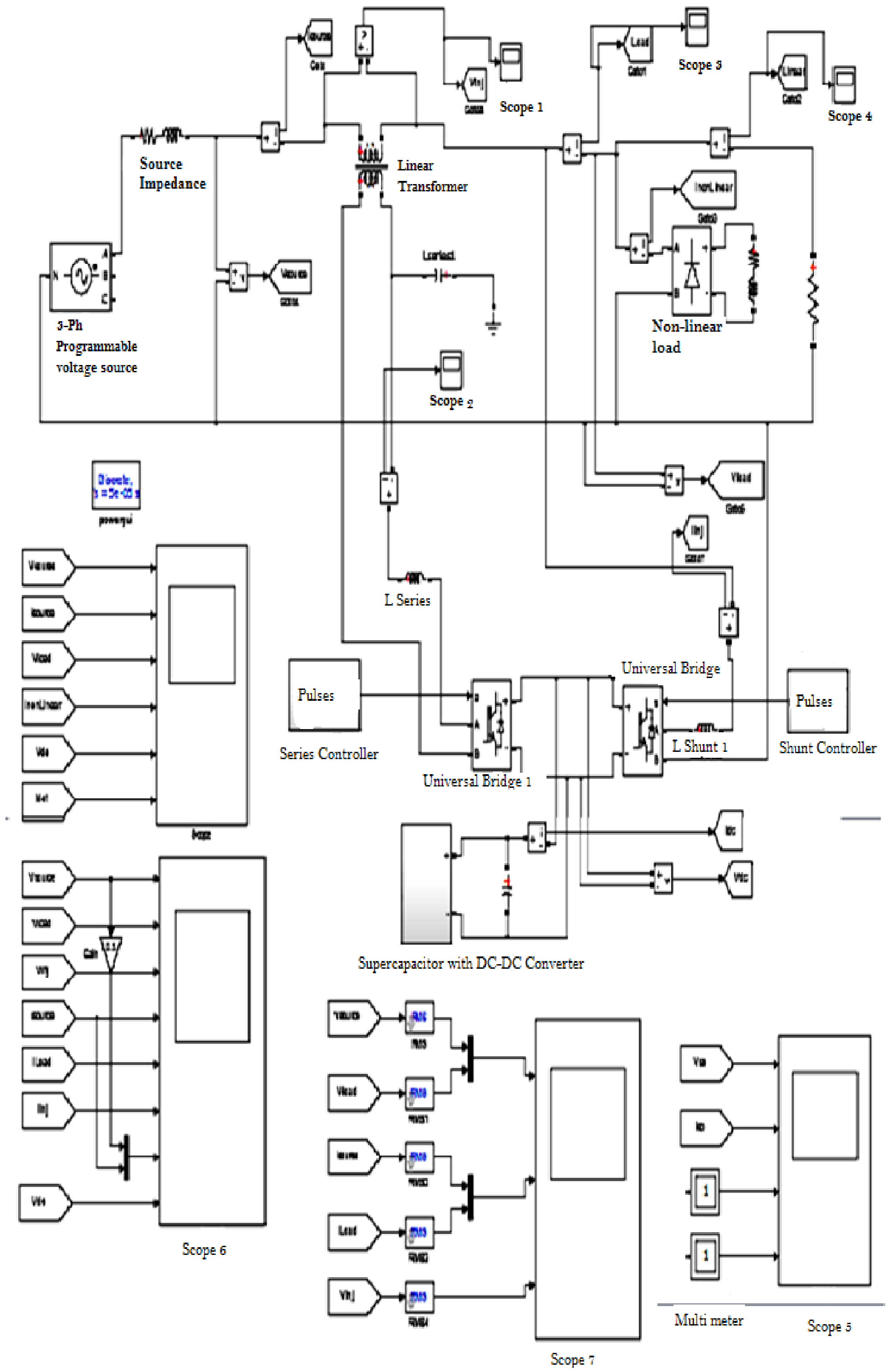



Fig.3.Simulink Block Diagram for the Proposed System using supercapacitor.

### 3.3. DC-DC Converter

The proposed DC/DC converter can operate in bi-directional mode. The operation voltage of the supercapacitor bank is in the range between 60-75V, while the DC link voltage is about 700V. The converter should have high current rating at the bank side and high voltage rating at the DC link side. The DC/DC converter boosts the supercapacitor voltage up to the nominal DC link voltage in discharge mode. The supercapacitor voltage is controlled between 60-75V, while the DC link voltage increases up to 700V.

## 4. **Fuel Cell based UPQC**

The fuel cell generation system which is considered of a reformer and a stack that generates electricity using electrochemical reaction.

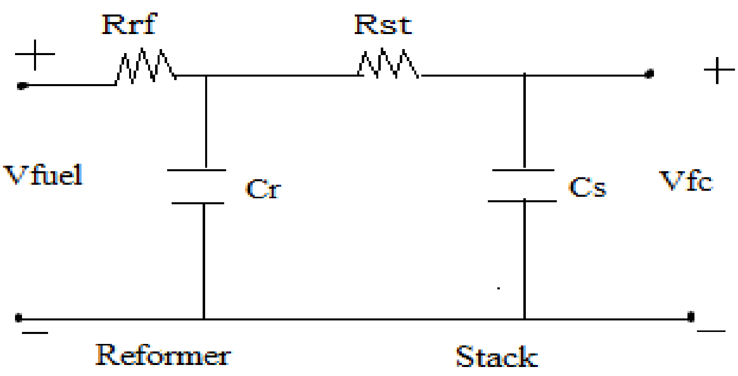



Fig.4 Equivalent circuit of a Fuel Cell System [28]

Fig.4 shows equivalent circuit of a fuel cell system [28]. It contains reformer and stack, the reformer produces usually hydrogen from fuels and then supplies it to the stacks. The stacks generate DC electric power by electrochemical reaction of hydrogen and oxygen which is in the air [29], [30-31]. The reformer is represented as a first order time delay circuit which has relatively long time constant for an electrical equivalent circuit. The stack is a collection of unit cells and the unit cells consist of electrolyte, separators and plates. Fuel cell output is the result of a chemical reaction and possesses nonlinear characteristics. The mathematical model [32] of the reformer and- stack are represented by equations (4) and (5).
The stack is also represented as a first order time delay circuit which has a relatively short time constant. The mathematical model of the reformer and stack are represented as

$$\frac{Vcr}{Vin} = \frac{\frac{1}{CrS}}{Rr + \frac{1}{CrS}} = \frac{1}{1 + RrCrS} = \frac{1}{1 + \tau rS} \tag{4}$$

$$\frac{Vcs}{Vcr} = \frac{\frac{1}{CsS}}{Rr + \frac{1}{CsS}} = \frac{1}{1 + RsCsS} = \frac{1}{1 + \tau sS} \tag{5}$$

Where $\tau r$ = RrCr is the time constant of the reformer
$\tau s$ = RsCs is the time constant of the stack, In general $\tau r > \tau s$ .

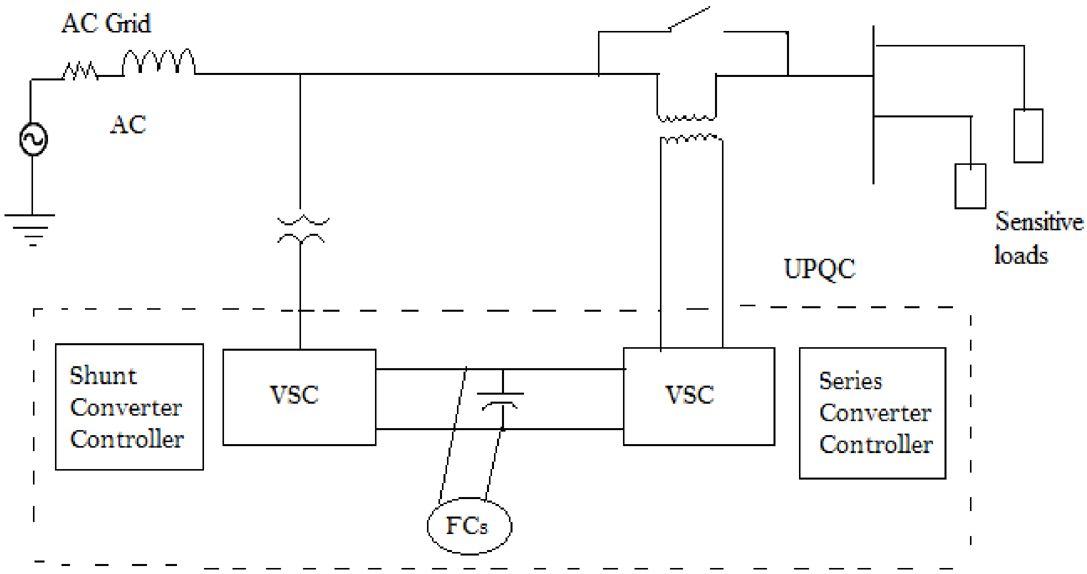



Fig.5 Combined operation of UPQC and Fuel Cell [32]

Fig.5 shows the operation of UPQC and Fuel Cell combinedly [32], normally UPQC has two voltage-source inverters in three-phase four-wire or three-phase three-wire configuration. One inverter called the series inverter is connected through transformers between the source and the common connection point. The other inverter called the shunt inverter is connected in parallel with the common connection point through transformers.
The series inverter operates as a voltage source, while the shunt inverter operates as a current source. UPQC has compensation capabilities for the harmonic current, reactive power compensation, voltage disturbances, and the power-flow control.
Fig.6 shows the waveforms of Vinj,Inj before injecting [31].

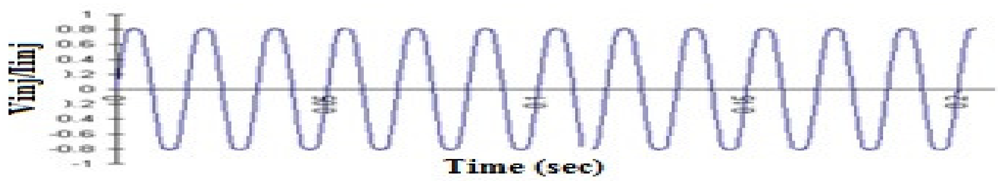
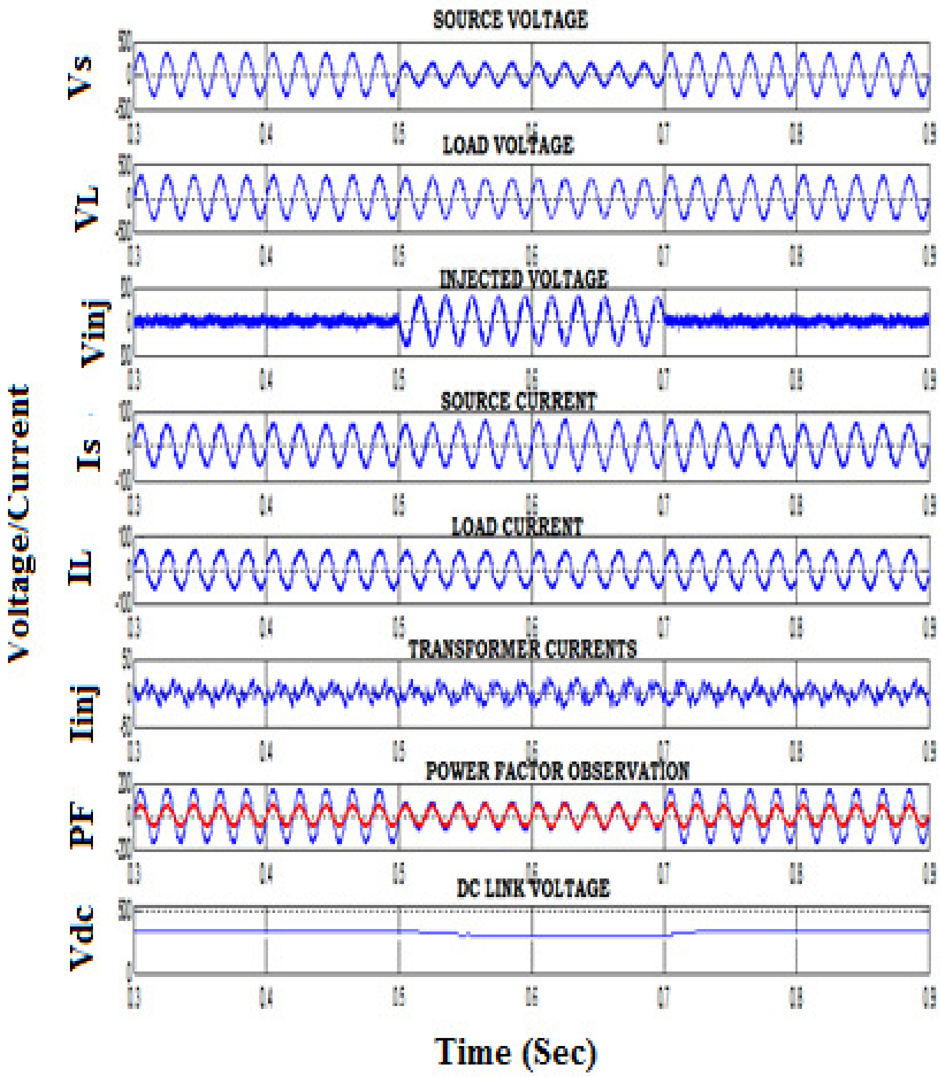
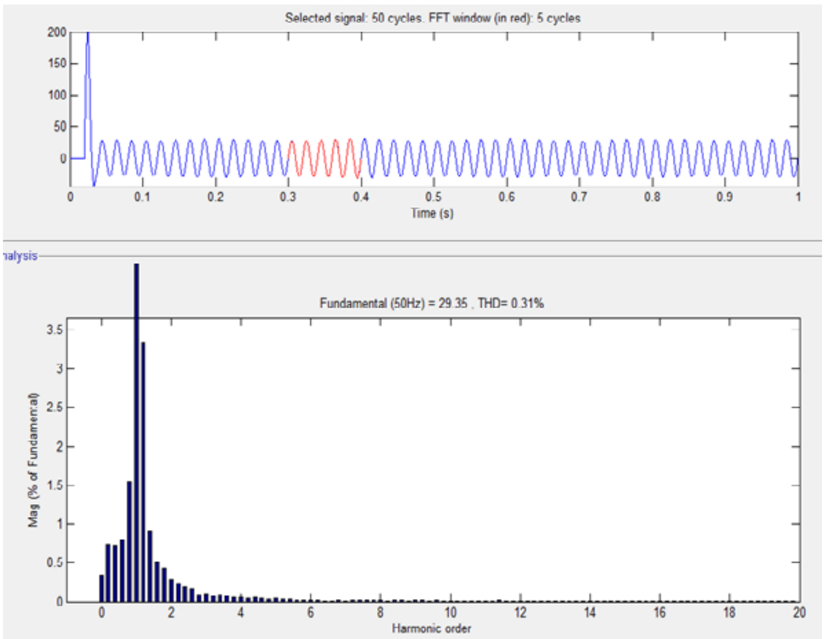



Fig.6 before injecting

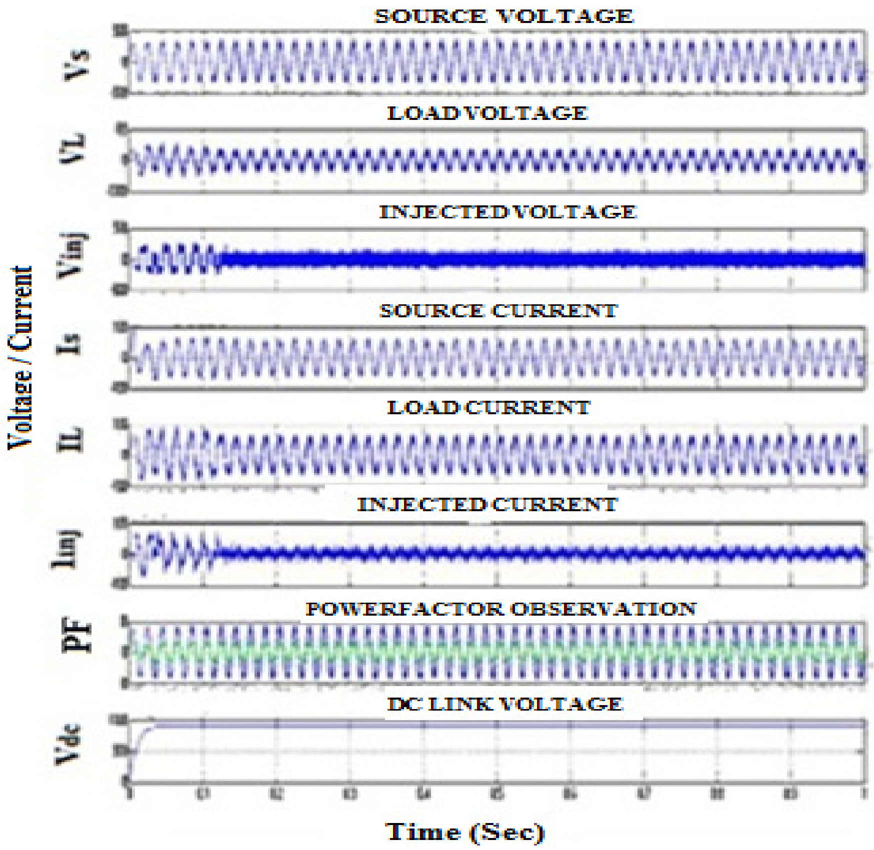
## 5. Comparative Study of Supercapacitor and Fuel cell based UPQC.

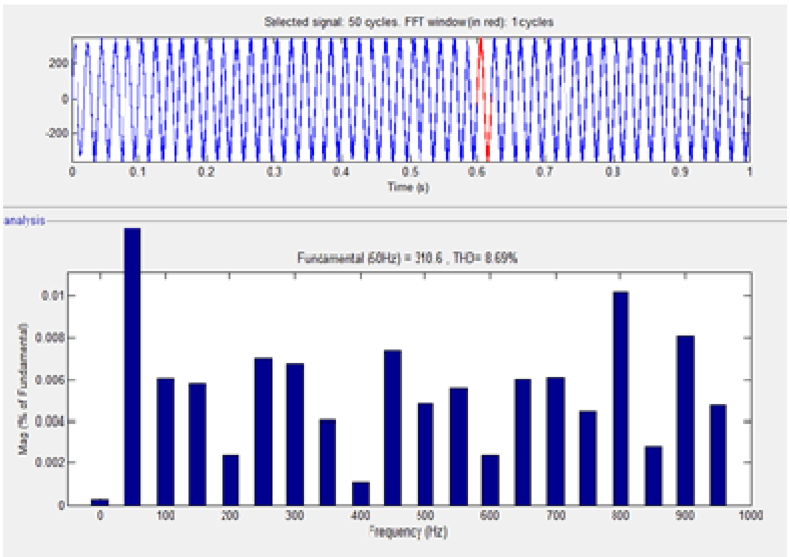



FFT ANALYSIS

Fig.7 With supercapacitor




FFT ANALYSIS

Fig.8 With fuel cell

Fig.7 shows the waveforms of various parameters of supercapacitor based UPQC and Fig.8 shows the waveforms of various parameters of fuel cell based UPQC. These waveforms shows source voltage (Vs), load voltage (VL), source current (Is), load current (IL), injected voltage (Vinj), injected current (Iinj), injected voltage (Vinj) and DC voltage (Vdc). After injecting current and voltage to UPQC source current and source voltage are sinusoidal. Fig.7 and Fig.8 shows harmonic spectra and total harmonic distortion on source side which is of 0.31%. The FFT analysis shows the THD of supercapacitor and fuel cell, the harmonic distortion is quite reduced in fuel cell as compared to supercapacitor as shown in FFT analysis, as the number of cycles depends upon the cycles comparing with fuel cell less in supercapacitor. The source current (Is) becomes sinusoidal and in phase with the source voltage (Vs). The THD of the source current has been improved comparing with supercapacitor to 0.09%. The DC link voltage of the back to back connected VSI is maintained to the reference value. TABLE I explains the analysis comparative results of a UPQC with supercapacitor and fuel cell.

TABLE I: PERFORMANCE OF UPQC WITH SUPERCAPACITOR AND FUEL CELL

| Control Method | Parameter | Magnitude Voltage & Current per phase (Vrms & Irms) | %THD |
|---|---|---|---|
| **UPQC With Supercapacitor** | Source Voltage (V) ($V_{Sabc\_rms}$) | 220V | 2.51% |
| | Load Voltage (V) ($V_{Labc\_rms}$) | 219.23 V | 0.58% |
| | Source Current (A) ($i_{Sabc\_rms}$) | 12.13 A | 3.10% |
| | Load Current (A) ($i_{Labc\_rms}$) | 12.31 A | 29.35% |
| | | | |
| **UPQC with Fuel Cell** | Source Voltage (V) ($V_{Sabc\_rms}$) | 220V | 1.05% |
| | Load Voltage (V) ($V_{Labc\_rms}$) | 219.23 V | 0.31% |
| | Source Current (A) ( $i_{Sabc\_rms}$) | 12.13 A | 1.66% |
| | Load Current (A) ( $i_{Labc\_rms}$) | 12.31 A | 21.15% |

## 6. Conclusion

The paper describes the analysis comparative results of a supercapacitor based unified power quality conditioner comparing with a fuel cell based unified power quality conditioner. Out of the custom power devices UPQC is the most effective device for mitigating the power quality problems. The performance of the proposed system consists of a DC/DC converter, supercapacitors and a fuel cell connected through DC line. The proposed system can compensated voltage sag and swells with improved power factor, voltage interruption and harmonics. The proposed UPQC has the ultimate capability of improving the power quality at the installation point in the distribution system.

## 7. Appendix

The operation of the system was demonstrated through simulation with MATLAB/SIMULINK software byusing the circuit parameters and the loads under consideration as follows:
Vs = 230V, f = 50Hz, Rl = 10, Ll = 25mH, Cdc = 4700uF, Vdc = 700V, Rs = 0.01, Ls = 50uH, Lsh = 8mH, Lse = 2.5mH.
Super Capacitor Ratings: Crated = 1000F, Rse = 2.1mohms, Vrated = 65V, Surge Voltage = 75V, N = 28, Np = 1, Initial Voltage = 60V, (if) leakage Current = 5.2mA, Temperature = 25 C.

Stern-Tafel Parameters:
N = 6, $r = 1.23*10^{-9}$, $\Delta V = 0.3V$, $\alpha = 0.3$, Charge Current=100A.

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