SAG MITIGATION OF DISTRIBUTED SYSTEM WITH UPQC WITH MINIMUM REAL POWER INJECTION

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THESIS CERTIFICATE

This is to certify that the thesis titled **SAG MITIGATION OF DISTRIBUTED SYSTEM WITH UPQC WITH MINMUM REAL POWER INJECTION**, submitted by **Leena P Markose**, to the Indian Institute of Technology, Madras, for the award of the degree of **Master of technology**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: Power Quality; Voltage Sags; Unified Power Quality Conditioner; Capacitor Bank

The quality of the Electrical power is affected by many factors like harmonic contamination due to non-linear loads, voltage and current flickering due to arc furnaces, sag and swell due to the switching of the loads etc. Power Quality (PQ) problems are much talked about in recent times due to the highly sensitive nature of the various equipments connected to the system. The widespread automation of critical processes has increased the demand for precise voltage at the load terminals. Various power filtering technology i.e. passive filters, active power filters and hybrid filters have been applied from time to time for giving the solution of power quality problems to users. The application of power electronics in power distribution system for the benefit of the customers is called custom power. The custom power devices include Distribution Static Compensator (DSTATCOM), Dynamic Voltage Restorer (DVR) and Unified Power Quality Conditioner (UPQC). In the present work, UPQC has been used to mitigate PQ problems due to its capability in handling both current and voltage related PQ problems simultaneously.

Voltage sags are one of the most commonly occurring power quality problem. For compensating voltage sags, the Series Active Power Filter (SEAPF) of UPQC injects a voltage in series with the source voltage. The angle between this voltage and the source current determine the amount of real and reactive power injected by the SEAPF. Active power injection/absorption is necessary for deep voltage sag/swell compensation. Reducing the active power injection by the SEAPF, the rating of the energy storage capacity of the DC-link can be brought down, which in turn will reduce the cost of UPQC. Minimizing the amount of real power flowing through the UPQC is the main objective of the present work. This angle of injection can be optimized in such a way that it satisfies the practical constraints which includes the maximum voltage available with SEAPF for compensation, the phase jump mitigation, and angle of voltage injec-

tion. Apart from this, voltage in the range of 0.9 pu to 1.05 pu is acceptable in the utility side, therefore complete sag mitigation is not required from the series active filter of UPQC. In order to further bring down the real power injection by the UPQC, a capacitor bank is provided at the terminal. This would boost the terminal voltage slightly making it possible for the UPQC to mitigate even deep sags of long duration. Simulation studies have been carried out to validate the proposed method.

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ABBREVIATIONS

AC	Alternating Current
ANFIS	Adaptive Neuro Fuzzy Inference System
APF	Active Power Filter
ARE	Algebraic Riccati Equation
CPD	Custom Power Devices
DC	Direct Current
DSTATCOM	Distribution Static Compensator
DVR	Dynamic Voltage Restorer
FIS	Fuzzy Inference System
GTO	Gate Turn Off Thyristor
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
LQR	Linear Quadratic Regulator
PCC	Point Of Common Coupling
PQ	Power Quality
pu	Per Unit
PWM	Pulse Width Modulation
RMS	Root Mean Square
SEAPF	Series Active Power Filter
SHAPF	Shunt Active Power Filter
THD	Total Harmonic Distortion
UPQC	Unified Power Quality Conditioner
VA	Volt Ampere
VSI	Voltage Source Inverter

NOTATION

ω	Fundamental frequency of the supply voltage in rad/s
δ	Phase jump
α	Angle at which SEAPF voltage is injected
θ	Angle of compensated voltage wrt terminal voltage
ϕ	Load angle
C_d	Series active power filter capacitor
C_f	Shunt active power filter capacitor
C_n	Shunt capacitor bank
i	Instantaneous current
I	RMS current
J	Performance Index
K	Feedback gain matrix
L_d	Series active power filter inductance
L_f	Interfacing inductance of SHAPF
L_s	Thevenin equivalent of source inductance
L_l	Load inductance
L_t	Leakage inductance of injection transformer
Q	State vector weighing matrix
R	Input vector weighing matrix
R_d	Series active power filter resistance
R_f	Interfacing resistance of SHAPF
R_s	Thevenin equivalent of source resistance
R_l	Load resistance
u_1, u_2	Switching functions for SEAPF and SHAPF
V	RMS voltage
v	Instantaneous voltage
x	per-unit sag
z	State vector

CHAPTER 1

INTRODUCTION

The production and distribution of electrical energy in higher capacities have resulted in never ending complexities and issues regarding the quality of the power produced. The continued interconnection of bulk power systems has highlighted the seriousness of power quality disturbances due to their wide propagation within the system. According to IEEE std. 519-1992, limits are established on harmonic currents and voltages at the point of common coupling (PCC). The limits of IEEE 519 are intended to assure that the electric utility can deliver relatively clean power to all of its customers and that the electric utility can protect its electrical equipment from overheating, loss of life from excessive harmonic currents and excessive voltage stress due to excessive harmonic voltage.

The advent of electronic power conversion has resulted in the usage of power converters that are generators of harmonic currents and are additional sources of line-voltage drops. Apart from the large scale harmonic current sources such as the arc furnaces, nowadays widely dispersed customer loads are also responsible for harmonic current injection. The proliferation of microelectronics has caused the usage of several sensitive equipments by the customers which are adversely affected by harmonics[1]. The modern electronic and electrical control devices are characterized by extreme sensitivity in power quality variations, which has led to growing concern over the quality of the power supplied to the customer. The economic aspect of power quality is also a prominent topic.

1.1 Power Quality Disturbances

Four system parameters frequency, amplitude,waveform and symmetry are used to describe voltage and power disturbances[1]. The frequency variation is not very prominent on the utility side. The amplitude variation can be for a short duration or can be in steady state condition. The voltage waveform can be non sinusoidal due to the presence of harmonic currents drawn by the load. The symmetry of voltage indicates the amount of balance present between the phases. Non symmetric voltage occurs due to single phase unbalanced loads connected to a three phase system. The prominent power quality disturbances are described below.

Voltage Sags

According to the IEEE voltage std.1100-2005 sag is defined as a decrease of RMS voltage from 0.1 to 0.9 per unit(pu), for a duration of 0.5 cycle to 1 minute.Voltage sag doesn't mean the absence of supply but a reduction in magnitude of the supplied voltage. Voltage sag is the most commonly occurring problem and usually the sag voltage doesn't go below 50 percent of the nominal voltage. Voltage sag is caused by faults on the system, transformer energizing, or heavy load switching. The faults that exist on power system can be classified into single line-to-ground, double line-to-ground fault and three-phase fault. Voltage sags can be classified into types: A,B,C etc depending on the fault types, transformer connection and load connections.

Voltage Interruptions

Interruption is defined as a 0.9 pu reduction in voltage magnitude for a period of less than one minute. An interruption is characterized by the duration as the magnitude is more or less constant. Based on the time, interruptions can be characterized into instantaneous, momentary, temporary and sustained. An interruption might follow a voltage sag if the sag is caused by a fault on the, source system. During the time required for the protection system to operate, the system sees the effect of the fault as a sag. Following circuit breaker operation, the system gets isolated and interruption occurs. As the Autoreclosure scheme operates, introduced delay can cause a momentary interruption[2].

Over voltages and Swells

According to the IEEE Std., voltage swell is defined as an increase in RMS voltage or current at the power frequency for durations from 0.5 cycle to 1.0 minute. Voltage swells are caused by switching off a large load from the system, energizing a capacitor bank, poor tap settings on the transformer and inadequate voltage regulation. Typical values are 1.1 pu to 1.8 pu and is usually associated with single line-to-ground faults where voltages of non-faulted phases rise. The severity of voltage swell during a fault condition is a function of fault location, system impedance and grounding[3].

Harmonics

As mentioned earlier, power electronic converters are nonlinear loads that draw non-sinusoidal currents from the supply which may further result in distortion of the voltage waveform downstream due to the presence of feeder impedances.The presence of harmonics in the system could also cause several unwanted effects in the system including excessive transformer heating or overloading and failure of power factor correcting capacitors. The maximum total harmonic distortion which is acceptable on the utility system is 5.0% at 0.23-69 kV, 2.5% at 69-138 kV and 1.5% at higher than 138 kV voltage levels (IEEE Std. 519-1992).

1.2 Power Quality Solutions

To provide an active and flexible solution for power quality problems, various efforts have been done from time to time. Among these power quality solutions, lossless passive filters, consists of L- C tuned components, have been widely used to suppress harmonics. Passive filters are advantageous as its initial cost is low and has high efficiency. On the other hand it has various drawbacks of instability, fixed compensation , resonance with supply as well as load and utility impedance. To overcome these limitations active power filters have been used.

The concept of custom power was introduced as a solution to voltage,active and reactive power compensation and power quality problems at the expense of high cost and network complexity. As FACTS controllers improve the reliability and quality of power transmission by simultaneously enhancing both power transfer capacity and stability-custom power devices enhance the quality and reliability of power delivered to the customer. With a custom power device, a customer(eg.A sensitive load) will be able to receive a pre-specified quality of electric power. Custom power devices are classified based on their power electronic controllers which can be either the network configuration type or the compensation type. The network configuration devices also called switchgear include the solid state and static versions of current limiting,current breaking and current transferring components. The compensation type either compensate a load or improve the quality of supply voltage. They are either connected in shunt or in series or in hybrid configuration[4]. The shunt, series and hybrid compensation devices are also called as DSTATCOM, DVR and UPQC respectively.

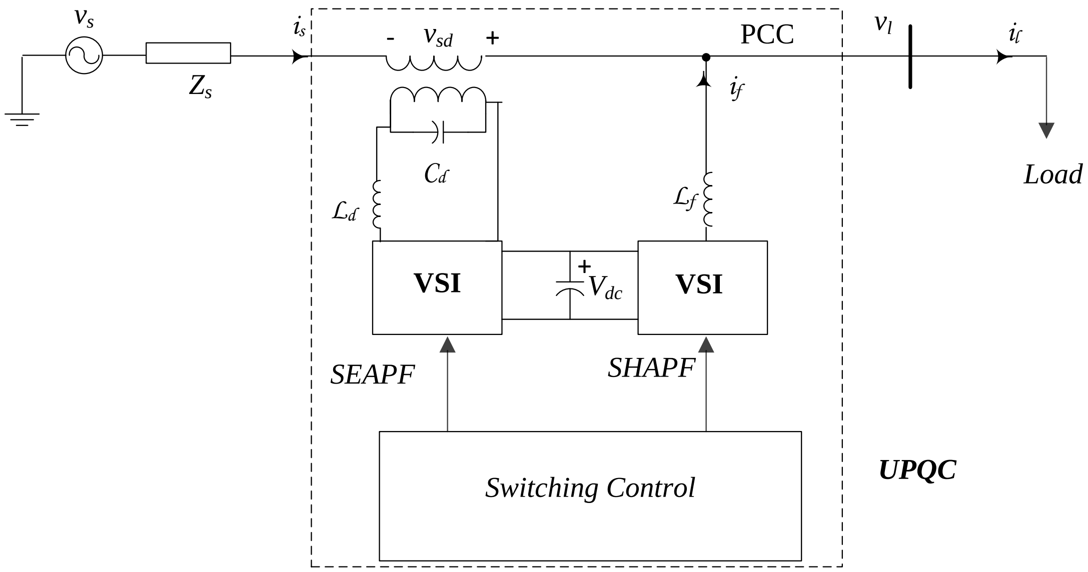

Figure 1.1 Single-line diagram of UPQC compensated distribution system

The Unified Power Quality Conditioner is a combination of shunt and series compensator connected through a DC-link. It is a flexible device which can remove the harmonics and unbalance in the load current at the same time ensuring balanced rated voltage appears at the load terminal. The schematic of a UPQC compensated system is shown in Figure 1.1. The power system represented by a non stiff source with voltage v_s and feeder impedance Z_s is catering to a load drawing a current i_l. The voltage at the Point Of Common Coupling (PCC), v_l is maintained at nominal voltage level by UPQC by injecting a voltage of v_{sd} in series with the source voltage. L_d and C_d represents the filter components of the series compensator. The source current i_s is made balanced and sinusoidal irrespective of the load current by injecting a compensating current i_f at the PCC through an interfacing inductor L_f. The voltage and current injected by the

UPQC are derived and generated using the VSI and the DC-link voltage V_{dc}. Thus both voltage and current compensation is achieved simultaneously by the UPQC at the PCC making it a better choice compared to other compensating devices.

1.3 Literature Survey

Extensive literature is available in the area of sag compensation by the UPQC.

Basu et al. [5], has evaluated the performance of the UPQC-Q configuration and has discussed the VA requirements of the shunt and series compensator separately as well as the total VA requirement. In UPQC-Q configuration, the DVR injects voltage at quadrature to the source current so that there is no active power consumption. Apart from it,the DVR also shares the VAR of the load with the DSTATCOM.

Basu et al. [6],has done a comparative study of the two common sag compensation methods UPQC-P and UPQC-Q regarding their VA requirements.For the same amount of sag compensation,the VA rating of the UPQC-Q scheme was found to be more than UPQC-P at higher power factors. This was found due to an increase in the Shunt Compensator rating at higher power factors. At low power factor required VA rating of UPQC-Q was found less than that of UPQC-P for similar sag compensation.

Khadkikar and Chandra [7],proposed the concept of optimal utilization of a Unified Power Quality Conditioner. 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 even in steady state conditions without any sag. The scheme was named as UPQC-S since the series inverter simultaneously delivers active and reactive powers.

Kolhatkar and Das[8], proposed an optimized UPQC which aims at the integration of series active and shunt active power filters with minimum volt-ampere (VA) loading of the UPQC. The DVR regulates the load voltage by injecting compensating voltage at an optimum angle. In case of unbalanced voltage sags, the minimization was done with respect to the positive sequence component. The proposed scheme was experimentally validated.

Siva Kumar et al. [9], proposed a new scheme of sag compensation with optimal Volt-Ampere (VA) loading on UPQC to mitigate deep and long duration unbalanced sag with phase jumps. During the process of mitigation, UPQC is supposed to inject real and reactive power into the system to mitigate current and voltage power quality problems. Particle Swarm Optimization (PSO) is utilized as a tool for evaluating the optimal VA loading of UPQC with constraints like magnitude of injected voltage from Series active power filter, Total Harmonic Distortion of source current and terminal voltage.

Siva Kumar et al.[10],presented a a new methodology 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.

Karanki et al. [11], proposed a UPQC topology for applications with non-stiff source which enables UPQC to have a reduced DC-link voltage without compromising its compensation capability. The topology uses a capacitor in series with the interfacing inductor of the shunt active filter, and the system neutral is connected to the negative terminal of the DC-link voltage to avoid the requirement of the fourth leg in the voltage source inverter (VSI) of the shunt active filter. The average switching frequency of the switches in the VSI was reduced and consequently the switching losses in the inverters also reduced.

1.4 Motivation

From the literature review it is clear that the energy storage capacity of the DC-link of the UPQC can be brought down by decreasing the real power injection by the UPQC. There is a tolerance for voltage at the load side. By adding a capacitor bank along with the UPQC, the terminal voltage can be boosted up thereby reducing the burden on the series VSI of the UPQC . This simple method of boosting up the terminal voltage is a commonly adopted one. The disadvantage of using the capacitance bank as a reactive source is the dependance of the reactive power supplied by it on the terminal voltage. This can be overcome by the combination of the capacitance bank and UPQC. An improvement in the terminal voltage profile leads to a decrease in the real power injection by the series VSI of UPQC. Thus the rating of the energy storage devices come down making this an economically viable solution.

1.5 Objectives

The main objective of the work done is to reduce the rating of the energy storage of the UPQC. Voltage sag compensation should be done by the series active filter of UPQC in such a way as to minimize the real power injection by UPQC. The sag compensation ability of UPQC has to be enhanced by adding a capacitor bank along with it. The equivalent circuit for the same has to be developed and modeled. The objective function for minimum real power injection by UPQC has to be formulated and optimized. ANFIS has to be trained for the real time implementation of the above optimization.

1.6 Organization Of The Thesis

In this chapter the various power quality problems have been dealt with along with the possible solutions to overcome those. The literature survey tracks the ongoing research in the area of minimization of the UPQC rating. Further the motivation and objectives of the work are presented.

In **Chapter 2** the basic structure of Unified Power Quality Conditioner is explained in detail. The classification of UPQC based on physical structure and voltage compensation is brought out. The various sag compensation techniques are explained in detail. The structure and modeling of a three-phase four wire UPQC compensated system is done. The LQR feedback control and reference current generation is explained in detail.

In **Chapter 3** the proposed structure is explained. From the single phase equivalent circuit, the state space model is derived. The formulation of objective function along with the constraints and the optimization algorithm used for minimizing is presented.ANFIS for real time implementation of the optimization process is introduced in this chapter. Finally the simulation results for the proposed system in case of balanced and unbalanced sags is presented and suitable comparisons are made.

In **Chapter 4** the conclusions are drawn and results are analyzed. The future scope for the work done is presented.

CHAPTER 2

UPQC AND VOLTAGE SAG COMPENSATION SCHEMES

2.1 Introduction

The Unified Power Quality Conditioner (UPQC) is a custom power device that is employed in the distribution system to mitigate the disturbances that affect the performance of sensitive or critical loads. It is a type of APF and is the only versatile device which can mitigate several power quality problems related with voltage and current simultaneously [12]. Apart from correcting voltage fluctuations and disturbances it prevents harmonic current from entering the power system. Optimal location and sizing of UPQC in a steady state condition can be obtained by minimizing UPQC size and power loss in the distribution network [13]. In this chapter the principle of operation of UPQC is explained. Different methods of sag compensation through UPQC are discussed.

2.2 Structure And Components Of UPQC

A Unified Power Quality Conditioner consists of a Series APF and a shunt APF. Active Power Filters are fundamentally voltage source or current source converters specifically designed and controlled to inject required amount of harmonic current or voltage into the system.

2.2.1 Shunt APF of UPQC

A state of the art shunt APF of UPQC is capable of canceling or suppressing the effect of poor load power factor, poor voltage regulation and the harmonics introduced by the load. It inhibits the DC offset or the unbalance in the load from appearing in the source side current, and if provided with an energy storage system, it can perform load leveling when the source fails [14]. A Shunt APF when used for load compensation in low voltage distribution systems is commonly referred to as Distribution Static Compensator (DSTATCOM).

The components of a DSTATCOM include a a three-phase voltage source inverter with a DC-link, AC filter, a coupling transformer and a control strategy as shown, in the single-line diagram of distribution system with DSTATCOM, in Fig. 2.1. In Fig. 2.1 v_s, i_s are the source voltage and current; v_l, i_l are the load voltage and current and R_s, L_s represents the feeder impedance. A capacitor filter (C_f shown in Fig. 2.1) is connected to the system in parallel with the load and the compensator to reduce switching ripples in the PCC voltage injected by switching of DSTATCOM. For reducing ripples in compensating currents, an interfacing inductor (L_f shown in Fig. 2.1) is used at the AC side of VSI.

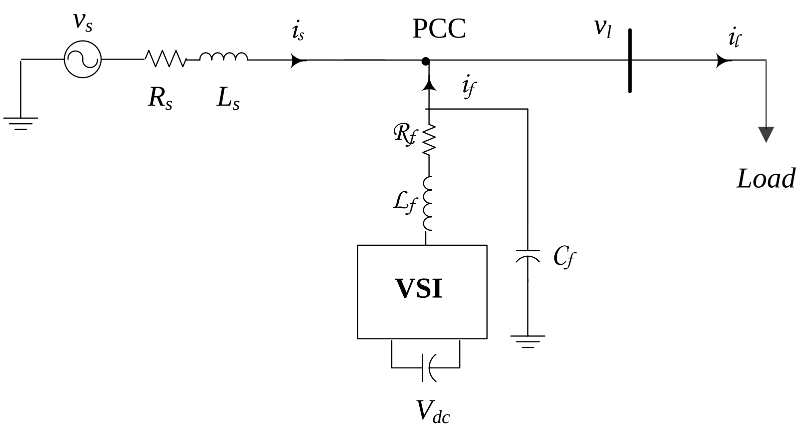

Figure 2.1 Single-line diagram of a DSTATCOM compensated distribution system

The controller of the DSTATCOM operates the inverter in such a way that the phase angle between the inverter voltage and the line voltage is dynamically adjusted so that the DSTATCOM generates or absorbs the desired VAr at the point of connection[15]. Apart from this, DSTATCOM also injects the load harmonic currents thus producing a clean source current. A DSTATCOM can operate in voltage or current control mode. In voltage control mode it ensures balanced sinusoidal voltages at the load terminal, whereas in current control mode production of balanced sinusoidal supply current is the aim.

2.2.2 Series APF of UPQC

A series APF, called as Dynamic Voltage Restorer (DVR), filters out the voltage harmonics formed due to nonlinear loads. DVR is a power electronic converter which mitigates voltage sags and swells and helps in producing balanced sinusoidal voltages at the load terminal. DVR injects adequate amount of voltage in series with the terminal voltage. A series injection transformer is used to connect the series inverter in the network and it injects a voltage of v_{sd} in series with the source voltage v_s as shown in Fig.2.2. A suitable turn ratio is often considered to reduce the current or and voltage rating of the series inverter. In order to cancel out the harmonics, DVR injects voltage with a negative polarity.

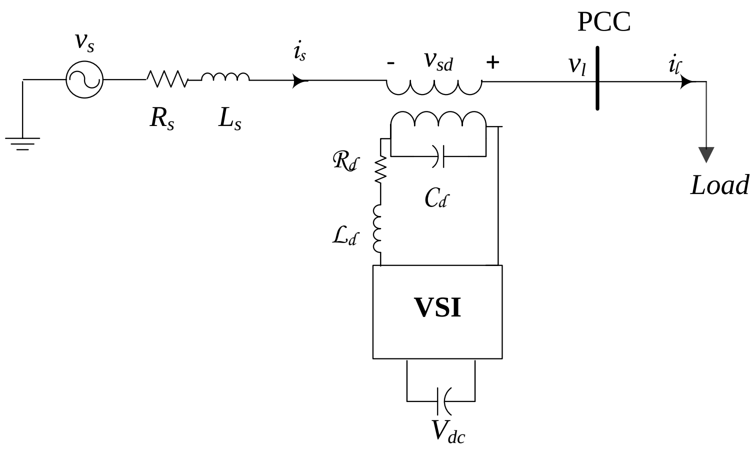

Figure 2.2 Single-line diagram of DVR compensated distribution system

The other components of a DVR are similar to that of a DSTATCOM. The higher switching frequencies are eliminated with the help of a passive low pass LC filter represented by L_d and C_d in Figure 2.2. The DVR exchanges reactive or active power or both with the power system depending upon the method in which it mitigates voltage related problems.

2.3 Operation Of UPQC

In most cases the three-phase system voltages and load currents are unbalanced and contain higher order frequency components. The shunt converter of UPQC forces the feeder current to become a balanced sinusoidal (harmonic-free) waveform, while the series converter ensures a balanced, sinusoidal and regulated load voltage.

2.3.1 Obtaining balanced voltage at load terminals

The imbalance or distortion of a three-phase system may consist of positive,negative and zero-sequence fundamental and harmonic components.The thevenin equivalent of the system voltage without compensation can be expressed as,

$$v_t(t) = v_t^{1+}(t) + v_t^{1-}(t) + v_t^{10}(t) + \sum v_t^h(t) \tag{2.1}$$

where the superscript 1 refer to the fundamental component and $+$, $-$ and 0 refer to the positive, negative and zero-sequence components respectively. $\sum v_t^h(t)$ represents the harmonics in the voltage. Further the fundamental positive-sequence and harmonic component is given by,

$$v_t^{1+}(t) = V_t^{1+} sin(\omega t) \tag{2.2}$$

$$\sum v_t^h(t) = \sum V_t^h sin(h\omega t + \xi_{vh}) \tag{2.3}$$

where superscript *h* is the harmonic order and ξ_{vh} is the angle corresponding to h^{th} harmonic order.The voltage at the PCC is expected to be sinusoidal with a fixed amplitude V_l,

$$v_l(t) = V_l sin(\omega t) \tag{2.4}$$

Hence the series converter has to compensate for the following components of the voltage,

$$v_{sd}(t) = v_l(t) - v_t(t) \tag{2.5}$$
$$= v_l(t) - v_t^{1+}(t) - v_t^{1-}(t) - v_t^{10}(t) - \sum v_t^h(t)$$

If there is no sag, ie. $V_l = V_t^{1+}$,then Eq. (2.6) reduces to,

$$v_{sd}(t) = -v_t^{1-}(t) - v_t^{10}(t) - \sum v_t^h(t) \tag{2.6}$$

The control system should automatically control the series converter so that its generated voltage at its output terminals is $v_{sd}(t)$ and matched with Eq. (2.6).

2.3.2 Obtaining balanced system current

The distorted nonlinear load current i_l can also be expressed as,

$$i_l(t) = i_l^{1+}(t) + i_l^{1-}(t) + i_l^{10}(t) + \sum i_l^h(t) \tag{2.7}$$

where $i_l^{1+}(t)$, $i_l^{1-}(t)$, $i_l^{10}(t)$ represent the positive,negative and zero-sequence components of the load current.$\sum i_l^h(t)$ represents the harmonic content in the load current. The fundamental positive-sequence component and the harmonic component can be expressed as,

$$i_l^{1+}(t) = I_l^{1+} sin(\omega t + \phi_l) \tag{2.8}$$

$$\sum i_l^h(t) = \sum I_l^h sin(h\omega t + \xi_{ih}) \tag{2.9}$$

where superscript h is the harmonic order and ξ_{ih} is the angle corresponding to the current of h^{th} harmonic order. ϕ_l is the load angle between the positive-sequence component of the load voltage and load current. The shunt converter is supposed to provide compensation of the load harmonic currents to reduce voltage distortion. It should act as a controlled current source and its output current must consist of harmonic,negative and zero-sequence currents to cancel the load current distortions. The shunt active filter is also responsible for maintaining the desired phase angle between the positive sequences of voltage and current at the load terminal. Taking these into account, the output current of the shunt converter must be controlled and must assume a wave shape as specified by Eq. (2.10).

$$i_f(t) = \frac{\beta|Q_{load}|}{V_l} cos(\omega t) + i_l^{1-}(t) + i_l^{10}(t) + \sum i_l^h(t) \tag{2.10}$$

where β is the amount of compensation that has to be provided by the shunt active filter of UPQC. This will ensure that the system current has a sinusoidal waveform and if full reactive compensation is provided by shunt UPQC then the source current is given by Eq. (2.12).

$$\begin{aligned} i_s(t) &= i_l(t) - i_f(t) \qquad (2.11) \\ &= I_l^{1+} cos(\phi_l) sin(\omega t) \end{aligned}$$

The equations (2.6) and (2.10) forms the reference voltage and current to be injected by the SEAPF and SHAPF respectively. If they are dynamically implemented by the UPQC controller, terminal load voltage and system current would be sinusoidal and balanced. The Control strategy of UPQC consists of sensing the voltages and currents, deriving the reference voltages and currents and generating the switching signals for semiconductor switches of UPQC. Once the reference currents and voltages have been derived, the gating signals to the switches in UPQC is generated using Pulse Width Modulation(PWM), Hysteresis or Fuzzy logic based control techniques.

2.4 Voltage Sag Compensation Through UPQC

Voltage sags and swells are commonly occurring problems in power system network. The phasor diagram of a UPQC compensated system without sag compensation is shown in Fig. 2.3. Here the phasors represent the RMS values of the voltages and currents. The superscript 1 shows that they are fundamental frequency components. $\vec{V}_t^1$ is the fundamental component of the terminal voltage appearing before UPQC series transformer. $\vec{V}_t^{1+}$ is the positive-sequence component of $\vec{V}_t^1$ and $\vec{I}_l^{1+}$ is the positive-sequence component of load current at fundamental frequency which is lagging $\vec{V}_t^{1+}$

by an angle of ϕ. In order to compensate for the reactive power drawn by the load, the SHAPF injects a current $\vec{I}_f^1$ perpendicular to the positive-sequence component of the terminal voltage making the source current $\vec{I}_s^1$ to be in phase with $\vec{V}_t^{1+}$. $\vec{V}_l^1$ is the required load voltage. The difference between the magnitudes of $\vec{V}_t^{1+}$ and $\vec{V}_l^1$ represents the voltage sag in the system.

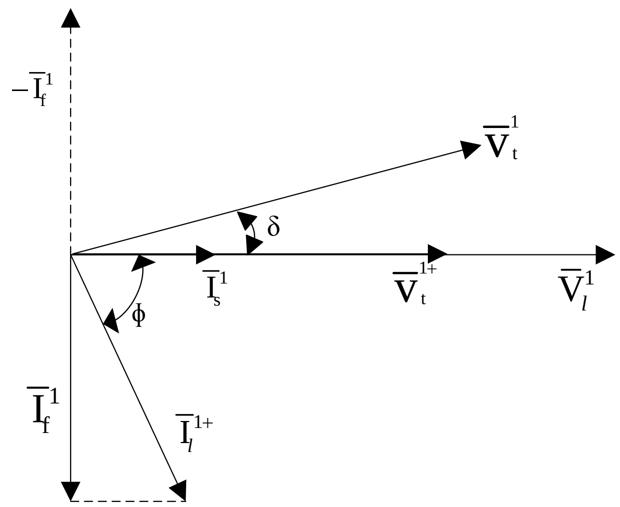

Figure 2.3 Phasor diagram of a UPQC compensated system without sag compensation

As specified earlier, the series active filter of UPQC can compensate source voltage sag/swell by injecting a series voltage with variable magnitude and angle with respect to the terminal voltage. By controlling the power angle, the amount of real and reactive power injected by the DVR is varied. Five methods have been suggested in literature for compensating sags. They are:

1. UPQC-P sag compensation
2. UPQC-Q sag compensation
3. UPQC-VAmin sag compensation
4. UPQC-S sag compensation
5. UPQC-presag Compensation

Each of the compensation method is explained below.

2.4.1 UPQC-P

The phasor diagram of the UPQC compensated distribution system through UPQC-P operation is shown in Fig. 2.4. Here the pre-sag quantities are represented by the subscript 1 and quantities during the sag condition are represented with the subscript 2. $\vec{V}_{t1}^{1}$ is the pre-sag voltage, where the superscript 1 indicates the fundamental component. $\vec{V}_{t2}^{1+}$ is the fundamental positive sequence component of the sag voltage $\vec{V}_{t2}^{1}$having a phase jump of δ. $\vec{I}_{l1}^{1}$ and $\vec{I}_{l2}^{1}$ are the load currents during pre-sag and sag conditions which in this case are equal and are lagging behind the positive sequence component of terminal voltage by an angle ϕ. $\vec{I}_{f1}^{1}$ is the compensating current injected by the DSTATCOM in order to make the source current $\vec{I}_{s1}^{1}$ in phase with the $\vec{V}_{t2}^{1+}$. The compensation voltage injected by the SEAPF is marked as $\vec{V}_{inj}^{1+}$.

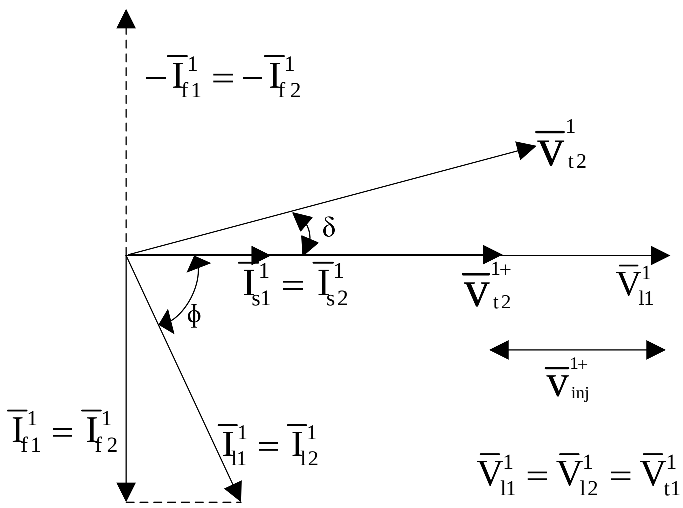

Figure 2.4 Phasor Diagram Of UPQC-P Compensation

In this method, the voltage injected by the SEAPF will be in phase with the source current. The magnitude of the voltage injected will be equal to the sag at the terminal side. When it comes to compensating unbalanced voltages with phase jumps, UPQC-P is not suitable. In such cases, the negative and zero sequences are compensated first by the series active filter, and then the positive sequence voltage is made equal to the pre-sag voltage. The in-phase component $\vec{V}_{inj}^{1+}$ injected is equal to the difference between pre-sag and reduced positive sequence voltage.

2.4.2 UPQC-Q

The phasor diagram of the UPQC compensated distribution system through UPQC-Q operation is shown in Fig. 2.5. In this method the voltage injected by the SEAPF $\vec{V}_{inj}^{1+}$ leads the source current by an angle of 90° thus supplying only reactive power. The load current during sag $\vec{I}_{l2}^{1}$ will lag the compensated load voltage $\vec{V}_{l2}^{1}$ by the load angle ϕ. The current injected by the SHAPF $\vec{I}_{f2}^{1}$, to account for the reactive power drawn by the load during sag condition is perpendicular to the compensated load voltage $\vec{V}_{l2}^{1}$. The compensated load voltage $\vec{V}_{l2}^{1}$ leads the pre-sag voltage by an angle θ. The maximum sag that can be compensated will be less than that for UPQC-P. Due to the absence of real power injection, the real power drawn by the UPQC will only cater to the losses incurred in the UPQC. Unbalanced voltage sag with phase jumps are taken care of by removing the negative and zero sequences and then injecting voltage in quadrature.

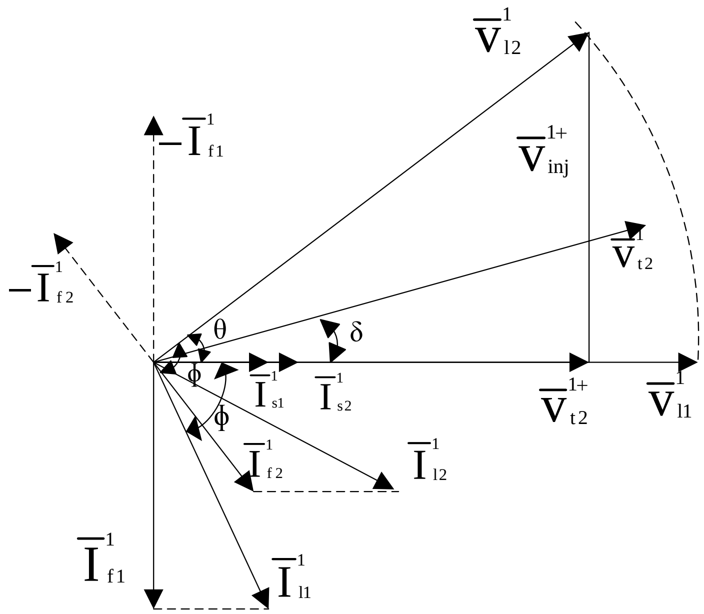

Figure 2.5 Phasor Diagram Of UPQC-Q Compensation

2.4.3 UPQC-VAmin

The phasor diagram of the UPQC compensated distribution system through UPQC-VAMin operation is shown in Fig. 2.6. The compensating voltage $\vec{V}_{inj}^{1+}$ is injected at an angle α with respect to the source current as shown in Fig. 2.6. This optimal angle is found out by minimizing the VA rating of the UPQC. The SEAPF will supply active and reactive power to the system in order to mitigate the sag. Besides the series voltage injection, the current drawn by the shunt inverter needs to be taken into account while determining the minimum VA loading of UPQC [12]. In case of unbalanced sags with voltage jumps,instead of separately compensating negative and zero sequence components, compensating voltage can be injected at an optimal angle that satisfies some set constraints to get balanced three phase load voltage.

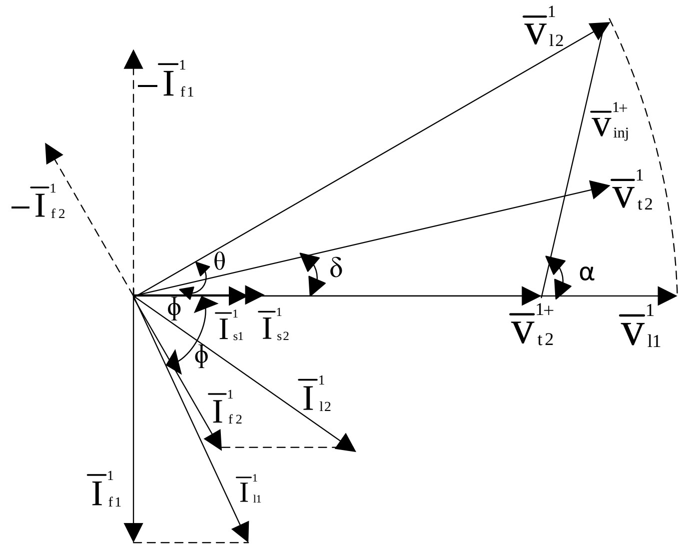

Figure 2.6 Phasor Diagram Of UPQC-VAMin Compensation

2.4.4 UPQC-S

The phasor diagram in Fig. 2.7 shows how voltage is injected at the steady state condition when there is no sag. Here the series inverter of UPQC is controlled to perform simultaneous voltage sag or swell compensation and load reactive power sharing with the shunt inverter. The Power Angle Control concept is integrated with active power control of series inverter thus reducing the required VA rating of the shunt inverter. The active power injected by the series inverter is taken by the shunt inverter from the source and transferred through the DC-link at steady state when there is no sag. As shown in Fig. 2.7 at steady state $\vec{V}_{inj}^{1}$ is injected at an angle α_{sr} with respect to terminal voltage thus introducing a phase jump of θ between the voltages at the load and terminal.

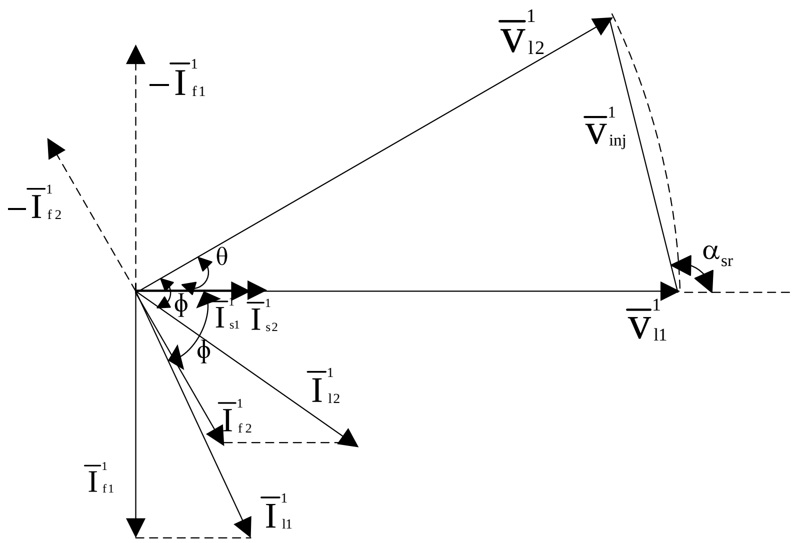

Figure 2.7 Phasor Diagram Of UPQC-S Compensation

2.4.5 UPQC-Presag

The vector voltage difference between the presag and the sag voltage given by $\vec{V}_{l1}^{1} - \vec{V}_{t1}^{1}$ is injected by the SEAPF. There is active and reactive power exchange between the UPQC and system.

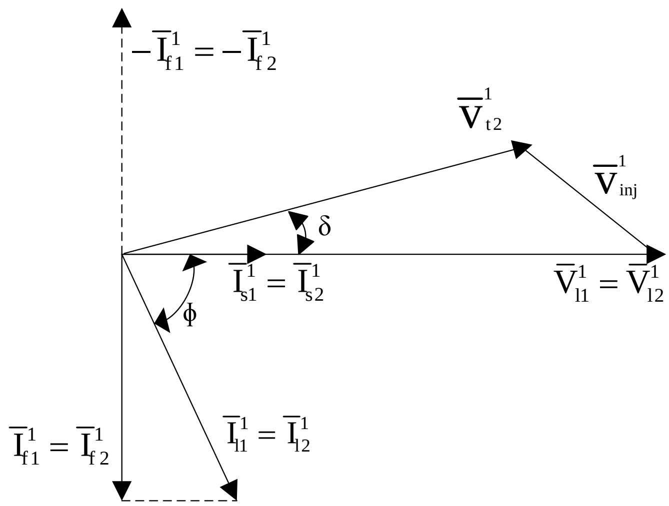

Figure 2.8 Phasor Diagram Of UPQC-Presag Compensation

2.5 Structure and Modeling Of UPQC

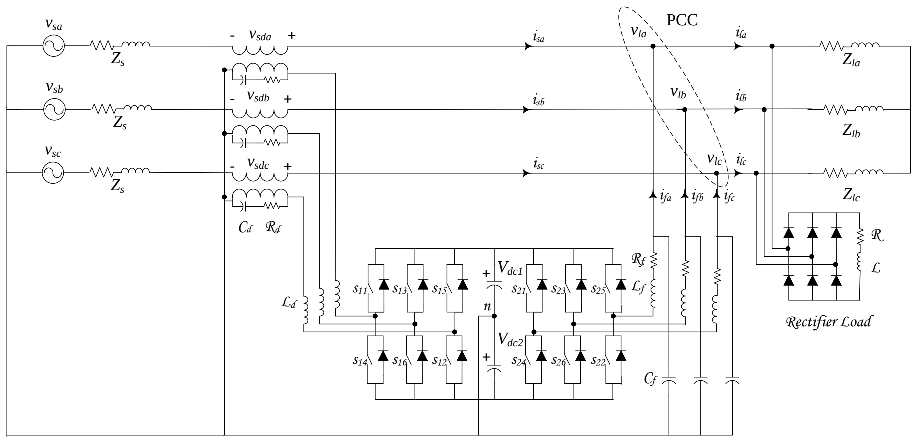

Figure 2.9 UPQC Compensated Three-Phase Four Wire Distribution System

A three-phase four wire system UPQC compensated system with neutral clamped voltage Source inverters is shown in Figure 2.9. The load consists of an unbalanced lagging power factor load and a rectifier load. The supply side is represented by Thevenin equivalent voltage sources v_{sa}, v_{sb}, v_{sc} and impedance Z_s. The UPQC consists of Series APF and Shunt APF. The SEAPF injects voltage through a coupling transformer connected in star. While the capacitor C_d,the resistor R_d and the inductor L_d constitutes the filter at the SEAPF side, the capacitor C_f is the filter at the SHAPF side. The resistance R_f and the inductance L_f represents the interfacing inductor. The DC-link consists of two storage capacitors with voltages V_{dc1} and V_{dc2}.

2.5.1 State space model

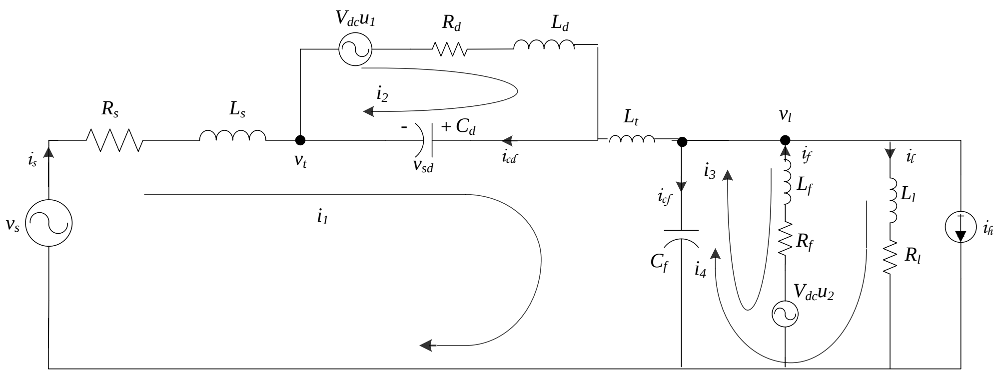

Figure 2.10 Single-Phase Equivalent Of UPQC Compensated System

The single phase equivalent of the Fig. 2.9 is shown in Fig. 2.10. Both the inverters are represented as voltage sources as they are connected to split capacitors with the same voltage V_{dc} maintained across them. L_t represents the leakage inductance of the series coupling transformer. The resistances R_d and R_f includes the switching losses in the inverter.R_l and L_l denotes the load resistance and inductance respectively.

For expressing as a state space model the state variables for the system can be taken as:

$$x = \begin{bmatrix} i_1 & i_2 & i_3 & i_4 & v_{sd} & v_l \end{bmatrix} \tag{2.12}$$

Writing mesh and node equations for the circuit using the state variables,

$$\frac{di_1}{dt} = -\frac{R_s i_1}{L_s + L_t} + \frac{v_{sd}}{L_s + L_t} - \frac{v_l}{L_s + L_t} + \frac{v_s}{L_s + L_t} \tag{2.13}$$

$$\frac{di_2}{dt} = -\frac{R_d i_2}{L_d} - \frac{v_{sd}}{L_d} + \frac{V_{dc} u_1}{L_d} \tag{2.14}$$

$$\frac{di_3}{dt} = -\frac{R_f i_3}{L_d} + \frac{v_l}{L_f} - \frac{V_{dc} u_2}{L_f} \tag{2.15}$$

$$\frac{di_4}{dt} = -\frac{R_l i_4}{L_l} + \frac{v_l}{L_l} \tag{2.16}$$

$$\frac{v_{sd}}{dt} = \frac{i_2}{C_d} - \frac{i_1}{C_d} \tag{2.17}$$

$$\frac{v_l}{dt} = -\frac{i_3}{C_f} - \frac{i_4}{C_f} + \frac{i_1}{C_f} - \frac{i_h}{C_f} \tag{2.18}$$

The inputs in the model are the Thevenin voltage v_s,the current drawn by the rectifier load i_h and the switching functions u_1 and u_2 for SEAPF and SHAPF respectively.

$$u^T = \begin{bmatrix} u_1 & u_2 & v_s & i_h \end{bmatrix} \tag{2.19}$$

Therefore the entire state space model can be written in the form

$$\dot{x} = Ax + Bu$$

$$\text{where} A = \begin{bmatrix} -\frac{R_s}{L_s+L_t} & 0 & 0 & 0 & \frac{1}{L_s+L_t} & -\frac{1}{L_s+L_t} \\ 0 & -\frac{R_d}{L_d} & 0 & 0 & -\frac{1}{L_d} & 0 \\ 0 & 0 & -\frac{R_f}{L_f} & 0 & 0 & \frac{1}{L_f} \\ 0 & 0 & 0 & -\frac{R_l}{L_l} & 0 & \frac{1}{L_l} \\ -\frac{1}{C_d} & \frac{1}{C_d} & 0 & 0 & 0 & 0 \\ \frac{1}{C_f} & 0 & -\frac{1}{C_f} & -\frac{1}{C_f} & 0 & 0 \end{bmatrix} \tag{2.20}$$

$$B = \begin{bmatrix} 0 & 0 & \frac{1}{L_s+L_t} & 0 \\ \frac{V_{dc}}{L_d} & 0 & 0 & 0 \\ 0 & -\frac{V_{dc}}{L_f} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{C_f} \end{bmatrix} \tag{2.21}$$

The state variables must be measurable to provide a feedback control mechanism. Therefore the state variables in Equation 2.13 are transformed to get a new set of variables that are physically available and are more important from the control point of view.

$$z = \begin{bmatrix} i_f & i_{cf} & v_l & i_{cd} & v_{sd} & i_l \end{bmatrix} \tag{2.22}$$

Here i_f is the shunt APF current, i_{cf} and i_{cd} are the capacitor filter currents in SHAPF and SEAPF respectively.The source current is represented as i_s and load current as i_l. v_{sd} is the SEAPF injected voltage and v_l is the voltage at the Point of Common Coupling.From Figure 2.10,

$$i_s = i_1 \qquad\qquad i_l = i_4 \tag{2.23}$$

$$i_f = i_4 - i_1 \qquad\qquad i_{cf} = i_1 - i_4 - i_3 \tag{2.24}$$

$$i_{cd} = i_2 - i_1 \tag{2.25}$$

The model is transformed using the transformation matrix P as,

$$z = Px$$

$$\dot{z} = PAP^{-1}z + PBu$$

$$\text{where} \quad P = \begin{bmatrix} -1 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & -1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

The control inputs for the system are the switching functions which are obtained by a feedback mechanism. The feedback controller used in the simulation is the Linear Quadratic Regulator. The Linear Quadratic regulator (LQR) algorithm is, at its core, an automated way of finding an appropriate state-feedback controller. It is a technique in modern control which uses state space approach to analyze a system.

$$u = -K(z - z_{ref}) \tag{2.26}$$

$$J = \int_0^\infty (z(t)^T Q z(t) + u(t)^T R u(t)) dt \tag{2.27}$$

The technique involves choosing a control law to minimize the cost function. The control input is given by Equation (2.26). This technique determines the feedback gain matrix that minimizes the cost function *J* given by Equation (2.27) in order to achieve some compromise between the use of control effort, the magnitude, and the speed of response that will guarantee a stable system. The matrices Q and R are called the state and control penalty matrices, respectively. For a LTI system,

$$K = R^{-1}B^T P \tag{2.28}$$

where P is the symmetric positive semidefinite solution of the Algebraic Riccati Equation(ARE) given by

$$0 = PA + A^T P + Q - PBR^{-1}BP \tag{2.29}$$

The error between the actual and reference state variables is fed into the LQR controller. The derivation of reference state variables is further discussed.

2.5.2 Generation of reference quantities

The SHAPF usually takes care of the unbalance and harmonics in the load current whereas the SEAPF deals with sags and harmonics in the incoming voltage. Besides this they act as a source of reactive power to maintain the power factor as high as possible. The reference quantities are obtained from the actual state variables. The load current and the terminal voltage before UPQC are sensed. The instantaneous current and voltage signals are resolved into their instantaneous zero, positive and negative sequence components. The symmetrical-sequence components at fundamental frequency are then extracted using the following expression[16].

$$v_{s1}^{+} = \frac{\sqrt{2}}{T}\int_{t_1}^{t_1+T} v_s^{+}(t)\exp^{-j(\omega t-\frac{\pi}{2})} \tag{2.30}$$

$$v_{s1}^{-} = \frac{\sqrt{2}}{T}\int_{t_1}^{t_1+T} v_s^{-}(t)\exp^{-j(\omega t-\frac{\pi}{2})} \tag{2.31}$$

$$v_{s1}^{0} = \frac{\sqrt{2}}{T}\int_{t_1}^{t_1+T} v_s^{0}(t)\exp^{-j(\omega t-\frac{\pi}{2})} \tag{2.32}$$

The subscript 1 corresponds to the fundamental frequency and the superscript represents the sequence. Once the harmonics are removed from the symmetrical components, the reference quantities at fundamental frequency are obtained as,

$$\begin{bmatrix} i_f^0 \\ i_f^+ \\ i_f^- \end{bmatrix} = \begin{bmatrix} i_{l1}^0 \\ i_c \\ i_{l1}^- \end{bmatrix} \tag{2.33}$$

$$\begin{bmatrix} i_{fa}^{ref} \\ i_{fb}^{ref} \\ i_{fc}^{ref} \end{bmatrix} = T^{-1} \times \begin{bmatrix} i_f^0 \\ i_f^+ \\ i_f^- \end{bmatrix} \tag{2.34}$$

$$\text{where} \quad i_c = \frac{\beta Q_{lavg}}{v_{l1}^{+}} \tag{2.35}$$

$$\begin{bmatrix} v_{sda}^{ref} \\ v_{sdb}^{ref} \\ v_{sdc}^{ref} \end{bmatrix} = \begin{bmatrix} V_{inja} \\ V_{injb} \\ V_{injc} \end{bmatrix} \tag{2.36}$$

$$v_l^{ref} = v_t + v_{sd}^{ref} \tag{2.37}$$

$$i_{cf}^{ref} = j\omega C_f v_l^{ref} \tag{2.38}$$

$$i_{cd}^{ref} = j\omega C_d v_{sd}^{ref} \tag{2.39}$$

Here β can take any value from 0 to 1. The three phases are represented by a, b, c in the subscript. The symmetrical components of the filter current are transformed to three phase currents using the transformation matrix given by,

$$T = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \tag{2.40}$$

where $a = e^{j\frac{2\pi}{3}}$. The harmonics in the load current and the terminal voltage are taken into account by modifying the reference current and voltage injected by SHAPF and SEAPF respectively.

$$i_f^{ref} = i_f^{1ref} + i_l^{har} \qquad\qquad v_{sd}^{ref} = v_{sd}^{1ref} - v_t^{har} \tag{2.41}$$

The reference quantities are then passed onto the LQR Controller to provide the control outputs. The switching functions u_1 and u_2 are synthesized by the Hysterisis Controller based on the control inputs by the following logic,

if $u(1) >$ limit, then u_1 = 1 which indicates the top switch

if $u(1) < -$limit, then u_1 = -1 which indicates the bottom switch

The error between the reference and actual state variables is made to go to zero by the LQR Controller. Thus balanced PCC voltages and source currents are obtained by the proper working of DVR and DSTATCOM.

2.6 Summary

The basic structure and operation of UPQC have been covered in this chapter. Different possible UPQC configurations based on sag compensation have been listed.The various voltage sag compensation techniques have their own advantages as well as disadvantages which will be discussed later on. A three-phase four wire UPQC compensated system has been modeled and the reference current generation for the same has been discussed. LQR based state feedback control of UPQC is presented.

CHAPTER 3

VOLTAGE SAG COMPENSATION SCHEMES THROUGH UPQC

3.1 Introduction

The economic considerations of a UPQC include the rating of the inverter switches, the VA rating of the coupling transformers, the filter specifications and the battery storage required to maintain the DC-link voltage. By reducing the amount of real power injection by the DVR the cost of UPQC can be brought down. Integrating a capacitor bank with the UPQC further helps in maintaining the terminal voltage at the required level thus reducing the load on the series APF of UPQC. In this chapter the proposed system of UPQC with a capacitor bank is modelled in state space. The objective function for minimizing real power injection by the UPQC is derived and is optimized using a gradient search algorithm. For real time implementation of the optimization process, Adaptive Neuro Fuzzy Inference Systems (ANFIS) is used. Simulations are done on a three-phase four wire system and the results are presented.

3.2 Drawbacks Of Existing Schemes

In Chapter 2 the different configurations and sag compensation schemes were seen briefly. The cost of energy storage can be brought down by reducing the amount of real power injection and absorption by the series APF of UPQC. UPQC-Q caters to this principle wherein real power injection is nearly zero. The proper working of this scheme requires high magnitudes of injection voltage during severe sags. This may result in a failure of the compensating system. This is explained clearly with the phasor diagram shown in Fig. 3.1. Here $\vec{V}_{l1}$ is the nominal load voltage and the operation of UPQC-Q during two sag conditions is shown. When the terminal voltage is given by $\vec{V}_{t2}$, the quadrature injection of a voltage of magnitude $|\vec{V}_{inj2\_q}|$ is sufficient for achieving the nominal voltage. But when the sag becomes more severe, ie.for a more reduced terminal voltage of $\vec{V}_{t3}$ the rated voltage V_{rated} is not enough for sag mitigation by quadrature injection. The magnitude of voltage needed to be injected in quadrature to attain the nominal load voltage, $|\vec{V}_{inj3\_q}|$ is ΔV more than V_{rated}. On the contrary the sag could be taken care of if the voltage is injected at an angle α with respect to terminal voltage as shown by $\vec{V}_{opt}$ in Fig.3.1.

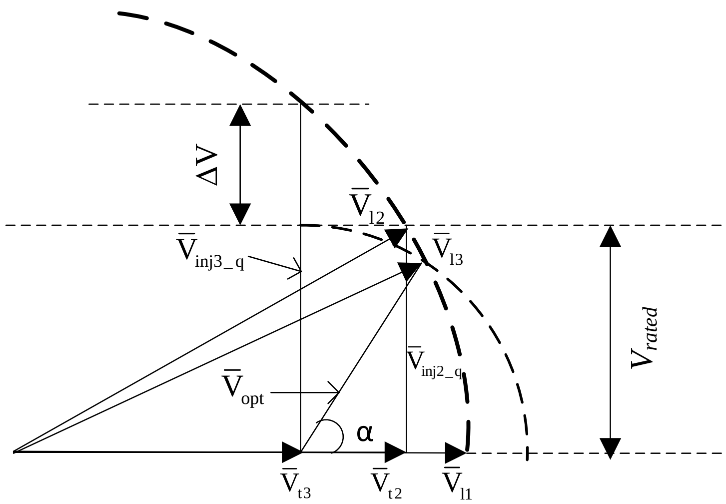

Figure 3.1 UPQC-Q Operation For Different Sags

In UPQC-P scheme the magnitude of injected voltage comes down whereas the cost of energy storage goes up. UPQC-VAmin minimizes the overall VA loading of the UPQC with respect to the positive-sequence component by injecting a series voltage through DVR at an optimum angle. The unbalanced voltage sags with phase jumps in all of the aforementioned operations are mitigated with respect to positive-sequence sag voltage. The SEAPF of UPQC is supposed to inject the negative, zero-sequence voltage other than positive-sequence voltage. In that case the available SEAPF injected voltage to achieve the nominal load voltage is,

$$V_{inj}^1 = \sqrt{(V_{rated})^2 - (V_{inj\_n0}^1)^2 - \sum_{i=2}^{n}(V_h^i)^2} \quad (3.1)$$

where V_{inj_n0} is the injected voltage by SEAPF to mitigate the negative and zero sequences, V_h is the harmonic voltage and i is the harmonic number[10]. Apart from reduction in the available voltage for sag mitigation, these methods require more VA.

In [9] VA minimization was done by optimizing the VA loading of UPQC subjected to some constraints without separate compensation of the negative and zero sequences. The above method was found to reduce the VA rating considerably. But optimizing the VA loading of UPQC does not lead to a lower rating of switching devices and interfacing transformer. The SEAPF of UPQC can supply 50% of the load power during a voltage sag of 0.5 pu[17]. Due to this reason the series injection transformer rating should be at least 50% of the load rating. Since the transformer rating and the DC-link voltage are fixed, the SEAPF rating is fixed and will not depend on optimal VA rating [18].

In [10] a method was proposed to minimize real power injection by UPQC,with practical constraints, such as the injected voltage limit on the series active filter, phase jump mitigation, and angle of voltage injection. The above method brings a reduction in the capacity of energy storage. Further diminution in the energy storage capacity can be brought out by placing a capacitor bank in front of the UPQC. The proposed method in this work integrates a capacitor bank with the UPQC in trying to reduce the battery backup required by the DC-link.

3.3 Proposed Method For Mitigation Of Voltage Sags

According to the Indian Electricity Grid Code(2010) the voltage at PCC is allowed to be between 0.9 pu and 1.05 pu. The UPQC need not necessarily correct the voltage sags and make the voltage at PCC exactly equal to 1 pu. It is sufficient to mitigate the sags by bringing the voltage up to 0.95 pu. This would help in bringing down the amount of real power that has to be injected. Another possible solution to reduce the real power injection by SEAPF is to use a capacitor bank along with the UPQC. A capacitor is a source of reactive power and injects reactive power into the system. The voltage variation between two buses is determined by the reactive power flow in the line between them.

$$Q = V_s \frac{\Delta V}{X} \tag{3.2}$$

where V_s is the sending end voltage and X is the reactance between the sending and receiving end. With a negative Q the receiving end voltage would be greater than the sending end voltage. This method has been the most primitive way of mitigating sags at the load terminal. The drawback is that the amount of reactive power injected depends on the terminal voltage. As the terminal voltage comes down, the reactive power injected also decreases. In the case of unbalanced voltage sags with phase jumps, this scheme wont be able to restore the PCC voltage to the balanced state.

Integration of a capacitor bank along with the UPQC would reduce the amount of sag that has to be compensated by the UPQC. During sag,due to the presence of the capacitor bank the terminal voltage will increase slightly and the rest of the dip can be compensated by the UPQC. Thus for compensating the same amount of sag the active power that the UPQC has to provide will come down. This in turn would reduce the capacity of the energy storage required. The magnitude and angle of the voltage injected by the SEAPF of UPQC is found out by optimizing the real power injected by the SEAPF. The optimization is done with the help of the fmincon function in MATLAB. For real time applications an Adaptive Neuro Fuzzy Inference System (ANFIS) has been trained for carrying out the optimization process.

3.3.1 Structure and modelling of the proposed system

The three-phase four wire system UPQC compensated system shown in Fig. 2.9 is modified by adding a star connected capacitor bank as shown in Figure 3.2.

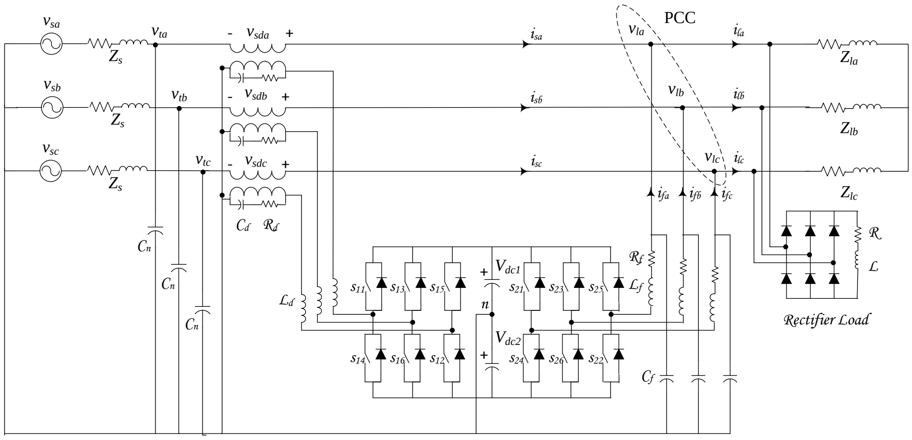

Figure 3.2 Proposed UPQC Compensated Three-Phase Four Wire Distribution System

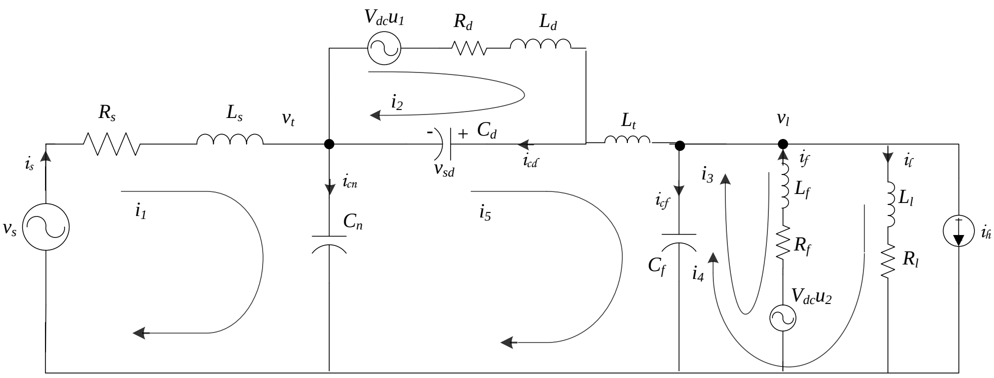

Figure 3.3 Single Phase Equivalent Of UPQC Compensated System

The single phase equivalent of the Figure 3.2 is shown in Figure 3.3. The addition of the capacitor bank increases the number of state variables by two in the state space model specified by the Equations (2.21) and (2.22). The modified state vector is given by,

$$x = \begin{bmatrix} i_1 & i_2 & i_3 & i_4 & i_5 & v_{sd} & v_t & v_l \end{bmatrix} \tag{3.3}$$

Writing the modified first order differential equations,

$$\frac{di_1}{dt} = -\frac{Ri_1}{L_s} + \frac{v_{sd}}{L_s} - \frac{v_l}{L_s} + \frac{v_s}{L_s} \tag{3.4}$$

$$\frac{di_2}{dt} = -\frac{R_d i_2}{L_d} - \frac{v_{sd}}{L_d} + \frac{V_{dc}u_1}{L_d} \tag{3.5}$$

$$\frac{di_3}{dt} = -\frac{R_f i_3}{L_d} + \frac{v_l}{L_f} - \frac{V_{dc}u_2}{L_f} \tag{3.6}$$

$$\frac{di_4}{dt} = -\frac{R_l i_4}{L_l} + \frac{v_l}{L_l} \tag{3.7}$$

$$\frac{di_5}{dt} = \frac{v_{sd}}{L_t} + \frac{v_t}{L_t} - \frac{v_l}{L_t} \tag{3.8}$$

$$\frac{v_{sd}}{dt} = \frac{i_2}{C_d} - \frac{i_5}{C_d} \tag{3.9}$$

$$\frac{v_t}{dt} = \frac{i_1}{C_n} - \frac{i_5}{C_n} \tag{3.10}$$

$$\frac{v_l}{dt} = -\frac{i_3}{C_f} - \frac{i_4}{C_f} + \frac{i_5}{C_f} - \frac{i_h}{C_f} \tag{3.11}$$

The modified *A* and *B* matrices are now given by,

$$A = \begin{bmatrix} -\frac{R_s}{L_s} & 0 & 0 & 0 & 0 & \frac{1}{L_s} & 0 & -\frac{1}{L_s} \\ 0 & -\frac{R_d}{L_d} & 0 & 0 & 0 & -\frac{1}{L_d} & 0 & 0 \\ 0 & 0 & -\frac{R_f}{L_f} & 0 & 0 & 0 & 0 & \frac{1}{L_f} \\ 0 & 0 & 0 & -\frac{R_l}{L_l} & 0 & 0 & 0 & \frac{1}{L_l} \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{L_t} & \frac{1}{L_t} & -\frac{1}{L_t} \\ 0 & \frac{1}{C_d} & 0 & 0 & -\frac{1}{C_d} & 0 & 0 & 0 \\ \frac{1}{C_n} & 0 & 0 & 0 & -\frac{1}{C_n} & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{C_f} & -\frac{1}{C_f} & \frac{1}{C_f} & 0 & 0 & 0 \end{bmatrix} \tag{3.12}$$

$$B = \begin{bmatrix} 0 & 0 & \frac{1}{L_s} & 0 \\ \frac{V_{dc}}{L_d} & 0 & 0 & 0 \\ 0 & -\frac{V_{dc}}{L_f} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{C_f} \end{bmatrix} \tag{3.13}$$

For physical measurement, the state variables are transformed as,

$$z = \begin{bmatrix} i_f & i_{cf} & v_l & i_{cd} & v_{sd} & v_t & i_l & i_{cn} \end{bmatrix} \tag{3.14}$$

Here i_{cn} is the current through the capacitor. From Figure 3.3,

$$i_s = i_1 \qquad\qquad i_l = i_4 \tag{3.15}$$

$$i_f = i_4 - i_5 \qquad\qquad i_{cf} = i_5 - i_4 - i_3 \tag{3.16}$$

$$i_{cd} = i_2 - i_5 \qquad\qquad i_{cn} = i_1 - i_5 \tag{3.17}$$

The model is transformed using the transformation matrix P as,

$$z = Px \tag{3.18}$$

$$\text{where} \quad P = \begin{bmatrix} 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & -1 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \end{bmatrix} \tag{3.19}$$

Thus the Equations 3.12, 3.13 and 3.19 completes the state space model of the system.

3.3.2 Formulation of objective function

In this work the SEAPF of UPQC compensates unbalanced sags with phase jumps by injecting voltage V_{inj} at an angle α with respect to the terminal voltage. V_{inj} and α are obtained by minimizing the objective function which is the real power injected by the SEAPF.

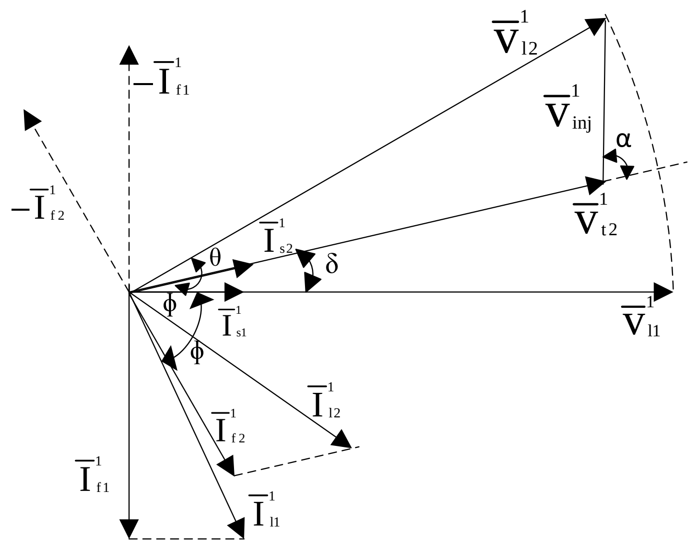

Figure 3.4 Phasor Diagram Of Optimal Real Power Injection By UPQC

In the phasor diagram shown in 3.4 the superscript 1 in all the quantities indicates the fundamental frequency component,the subscript 1 indicates pre-sag condition and subscript 2 indicates sag condition. $\vec{V_t}$ is the terminal voltage ,$\vec{I_l}$ is the load current and $\vec{I_f}$ is the compensating current injected by the DSTATCOM.$\vec{I_s}$ represents the current flowing through the series coupling transformer and $\vec{V_l}$ represents the PCC voltage.δ is the phase jump, ϕ is the load angle and θ is the angle shift in load voltage from terminal voltage due to the action of SEAPF. The magnitudes of all these phasors are the RMS values of the corresponding quantities. In pre-sag condition,

$$V_{t1}^1 = V_{l1}^1 \tag{3.20}$$

V_{t1}^1,the magnitude of terminal voltage during sag is given by,

$$V_{t2}^1 = V_{l1}^1(1 - x) \tag{3.21}$$

where x is the sag in per unit.From the phasor diagram,

$$V_{inj}^1 = \sqrt{(V_{l2}^1 \cos\theta - V_{t2}^1)^2 + (V_{l2}^1 \sin\theta)^2} \tag{3.22}$$

$$V_{l2}^1 = V_{l1}^1 \tag{3.23}$$

$$\tan(\alpha) = \frac{V_{l2}^1 \sin\theta}{V_{l2}^1 \cos\theta - V_{t2}^1} \tag{3.24}$$

During sag, the load angle and magnitude of load current remains the same.

$$I_{s2}^1 + I_{f2}^1 e^{-j(\frac{\pi}{2}-\theta)} = I_{l2}^1 e^{-j(\phi-\theta)} \tag{3.25}$$

Equating the real and imaginary parts,

$$I_{f2}^1 = I_{l2}^1 \frac{\sin(\phi - \theta)}{\cos(\theta)} \tag{3.26}$$

$$I_{s2}^1 = I_{l2}^1 \cos(\phi - \theta) - I_{f2}^1 \sin(\theta) \tag{3.27}$$

Replacing I_{f2}^1 in Equation 3.27 by Equation 3.26 gives,

$$I_{s2}^1 = I_{l2}^1 \frac{\cos(\phi)}{\cos(\theta)} \tag{3.28}$$

The active power injected by SEAPF for each phase is given by,

$$P_{inj\_j} = V_{inj\_j}^1 I_{s2\_j}^1 \cos(\alpha_j) \tag{3.29}$$

where j= a, b, c. Figure 3.5 shows the phasor diagram for a three-phase system with unbalanced voltages. Here $\vec{V}_{t1j}^1$, $\vec{V}_{t2j}^1$, $\vec{V}_{injj}^1$ represents the pre-sag, sag, injected voltage respectively for the $j_t h$ phase. During optimization of the objective function, there are some constraints that has to be satisfied. The three phase resultant PCC voltages should have a 120° phase shift with respect to each other as shown in Figure 3.5. Also the V_{inj}^1 has a rated value which cannot be exceeded.

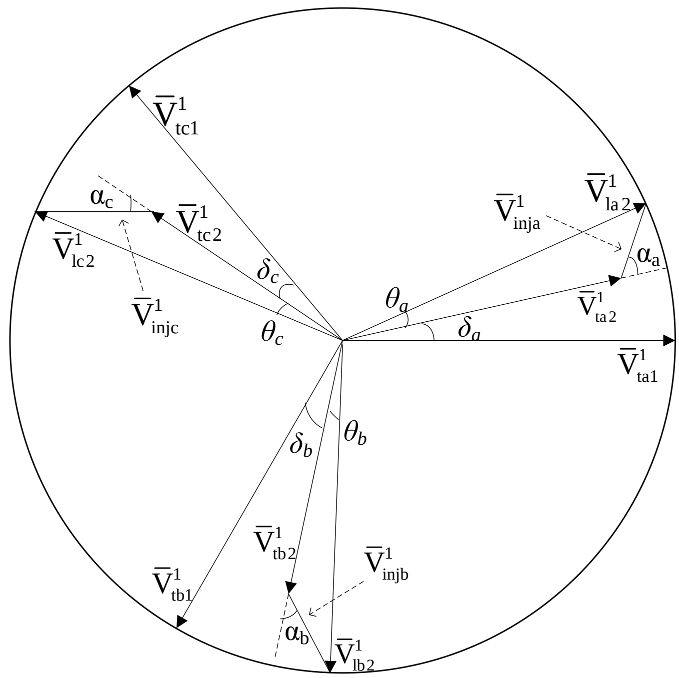

Figure 3.5 Phasor Diagram Showing The Three-Phase Unbalanced Voltages With Phase Jumps

With the constraints the objective function finally comes down to,

$$\text{Minimize} \quad P_{inj}(\theta) = \sum_{j=a,b,c} V^1_{inj\_j} I^1_{s2\_j} \cos(\alpha_j) \tag{3.30}$$

$$\text{Subjected to:} \quad V_{inj\_j} \leq 0.5$$

$$\theta_a + \delta_a = \theta_b + \delta_b = \theta_c + \delta_c$$

$$-90^{\circ} \leq \theta_j \leq 90^{\circ}$$

$$\text{where} \quad V_{inj\_j} = \sqrt{(V^1_{inj\_j})^2 + \sum_{i=2}^{n} (V^i_{har\_j})^2} \tag{3.31}$$

where $V^i_{har\_j}$ is the i^{th} harmonic terminal voltage of phase j which also the DVR has to inject if the source contains voltage harmonics.

3.3.3 Optimization of objective function

The optimal solution for the objective function that satisfies the equality and inequality constraints can be found out by using any optimization algorithms. In the work done, the fmincon function in MATLAB using interior point algorithm has been used. The interior-point approach to constrained minimization is to solve a sequence of approximate minimization problems. The original problem given by,

$$\min_{x} f(x) \tag{3.32}$$

Subjected to:

$$h(x) = 0$$

$$g(x) \leq 0$$

For each $\mu \geq 0$, the approximate problem is,

$$\min_{x,s} f_\mu(x,s) = \min_{x,s} f(x) - \mu \sum_i \ln(s_i), \text{subject to } \; h(x) = 0 \;\text{ and }\; g(x) + s = 0 \tag{3.33}$$

There are as many slack variables s_i as there are inequality constraints g. The s_i are restricted to be positive to keep $\ln(s_i)$ bounded. As μ decreases to zero, the minimum of f_μ should approach the minimum of f. The added logarithmic term known as the barrier function makes the objective function a sequence of equality constrained problems. To solve the approximate problem,the algorithm first attempts to take a direct step wherein it tries to solve the Karush-Kuhn-Tucker (KKT) equations. The KKT equations are analogous to the condition that at a minimum the gradient must be zero , but modified to take constraints into account. If the direct step method fails,the algorithm uses a conjugate gradient step using a trust region.In this approach the aim is to minimize a quadratic approximation to the approximate problem in a trust region, subject to linearized constraints. At each iteration the algorithm decreases a merit function given by,

$$f_\mu(x,s) + v||h(x), g(x) + s|| \tag{3.34}$$

The parameter v may increase with iteration number in order to force the solution towards feasibility. If an attempted step does not decrease the merit function, the algorithm rejects the attempted step, and attempts a new shorter step.

3.3.4 Optimization using trained ANFIS

Adaptive Neural Fuzzy Inference System (ANFIS)is a product by combining the fuzzy inference system with the neural networks. ANFIS fully makes use of the excellent characteristics of the neural networks and the fuzzy inference system, and is widely applied in many fields of fuzzy controller design and model identification. Being iterative algorithms all optimization algorithms take some time to converge to an optimal solution. When the compensation system is made on-line, this time delay cannot be tolerated. To avoid this here an ANFIS system is trained to imitate the behaviour of the optimization process. As a special neural network, ANFIS can approximate all nonlinear systems with less training data and quicker learning speed and higher precision. The fuzzy inference system implemented in ANFIS is the Takagi-Sugeno-Kang Fuzzy system.

A fuzzy logic system (FLS) can be defined as the nonlinear mapping of an input data set to a scalar output data. Fuzzy logic converts human supplied rules into their mathematical equivalents. A FLS basically consists of the fuzzifier, rules, inference engine, and the defuzzifier. An adaptive network is a network structure consisting of nodes and directional links through which the nodes are connected. The adaptive network forces the output of each node to depend on the parameters pertaining to the corresponding node and then the learning algorithm indicates how these parameters should be changed to minimize a defined error measure.

In ANFIS,the adaptive network structure maps inputs through input membership functions and associated parameters and then onto outputs through output membership functions and associated parameters. In the ANFIS structure in Figure 3.6, the layer 1 fuzzifies the inputs using standard membership functions which are then aggregated in layer 2 and passed onto the next layer. The layer 3 determines the ratio of firing strength of each rule to the sum of firing strength of all the rules. Layer 4 calculates the weighted output for each linear function of the inputs using the ratio of rule strengths and output parameters. The final layer aggregates all the linear functions to give the output.

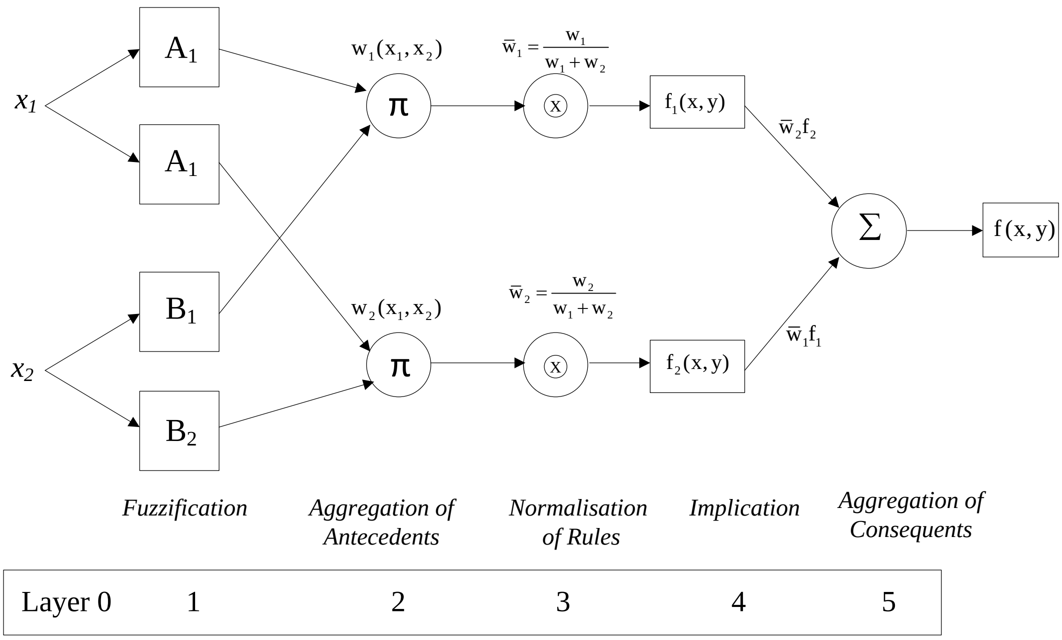

Figure 3.6 Typical ANFIS Structure For Two Inputs

The parameters associated with the membership functions are changed through the learning process. The computation of these parameters is facilitated by a gradient vector. The gradient vector provides a measure of how well the fuzzy inference system models the input/output data for a given set of parameters. When the gradient vector is obtained, any of several optimization routines can be applied in order to adjust the parameters to reduce some error measure. The error measure is usually defined by the sum of the squared difference between actual and desired outputs[19].

ANFIS in MATLAB implements two methods to identify the inference parameters,namely grid partitioning and subtractive clustering. Grid partitioning is a subjective approach, in which the number of clusters into which each variable is segmented is initially provided by the user. The number of rules is determined by multiplying the number of clusters of each input variable. In subtractive clustering method, the rule extraction method first determines the number of rules and antecedent membership functions and then uses linear least squares estimation to determine each rules consequent equations[19]. Since ANFIS implements an adaptive learning algorithm,it uses either back propagation or a combination of least squares estimation and back propagation for parameter estimation.

3.4 Simulation Studies

Simulation was done for a three-phase four wire system with neutral clamped VSI's in the UPQC. The system parameters considered are given in Table3.1. All the values are given in per unit with the base as 5 KVA and 230 V.

System Parameters	**Values in pu**
System Voltage & Frequency	1.0 pu(L-N),50 Hz
Load	Z_{la}=0.5+j1.0,Z_{lb}=1.2+j2.8,
	Z_{lc}=1.0+j4.25
Feeder Impedence	Z_s=0.05+j0.1
Shunt capacitive reactance	X_{cn}=-j1.5
SHAPF filter specifications	X_{cf}=-j7.02, X_{lf}=j0.1
SEAPF filter specifications	X_{cd}=-j4.0, X_{ld}=j0.04
Transformer Leakage Reactance	X_t=j0.1
DC Capacitor Voltage	2.5
Load Current for three-phase rectifier load	1.0

Table 3.1 System Parameters

The control signals required by the UPQC is generated by the LQR controller. The gain matrix K of the LQR Controller is obtained from the system parameters and the Q and R matrices as explained in Equations 2.28 and 2.29. The Q and R matrices are decided based on the weight that has to be given to the state variables and the inputs. A suitable Q matrix would be a diagonal matrix with the values given by[18],

$$Q = \text{diag}\begin{bmatrix}20 & 1 & 10 & 1 & 10 & 0 & 0 & 0\end{bmatrix} \tag{3.35}$$

$$R = \begin{bmatrix}0.1 & 0\\ 0 & 0.1\end{bmatrix} \tag{3.36}$$

Using this, the gain matrix was found to be,

$$K = \begin{bmatrix}10.6164 & 4.4509 & 17.5595 & -0.2249 & -5.6283 & -7.3903 & -0.4109 & -0.4624\\ -9.1250 & -0.2249 & -3.4344 & 3.8402 & 14.9933 & 8.7842 & 0.4871 & 0.4539\end{bmatrix} \tag{3.37}$$

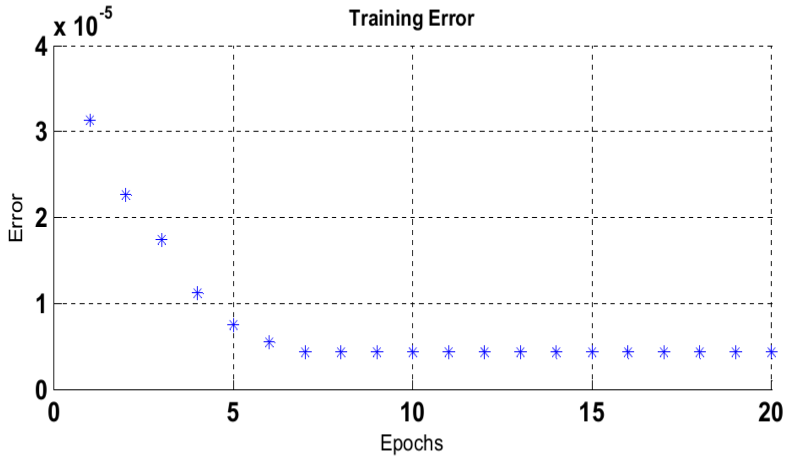

Figure 3.7 Training Error Of The ANFIS

To decouple SEAPF and SHAPF control and to avoid complexity of determining the load and the capacitor bank reference currents, those terms are omitted from the gain matrix. So the new matrix would be,

$$K = \begin{bmatrix} 10.6164 & 4.4509 & 17.5595 & 0 & 0 \\ 0 & 0 & 0 & 3.8402 & 14.9933 \end{bmatrix} \tag{3.38}$$

The simulation was done for the cases of balanced, unbalanced sags and also unbalanced sags with phase-jumps. The source was harmonic free and the load considered was a combination of rectifier load and an unbalanced lagging power factor load.

3.4.1 ANFIS training and testing

In order to train the ANFIS the input variables and the output of the optimization process are given as data to the ANFIS. One of the constraints of ANFIS is being able to give only a single output. In the case of balanced and unbalanced sags without phase jumps,only one output is sufficient. When phase jumps are also considered,the above constraint results in the decoupled calculation of the optimal angles for all the three phases. The input data would be the RMS value of the terminal voltage at fundamental frequency and the phase jump angle for all the three phases.

In order to train ANFIS, a set of 310 data samples are selected which constitutes different combinations of voltage unbalances and phase jumps. Using the optimization algorithm to minimize real power injection, the values of the angle between the compensated load voltage and the terminal sag voltage were calculated and was given to ANFIS as the output data. The FIS is generated using the Subtractive Clustering method available in the ANFIS toolbox of MATLAB. The plot showing the training error for each epoch is shown in Figure 3.7. The error remains constant at 4.36387×10^{-6} after 7^{th} epoch.

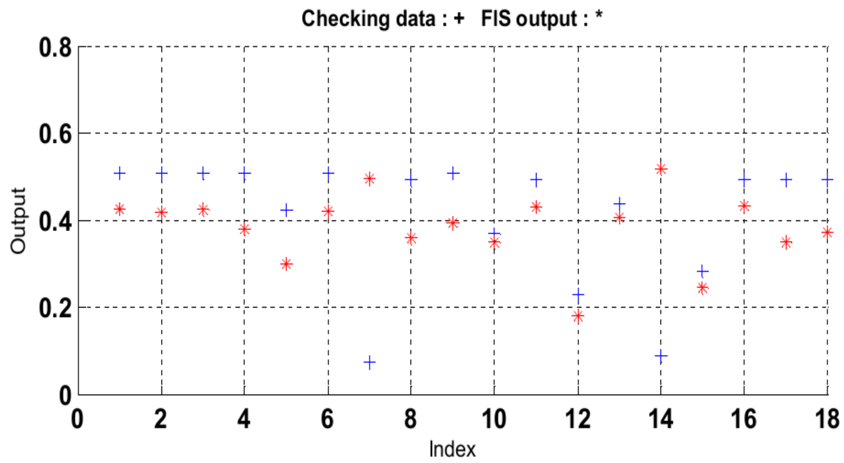

Figure 3.8 Checking Data Error With ANFIS

The trained ANFIS was tested against a sample of 18 data sets which is shown in Figure 3.8. The + represents the checking data whereas the $*$ represents the FIS output. The average error was found to be 0.166 radians.

3.4.2 Balanced sag mitigation

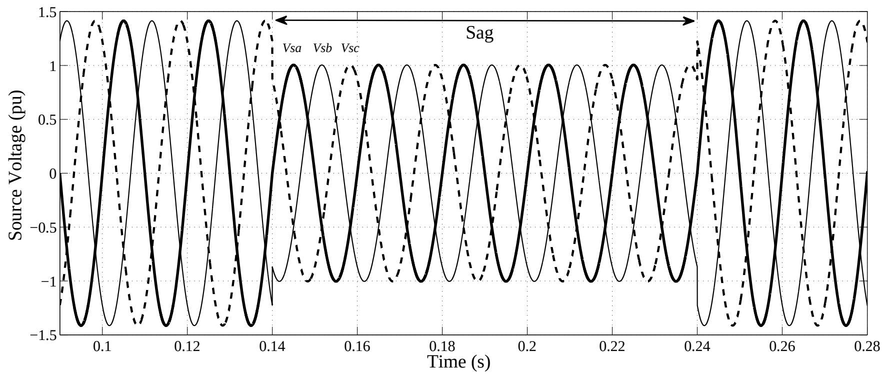

Figure 3.9 Source Voltage With Balanced Sag

A balanced sag as shown in Figure 3.9 is the one in which there is an equal reduction in the magnitude of the terminal voltage in all three phases. The sag was introduced by modifying the value of the supply voltage in the model. The sag was introduced between $t = 0.14$ s and $t = 0.24$ s. During sag period, the phases have an RMS value of 0.71 pu with no phase jump. The load consists of an unbalanced load as well as a nonlinear load.

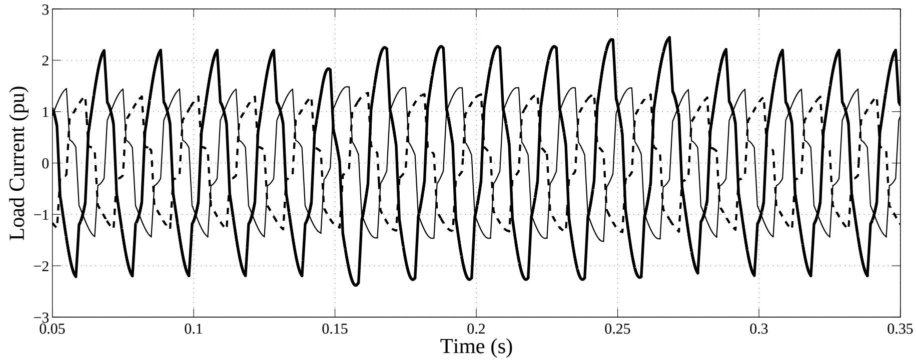

Figure 3.10 Load Currents

The UPQC injects compensating voltage and current in order to get balanced source current and rated voltage at the PCC. Here the UPQC will compensate the terminal voltage only till 0.95 pu which is well within the value specified in the Indian Grid Code.

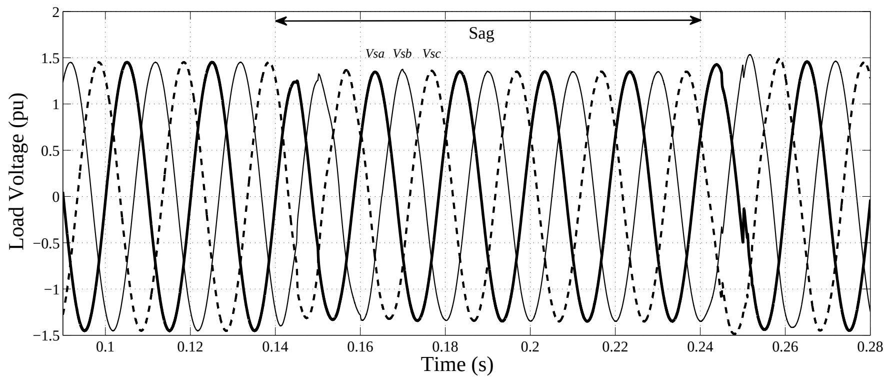

Figure 3.11 UPQC Compensated Load Voltage During Balanced Sag

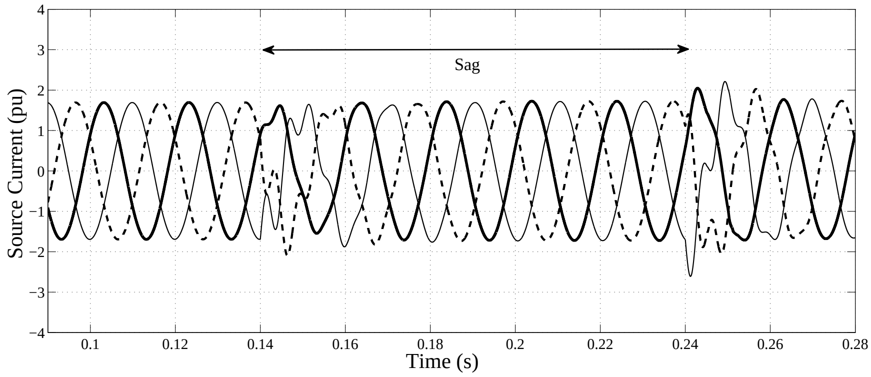

Figure 3.12 UPQC Compensated Source Currents During Balanced Sag

The RMS value of terminal voltage in the pre-sag condition is slightly greater than 1.0 pu due to the presence of the capacitor bank. During sag, the load voltage is maintained at 0.95 pu. There is no active power injection by the SEAPF when there is no sag. The SEAPF wont act if the reduction in terminal voltage is within the specified limits. During this time the entire reactive power needed by the load is supplied by the SHAPF. The net active power and reactive power injected by the DVR during the sag period is shown in Figure 3.13 and Figure 3.14 respectively.

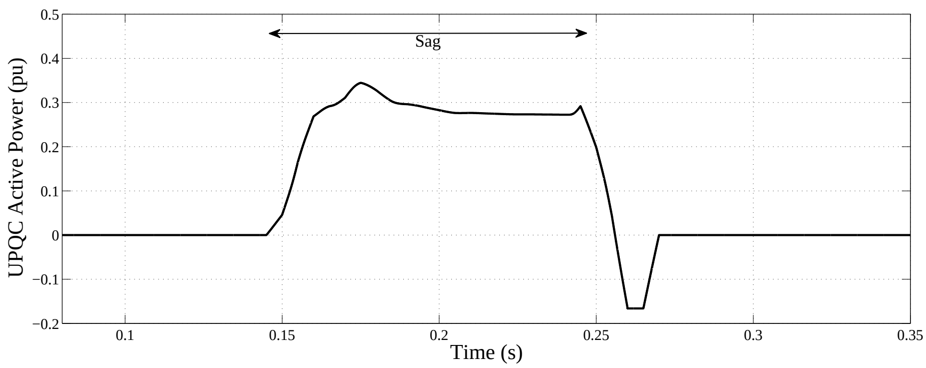

Figure 3.13 Active Power Injected By UPQC During Balanced Sag

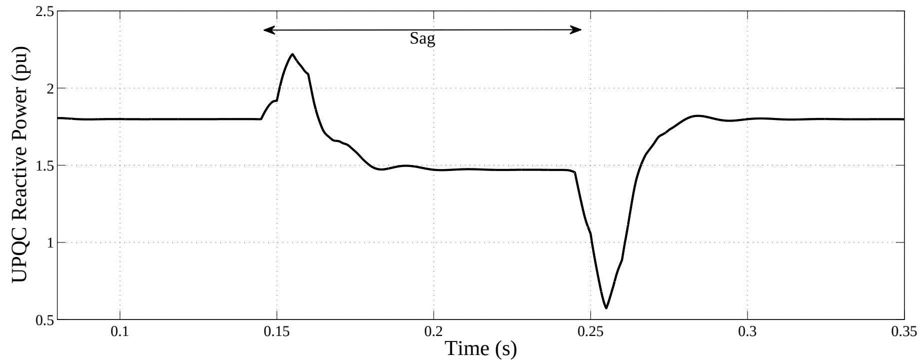

Figure 3.14 Reactive Power Injected By UPQC During Balanced Sag

During sag, the SEAPF injects an active power of 0.28 pu to compensate the sag in the three phases. It also shares the load reactive power requirement with the SHAPF.

3.4.3 Unbalanced sag mitigation

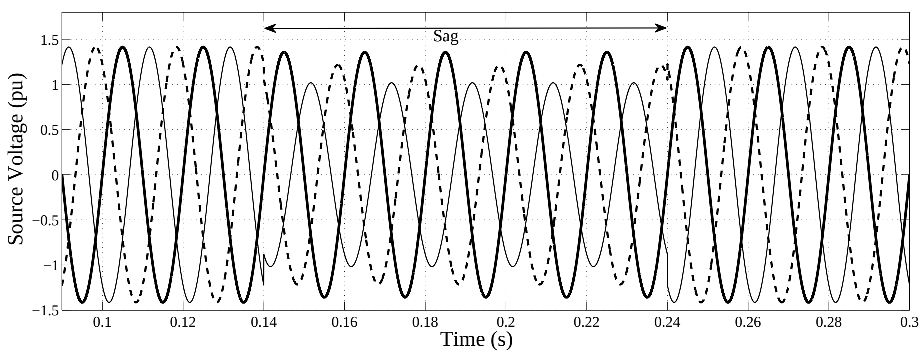

Figure 3.15 Source Voltage With Unbalanced Sag

The sag is said to be unbalanced when there is a non uniform reduction in voltage magnitude in the three pases as shown in Figure 3.15. The terminal voltages considered were phase-a at 0.96 pu, phase-b at 0.72 pu and phase-c at 0.86 pu. The sag is applied between $t = 0.14$ s and $t = 0.24$ s.

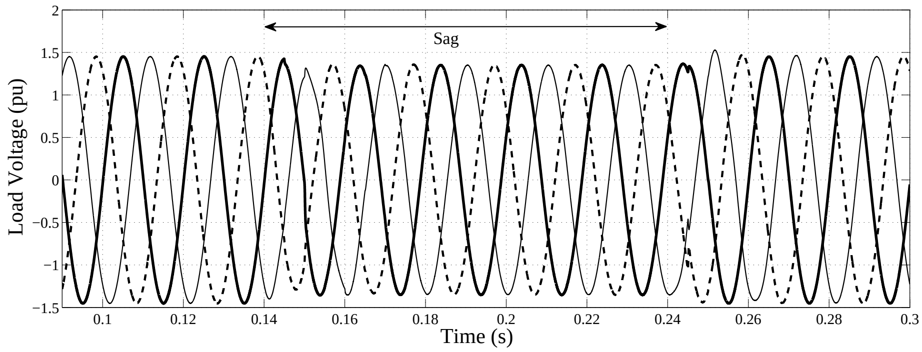

Figure 3.16 UPQC Compensated Load Voltages During Unbalanced Sag

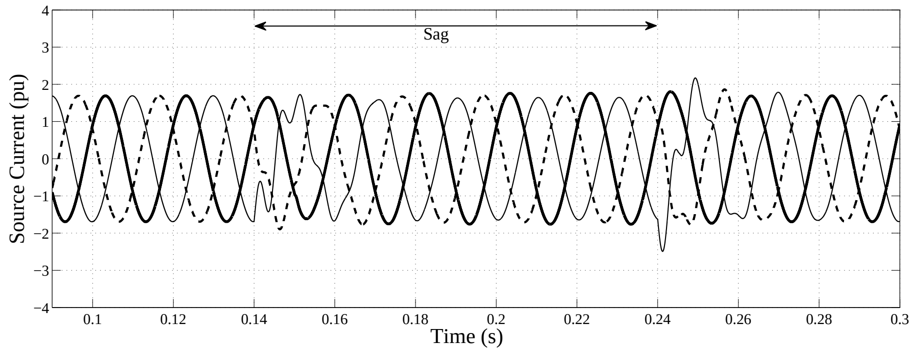

Figure 3.17 UPQC Compensated Source Currents During Unbalanced Sag

The PCC Voltage and source current are obtained as shown as 3.16 and 3.17 respectively. It can be seen that after sag mitigation the PCC voltages are balanced. The net active power injected by the SEAPF would be less as during the sag period, one of the phases has RMS voltage greater than 0.95 pu. So the SEAPF considers this as a swell and tries to bring down that phase voltage to 0.95 pu, which results in absorbing power from the system. Therefore the overall power injection comes down.

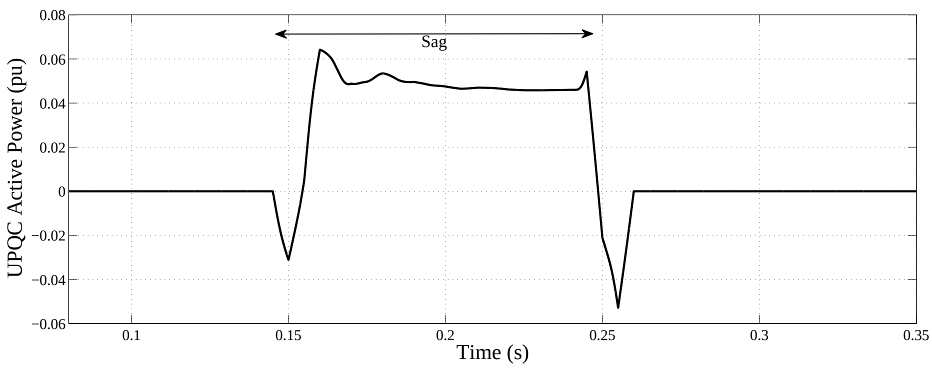

Figure 3.18 Active Power Injected By UPQC During Unbalanced Sag

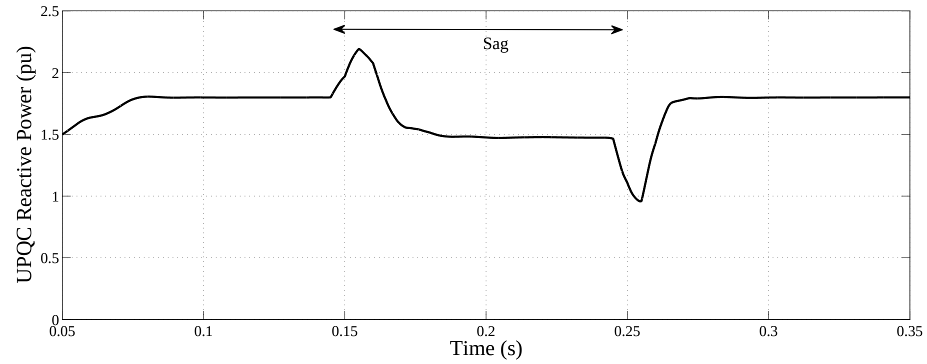

Figure 3.19 Reactive Power Injected By UPQC During Unbalanced Sag

The reactive power consumed by the load considered is around 1.8 pu. When the SEAPF operates, it tries to keep the load terminal voltage at 0.95 pu, as a result of which the reactive and active power consumed by the load decreases.

3.4.4 Mitigation of unbalanced sags with phase jumps

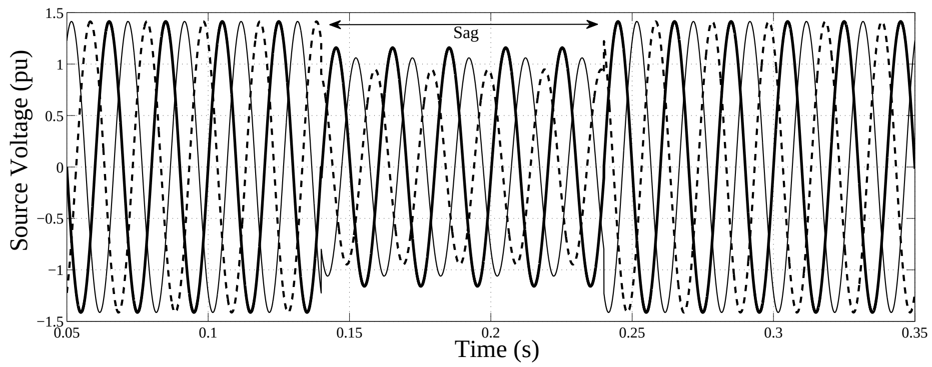

Figure 3.20 Source Voltage With Unbalanced Sags Having Phase Jumps

In this case the along with reduction in magnitudes, there will be also phase jump in the phases. The case considered has phase-a voltage at 0.82 pu and angle -5°, phase-b voltage of 0.75 pu and angle -131° and phase-c voltage of 0.67 pu and angle 107°.This is shown in Figure 3.20.

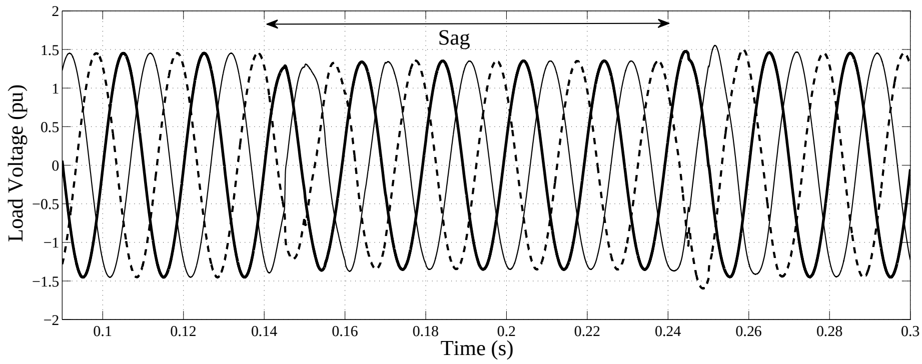

Figure 3.21 UPQC Compensated Load Voltage During Unbalanced Sag With Phase Jumps

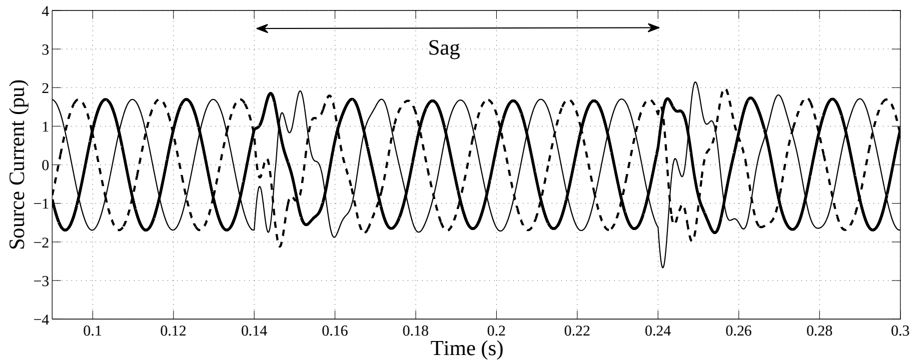

Figure 3.22 UPQC Compensated Source Currents During Unbalanced Sag With Phase Jumps

The compensated load voltage and source current is shown in Figure 3.21 and Figure 3.22. The net active power injected by the SEAPF comes around to 0.25 pu which is lesser than that obtained without the capacitor bank. The source current in all the three cases is slightly high due to the reactive current injected by the capacitance bank.

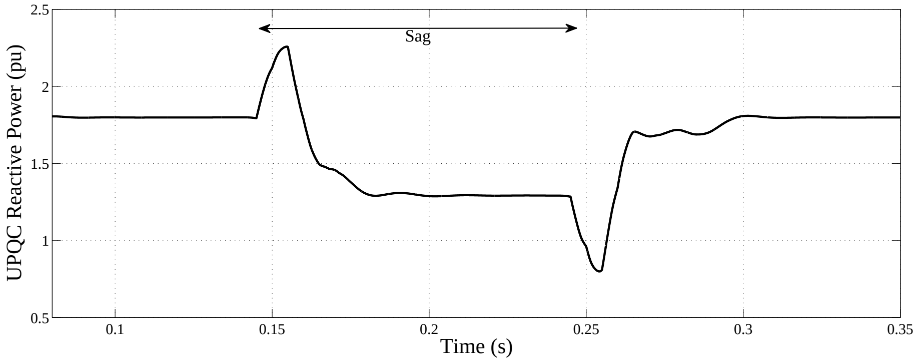

Figure 3.23 Reactive Power Injected By UPQC During Unbalanced Sag With Phase Jumps

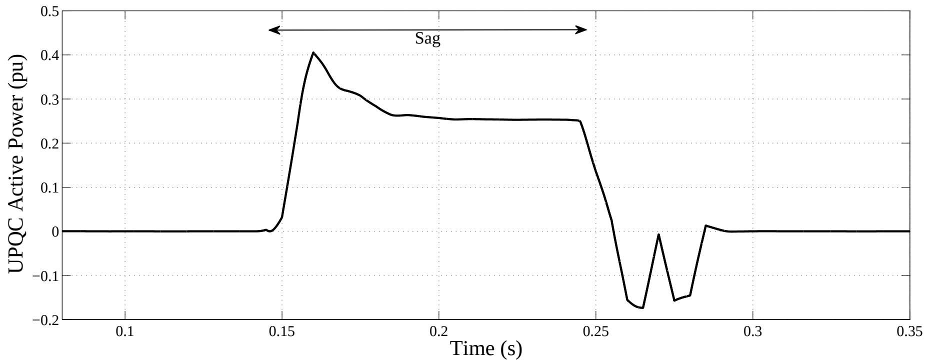

Figure 3.24 Active Power Injected By UPQC During Unbalanced Sag With Phase Jumps

The optimum real power injected by the SEAPF in all the three cases are compared with the method proposed in [10] and is tabulated in Table 3.2.

Sag Type	**Proposed Method**	**Optimal Real Power Injection Method[10]**
Balanced Sag	0.28 pu	0.825 pu
Unbalanced Sag	0.05 pu	0.35 pu
Unbalanced Sag With Phase Jumps	0.25 pu	0.8 pu

Table 3.2 Comparison of Active Power Injected by SEAPF

It is evident from the comparison that the real power injection by DVR has come down due to the presence of the capacitor bank and reduction in the reference magnitude of the load voltage from 1.0 pu to 0.95 pu. Thus severe sags can also be compensated. The system was able to effectively compensate sags with about 40% reduction in terminal voltage magnitude and with phase jumps up to 20°.The increase in terminal voltage due to the presence of capacitance can be used for charging the energy storage unit of the DVR under normal conditions.

3.5 Summary

The method of integrating a capacitor bank along with the UPQC has been explained.The state space model of the circuit was obtained and objective function for real power minimization by SEAPF was formulated.The gradient search algorithm to find the optimal solution and the ANFIS training to make the scheme online was explained.The proposed method was implemented in a three phase four wire distribution system and the simulation results were presented.It was observed that the proposed method brings down the real power injected by the SEAPF thereby reducing the required real power storage rating of the UPQC.

CHAPTER 4

CONCLUSION

4.1 Summary

Service reliability and quality of power have become growing concerns for many industrial facilities, especially with the increasing sensitivity of electronic equipment and automated controls. A modern power system should provide reliable and uninterrupted services to its customers at a rated voltage and frequency within constrained variation limits. Although utilities do their best to supply reliable, high-quality power, periodic sags and surges on utility lines will continue to be a fact of life. Even a brief shutdown of certain process equipment can result in large additional production costs so it is necessary to protect such equipments from the effects of power surges, sags, and other disturbances.

The electrical system should not only be able to provide cheap, safe and secure energy to the consumer, but also to compensate for the continually changing load demand. During that process the quality of power could be distorted by faults on the system, or by the switching of heavy loads within the customers facilities. The resulting voltage sags are not complete interruption of power, they constitutes of temporary drop below 90 percent of the nominal voltage level. Voltage sags are probably the most significant power quality (PQ) problem facing industrial customers today, and they can be a significant problem for large commercial customers as well.

Passive and active filters have been used for maintaining power quality. Custom Power embraces a family of power electronic devices which is applicable to distribution systems to provide power quality solutions. This technology has been made achievable due to the extensive availability of cost effective high power semiconductor devices such as Gate Turn Off (GTO) thyristors and Insulated Gate Bipolar Transistors (IGBTs), low cost microprocessors and techniques developed in the area of power electronics.

In this work the different sag compensation techniques presented in literature were explained.A three phase four wire UPQC compensated system was modeled in state space. The system was controlled with the help of an LQR Controller. The control signals obtained were transformed into switching functions of the inverter using a hysteresis controller.The quadrature sag compensation technique fails to compensate severe sags.Real power injection by the DVR was found necessary in such cases. The minimization of real power injection by the UPQC would help in bringing down the cost associated with the energy storage devices.The objective function for the same was optimized with the help of a gradient search algorithm.

A new scheme of using a capacitive bank along with the UPQC was proposed. The capacitive reactance would help in boosting the terminal voltage to a certain extent thereby reducing the load on DVR for sag compensation. During steady state conditions, due to the presence of the capacitive bank, the voltage rises and this swell can be used for the charging of energy storage device of the DVR.During light load conditions, the capacitance can be mechanically removed. Any variation in load voltage between 0.9 pu and 1.05 pu is in the acceptable range. The power rating of the UPQC can be further reduced by mitigating the sag voltage only till 0.95 pu.Thus the UPQC will be able to support deep sags for a longer duration of time.The above proposals were simulated in a three phase four wire distribution system having balanced, and unbalanced sags with phase jumps. and the results were presented.The system was able to effectively compensate sags with 40% reduction in magnitude and with phase jumps upto 20°. The active power injection by the UPQC in the proposed method was compared with the case in which UPQC acts alone and was found to be lesser.

4.2 Scope For Future Work

The work done was aimed at reducing the real power injection by the SEAPF. The proposed method used a simple fixed capacitor bank along with the UPQC. The reactive power and the terminal voltage boost given by this setup will depend on the source voltage at the terminal. As the sag becomes more severe, the effectiveness of the capacitor bank will reduce. A better way of achieving the same result would be integrating a variable capacitor bank or a Static Var Compensator with the UPQC. Further the harmonics in the source could be considered for the proposed scheme and can be analysed.

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