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DESIGN AND IMPLEMENTATION OF UNIFIED POWER QUALITY CONTROLLER

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ABSTRACT

Power line disturbances such as voltage dips and fluctuations, momentary interruptions, harmonics and transients incur a heavy loss to electric utility customer. Except the power outages and transients due to lightning , other power quality problems like sags, swells, short term interruption, harmonics , distortions occur either due to some faults in distribution feeders or interference from loads. During short circuits or fault clearing process in feeder, the neighboring feeders can get affected with sags or swells in the supply voltage. In this paper authors have proposed new Unified Power Quality controller (UPQC) that protects the load from these power quality issues as well as regulates the terminal voltage of the load. Authors have also explained the system configuration, control strategy and practical implementation of the UPQC.

KEYWORDS: Dynamic Voltage Restorer (DVR), Power Quality, STATCOM, Unified Power Quality Controller.

I. INTRODUCTION

Increased use of non-linear loads, such as uncontrolled/controlled rectifiers, converters, arc furnaces has caused an increase in harmonic injection and reactive power into the power distribution system. To solve these problems shunt active filters have been developed [1] [2]. Another cause for the degradation of power quality in the utility or industrial power system is the distortion/harmonics present in the voltage at the distribution substation. The power quality problems in voltage encompass voltage sag, voltage swell, flicker, voltage outage, harmonics distortion and voltage is expected to be within certain limit specified by the supplier. Voltage sags are the one of the common power quality issues encountered by the industrial customers [3].

UPQC is an active series / shunt power line conditioner. It is combination of a STATCOM as well as a series compensating stage connected before the load in series with the mains using a matching transformer. UPQC is used to compensate voltage and current harmonics, control input power factor to near unity as well as regulate the load voltage. It can be installed by the electric utilities to damp out harmonic propagation caused by resonance with line impedance and passive shunt compensators.

The UPQC is made out of two voltage-source inverters one inverter is connected to the power system through a shunt transformer, whereas the other inverter is inserted into the transmission line through a series transformer. These two voltage-source inverters are coupled on their dc sides through a common dc capacitor link. From the control perspective, the UPQC can be decoupled into two branches; the parallel branch formed by the shunt transformer, voltage source inverter and dc capacitor operating as a STATCOM, and the series branch composed of the series transformer, a voltage source inverter and the dc capacitor which behaves as a SSSC. The basic UPQC structure is shown in Fig. 1.

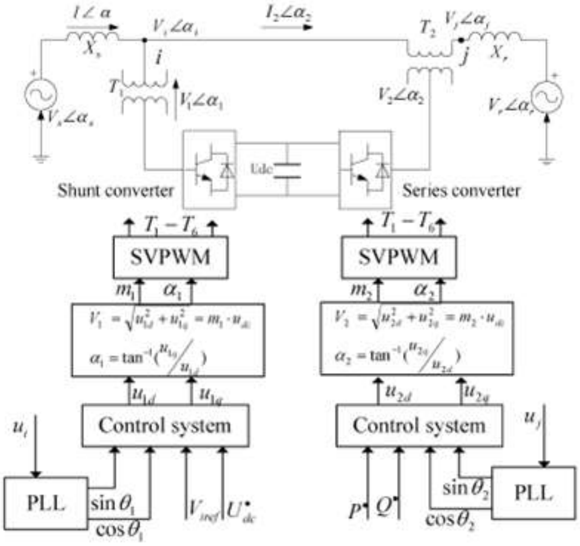

Fig.1. UPQC Connected to Transmission Line

The main objective of the series inverter is to produce and inject this voltage of fundamental frequency into the transmission line through the series transformer. The series inverter exchanges real and reactive power at its ac terminals, while the shunt inverter provides the required real power at the dc terminals, so that real power flows freely between the controller shunt and series ac terminals through the common dc link. The reactive power is generated/absorbed independently by each inverter and does not flow through the dc link. Due to the inherent and unique characteristics of the UPQC to independently control the real and reactive power, the control strategies of the controller can vary widely. However, in most cases, it is anticipated that the UPQC will be used to control its bus voltage by locally generating or absorbing reactive power, as well as control power flows on the transmission line by regulating the magnitude and phase shift of the series injected synchronous voltage. This control mode is referred as Automatic Volt- age Control Mode for the shunt inverter, and Automatic Power Flow Control Mode for the series inverter. Since the UPQC is able to force a desired power flow through the transmission line in steady state as well as in dynamic conditions, the Automatic Power Flow Control Mode feature can be enhanced to damp power oscillation in power networks.

II. SYSTEM CONFIGURATION

A. Shunt Inverter

The shunt inverter is operated in such a way as to draw a controlled current from the line. One component of this current is automatically determined by the requirement to balance the real power of the series inverter. The remaining current component is reactive and can be set to any desired reference level (inductive or capacitive) within the capability of the inverter. The reactive compensation control modes of the shunt inverter are very similar to those commonly employed on conventional static VAR compensators.

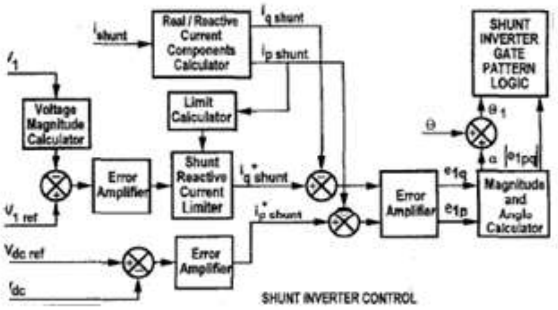

Fig. 2. Shunt Inverter Control Strategy

VAR Control Mode: In VAR control mode the reference input is an inductive or capacitive VAR request. The shunt inverter control translates the VAR reference into a corresponding shunt current request and adjusts the gating of the inverter to establish the desired current. The control uses current feedback signals obtained from current transformers (CTs) typically located on the bushings of the shunt coupling transformer. A feedback signal representing the dc bus voltage, V_{dc}, is also required.

Automatic Voltage Control Mode: In voltage control mode, the shunt inverter reactive current is automatically regulated to maintain the transmission line voltage at the point of connection to a reference value, with a defined droop characteristic. The droop factor defines the per unit voltage error per unit of inverter reactive current within the current range of the inverter. The automatic voltage control uses voltage feedback signals obtained from accurate potential transformers (PTs) measuring the voltage, VI, at the substation bus feeding the shunt coupling transformer.

B. Series Inverter

The series inverter controls the magnitude and angle of the voltage injected in series with the line. This voltage injection is always intended to influence the flow of power on the line, but the actual value of the injected voltage can be determined in several different ways. These include:

Direct Voltage Injection Mode: The series inverter simply generates a voltage vector with magnitude and phase angle requested by reference input. A special case of direct voltage injection is when the injected voltage is kept in quadrature with the line current to provide purely reactive series compensation. The series inverter injects the appropriate voltage so that the voltage V, is phase shifted relative to the voltage VI by an angle specified by reference input.

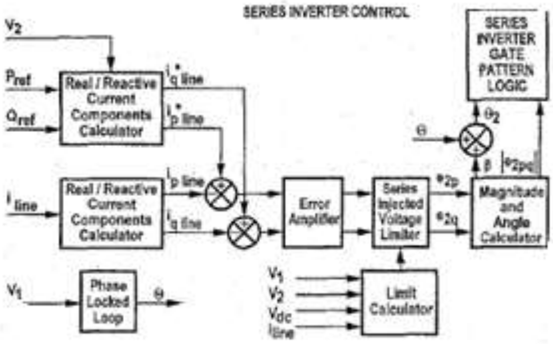

Fig. 3. Shunt Series Inverter Control Strategy

Line Impedance Emulation Mode: The series injected voltage is controlled in proportion to the line current so that the series insertion transformer appears as impedance when viewed from the line. The desired impedance is specified by reference input and in general it may be complex impedance with resistive and reactive components of either polarity. Naturally care must be taken in this mode to avoid values of negative resistance or capacitive reactance that would cause resonance or instability.

Automatic Power Flow Control Mode: The UPQC has the unique capability of independently controlling both the real power flow. P, on a transmission line and the reactive power, Q, at a specified point. This capability can be appreciated by interpreting the series injected voltage, V_{ij}*; as a controllable two dimensional vector quantity. This injected voltage vector can be chosen appropriately to force any desired current vector (within limits) to flow on the line, hence establishing a corresponding power flow. In automatic power flow control mode, the series injected voltage is determined automatically and continuously by a vector control system to ensure that the desired P and Q are maintained despite system changes. The transmission line containing the UPQC thus appears to the rest of the power system as a high impedance power source or sink. This is an extremely powerful mode of operation that has not previously been achievable with conventional line compensating equipment. It has far reaching possibilities in regard to power flow scheduling. Automatic power flow control can also be used dynamically for power oscillation damping as discussed in a later section. In each of the control modes for the series inverter, the feedback signals representing VI are used, together with additional feedback signals from PTs measuring V, on the line side of the series insertion transformer. The control system also makes use, as needed, of transmission line current feedback signals typically obtained from CTs located on the primary bushings of the series insertion transformer.

C. Stand Alone and Alternative Modes

Depending on the requirements of a particular installation, switchgear can be provided that will allow either of the two inverters to operate independently of the other by disconnecting their common dc terminals and splitting the capacitor bank. In this case, the shunt inverter operates as a stand-alone STATCOM, and the series inverter as a SSSC. Under this condition neither inverter is capable of absorbing or generating real power so that only operation in the reactive power domain is possible. In the case of the series inverter this means that any injected voltage must be in quadrature with the line current. Line power can still be controlled, but the P and Q cannot be varied independently. In the impedance emulation mode, only reactive impedance can be emulated. Alternative arrangements are possible depending on the installation. For example, by utilizing spare transformers, additional current feedback transducers, and appropriate switchgear, the series inverter can operate as a second shunt inverter and vice versa if desired. In this way an installation can be designed to be very flexible to cover every envisaged operating requirement.

III. CONTROL STRATEGY

Various control algorithms for shunt and series active filters such as instantaneous power theory, instantaneous symmetrical components theory [5-7] and synchronous reference frame method [8] have been reported. Later, the instantaneous power theory was extended to three-phase four-wire system [9]. Many modifications of the above method have also been reported [10-11]. Most of these control strategies require computations using grid voltage sensed at Point of Common Coupling (PCC). But the utility source harmonics and the noise in the feedback circuit for grid voltage restrict direct use of the voltage signals in the control algorithm. Some works have been reported on the use of PLL to remove the effect of harmonics and noise in the grid voltage. But the design of a high performance PLL is not so easy when various non idealities like multiple zero crossing in the grid voltage are occurring. In this paper, a simple and efficient method mentioned in [12] is used for the unit vector generation, which will minimize the effect of harmonics and noise present in the grid voltage feedback. The control schemes used for the shunt and series active filters are explained below.

Shunt Active Filter

In this paper, synchronous d-q reference frame based Control strategy is presented. The control law is derived for

(i) Maintaining the DC bus to the set reference value
(ii) Compensation of reactive and harmonic power drawn from the grid by the load.

The control scheme is presented in Fig. 2. The three phase currents of the load and the converter are transformed into the synchronously rotating reference frame using (1) and (2).

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\omega t & \sin\omega t \\ -\sin\omega t & \cos\omega t \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (2)$$

The unit vector required for this transformation is generated with grid voltages as described in [12]. The first step in the control scheme is orienting the converter and load current along the grid voltage. The load current will be a composite current containing fundamental and harmonics. After orientation, the fundamental component in the load current becomes d.c. quantity and the a.c. quantity in d and q axis represents the harmonics. The control scheme consists of an outer voltage control loop and an inner current control loop. The PI controller of the voltage control loop gives a current command required to maintain the D.C. bus to the set value. The current command is added with the a.c. component present in the d-axis of the load current after orientation, to get the current reference for the d-axis current controller. The reference for the q-axis current controller is q-axis quantity obtained after the orientation of load current. The control law along the d and q axis is given below.

$$V_d = i_d R + L\frac{di_d}{dt} - \omega L i_q + V_g \qquad (3)$$

$$V_q = i_q R + L\frac{di_q}{dt} + \omega L i_d \qquad (4)$$

Here *R* and *L* are the resistance and inductance of the series link choke. *Vd* and *Vq* are d and q axis voltage commands respectively. There are two PI current controllers to control the d-axis and q-axis current of the converter. The outputs of these current controllers are added with feed forward terms based on (3) and (4) to generate the d-axis and q-axis voltage references for the converter. Fig. 4 explains the control diagram for shunt controller of UPQC. As discussed this control block divides into two section inner current control system loop and outer voltage control system loop.

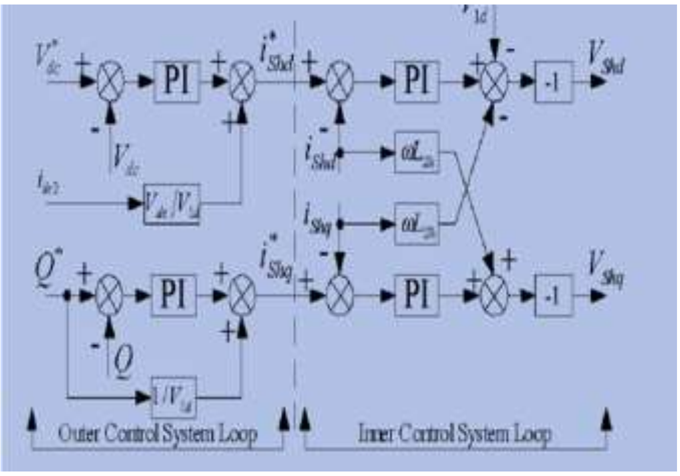

Fig. 4 control strategy for the shunt converter

Finally, d-q voltage references are transformed back to 3-phase stationary voltage references using the unit vectors. These reference signals are fed to the PWM modulator to generate the gate pulses for the converter.

Series Active Filter

The control for series active filter is derived to keep the phase voltage within the limits specified by the supplier. Fig. 5 describes the control strategy for series converter.

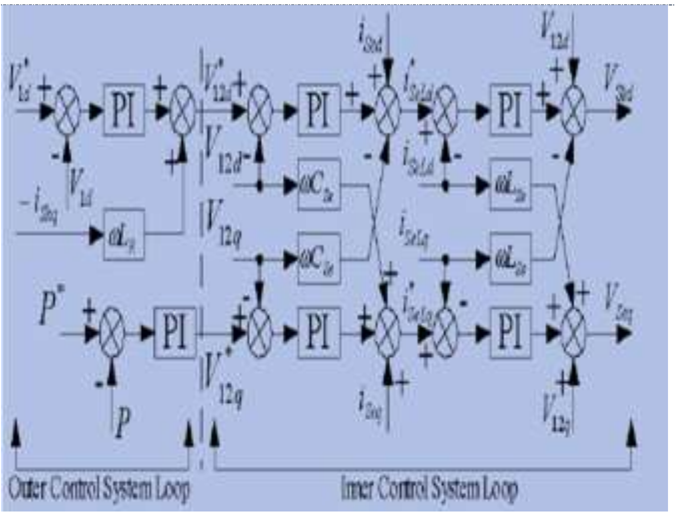

Fig. 5 control strategy for series converter

IV. SOFTWARE AND HARDWARE:

The software has been developed for 10 KVA UPQC. Coding for DSP TMS320F240 has been developed according to the control algorithm for the STATCOM and DVR in the assembly language of Digital Signal Processor.

The control algorithm explained was tested in a 10kVA UPQC system consisting of International rectifier IGBT based shunt and series converter stack module with external six channel gate driver and a DC bus capacitance of 2200μF 450 V DC. Fig.2- 3 shows shunt and series active filter converter module.

The series link inductor of 5.4 mH,16 A 3 phase amorphous core for shunt active filter and 9.6 m H, 680μF LC filter for series active filter are used. Hall effect current sensors LA 55 P (1 x 3 for Grid Current and 1 x 2 STATCOM Current) are used for both series and shunt active filter current feedback. The DC bus voltage is 800V. The Power stack is air-cooled. The interior view of the UPQC is shown in Fig.4 - 5. The digital controller for this system is built around Texas Instrument DSP TMS320F240. The digital controller has simultaneous sampling, 12bit ADC with maximum conversion time of 6.6μs. It can drive one 3-phase converter and 3 single phase converters through electrical link. The carrier frequencies for the both converters are 10 kHz. The controller will block the gate pulses to the converter if any abnormalities present in the system such as over current, DC over voltage, gate driver under voltage and over temperature. The 10KVA proto model of UPQC is working in the Veeral Control P Ltd. Gandhinagar with light and fan of the centre as load.

V. RESULT

The 10 KVA UPQC is tested at Veeral Control P. Ltd. Gandhinagar according to the test procedure given in above section at 80^0 C . The rating of the 10 KVA UPQC is given in Table 1. The Grid Current, Load current and STATCOM Current are shown in Fig.7 under a condition that utility side voltage contains higher amplitude for the set reference load voltage in the control law. So the series active filter operates in the buck mode to keep the load voltage at 415V. The actual load voltage is regulated to 415V±1%.

Table 1 Rating Of IGBT Based UPQC

IGBT Converter	
(Unified Power Quality Controller)	
KVA	10 KVA
Input	415 V ac + 20 % 3 phase 50 HZ

Output	415 V ac + 1 % 3 phase 50 HZ
Ac Current	14 A Nominal 21.8 A for 1 min.

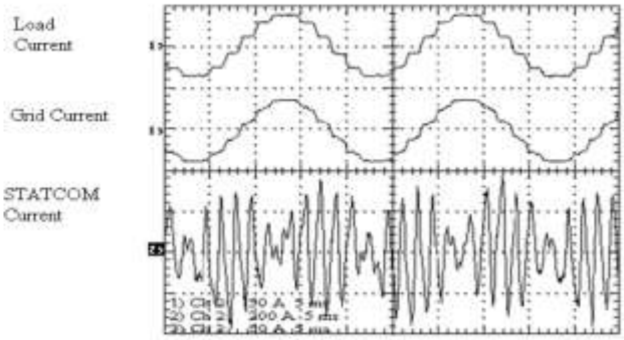

Fig.6 Load Current, Grid current and STATCOM Current

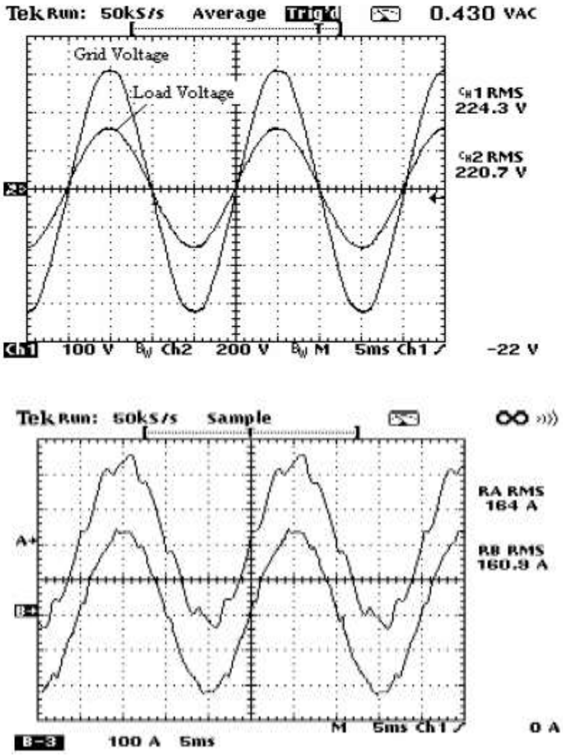

Fig.7 (a) Grid and Load Voltage Waveform
(b) Grid and Load Current Waveform

The harmonic analysis of grid current with and without compensation is tabulated in Table. 2. The Total Harmonic Distortion (THD) of grid current without compensation shows 7.69% with fifth and seventh is coming up to 2.1% and 8.2% respectively. The THD of grid current is reduced to 4.0% with harmonic compensation and the dominating fifth and seventh is drastically reduced to 0.4% and 1.9% respectively.

Table 2 shows the grid current harmonic comparison before and after compensation. Graph is also supported the above tabled information. Table 2 is also supported by the graph shown below it. Graph shows the variation of the grid current harmonic comparison before and after compensation versus the order of the harmonic. This graph is also expressed the quality of the UPQC which shows the reduction in 5th and 7th harmonic considerably.

Table 2 Grid Current Harmonic Comparison Before And After Compensation

HARMONIC	BEFORE HARMONIC COMPENSATION %	AFTER HARMONIC COMPENSATION %
THD	7.69	4.00
3	0.7	0.4
5	2.1	0.4
7	8.2	1.9
9	0.3	0.2
11	1.9	1.7
13	2.6	2.3
15	0.1	0.3
17	0.4	0.3

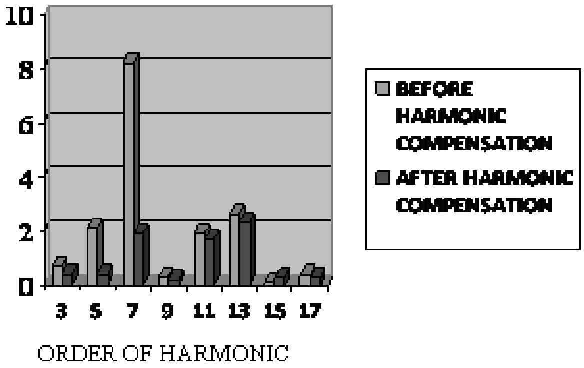

Fig. 8 Graph of grid current versus the order of harmonic

VI. CONCLUSION

In this paper, An Unified Power Quality Controller (UPQC) is proposed which consists of 1x3 phase shunt active filter and 3x1 phase series active filter sharing a common DC link. The UPQC has the ability to improve both line voltage and load current qualities, including voltage amplitude, sag, swell, voltage unbalance and reactive and harmonic currents.

The proposed UPQC provides a multifunctional, high performance, cost effective and reliable solution for total power quality control. It is suitable for commercial and industrial applications.

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