Experimental Verification of Unified Power Quality Conditioner with Transformation Less Combined Mode Control

S. Srinath^{*}, Anu G. Kumar⁺, M. P. Selvan[#]

* Research Scholar, ⁺PG student, [#]Assistant Professor, Dept. of EEE, National Institute of Technology Tiruchirappalli Tamilnadu, India srinaths_1976@yahoo.com, anugkumar8@yahoo.co.in, selvanmp@nitt.edu

Abstract— This paper presents the performance analysis of a Unified Power Quality Conditioner (UPQC) with transformation less Combined Mode Control (CMC) approach. DSP controller TMS320LF2407A is used to realize the switching pulses for the APFs of UPQC. The %THD of load voltage and source current has been considered as a measure for assessing the performance. The experimental results confirm the satisfactory operation of UPQC in mitigating the harmonics.

Keywords- Power Quality, Unified Power Quality Conditioner(UPQC), Series Active Power Filter (SAPF), Shunt/Parallel Active Filter (PAPF), Voltage Source Inverter (VSI), Hysteresis Control, Sinusoidal Pulse Width Modulation (SPWM), DSP Controller.

NOMENCLATURE

V _s	Supply voltage / phase, V
V _{inj}	Injected voltage from SAPF / phase, V
Vpcc	Voltage at PCC / phase, V
Z_L	Line impedance/phase (R_L + jX_L), Ω
c.	Fundamental system frequency, Hz
c c	Carrier Frequency, Hz
V	Number of Pulses
V _{inj}	Injected/compensating Voltage/phase, V
V_L	Load Voltage/phase, V
\mathbf{R}_{L}	Load Resistance, Ω
V _{dc}	DC Link Voltage, V
L_{f}	Filter Inductance, mH)
\hat{C}_{f}	Filter Capacitance, µF
PAPF	PAPF current, A
1	Load current, A
s	Source current, A
ref	Reference current, A

I. INTRODUCTION

POWER quality in the distribution system becomes a critical issue due to the tremendous increase in the use of loads with nonlinear characteristics. The poor power quality has a significant influence on the functioning of sophisticated sensitive equipments. Power quality problems include voltage sag, swell, unbalance, transient, interruption and distortion in the sinusoidal waveform [1].Distorted voltage and current may lead to failure or mal-operation of sensitive loads connected at Point of Common Coupling (PCC) .The harmonics present in the current drawn by the nonlinear loads from the sinusoidal supply results in distortion in the voltage at PCC [2].

Traditionally, passive filters were used to eliminate harmonics generated by large loads due to their simplicity, low cost and high efficiency. The supply impedance strongly influences the compensation characteristics of passive filters and they are highly susceptible to series and parallel resonance with the supply. Moreover, passive filters eliminate the very selectively. With harmonics the vast development in the field of power electronics, Active Power Filters (APFs) were introduced as custom power devices for mitigating the power quality problems. APFs include Series Active Power Filter (SAPF) and Parallel Active Power Filter (PAPF). PAPF is employed for current harmonic elimination and SAPF is employed for voltage harmonic elimination [3-4].

A universal solution to all power quality problems including load voltage and source current harmonic elimination can be obtained by integrating the SAPF and PAPF into a single unit called as Unified Power Quality Conditioner (UPQC).

II. UNIFIED POWER QUALITY CONDITIONER

A. Principle of Operation

The schematic diagram of UPQC is shown in Fig.1. The UPQC consists of two back to back connected voltage-source inverters connected through a common dc-link capacitor. The main objective of PAPF is to compensate for the reactive power demanded by the load, eliminate the harmonics from the supply current, and regulate the dc-link voltage [5]. SAPF isolates voltage harmonics between source and load and regulates the load voltage.

Several control methods were proposed in the literature for elimination of harmonics using active

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filters such as instantaneous active and reactive power method or so called *p-q method*, i_{d} - i_q method, etc., [6,7]. These methods involve the use of intermediate mathematical transformation to generate the reference quantities for APFs of UPQC. Also, different switching schemes for VSI like Sinusoidal Pulse Width Modulation (SPWM), Space Vector Pulse Width Modulation (SVPWM), Hysteresis PWM, etc., were also attempted in the literature [8-11].

In this paper, an attempt is made to experimentally verify the performance of UPQC employing a transformation less combined mode control approach proposed in [12] which utilizes hysteresis based switching for current control in PAPF and SPWM based switching for voltage control in SAPF.



Fig. 1 Schematic diagram of UPQC

The PAPF operates in such a way to force the source current in phase with the source voltage, hence the input power factor is always maintained at unity and the SAPF maintains the load voltage at the desired level with good quality.

B. Compensation Technique

The objective of the compensation technique is to guarantee balanced and sinusoidal voltage at the load terminals. The control algorithm derives the reference of the compensation signals to be injected by the APFs. Various approaches are available in the deriving the reference literature for of the compensation current/voltage from the measured distorted quantities, which can be grouped into frequency-domain approach time-domain and approach.

The frequency-domain approach implies the use of the Fourier Transform and its analysis, which leads to huge calculations and thus making the control approach complex. In time-domain approach, the traditional concepts of circuit analysis and algebraic transformations associated with changing of reference frames like instantaneous p-q theory, synchronous d-q reference frame theory etc., are used. Sometimes, suitable analog or digital filters are employed for separating the successive harmonic components, thus simplifying the control task.

The choice of control algorithm therefore decides the accuracy and response time. The calculation steps involved in the control technique have to be minimal to obtain faster response.

C. Transformationless Control Approach using SPWM based Switching for SAPF

The objective of SAPF is to maintain the load voltage at the terminals of sensitive load sinusoidal at fundamental frequency and desired magnitude [12]. The time domain based unit vector templates are used in this work to calculate the reference voltage and SPWM based switching is used to generate the triggering pulse for the VSI of SAPF as shown in Fig. 2.

Initially, the supply voltage is sensed and multiplied by a factor $K = 1/V_{sm}$, where V_{sm} represents the peak value of supply voltage under consideration. This gives a unity source voltage profile.



Fig. 2 Schematic diagram of SAPF control

For a given load, the desired load voltage is a fixed quantity. Let V_{Lm} represents the peak amplitude of desired load voltage. The unit vector template is multiplied with V_{Lm} to generate the profile of the desired load voltage.

$$V_{Ldes} = V_{Lm} \times u = V_{Lm} \sin(\omega t)$$
(1)

The reference load voltage is compared with actual load voltage to derive the reference waveform for carrying out the Sinusoidal Pulse Width Modulation (SPWM) based switching.

D. Transformationless Control Approach using Hysteresis based Switching for PAPF

The source current / Load current when PAPF is not in operation, consists of real and reactive

components of fundamental current as well as harmonic component.

Thus



Fig. 3 Schematic diagram of PAPF control

The schematic diagram of PAPF control is presented in Fig. 3. In this control, the real component of the fundamental load current is extracted and compared with the actual load current. The reference current thus obtained consists of both reactive and harmonic components of load current. This is compared with the actual PAPF current and the triggering pulses are generated further using hysteresis control algorithm.

III. EXPERIMENTAL VERIFICATION

The prototype model of UPQC has been built in the laboratory with the proposed transformation less CMC approach implemented using DSP controller TMS320LF2407A.

A. System Parameters for Hardware Implementation

The system and APF parameters are furnished in Table I and Table II respectively.

System Parameter	Data
Input source voltage	53 V (rms)
phase-neutral (V _s)	50Hz
Resistance of the line (R_s)	5 Ω
Inductance of the line (L_s)	10 mH
Diode bridge Rectifier fed R-L load	25 Ω
	20mH

TABLE I SYSTEM PARAMETERS

B. Digital implementation of Control Algorithm for SAPF and PAPF

1) SAPF Control

The digital implementation of control algorithm discussed in section II and generation of switching

pulses have been carried out using TMS320LF 2407 EVM DSP controller.

For SAPF, the input supply voltage and actual load voltage are sensed using voltage sensors. LEM LV20P Hall Effect sensor is used for sensing the voltage levels at the terminals of source as shown in Fig. 4.

FABLE II	APF PARAMETERS
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Details	Parameters	Data	
SAPF	DC link Voltage (V_{dc}) Filter resistance (R_f) Filter inductor (L_f) Filter Capacitance (C_f)	90 V 10Ω 10mH 4 μF	
Series Injection Transformer	Power Rating Transformation ratio	1.5 kVA 150V/150V	
PAPF	Three phase VSI Filter resistance (R _f)	40Ω	
Shunt Transformer	Power Rating Transformation ratio	2.5 kVA 230V/230V	

The load voltage at the load terminals is also sensed through similar voltage sensors. These voltage sensors are responsible for stepping down the voltage of the power circuit to be within the maximum input voltage limit specified for the DSP (i.e. 0-3.3V). This is achieved by suitable design of primary and secondary resistances while maintaining the current levels in primary and secondary within specified limits. The output of the voltage sensors are fed to the Analog to Digital Converter (ADC) available in the EVM board.



Fig. 4 Voltage sensor circuit

Further, unit vector template in accordance with the sensed source voltage is generated inside DSP. This is then multiplied with peak value of desired load voltage to obtain the digital equivalent of the desired load voltage profile. The actual load voltage is compared with sensed load voltage to obtain the voltage modulation signal for SPWM operation. It is compared with the triangular carrier ($v_c(t)$) generated inside to produce the triggering pulses through PWM port of DSP EVM board. The flowchart shown in Fig. 5 illustrates the digital implementation of SAPF control algorithm.



Fig. 5 Digital implementation of SAPF control Algorithm

2) PAPF control

For PAPF, assuming sinusoidal voltage source, the real part of fundamental load current is calculated in real time using Fluke Power Quality analyzer in real time. Using a suitable voltage sensor circuit design, the equivalent voltage of the real part of the fundamental load current has been derived from the source voltage itself. Hence, the voltage sensor used to measure the source voltage in SAPF control has been used for the same purpose. This technique avoids the determination of the phase angle of the supply voltage in practice. A sampling frequency of 20kHz is used in ADC of DSP.

Determination of reference current (i_{ref}) is made by eliminating the real part of the fundamental

component of load current from the actual sensed load current as shown in Fig. 6. The reference current is calculated as given in (3).

i_{load}	=	i_{freal} + i_{freac} + i_{har}	(3)
$i_{load} - i_{freal}$	=	$i_{freac} + i_{har}$	
i _{ref}	=	$i_{freac} + i_{har}$	

This reference current when injected, cancels out the harmonic and reactive components of load current so that the source current is sinusoidal and harmonic free at unity power factor. A hysteresis band is fixed along this determined reference current. The actual PAPF current is also sensed and given as an input to the ADC of DSP controller and the photograph of corresponding current sensor circuit is shown in Fig. 6.



Fig. 6 Current sensor circuit



Fig. 7 Digital implementation of PAPF control algorithm

The switching signals are obtained from the Digital to Analog Converter (DAC) of EVM board, based on the developed control algorithm shown in Fig. 7, such that the PAPF current should follow the reference current within the hysteresis band. The hardware setup and the experimental results are presented in the next section.

IV. EXPERIMENTAL RESULTS

A photograph of the complete experimental prototype of distribution system connected with a three phase UPQC is built in the laboratory using Semikron made VSI. The system is connected using toggle switches (S_1 to S_4) as indicated in the schematic diagram of the experimental setup shown in Fig. 8, to realize the individual operation of APFs and UPQC. The photograph of complete experimental setup built in the laboratory is shown in Fig. 9.

Fig. 9 Experimental Setup of UPQC in laboratory

The experimental results of source voltage, load voltage, source/load current, and its corresponding harmonic spectrum before and after compensation are shown from Figs. 10 - 17.







Fig 12 Harmonic spectrum of source current before compensation







Fig. 14 Load voltage and Source current after compensation (UPQC ON)



Fig 15 Harmonic spectrum of load voltage after compensation (UPQC ON)



Fig 16 Harmonic spectrum of Source current after compensation (UPQC ON)

The source voltage and the corresponding source current when a nonlinear load is supplied from the sinusoidal supply voltage is shown in Fig. 10. The nonlinear load current results in a distorted voltage at the load terminals as shown in Fig. 11. The respective % THD of load voltage and source current is depicted in Fig. 12 and Fig. 13. Once the UPQC is switched ON, by the subsequent switching of PAPF and SAPF, a transition occurs in the load voltage and source current waveforms as depicted in Fig. 14. The corresponding %THD of load voltage and source current are also brought to a low value as observed from Fig. 15 and Fig. 16 respectively.

V. CONCLUSION

performance UPOC The of using а transformation less combined mode control is discussed in detail. The algorithm for implementing the control strategy for APFs is also explained. The digital implementation of the proposed control is carried out with DSP controller TMS320LF2407A and tested on a prototype of the UPQC connected distribution system built in the laboratory. The experimental results show better performance of the proposed control for UPQC in maintaining the load voltage and source current harmonics.

REFERENCES

- H. Akagi, Y. Tsukamoto, A. Nabae, "Analysis and Design of an Active Power Filter using Quad Series Voltage Source PWM Convertors", *IEEE Transactions on Industry Applications*, Vol.5, No.1, pp. 93-98, 1990.
- [2] K. G. Firouzjah, A. Sheikholeslami, M. R. Karami Mollaei, M. Khaleghi, "A New Harmonic Detection Method for Shunt Active Filter Based on Wavelet Transform" *Journal of Applied Sciences Research*, pp. 1561-1568, 2008.
- [3] Singh, K. Al-Haddad, A. Chandra, "A review of active filters for power quality improvement", *IEEE Transactions on Industrial Electronics*, Vol. 46, No. 5, pp. 960-971, 1999.
- [4] H. Akagi "Active harmonic filters", *Proceedings of IEEE*, Vol. 93, No. 12, pp.2128- 2141, 2005.
- [5] Sincy George and VivekAgarwal, "A DSP-based control algorithm for series active filter for optimized compensation under nonsinusoidal and Unbalanced Voltage Conditions". IEEE Transactions on Power Delivery, vol. 22, no. 1, pp.1537-1541,2007.
 [6] S. Bhattacharya, D. M. Divan, "Synchronous frame based
- [6] S. Bhattacharya, D. M. Divan, "Synchronous frame based controller implementation for a hybrid series active filter system", *IEEE/IAS Annual Meeting*, pp.2531-2540, 1995.
- [7] Maria Isabel Milanes Montero, Enrique Romero Cadaval, Fermin Barrero Gonzalez., "Comparison of control strategies for shunt active power filters in three phase four wire systems", *IEEE Transactions on Power Electronics*, Vol.22, No.1, pp. 229-236, 2007.

- [8] L. Moran, P. Godoy, R. Wallace, J. Dixon, "A new current control strategy for active power filters using three PWM voltage source inverters", *IEEE Power Electronics Specialists Conference*, pp. 3-9, 20-24 June 1993.
- [9] J. Chelladurai, G. Sarvana Ilango, C.Nagamani, S. Senthil Kumar., "Investigation of various PWM techniques for shunt active filters" *World Academy of Science, Engineering and Technology*, Vol. 39, pp. 192-198, 2008.
- [10] G.D Holmes, T.A.Lipo, "Pulse Width Modulation for Power Converters-Principles and Practice", *IEEE Press Series on Power Engineering*, John Wiley and Sons, Piscataway, NJ, USA 2003.
- [11] H. Fujitha, H. Akagi, "The unified power quality conditioner, integration of series and shunt active filter", *IEEE Transactions on Power Electronics*, Vol.13, No.2, pp. 315-322, 1998.
- [12] S. Srinath, M.P. Selvan, "A combined mode control for UPQC connected to a low voltage distribution system", *Australian Journal of Electrical Engineering*, Vol. 8, No.3, pp. 257-270, 2011.