# Unified Power Quality Conditioner (UPQC) During Voltage Sag and Swell

*Sudharshan Rao Gandimeni and Vijay Kumar K.*

**ABSTRACT: This paper deals with conceptual study of unified power quality conditioner (UPQC) during voltage sag and swell on the power distribution network and researches profoundly on the coordinated control of UPQC (Unified Power Quality Conditioner). By analyzing the radical reasons of coupling effect between UPQC series unit and shunt unit, a simple and practical coordinated control strategy for UPQC series unit and shunt unit is proposed. Therefore, the complex degree of the whole UPQC control system is simplified greatly. The coordinated control between UPQC series unit and shunt unit is implemented by the proposed strategy. Finally, the unified power quality multi-function control of UPQC is achieved. Based on injected voltage phase angle with respect to the utility or PCC voltage phase angle, thus the UPQC can work in zero active power consumption mode, active power absorption mode and active power delivering mode. The series active power filter (APF) part of UPQC works in active power delivering mode and absorption mode during voltage sag and swell condition, respectively. The shunt APF part of UPQC during these conditions helps series APF by maintaining dc link voltage at constant level. This paper introduces a new concept of optimal utilization of a UPQC. The series inverter of UPQC is controlled to perform simultaneous 1) voltage sag/swell compensation and 2) load reactive power sharing with the shunt inverter. The active power control approach is used to compensate voltage sag/swell and is integrated with theory of power angle control (PAC) of UPQC to coordinate the load reactive power between the two inverters. The MATLAB / SIMULINK results are provided in order to verify the analysis. The author presents results with balanced, unbalanced and nonlinear loads at load bus.**

***Keywords : UPQC, Power Quality, Distribution System, Sag, Swell and APF.***

## 1. INTRODUCTION

With the increase in the complexion of the power distribution system and the loads, it is very possible that several kinds of power quality disturbances are in a distribution system or a power load simultaneously, and it is therefore important to introduce UPQC (Unified Power Quality Conditioner). UPQC is the emerging device of Custom Power, which combines the functions of series voltage compensator, shunts current compensator and energy storage device. Multiple power quality regulation functions are implemented in UPQC simultaneously, with a higher performance ratio.

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In [1-9], several control methods have been applied in UPQC. Fig.1 shows a typical main circuit topological structure of UPQC, the inner department of imagined line is UPQC, which is composed by series unit and shunt unit as well as DC storage unit. The series unit has the functions of DVR (Dynamic Voltage Restorer) and DUPS (Dynamic Uninterruptible Power Supply), while the shunt unit has the functions of SVG (Static Var Generator) and APF (Active Power Filter), and the energy storage unit has the functions of BESS (Battery Energy Storage System) or super capacitor energy storage system.

One of the serious problems in electrical systems is the increasing number of electronic components of devices that are used by industry as well as residences. These devices, which need high-quality energy to work properly, at the same time, are the most responsible ones for injections of harmonics in the distribution system. Therefore, devices that soften this drawback have been developed. One of them is the UPQC, It consists of a shunt active filter together with a series-active filter. This combination allows a simultaneous compensation of the load currents and the supply voltages, so that compensated current drawn from the network and the compensated supply voltage delivered to the load are sinusoidal, balanced and minimized. The series- and shunt-active filters are connected in a back-to-back configuration, in which the shunt converter is responsible for regulating the common DC-link voltage.

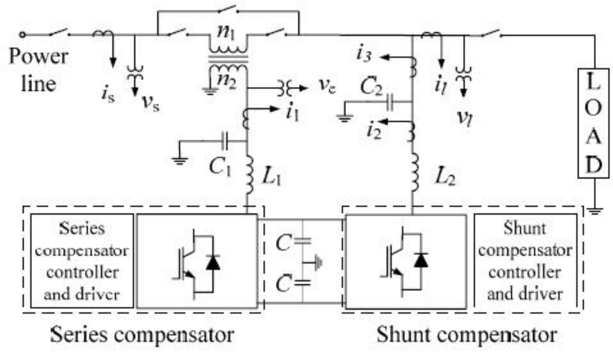



Fig.1 Circuit configuration of the proposed UPQC

The UPQC is one of the major custom power solutions, which is capable of mitigating the effect of supply voltage sag at the load end or at the point of common coupling (PCC) in a distributed network. It also prevents the propagation of the load current harmonics to the utility and improves the input power factor of the load. The control of series compensator (SERC) of the UPQC is such that it injects voltage in quadrature advance to the supply current. Thus, the SERC consumes no active power at steady state. The other advantage of the proposed control scheme is that the SERC can share the lagging VAR demand of the load with the shunt compensator (SHUC) and can ease its loading. The UPQC employing this type of quadrature voltage injection in series is termed as UPQC-Q. The VA requirement issues of SERC and SHUCs of a UPQC-Q are discussed. A PC-based new hybrid control has been proposed and the performance of the UPQC-Q.

The UPQC is a versatile device which could function as series active filter and shunt active filter. UPQC can simultaneously fulfill different objectives like, maintaining a balanced sinusoidal (harmonic free) nominal voltage at the load bus, eliminating harmonics in the source currents, load balancing and power factor correction. Keeping the cost effectiveness of UPQC, it is desirable to have a minimum VA loading of the UPQC, for a given system without compromising compensation capability. For UPQC, its series compensator and parallel compensator can be regarded as two dc voltage inverter. Therefore, maintaining a constant value for dc voltage is necessary for UPQC to performance normally. The constant dc voltage is related to the power balance between UPQC and sources, namely when the input active power of UPQC is equivalent to its consumption theoretically. So the controlling of dc voltage involves in the active current of sources. If the input signal of the controller is the error of dc voltage, its output signal should be the active current of sources. Under this circumstance, to get a mathematical model of its closed loop controller, finding the dc voltages expressed as a function of the active current of sources is critical. This paper proposed a method of design the dc voltage controller by using the small signal model of UPQC, with which mathematical relationship between dc voltages and the active current of sources is deduced. Based on that the mathematical model of closed loop of dc voltage is promoted. Parameters of the controller is calculated with it. A example is proposed in the last. The experiment results show that the dc control system has good stability margin and close-loop bandwidth, which verified the effectively.

UPQC is a series-parallel element in the Flexible AC Transmission System (FACTS) family. In this paper, a UPQC with cascaded multilevel inverter is proposed. Voltage sag, unbalance and load power factor in distribution system is mitigated using proposed multilevel UPQC. There is no need of using transformer and filter when multilevel UPQC is applied and it is one of its advantages. SPWM (Sinusoidal Natural Pulse Width Modulation) scheme is used for pulse generation to control multilevel inverters. The results showed the effectiveness of the proposed method. For UPQC, its series compensator and parallel compensator can be regarded as two dc voltage inverter. Therefore, maintaining a constant value for dc voltage is necessary for UPQC to performance normally. The constant dc voltage is related to the power balance between UPQC and sources, namely when the input active power of UPQC is equivalent to its consumption theoretically. So the controlling of dc voltage involves in the active current of sources. If the input signal of the controller is the error of dc voltage, its output signal should be the active current of sources. Under this circumstance, to get a mathematical model of its closed loop controller, finding the dc voltages expressed as a function of the active current of sources is critical. This paper proposed a method of design the dc voltage controller by using the small signal model of UPQC, with which mathematical relationship between dc voltages and the active current of sources is deduced. Based on that the mathematical model of closed loop of dc voltage is promoted. Parameters of the controller is calculated with it. A example is proposed in the last. The simulation results show that the dc control system has good stability margin and close-loop bandwidth, which verified the effectivity.

In this paper, a new methodology is proposed to mitigate the unbalanced voltage sag with phase jumps by UPQC. UPQC is used to mitigate both voltage and current power quality (PQ) problems. During the process of mitigation, UPQC is supposed to inject real and reactive power into the system to mitigate current (shunt) and voltage (series) power quality (PQ) problems. As per the sensitive load concerns, deep and long duration sags are more vulnerable than shallow and short duration sags. To resolve these issues a new methodology is proposed with optimal Volt-Ampere (VA) loading on UPQC to mitigate deep and long duration unbalanced sag with phase jumps. The proposed method has been validated through detailed simulation studies.

This paper presents a new synchronous-reference frame (SRF)-based control method to compensate PQ problems through a three-phase four-wire UPQC under unbalanced and distorted load conditions. The proposed UPQC system can improve the power quality at the point of common coupling on power distribution systems under unbalanced and distorted load conditions. The simulation results based on Matlab/Simulink are discussed in detail to support the SRF-based control method presented in this paper. The proposed approach is also validated through experimental study with the UPQC hardware prototype.

The unified power quality conditioner is a power conditioning device, which is a integration of back to back connected shunt active power filter (APF) and series APF to a common DC link voltage. For improvement of power quality (PQ) problems in a three-phase four-wire distribution system, two topologies are proposed in this paper. A comparative analysis of these topologies along with the most common four-leg voltage source inverter (VSI) based topology of four-wire UPQC is discussed in this work. The performance of each topology of UPQC is evaluated for different PQ problems like power-factor correction, load balancing, current harmonic mitigation, voltage harmonic mitigation and source neutral current mitigation. The synchronous reference frame (SRF) theory is used as a control strategy of series and shunt APFs. The UPQC is used to mitigate the current and voltage-related power-quality (PQ) problems simultaneously in power distribution systems. Among all of the PQ problems, voltage sag is a crucial problem in distribution systems. In this paper, a new methodology is proposed to mitigate the unbalanced voltage sag with phase jumps by UPQC with minimum real power injection. To obtain the minimum real power injection by UPQC, an objective function is derived along with practical constraints, such as the injected voltage limit on the series active filter, phase jump mitigation, and angle of voltage injection. Particle swarm optimization (PSO) has been used to find the solution of the objective function derived for minimizing real power injection of UPQC along with the constraints. Adaptive neuro-fuzzy inference systems have been used to make the proposed methodology online for minimum real power injection with UPQC by using the PSO-based data for different voltage sag conditions. The proposed method has been validated through detailed simulation and experimental studies.

This paper presents a comprehensive review on the UPQC to enhance the electric power quality at distribution levels. This is intended to present a broad overview on the different possible UPQC system configurations for single-phase (two-wire) and three-phase (three-wire and four-wire) networks, different compensation approaches and recent developments in the field. It is noticed that several researchers have used different names for the UPQC based on the unique function, task, application or topology under consideration. Therefore, an acronymic list is developed and presented to highlight the distinguishing feature offered by a particular UPQC. In all 12 acronyms are listed, namely, UPQCD, UPQC-DG, UPQC-I, UPQC-L, UPQC-MC, UPQC-MD, UPQC-ML, UPQC-P, UPQC-Q, UPQC-R, UPQC-S and UPQCVAmin. More than 150 papers on the topic are rigorously studied and meticulously classified to form these acronyms and are discussed in the paper.

UPQC series unit and shunt unit cannot only operate independently to realize their own functions, but also be unified to realize their synthetic functions. To control the UPQC series unit and shunt unit as a whole, it is necessary to solve its coordinated control to make full use of its great synthetic functions. In view of this, a coordinated control strategy of UPQC series unit and shunt unit is proposed, and its validity is testified. In addition, the controller design of UPQC series unit and shunt unit is based on H∞ model matching technology about power quality waveform tracking compensation, which has been stated in detail in [10]. Besides, other control methods such as deadbeat control also can be applied into the proposed coordinated control strategy to design the synthetic controller of UPQC.

The configuration of UPQC series unit and shunt unit in distribution system is shown in Fig.1, the series unit operated as the controlled voltage source uDVR and the shunt unit as the controlled current source iAPF. UPQC series unit and shunt unit are unified, and then, there are interactions due to the two kinds of coupling between series unit and shunt unit in the main circuit:

- The interaction between the output voltage compensation of the series unit and the output current compensation of the shunt unit due to their electric connection with the outer distributed line.
- The interaction between their inverters due to their sharing with the inner DC capacitor of energy storage unit.

The coupling interaction between the series unit and the shunt unit increases the complexion of UPQC unified coordinated control. How to solve this problem? An effective method is introduced to control the coupling effect between series unit and shunt unit, which can make the UPQC function unified and diversity, moreover make the control manner simple and independent with each of the units. The control method that can handle the coupling effect between UPQC series unit and shunt unit is addressed next.

The UPQC, an integration of shunt and series APF is one of the most suitable as well as effective device in this concern [8- 12]. A UPQC tackles both current as well as voltage related power quality problems simultaneously. Recently more attention is being paid on mitigation of voltage sags and swells using UPQC [8-12]. The common cause of voltage sag and swell is sudden change of line current flowing through the source impedance. This paper is based on the steady state analysis of UPQC during different operating conditions. The purpose is to maintain sinusoidal source current with unity power factor operation along with load bus voltage regulation. The major concern is the flow of active and reactive power during these conditions, which decide to amount of current flowing through the active filters and through the supply. This analysis can be useful for selection of device ratings.

The use of nonlinear and impact loads bring about harmonics and reactive power loading variance in power system, which has a strong impact on the other loads in the same system. Employment of UPQC (unified power quality conditioner) could decrease impact on transmission and distribution harmonics and neutral-line current caused by unbalance and nonlinear load, enhance custom power quality meanwhile supply balance and sinusoidal voltage to load and enhance power distribution reliability [1]-[3] Fig.1 shows the circuit configuration of the proposed UPQC, which is a three-phase four-wire UPQC, being formed of series compensator and shunt compensator. Usually there are two control scheme of UPQC, one is most used ,known as indirect control strategy, in which series compensator work by way of voltage source compensating mainly voltage distortion and fundamental wave deviation supplying rated balance sinusoidal voltage for load and shunt compensator as current source compensating the harmonics, reactive current in load. The other is direct control strategy in which series compensator work as sinusoidal current source shunt compensator as sinusoidal voltage source. The power factor of power line can be unity because of series compensation current having the same phase with system voltage and the load can get balance, rated sinusoidal voltage. Employing this strategy, series compensator isolate the voltage disturbance between power line and load as well as shunt compensator prevent the reactive power, harmonic and neutral current on the load side into power line .Additionally, another benefit from the direct control strategy is that it is not necessary to change the work mode when power line dumping or restoring, for shunt compensator all along is controlled as sinusoidal voltage source .[4]- [8].

This paper presents a method of detecting compensation signals and a control scheme based on it. Because the p-q-r transformation is sophisticated, this paper presents a improved p-q-r algorithm, which simplify the calculations. Based on the improved p-q-r theory, the calculating method of compensating current and voltage are proposed. With introducing its principle and control schematic diagram in detail, a composite control strategy combining of the ordinary direct and indirect control strategy is presented, too. Simulation results using MATLAB/ SIMULINK show that the harmonic current and reactive power of load as well as neutral current are compensated well .So the proposed strategy is feasible and effective.

## 2. STEADY - STATE POWER FLOW ANALYSIS:

The powers due to harmonics quantities are negligible as compared to the power at fundamental component, therefore, the harmonic power is neglected and the steady state operating analysis is done on the basis of fundamental frequency component only. The UPQC is controlled in such a way that the voltage at load bus is always sinusoidal and at desired magnitude. Therefore the voltage injected by series APF must be equal to the difference between the supply voltage and the ideal load voltage. Thus the series APF acts as controlled voltage source. The function of shunt APF is to maintain the dc link voltage at constant level. In addition to this the shunt APF provides the var required by the load, such that the input power factor will be unity and only fundamental active power will be supplied by the source. The voltage injected by series APF can vary from $0^0$ to $360^0$. Depending on the voltage injected by series APF, there can be a phase angle difference between the load voltage and the source voltage. However, in changing the voltage phase angle of series APF, the amplitude of voltage injected can increase, thus increasing the required kVA rating of series APF [7].

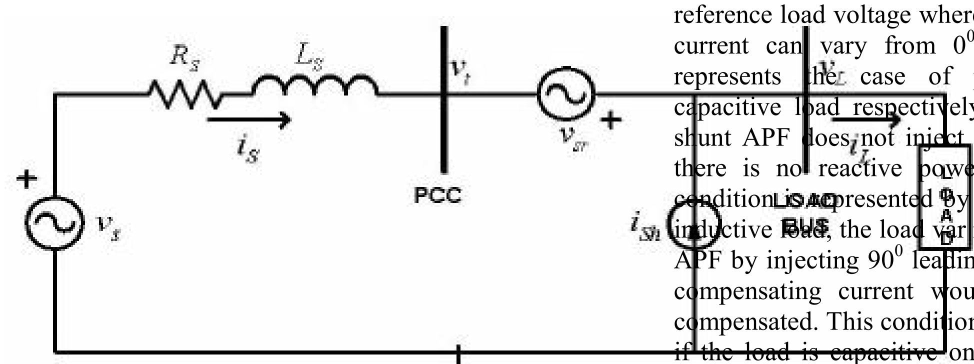



**Fig. 2: Equivalent Circuit Diagram**

In the following analysis the load voltage is assumed to be in phase with terminal voltage even during voltage sag and swell condition. This is done by injecting the series voltage in phase or out of phase with respective to the source voltage during voltage sag and swell condition respectively. This suggests the real power flow through the series APF. The voltage injected by series APF could be positive or negative, depending on the source voltage magnitude, absorbing or supplying the real power. In this particular condition, the series APF could not handle reactive power and the load reactive power is supplied by shunt APF alone. The equivalent circuit of a phase for UPQC is shown in the Fig. 2. The source voltage, terminal voltage at PCC and load voltage are denoted by $V_s$, $V_t$ and $V_L$ respectively. The source and load currents are denoted by is and $i_L$ respectively. The voltage injected by series APF is denoted by $v_{Sr}$, where as the current injected by shunt APF is denoted by $i_{Sh}$.

Suitable model for the analysis and control of the UPQC was quite difficult to obtain, which prohibited not only the analysis and comparison between existing control strategies, but also the industrial applications, as no generalized method to design the control loop for different disturbances. In this paper, a unified DC voltage compensator design is proposed for UPQC based on the system instantaneous energy equilibrium model. The main circuit model of UPQC is derived firstly, including both the steady state model and the small signal model. Subsequently, four existing control strategies for the shunt converter control are found and modeled in detail, which are combined with UPQC main circuit model, and the whole control system are obtained accordingly. The UPQC whole system model are compared and evaluated in different disturbances. And then the unified compensator design method for the DC link voltage control is proposed, the worst control strategy is then chosen as an example for the detailed compensator design, based on the newly proposed model. Finally, the computer simulation and prototype experiment are done to verify the validity all the analysis and control.

Fig. 3 shows variation of angle during different modes of operations of UPQC, represented by zones. Figure consists of seven zones of operations. The x axis represents the reference load voltage whereas the shunt APF compensating current can vary from $0^0$ to $360^0$. Zone I, II and III represents the case of pure resistive, inductive and capacitive load respectively. If the load is pure resistive, shunt APF does not inject any compensating current since there is no reactive power demand from the load, this condition is represented by zone I. Considering the case of inductive load, the load var requirement is supplied by shunt APF by injecting $90^0$ leading current. The magnitude of the compensating current would depend on the vars to be compensated. This condition is represented by zone II. Now, if the load is capacitive one, theoretically, the load would draw leading current from the source, i.e. load generates vars. This load generated vars are compensated by shunt APF by injecting $90^0$ lagging current. The magnitude of compensating current depends on the vars to be cancelled out, represented by zone III. During the operation of UPQC in zone II and III larger the var compensation more would be the compensating current magnitude.

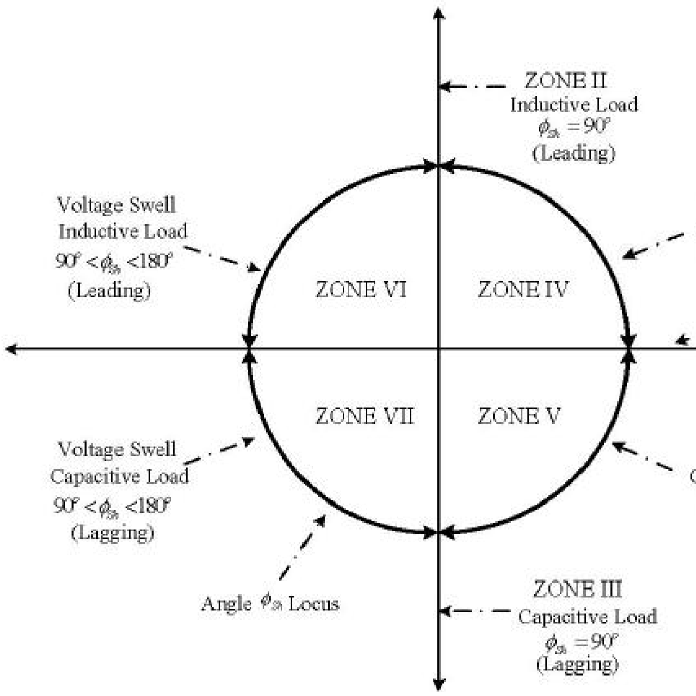



**Fig. 3 : Zones in Operation of UPQU**

Zone IV and zone V represents the operating region of UPQC during the voltage sag on the system for inductive and capacitive type of the loads respectively. During the voltage sag as discussed previously, shunt APF draws the required active power from the source by taking extra current from the source. In order to have real power exchange between source, UPQC and load, the angle OSh should not be 900. For inductive type of the load, this angle could be anything between 00 to 900 leading and for capacitive type of the load, between $0^0$ to $90^0$ lagging. This angle variation mainly depends on the 00 of sag need to be compensated and load var requirement.

Zone VI and zone VII represents the operating region of UPQC during the voltage swell on the system for inductive and capacitive type of the loads respectively. During the voltage swell as discussed previously, shunt APF feeds back the extra active power from the source by taking reduced current from the source. In order to achieve this angle , iSh would be between $90^0$ to $180^0$ leading and between $90^0$ to $180^0$ lagging for inductive and capacitive type of load respectively.

### 3. THE IMPROVED P-Q-R THEORY

Voltage at three-phase a-b-c coordinates can be transformed to dq0 as

$$\begin{bmatrix} e_\alpha \\ e_\beta \\ e_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \mathbf{C}_{\alpha\beta 0} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

A UPQC that combines the operations of a Distribution Static Compensator (DSTATCOM) and Dynamic Voltage Regulator (DVR) together. We have analyzed the operation of a UPQC that combines the operations of a Distribution Static Compensator (DSTATCOM) and Dynamic Voltage Restorer (DVR) together. The series component of the UPQC inserts voltage so as to maintain the voltage at the Point of Common Coupling (PCC) balanced and free of distortion. Simultaneously, the shunt component of the UPQC injects current in the a.c. system such that the currents entering the bus to which the UPQC is connected are balanced sinusoids. Both these objectives must be met irrespective of unbalance or distortion in either source or load sides.

The proposed control strategy is aimed to generate reference signals for both shunt and series APFs of UPQC. In the following section, an approach based on SRF theory is used to get reference signals for the series and shunt APFs. A. Reference voltage signal generation for series APF The control strategy for series AF is shown in Fig.4. Since, the supply voltage is distorted, a phase locked loop (PLL) is used to achieve synchronization with the supply voltage [8].Three-phase distorted supply voltages are sensed and given to PLL which generates two quadrature unit vectors (sinwt, coswt).The sensed supply voltage is multiplied with a suitable value of gain before being given as an input to PLL. A distortion free, balanced and a constant magnitude three phase voltage has'd' component only, while 'q' and '0' component will be zero. Hence, with the help of unit vectors (sinwt, coswt) obtained from PLL, an inverse Parks transformation is done for the desired peak value of the PCC voltage using bellow eqn.

$$\begin{bmatrix} v_{la}^* \\ v_{lb}^* \\ v_{lc}^* \end{bmatrix} \quad \frac{2}{3} \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos\left(\theta - \frac{2\Pi}{3}\right) & -\sin\left(\theta - \frac{2\Pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\Pi}{3}\right) & -\sin\left(\theta + \frac{2\Pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} v_d \\ 0 \\ 0 \end{bmatrix}$$

The computed reference voltages from above eqn are then given to the hysteresis controller along with the sensed three phase actual load voltages(vla, vlb and vlc).The output of the hysteresis controller is switching signals to the six switches of the VSI of series AF. The hysteresis controller generates the switching signals such that the voltage at PCC becomes the desired sinusoidal reference voltage. Therefore, the injected voltage across the series transformer through the ripple filter cancels out the harmonics present in the supply voltage. The control scheme to ger the reference source (I * sa, I * sb and I * sc ) using SRF theory is depicted in Fig.5.

With the help of unit vectors (sinwt, coswt) the load currents are transformed in to d-q-0 components using Park's transformation as per the eqn. (2)

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta-\frac{2\Pi}{3}\right) & \cos\left(\theta-\frac{2\Pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta-\frac{2\Pi}{3}\right) & -\sin\left(\theta+\frac{2\Pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

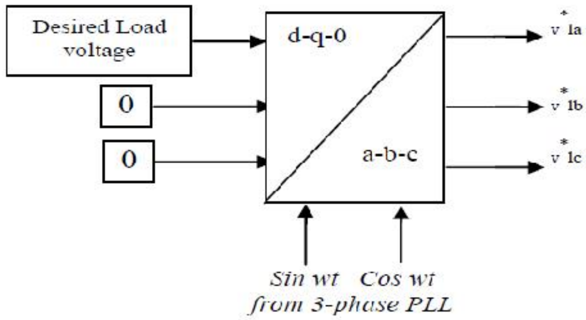



**Fig. 4: Control Scheme of Series APF using SRF Theory**

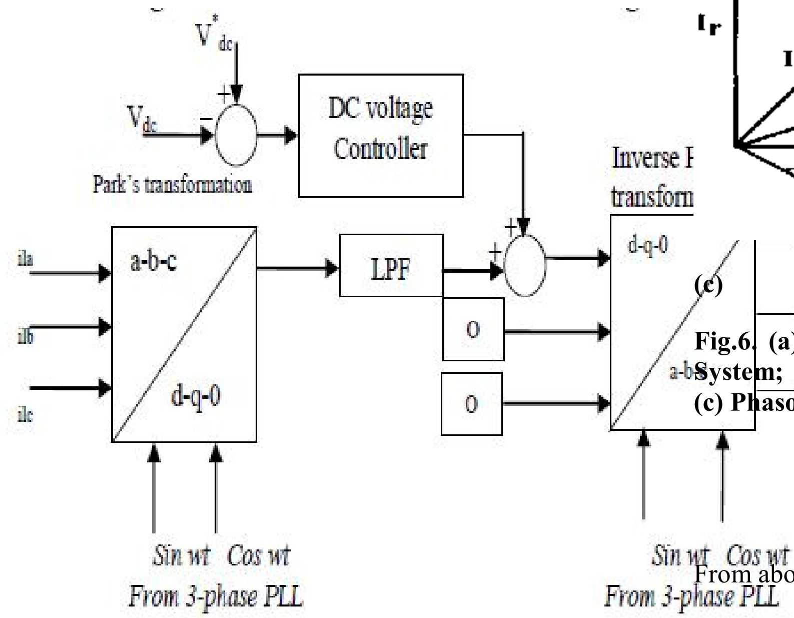



**Fig. 5 : Control Scheme of Shunt APF using SRF Theory**

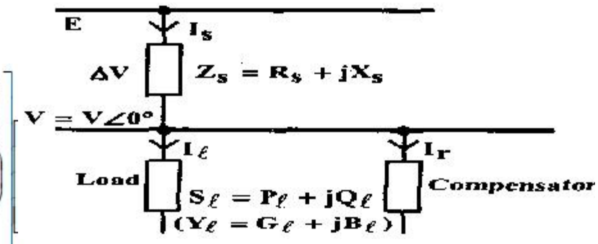
## 4. MODELLING OF DSTATCOM

### 4.1. Voltage Regulation Without Compensator

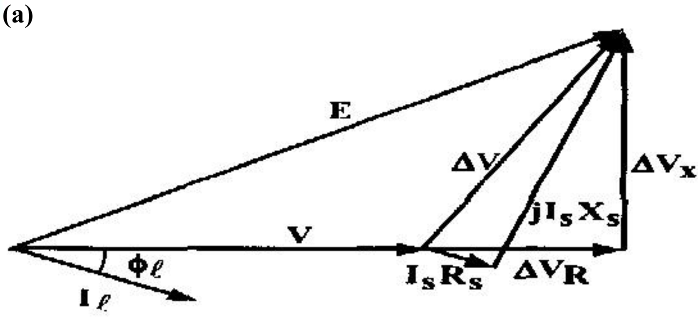
Voltage E and V mean source voltage and PCC voltage respectively. Without a voltage compensator, the PCC voltage drop caused by the load current, $I_L$ is as shown in Fig.6 (b) as $\Delta V$

$$I_S = I_L + I_R$$

Where IR is the compensating current




**(a)**

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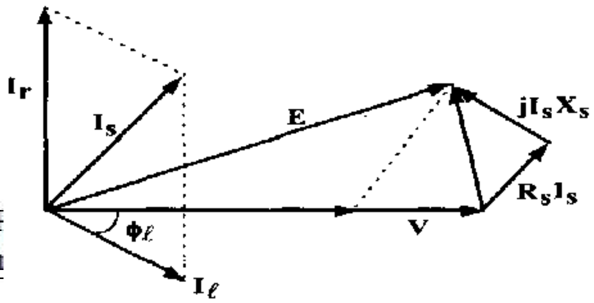


**(c)**

**Fig.6. (a) The Equivalent Circuit Of Load And Supply System; (b) Phasor of Uncompensated Line; (c) Phasor of the Compensated Line**

$\Delta V = E - V = ZSIL$

$S = VI^*$, $S\_ = V^*I$

From above equation

$$I_L = \left(\frac{P_L - jQ_L}{V}\right)$$

So that
$$\Delta V = \left(R_S + jX_S\right)\left(\frac{P_L - jQ_L}{V}\right)$$

$$= \left(\frac{R_S P_L - X_S Q_L}{V}\right) + J\left(\frac{X_S P_L + R_S Q_L}{V}\right)$$

$$= \Delta V_R + \Delta V_X$$

The voltage change has a component ΔVR in phase with V and a component ΔVx , in quadrature with V, which are illustrated in Fig.6(b). it is clear that both magnitude and phase of V , relative to the supply voltage E, are the functions magnitude and phase of load current, namely voltage drop depends on the both the real and reactive power of the load. The component ΔV can be written as :

$$\Delta V = I_S R_s - jI_S X_s$$

### 4.2. Voltage Regulation Using The DSTATCOM

Fig. 6(c) shows the vector diagram with voltage compensation. By adding a compensator in parallel with the load, it is possible to make $|E| = |V|$ by controlling the current of the compensator.

$$I_S = I_L + I_R$$

Where $I_R$ is compensator current

**Basic Operating Principle :** Basic operating principle of a DSATCOM is similar to that of synchronous machine. The synchronous machine will provide lagging current when under excited and leading current when over excited.

DSTATCOM can generate and absorb reactive power similar to that of synchronous machine and it can also exchange real power if provided with an external device DC source.

*Exchange Of Reactive Power :* if the output voltage of the voltage source converter is greater than the system voltage then the DSATCOM will act as capacitor and generate reactive power(i.e.. provide lagging current to the system)

*Exchange Of Real Power :* as the switching devices are not loss less there is a need for the DC capacitor to provide the required real power to the switches. Hence there is a need for real power exchange with an AC system to make the capacitor voltage constant in case of direct voltage control. There is also a real power exchange with the AC system if DSTATCOM id provided with an external DC source to regulate the voltage incase of very low voltage in the distribution system or in case of faults. And if the VSC output voltage leads the system voltage then the real power from the capacitor or the DC source will be supplied to the AC system to regulate the system voltage to the =1p.u or to make the capacitor voltage constant.

Hence the exchange of real power and reactive power of the voltage source converter with AC system is the major required phenomenon for the regulation in the transmission as well as in the distribution system. For reactive power compensation, DSTATCOM provides reactive power as needed by the load and therefore the source current remains at unity power factor (UPF). Since only real power is being supplied by the source, load balancing is achieved by making the source reference current balanced. The reference source current used to decide the switching of the DSTATCOM has real fundamental frequency component of the load current which is being extracted by these techniques.

A STATCOM at the transmission level handles only fundamental reactive power and provides voltage support while as a DSTATCOM is employed at the distribution level or at the load end for power factor improvement and voltage regulation. DSTATCOM can be one of the viable alternatives to SVC in a distribution network. Additionally, a DSTATCOM can also behave as a shunt active filter, to eliminate unbalance or distortions in the source current or the supply voltage as per the IEEE-519 standard limits. Since a DSTATCOM is such a multifunctional device, the main objective of any control algorithm should be to make it flexible and easy to implement in addition to exploiting its multi functionality to the maximum.

The main objective of any compensation scheme is that it should have a fast response, flexible and easy to implement. The control algorithms of a DSTATCOM are mainly implemented in the following steps:

- Measurements of system voltages and current and
- signal conditioning
- Calculation of compensating signals
- Generation of firing angles of switching devices

Generation of proper PWM firing is the most important part of DSTATCOM control and has a great impact on the compensation objectives, transient as well as steady state performance. Since a DSTATCOM shares many concepts to that of a STATCOM at transmission level, a few control algorithms have been directly implemented to a DSTATCOM, incorporating Pulse Width Modulation (PWM) switching, rather than Fundamental Frequency switching (FFS) methods. This project makes attempt to compare the following schemes of a DSTATCOM for reactive power compensation and power factor correction based on:

1. Phase Shift Control
2. Decoupled Current Control (p-q theory)
3. Regulation of ac bus and dc link voltage
4. Synchronous Reference Frame (SRF) Method
5. Adaline Based Control Algorithm (in this paper we are not discussing about this controller)

The performance of DSTATCOM with different control schemes have been tested through digital simulations with the different system parameters. The switch on time of the DSTATCOM and the load change time are also mentioned.

**Phase Shift Control :** In this control algorithm the voltage regulation is achieved in a DSTATCOM by the measurement of the rms voltage at the load point and no reactive power measurements are required. Fig.7 shows the block diagram of the implemented scheme.

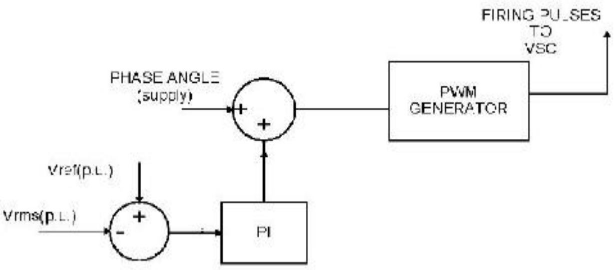


**Fig. 7 : Block Diagram Of Phase Shift Control**

Sinusoidal PWM technique is used which is simple and gives a good response. The error signal obtained by comparing the measured system rms voltage and the reference voltage, is fed to a PI controller which generates the angle which decides the necessary phase shift between the output voltage of the VSC and the AC terminal voltage. This angle is summed with the phase angle of the balanced supply voltages, assumed to be equally spaced at 120 degrees, to produce the desired synchronizing signal required to operate the PWM generator. In this algorithm the D.C. voltage is maintained constant using a separate dc source.

**Decoupled Current Control p-q Theory :** This algorithm requires the measurement of instantaneous values of three phase voltage and current. Fig.5. shows the block diagram representation of the control scheme. The compensation is achieved by the control of id and iq. Using the definition of the instantaneous reactive power theory for a balanced three phase three wire system, the quadrature component of the voltage is always zero, the real (p) and the reactive power (q) injected into the system by the DSTATCOM can be expressed under the dq reference frame as:

$$p = v_d i_d + v_q i_q$$
$$q = v_q i_d - v_d i_q$$

Since vq=0, id and iq completely describe the instantaneous value of real and reactive powers produced by the DSTATCOM when the system voltage remains constant. Therefore the instantaneous three phase current measured is transformed by abc to dqo transformation. The decoupled d-axis component id and q axis component iq are regulated by two separate PI regulators. The instantaneous id reference and the instantaneous iq reference are obtained by the control of the dc voltage and the ac terminal voltage measured. Thus, instantaneous current tracking control is achieved using four PI regulators. A Phase Locked Loop (PLL) is used to synchronize the control loop to the ac supply so as to operate in the abc to dqo reference frame. The instantaneous active and reactive powers p and q can be decomposed into an average and an oscillatory component.

$$p = \bar{p} + \tilde{p} \quad \text{and} \quad q = \bar{q} + \tilde{q}$$

Where $\bar{p}$ and q are the average part and $\tilde{p}$ and $\tilde{q}$ are oscillatory part of real and reactive instantaneous powers. The compensating currents are calculated to compensate the instantaneous reactive power and the oscillatory component of the instantaneous active power. In this case the source transmits only the non-oscillating component of active power.

Therefore the reference source currents $i^*_{s\alpha}$ and $i^*_{s\beta}$ in α-β coordinate are expressed as:

$$\begin{bmatrix} i^*_{s\alpha} \\ i^*_{s\beta} \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} \bar{p} \\ 0 \end{bmatrix}$$

These currents can be transformed in a-b-c quantities to find the reference currents in a-b-c coordinate.

$$\begin{bmatrix} i^*_{sa} \\ i^*_{sb} \\ i^*_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} i_o \\ i_\alpha \\ i_\beta \end{bmatrix}$$

Where $i_o$ is the zero sequence components which is zero in 3-phase 3-wire system and the corresponding block diagram is shown in Fig. 8.

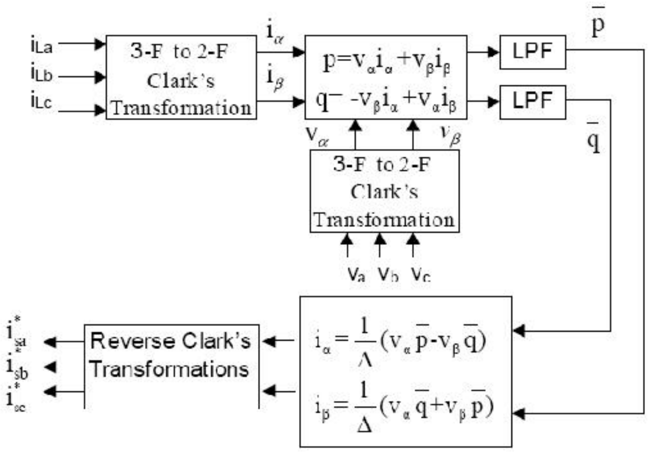


**Fig. 8 : Block Diagram Of Decoupled Theory Based Control Of DSTATCOM**

**Synchronous Rotating Frame Theory :** The synchronous reference frame theory is based on the transformation of the currents in synchronously rotating d-q frame. Fig.9 explains the basic building blocks of the theory. If θ is the transformation angle, then the currents transformation from α-β to d-q frame is defined as:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

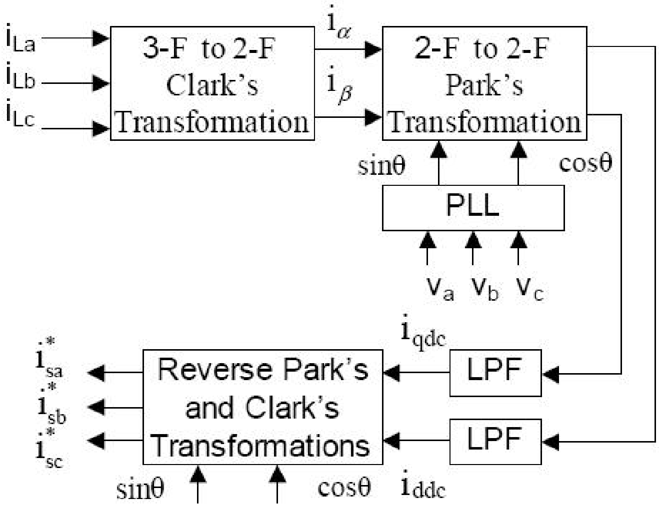


**Fig. 9 : Block Diagram For Synchronous Frame Theory**

SRF isolator extracts the dc component by low pass filters (LPF) for each id and iq realized by moving averager at 100Hz. The extracted DC components iddc and iqdc are transformed back into α-β frame as shown below:

$$\begin{bmatrix} i_{\alpha dc} \\ i_{\beta dc} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{ddc} \\ i_{qdc} \end{bmatrix}$$

From here the transformation can be made to obtain three phase reference currents in a-b-c coordinates using. The reactive power compensation can also be provided by keeping iq component zero for calculating reference currents.

## 5. MODELLING OF DVR

Power quality has a significant influence on high-technology equipments related to communication, advanced control, automation, precise manufacturing technique and on-line service. For example, voltage sag can have a bad influence on the products of semiconductor fabrication with considerable financial losses. Power quality problems include transients, sags, interruptions and other distortions to the sinusoidal waveform. One of the most important power quality issues is voltage sag that is a sudden short duration reduction in voltage magnitude between 10 and 90% compared to nominal voltage. Voltage sag is deemed as a momentary decrease in the rms voltage, with duration ranging from half a cycle up to one minute. Deep voltage sags, even of relatively short duration, can have significant costs because of the proliferation of voltage-sensitive computer-based and variable speed drive loads. The fraction of load that is sensitive to low voltage is expected to grow rapidly in the coming decades. Studies have shown that transmission faults, while relatively rare, can cause widespread sags that may constitute a major source of process interruptions for very long distances from the faulted point. Distribution faults are considerably more common but the resulting sags are more limited in geographic extent. The majority of voltage sags are within 40%of the nominal voltage. Therefore, by designing drives and other critical loads capable of riding through sags with magnitude of up to 40%, interruption of processes can be reduced significantly. The DVR can correct sags resulting from faults in either the transmission or the distribution system.

The voltage generated by power stations has a sinusoidal waveform with a constant frequency. Any disturbances to voltage waveform can result in problems related with the operation of electrical and electronic devices. Users need constant sine wave shape, constant frequency and symmetrical voltage with a constant rms value to continue the production. This increasing interest to improve overall efficiency and eliminate variations in the industry have resulted more complex instruments that are sensitive to voltage disturbances. The typical power quality disturbances are voltage sags, voltage swells, interruptions, phase shifts, harmonics and transients. Among the disturbances, voltage sag is considered the most severe since the sensitive loads are very susceptible to temporary changes in the voltage.

Voltage sag (dip) is a short duration reduction in voltage magnitude between 10% to 90% compared to nominal voltage from half a cycle to a few seconds. The characterization of voltage sags is related with the magnitude of remaining voltage during sag and duration of sag [2, 5]. The magnitude has more influence than the duration on the system. Voltage sags are generally within 40% of the nominal voltage in industry. They can cause damaged product, lost production, restarting expenses and danger of breakdown. Motor starting, transformer energizing, earth faults and short circuit faults will cause short duration increase in current and this will cause voltage sags on the line.

The wide area solution is required to mitigate voltage sags and improve power quality. One new approach is using a DVR [1, 8]. The basic operation principle is detecting the voltage sag and injecting the missing voltage in series to the bus as shown in Fig.1. DVR has become a cost effective solution for the protection of sensitive loads from voltage sags. Unlike UPS, the DVR is specifically designed for large loads ranging from a few MVA up to 50MVA or higher [5]. The DVR is fast, flexible and efficient solution to voltage sag problems, [4, 8].

## 6. RESULTS

The performance of the designed DVR is evaluated by using the Matlab / Simulink program as a The proposed UPQC and its control schemes have been tested through extensive case study simulations using Matlab. In this section, simulation results are presented, and the performance of the proposed UPQC system is shown in Fig. 10 and the control model in simulink as shown in Fig. 11.

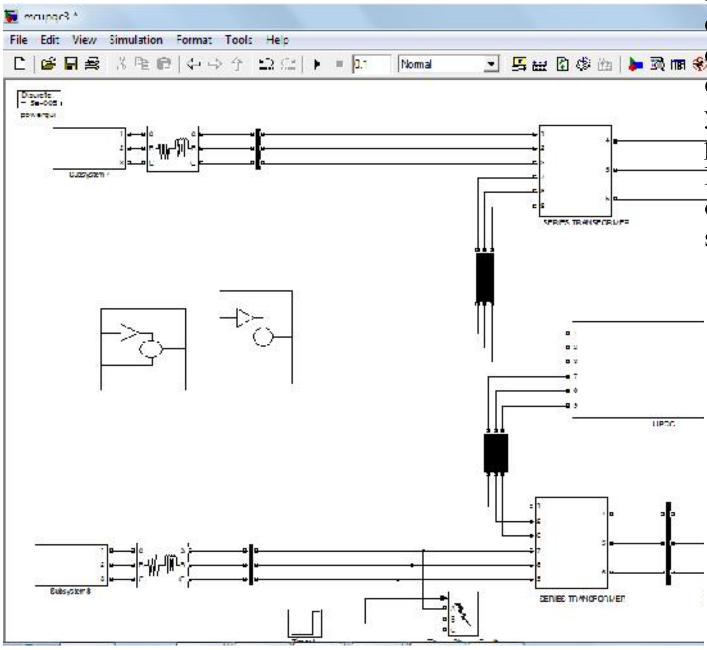

**Fig. 10 : Matlab/Simulink File of UPQC**

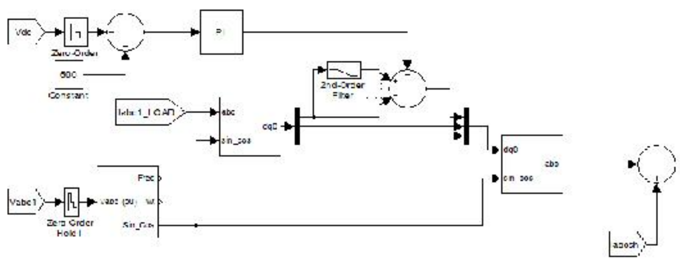

**Fig. 11 : Controller of UPQC**

The distorted nonlinear load current is compensated very well, and the total harmonic distortion (THD) of the feeder current is reduced from 28.5% to less than 5%. Also, the dc voltage regulation loop has functioned properly under all disturbances, such as sag/swell in both feeders.

### 6.1. Upstream Fault on Feeder2

When a fault occurs in Feeder2 (in any form of L-G, L-L-G, and L-L-L-G faults), the voltage across the sensitive/critical load L2 is involved in sag/swell or interruption. This voltage imperfection can be compensated for by VSC2. In this case, the power required by load L2 is supplied through VSC2 and VSC3. This implies that the power semiconductor switches of VSC2 and VSC3 must be rated such that total power transfer is possible. This may increase the cost of the device, but the benefit that may be obtained can offset the expense. In the proposed configuration, the sensitive/critical load on Feeder2 is fully protected against distortion, sag/swell, and interruption. Furthermore, the regulated voltage across the sensitive load on Feeder1 can supply several customers who are also protected against distortion, sag/swell, and momentary interruption. Therefore, the cost of the MC-UPQC must be balanced against the cost of interruption, based on reliability indices, such as the customer average interruption duration index (CAIDI) and customer average interruption frequency index (CAIFI). It is expected that the MC-UPQC cost can be recovered in a few years by charging higher tariffs for the protected lines. The performance of the MC-UPQC under a fault condition on Feeder2 is tested by applying a three-phase fault to ground on Feeder2 between $0.3s<t<0.4$ s. Simulation results are shown in Fig. 12.

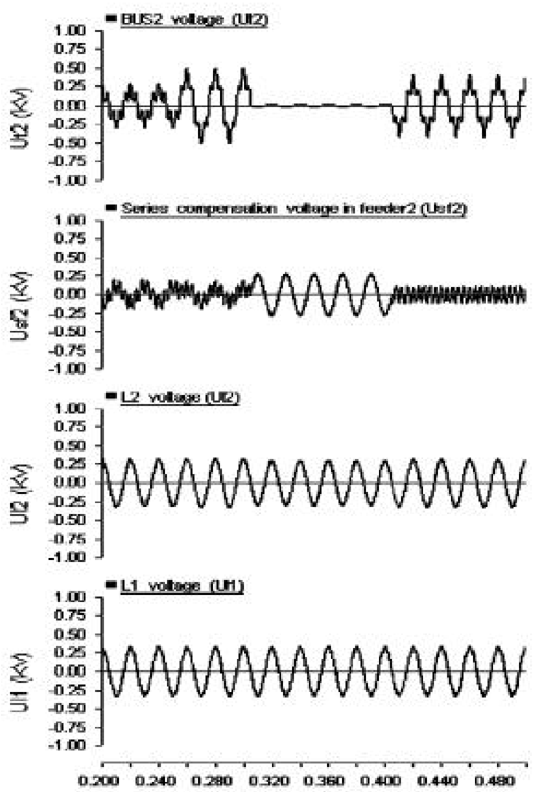


**Fig12: Simulation Results For An Upstream Fault On Feeder2:**
**BUS2 Voltage, Compensating Voltage, And Loads L1 and L2 Voltages**

### 6.2. Load Change

To evaluate the system behavior during a load change, the nonlinear load L1 is doubled by reducing its resistance to half at t=0.5 s. The other load, however, is kept unchanged. The system response is shown in Fig. 13.

It can be seen that as load L1 changes, the load voltages $u_{l1}$ and $u_{l2}$ remain undisturbed, the dc bus voltage is regulated, and the nonlinear load current is compensated.

### 6.3. Unbalance Voltage

The control strategies for shunt and series VSCs, which are introduced in Section II, are based on the d–q method. They are capable of compensating for the unbalanced source voltage and unbalanced load current. To evaluate the control system capability for unbalanced voltage compensation, a new simulation is performed. In this new simulation, the BUS2 voltage and the harmonic components of BUS1 voltage are similar to those given in Section IV. However, the fundamental component of the BUS1 voltage $(U_{t1,\text{fundaental}})$ is an unbalanced three-phase voltage with an unbalance factor $(U_{-}/U_{+})$ of 40%. This unbalance voltage is given by

$$U_{t1,\text{fundamental}} = \left[ \begin{array}{l} 0.31\cos(\omega t + 46^{\circ} \\ 0.31\cos(\omega t - 106^{\circ} \\ 0.155\cos(\omega t - 210 \end{array} \right.$$

The simulation results for the three-phase BUS1 voltage series compensation voltage, and load voltage in feeder 1 are shown in Fig. 14.

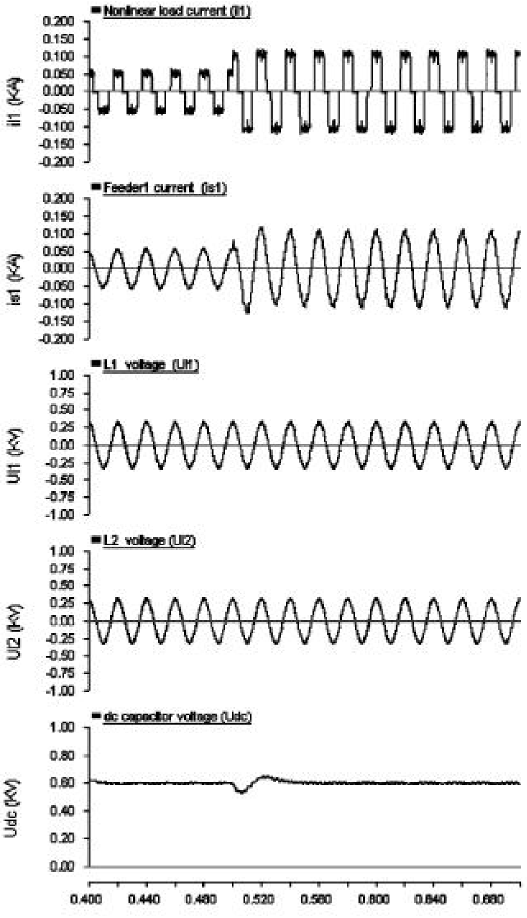


**Fig. 13 : Simulation Results For Load Change: Nonlinear Load Current, Feeder1 Current, Load L1 Voltage, Load L2 voltage, and dc-link Capacitor Voltage**

The simulation results show that the harmonic components and unbalance of BUS1 voltage are compensated for by injecting the proper series voltage. In this figure, the load voltage is a three-phase sinusoidal balance voltage with regulated amplitude.

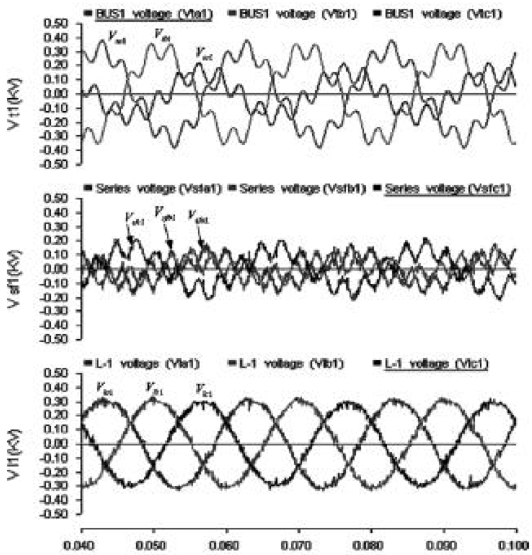


**Fig. 14 : BUS1 Voltage, Series Compensating Voltage, and Load Voltage in Feeder1 Under Unbalanced Source Voltage**

## 7. CONCLUSION

In this paper, a new configuration for simultaneous compensation of voltage and current in adjacent feeders has been proposed. The new configuration is named multi-converter unified power-quality conditioner (MC-UPQC). Compared to a conventional UPQC, the proposed topology is capable of fully protecting critical and sensitive loads against distortions, sags/swell, and interruption in two-feeder systems. The idea can be theoretically extended to multibus/multifeeder systems by adding more series VSCs. The performance of the MC-UPQC is evaluated under various disturbance conditions and it is shown that the proposed MC-UPQC offers the following advantages :

1) Power transfer between two adjacent feeders for sag/swell and interruption compensation;

2) Compensation for interruptions without the need for a battery storage system and, consequently, without storage capacity limitation;

3) Sharing power compensation capabilities between two adjacent feeders which are not connected.

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