Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Optimal Unified Power Quality Conditioner with Improved Compensation Performance under Distorted Voltages

S.M.R. Rafiei , *Senior Member, IEEE*, Reza Asadi , G. Griva, and R. Bojoi

***Abstract*-** **In this paper, practical applications of Optimal and Flexible Controlled (OFC) active filters operating under distorted voltages with non-ideal compensator systems are investigated. In the previous works, the compensator system is regarded as an ideal Inverter. On the contrary, this paper takes into account a set of important limitations of the real compensators in frequency domain. Some restrictions are caused by the inverter's bandwidth limitation. To overcome the tracking error, several approaches are suggested. In a very effective approach, each single-phase inverter is treated as a multivariable system in frequency domain to be compensated by means of a simple identification/ equalizer system quite suitable for the OFC system under study. It is shown that using a series compensator besides removing the load voltage harmonics, can significantly improve the tracking performance of the shunt compensator. Extensive simulation results obtained in Matlab/Simlulink environment prove the feasibility and superiority of the proposed approaches.**

***Index Terms*- Optimal Active Filter, Perfect Tracking, UPQC, Distorted Voltage**

Nomenclature:

η :	Power factor
N:	Highest order considered for voltage harmonics
$\square^*_0$:	A scalar to balance active power
$\mathbf{i}^* = [i^*_a, i^*_b, i^*_c]^T$:	Desired load current vector
$\mathbf{e} = [e_a, e_b, e_c]^T$:	Voltage vector of the load
$\mathbf{e}^* = [e^*_a, e^*_b, e^*_c]^T$	Virtual voltage vector of the load
e(s) :	Laplace transform of **e**
e*(s) :	Laplace transform of $\mathbf{e}^*$
G(s) :	Transfer matrix of filter banks
P_{dc} :	Load active power
i_n^0, i_n^-, i_n^+ :	Zero, negative, and positive sequences for n^{th} harmonic
H_a^i, H_b^i, H_c^i :	THDs of phases a, b, and c currents
$H_{a,n}^i, H_{b,n}^i, H_{c,n}^i$:	Harmonic factors of the n^{th} harmonic of phase a, b, and c currents of load
i_n^0/i_1^+ and i_n^-/i_1^+ :	Measure of current unbalance for the n^{th} harmonic
u_n^0 and u_n^- :	Adjustable bounds on i_n^0/i_1^+ and i_n^-/i_1^+
$G_a(i)$, $G_b(i)$, $G_c(i)$:	Scalar gains of filter banks for i^{th} harmonic
$\gamma_a, \gamma_b, \gamma_c$:	Upper bounds on THDs of phases a, b, and c currents
$\lambda_{a,n}, \lambda_{b,n}, \lambda_{c,n}$:	Upper bounds on Harmonic Factors of the n^{th} harmonic of phases a, b, and c currents

I. INTRODUCTION

Today utility network still significantly suffers from some low power quality factors. Harmonics generated by nonlinear loads, voltage sag, and high frequency components caused by switched capacitors are some known sources seriously degrading the quality of supply in the power network. Active Power Filters (APF) or Line Conditioners (LC) are modern tools to improve the power quality on whole and mitigate the harmonics in particular [1]-[10]. Ref [1] was the first to address some mismatch between power factor correction and harmonics cancellation under distorted voltage conditions. That proposes an approach called Optimal and Flexible Control (OFC) which compromises between some favorite power quality indices via an optimization algorithm. The concept can also be extended for many other power quality factors need compromising. The OFC filters are inherently complicated and time consuming systems with rather high burden of real time calculations. Ref [2] presents a modified OFC system where a Neural Network (NN) system replaces the optimization process used in the classic OFC. Also, [3] addresses transient behavior of the OFC APFs operating under non-stiff voltage conditions that is where the source impedance is significant. That may cause instability or poor transient response for the system due to unwanted feedback introduced by the aforementioned impedance. In line of the

S.M.R. Rafiei, G. Griva, and R. Bojoi are with the Department of Electrical Engineering, Politecnico di Torino, C.so Duca degli Abruzzi, 24, 10129, Torino, Italy (rafiei@ieee.org)

R. Asadi, is with National Iranian Oil Company-North Drilling Company, Iran (R.Asadi@Northdrilling.com)

978-1-4244-2235-7/09/$25.00 ©2009 IEEE

OFC systems, [4] presents and interesting simplified version of the OFC [1] with practical implementation performed by means of DSP processors. Such simplifications are crucial to the field, as despite the interesting performance and high functionality of such APFs, they still suffer from high complexity and cost preventing them from widespread applications in the power networks.

The OFC filters and their variants [1]-[8] which can be called "Optimal APF Family" appear with some interesting features and high functionality. However, the important practical issue has been omitted in all the previous works is the adverse impact of the limitations of the practical compensator system should synthesize the optimal compensating currents calculated by the control algorithm. There are many known limitations for any inverter system that prevent it from perfect tracking. These limitations can simply be categorized into two following types:

a) Frequency domain limitations (such as Inverter's bandwidth and external disturbances mainly load voltage)
b) Time domain limitations (such as Inverter's Slew Rate and maximum peak current)

From frequency point of view, an inverter like any other low pass system has limited bandwidth which introduces some phase and amplitude errors at various frequencies. Also, from control point of view, the current harmonics injected to the compensator by the load voltage harmonics can be regarded as some external disturbances, which worsen the inverter's tracking performance.

In this paper we are going to deal with some of the aforementioned non-idealities of OFC filters preventing them form perfect tracking. The main idea is to modify the control algorithm of the OFC system to compensate the imperfect tracking performance of the Inverter system. In the main approach, here, we do not improve the Inverter system. Instead, the Inverter's reference signal is modified by the OFC control system so that the overall compensation ability of the whole OFC based APF is improved. Moreover, the paper investigates the impact of the load voltage harmonics on the performance of the parallel APFs. One proposal of the paper is to use Unified Power Quality Conditioner (UPQC) [9]-[10] filters to compensate load voltage harmonics, load current harmonics, and power factor simultaneously. Besides that, it is shown that using a UPQC, which improves the load voltage harmonics using a series APF, can also significantly improve the tracking performance of the parallel APF embedded in the UPQC system. The structure of the paper is as follows. In Section II, a brief review of the OFC system is presented. Section III explores the problems arise by imperfect tracking performance of the inverters along with the external disturbances with some examples. Section III suggests some approaches to mitigate the imperfect tracking issues. In section IV, as an interesting solution, the OFC system along with the techniques used for improving the tracking performance is used for controlling a UPQC system. Section V presents concluding remarks.

II. Review Of OFC

Here, a brief review of the OFC algorithm is presented. Fig. 1 shows the structure of an under compensating system

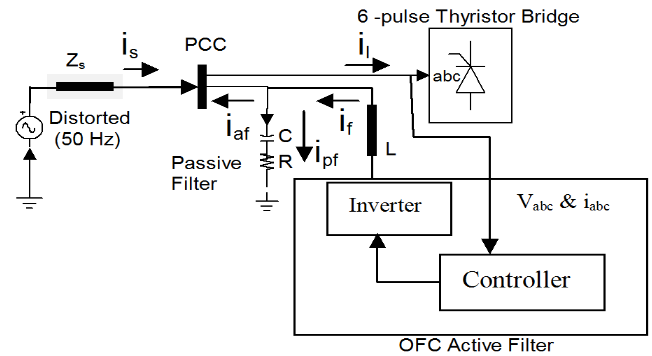

Fig. 1 OFC Based Active Filtering System
(L_s=20mH, C=10µF, R=50Ω, L=4mH)

by means of an OFC based shunt active filter. The active filter consists of the control algorithm, Filter Banks, and three single phase hysteresis controlled Inverters with their output high pass filters to reject the high frequency ripples produced by the switching actions of the Inverters. The passive filters components are L, R, and C as identified in Fig.1.

A. OFC Structure

Fig. 2 shows the block diagram of the OFC system [1]. The OFC structure in a-b-c frame [1]-[3] is characterized by the following equations:

$$i^* = \Psi_0^* . e^* \quad (1)$$

$$e^*(s) = G(s).e(s) \quad (2)$$

Where Ψ^*_0 is a constant scalar for balancing the active power of the compensated load and voltage vector $\mathbf{e}^*$ is a filtered version of the load actual voltage, **e**. Filter bank **G(s)** is designed based on a selected compensation strategy through an optimization algorithm [1].

B. Compensation Strategy

The following indicates one of the most interesting load compensation strategies that can be realized by the OFC system used in [1]-[3].

Max $\eta\,(\boldsymbol{G})$

Subject to:

$$H_a^i \le \gamma_a, \quad H_b^i \le \gamma_b, \quad H_c^i \le \gamma_c, \quad H_{a,n}^i \le \lambda_{a,n},$$
$$H_{b,n}^i \le \lambda_{b,n}, \; H_{c,n}^i \le \lambda_{c,n}, \frac{i_n^-}{i_1^+} \le u_n^-, \; \frac{i_n^0}{i_1^+} \le u_n^0, \; n=1,2,...,N \quad (3)$$

For example, the harmonic constraints can be selected according to the IEEE standards for harmonics [11]. Moreover, any other power quality indices, e.g. THD of the compensated load currents can be considered as the cost function as well [1].

C. Control Algorithm

Considering the first N terms of the Fourier series for e and e^*, we have:

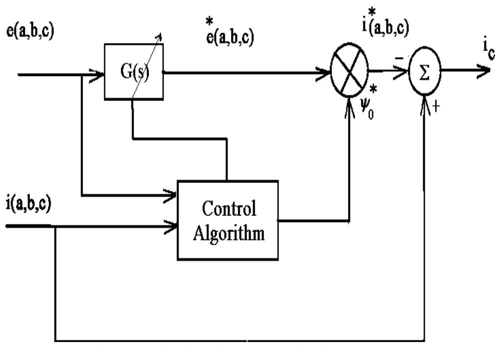

Fig. 2: Block Diagram of The OFC System

$$e_a = e_{a_0} + \sum_{i=1}^{N} e_{a_i} \cos(i\omega t + \varphi_{a_i}) \qquad (4)$$

$$e^*_{a_i} = e_{a_i}.G_a(i) \qquad , \qquad i = 1,2,3,\ldots,N \qquad (5)$$

Similar equations can also be developed for phases b and c. The phase responses of the filters for all harmonic frequencies are set to zero. Neglecting the dc components, the effective load voltage E, the effective filtered voltage E^*, and $\varepsilon^*_{dc} = (e^T.e^*)_{dc}$ can be represented by the Fourier series coefficients of **e** and the filter gains as [3]:

$$E = \sqrt{\frac{1}{2}\sum_{i=1}^{N}(e^2_{a_i} + e^2_{b_i} + e^2_{c_i})} \qquad (6)$$

$$E^* = \sqrt{\frac{1}{2}\sum_{i=1}^{N}(e^2_{a_i}G^2_a(i) + e^2_{b_i}G^2_b(i) + e^2_{c_i}G^2_c(i))} \qquad (7)$$

$$\varepsilon^*_{dc} = \frac{1}{2}\sum_{i=1}^{N}(e^2_{a_i}G_a(i) + e^2_{b_i}G_b(i) + e^2_{c_i}G_c(i)) \qquad (8)$$

The desired load current ($\mathbf{i}^* = \Psi^*_0.\mathbf{e}^*$) is calculated by solving the non-linear programming problem introduced by the compensation strategy e.g. (3), to determine the optimal values of $G_a(i)$, $G_b(i)$, $G_c(i)$ Power factor η is calculated by (9) and is a function of the filter bank gains and the load voltage harmonics. After calculating the optimal values of the filter bank gains, parameter ψ^*_0 is calculated by (10) to balance the active power of the load.

$$\eta = \frac{P_{dc}}{E.I^*} = \frac{P_{dc}}{\psi^*_0 E.E^*} = \frac{(e^T e^*)_{dc}}{E.E^*} \qquad (9)$$

$$\psi^*_0 = \frac{P_{dc}}{\varepsilon^*_{dc}} \qquad (10)$$

Finally, the power factor can be rewritten as:

$$\eta = \frac{\frac{1}{2}\sum_{i=1}^{N}(e^2_{a_i}G_a(i) + e^2_{b_i}G_b(i) + e^2_{c_i}G_c(i))}{\sqrt{\frac{1}{2}\sum_{i=1}^{N}(e^2_{a_i}G^2_a(i) + e^2_{b_i}G^2_b(i) + e^2_{c_i}G^2_c(i))}\sqrt{\frac{1}{2}\sum_{i=1}^{N}(e^2_{a_i} + e^2_{b_i} + e^2_{c_i})}} \qquad (11)$$

Hence, the compensating current is calculated as follows.

$$i_{cr}(t) = i_L(t) - i^*(t) \qquad (12)$$

This current is applied to the compensator system which is usually a three phase Inverter system with PWM or Hysteresis controllers. However, as already addressed, the output current of the compensator i_{af} (see Fig. 1) is not exactly the same $i_{cr}(t)$ calculated. That is due to some non-idealities in the compensator system including phase and gain errors introduced by the inverters and their output passive filters.

III. FREQUENCY DOMAIN LIMITATIONS

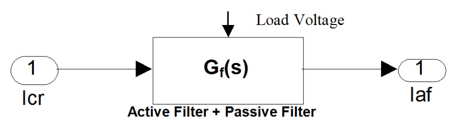

Fig. 3 Block Diagram of the Entire Compensator

Imperfect tracking are partly due to frequency domain characteristics of the compensator system. Some of them are:

a. Bandwidth limitation of the Inverter system associated with the passive filters to remove the high frequency ripples.
b. External disturbances imposed by the distorted load voltage

Fig. 3 depicts the block diagram of the entire compensator denoted by $G_f(s)$ including the Inverter and its HPF dynamics as well as the effect of the load voltage as an external disturbance. To highlight the adverse impact of such limitations, a nonlinear load supplied with a distorted source voltage is considered as shown in Fig. 1. The control algorithm is based on (3) where the harmonics constraints are taken according to the IEEE 519 standards [11],[1]. There is a hysteresis controlled Inverter in each phase accompanied by a High Pass Filter (HPF) to suppress the high frequency ripples introduced by the inverter. Also the number of harmonics considered for the OFC realization N equals 13. Fig.4 shows the waveforms of the source and load voltages, and the load current before compensation. The source voltage is intentionally assumed to be much distorted with 7^{th} harmonic (14.28 %) and 13^{th} harmonics (7.69%) to better show the behavior of the active filter under severe conditions.

Also, Fig.5 indicates the load current, the reference current calculated by the OFC system (as a reference to the

Inverter), as well as the synthesized current by the compensator, the load current if an ideal compensator could be used, and finally the exact source current compensated with the real world compensator. As seen the resulting source current is much more distorted than expected. Table I summarizes the power factor and THD of the source current of the uncompensated and compensated systems. As seen, the resulting THD (reached) is 8.5% which is much higher than the predefined level and expected by the OFC algorithm (desired). It confirms significant adverse effect of the Inverter and its HPF as well as the load voltage distortion on the tracking performance of the compensator even though a fast hysteresis controlled Inverter is used. The situation could be much worth when Current Regulated PWM (CRPWM) Inverters were used, as they introduce much higher phase error compared to Hysteresis controlled Inverters .To better discover the tracking error, the enlarged waveforms of the reference signal produced by the OFC system ($i_{cr}(t)$), output current of the Inverter (i_f), and the exact output of the compensator (i_{af}) are shown in Fig. 6. As seen, the outer loop current that is the current after the HPF filter has lower ripple, but it is more distorted in terms of low frequency components due to phase delay and amplitude error imposed by the HPF filter.

A. Control of single-phase Inverters

Recently, some advanced control systems such as deadbeat [12], sliding mode [13], predictive [14],[15], adaptive [16], multi rate feed forward [17], and adaptive predictive [18] control systems have found successful applications for reducing the tracking error of Inverters. Deadbeat and predictive control strategies provide good tracking ability, but they require the exact model of the inverter. Another control approach has been developed based on the concept of Synchronous frame PI controller [19],[20]. In this approach, a high gain notch filter is inserted in the feedback loop to provide high loop gain and therefore guaranty a low tracking error at the center frequency of the notch filter. However, this control system as well as the other advanced control schemes are rather complicated and require high bandwidth to track a harmonic reference signal. It seems much difficult and impractical to use the Synchronous frame PI controllers for such references, as it requires a controller for each harmonic leading to a much complicated and expensive system. Almost all the addressed approaches are not suitable for high bandwidth harmonic references. In the rest, the following simple alternative approaches are presented to improve the tracking performance of the compensator.

- High gain multi-loop Hysteresis Controller
- Filtered Feed Forward Controller
- Adaptive Phase and Gain Compensator [21]

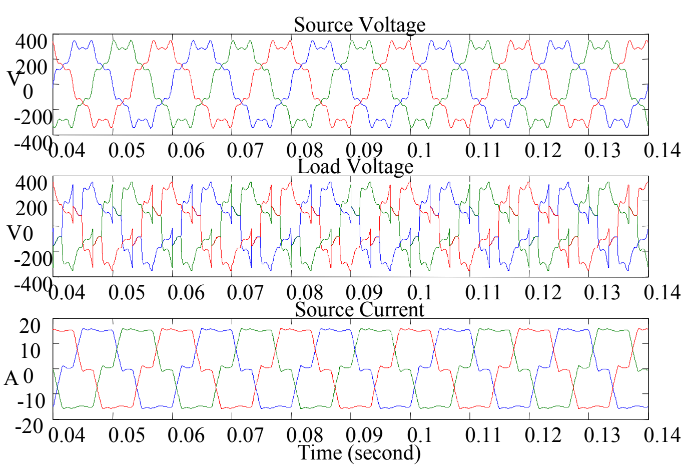

Fig. 4 Source and Load Voltages and Source Currents Before Compensation

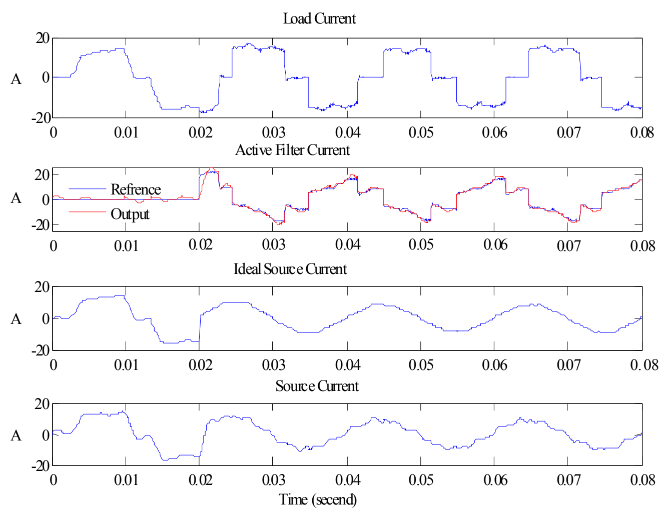

Fig. 5 Up to Down : Phase a Currents of The Load, Reference and Real Compensator, Ideally Compensated load, Non-Ideally Compensated Load

B. High Gain Multi Loop Approach.

To improve the Inverter's dynamics, it is possible to decrease the hysteresis band. That of course leads to higher switching

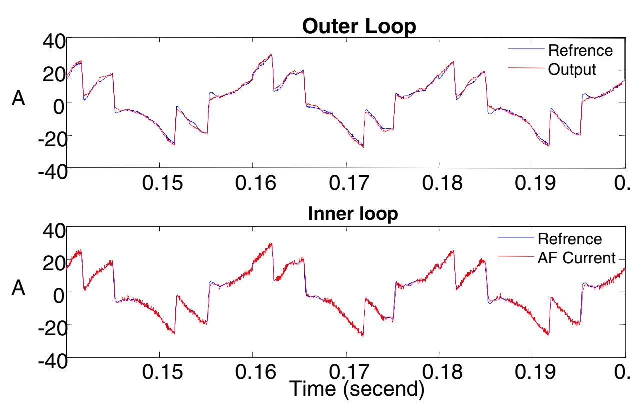

Fig.6: Up: Reference Signal & Compensator Current
Down: Reference Signal & Inverter Current

frequency increasing the loss. Moreover, that will not compensate the dynamic of the HPF filter. In this approach, another feedback loop is added based on the exact output current of the compensator that is i_{af} as shown in Fig. 7. Because i_{af} contains less high frequency ripples we can increase the gain k appears in the figure with rather low impact on the average switching frequency of the Inverter. For this study, the hysteresis band delta and the controller gain k equal 0.5 and 10 respectively. Fig. 8 show the simulation result of the proposed approach and as reflected in Table I, the THD of the source current is 5.5% showing significant improvement.

C. Filtered Feed Forward Control

To better mitigate the effect of the load voltage harmonics, the current of the HPF's resistor R ($i_{pf}(t)$) is used. This current is measured and its low frequency components are somehow considered as the undesired harmonics imposed by the load voltage. This set of low frequency harmonics denoted by $i_{pf_w}(t)$ is extracted from the original signal by means of a FFT operator and a moving window over time with length of T which is one period of the reference signal, and $i_{pf_d}(t)$ is the high frequency components as defined by (13)-(15).

$$i_{pf}(t) = i_{pf_w}(t) + i_{pf_d}(t) \tag{13}$$

$$i_{pf_w}(t) = \sum_{i=1}^{N} a_i \sin(i\omega t + \theta_i) \tag{14}$$

$$i_{pf_d}(t) = \sum_{i=N+1}^{\infty} a_i \sin(i\omega t + \theta_i) \tag{15}$$

Then, only the low frequency signal is used to correct (modify) the reference signal as follows:

$$i_{cr_m}(t) = i_{cr}(t) + i_{pf_w}(t) \tag{16}$$

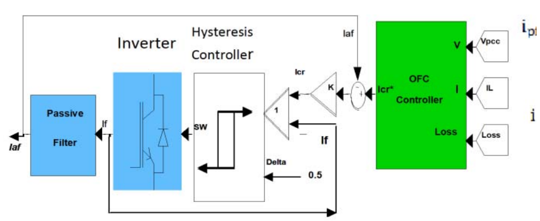

Fig.7 Block Diagram of the Compensator with Multi-Loop High Gain

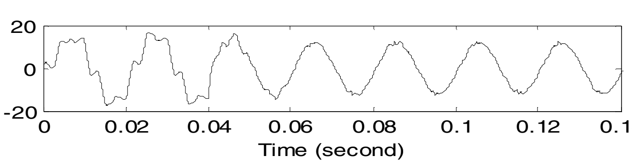

Fig. 8 Phase a Current of The Compensated Load with High Gain Control

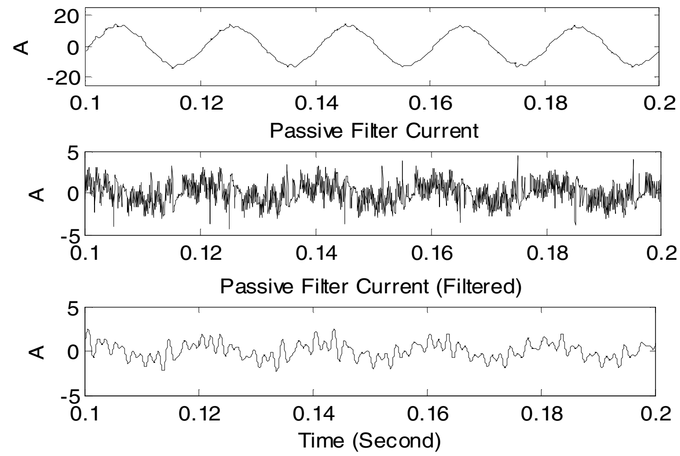

Fig. 9 Up to Down : Phase a Current of The Compensated Load with Filtered Feed Forward Control, Passive Filter Current, and Passive Filter Current after Removing The High Frequency Ripples by FFT Operator

Hence, the output current of the compensator should try to follow the modified reference which results in mitigating the impact of the load voltage. The simulation results are given by Fig. 9, and as seen there is improvement in the output current. This is also confirmed by the numerical results shown in Table I showing a THD equals 5.48% which is better than the results of the other approaches already discussed.

D. Adaptive Phase and Gain Compensator

In this new approach which initially proposed by the author [21], the Inverter system under control is treated as Multi Input Multi Output (MIMO) plant in frequency domain as shown in Fig. 10. The inputs A_i and □$_i$ are gains and amplitudes of the harmonic components of the reference signal respectively and the outputs are also the gains and

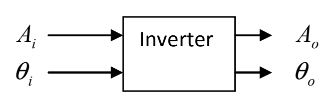

Fig. 10 Block Diagram of An Inverter as A MIMO System

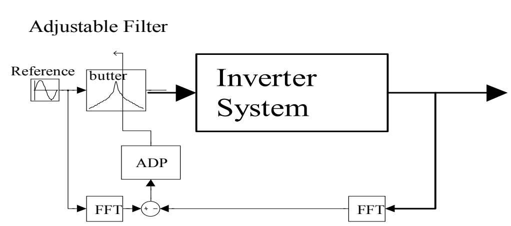

Fig. 11 Block Diagram of The Adaptive Phase and Gain Controller

amplitudes of the harmonic components of the output current. In ideal case, the output quantities should track the input variables in steady state. In this strategy, the phase and gain error of the Inverter at each harmonic is calculated. Then the phase error is compensated by adjusting frequency characteristics of the BPF as shown in Fig. 11. It should be noted that in contrast to other classic control systems, here we need the Inverter system to successfully synthesis a current with harmonics only at some specified frequencies not a wide band signal with continuous spectrum. The situation however may become rather complicated and expensive for active filtering applications where there are many harmonics to be tracked. In such cases we need a set of BPFs each for one of the harmonics. However, this control approach is still the best candidate for OFC based active filters, because we would not need any BPF. In the OFC, the compensating current is synthesized term by term based on its Fourier series [3]. Hence it is much easy to modify the amplitude and phase of each harmonics directly. Using (12) and considering only N terms for the currents and voltages under study, the reference current can be expressed as follows;

$$i_{cr}(t) = \sum_{i=1}^{N} i_{cr_i}.\sin(i\omega t + \gamma_i) \qquad (17)$$

On the other hand, the characteristics of the transfer function $G_f(s)$ between the reference current and the output current of the compensator can be identified by the FFT operators as expressed by (18). $\vec{(.)}$ denotes complex phasors of the quantities.

$$\vec{G}_{f_i} = \frac{\left|\vec{i}_{af_i}\right|}{\left|\vec{i}_{cr_i}\right|}\angle(\angle\vec{i}_{af_i} - \angle\vec{i}_{af_i}) \quad ; i = 1,2,3,\ldots,N \qquad (18)$$

Hence, each phasor harmonic of the reference signal can be modified to overcome the gain and phase errors introduced by the Inverter and its output filter as follows:

$$\vec{i}_{cr_{m_i}} = \frac{\vec{i}_{cr_i}}{\vec{G}_{f_i}} \qquad (19)$$

These modified components are used to correct the compensating current (17). Besides correcting the frequency characteristics of the Inverter system, this approach can also mitigate parts of the harmonics imposed by the load voltage.

Fig. 12 shows the simulation results of the system with the proposed approach. The resulting THD, as shown in Table I, has further reduced to 5.44% showing the successful performance of the proposed control approach with of course simple structure and with no need to expensive hardware and/ or software facilities. The reached THD is sufficiently close to the acceptable level suggested by IEEE-519 standards. As seen, this control approach looks to be the most suitable approach for OFC filters. However, the performance can certainly be improved by increasing N.

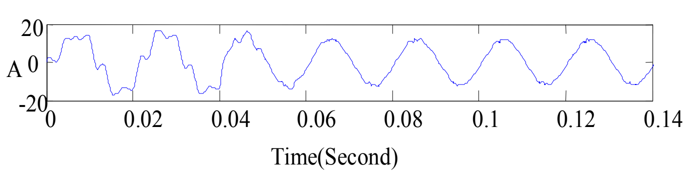

Fig. 12 Phase a Currents of the Compensated Load with Adaptive Phase and Gain Controller

IV. UPQC Based Optimal Active Filtering

As seen in Table 1 and addressed in the previous section, the adaptive controller introduced in the previous section can provide the best performance compared to the other controllers under study. In this section, the impact of load voltage harmonics on the performance of the parallel active filter is further investigated. Traditionally, UPQC system is used to mitigate both the load voltage and load current harmonics. An interesting idea could be use of a UPQC topology with an OFC controlled shunt APF. This way, the parallel APF, compensates the source current harmonics compromising between current THD and power factor [1]. In the same time, the series APF (see Fig. 13) is in charge of providing the load with a near sinusoidal and balance voltage . It is also shown that the series APF besides providing the load with a near sinusoidal voltage without negative and zero sequences, can significantly improve the performance of the parallel APF via improving the load voltage waveform. Fig. 13 shows the Optimal UPQC system under study. Fig. 14 shows the load voltage before and after starting up the series APF where the shunt APF is still off. Also, Fig. 15 shows the load and source currents where the parallel APF also operates. In this case the simplest control system that is a simple hysteresis controller for the shunt compensator is used. The results summarized in Table I show that the current THD and Power Factor of the compensated load have significantly been improved. The best results can be achieved by the Optimal UPQC with the aforementioned adaptive controller. This can also be seen in Fig. 16 that shows a less distorted waveform for the source current. It is worth mentioning that there are some changes in the desired THD and power factor for different compensator as appear in Tables I. That is because every compensator with different controller produces different source current that causes different voltage situation due to existence of the source impedance.

Table I: Comparative Results of Some Different Control Approaches

D: Desired R: Reached		Power Factor %			THDi %			THDv % Load
		Source		Load	Source		Load	
		D	**R**		**D**	**R**		
Uncompensated		-	71.19	81.60	-	39.3	39.30	42.64
OFC	Uncorrected	96.00	98.09	64.54	4.80	**8.50**	31.65	25.04
	Closed Loop	96.18	94.19	68.08	4.56	**5.50**	30.86	26.29
	Feed Forward	95.94	96.02	68.10	4.60	**5.48**	31.00	28.64
	Adaptive	96.48	96.57	66.09	4.75	**5.43**	31.45	28.93
UPQC With OFC	Uncorrected	95.86	95.55	73.72	4.80	**5.87**	31.52	2.17
	Adaptive	96.52	96.42	73.72	4.80	**5.27**	31.52	2.18

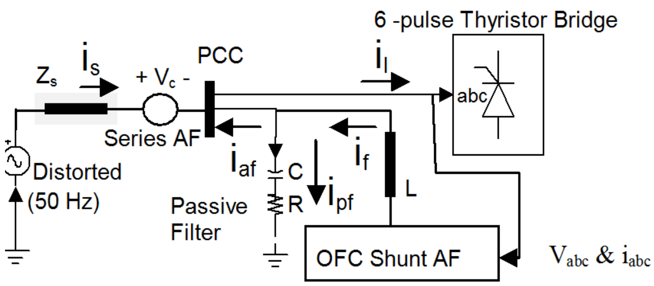

Fig. 13 Optimal UPQC with OFC Based Shunt AF

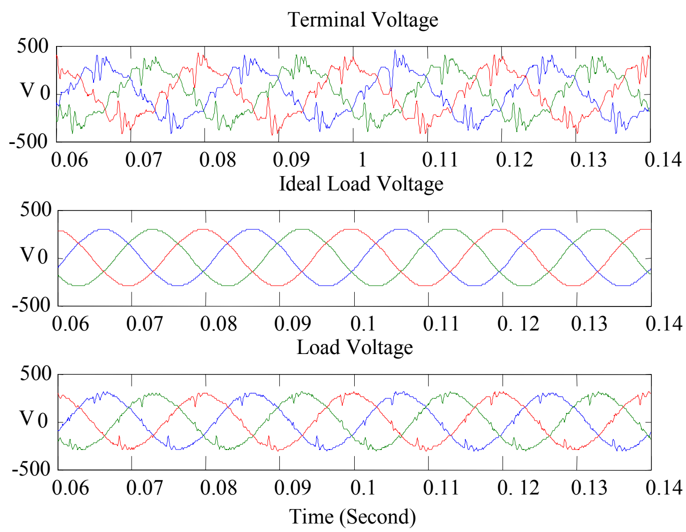

Fig. 14 Up to Down: Uncompensated Load voltage, Ideal Load Voltage (after removing all harmonics and negative and zero sequences), and The Resulting Load Voltage after Applying the Series Active Filter and Adaptive Phase and Gain Correction

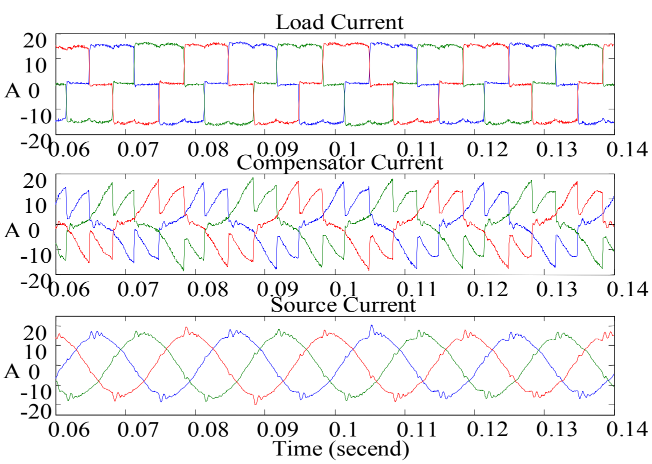

Fig. 15 The Uncompensated Load Currents, The Compensating Currents, and The Compensated Current with OFC Based UPQC

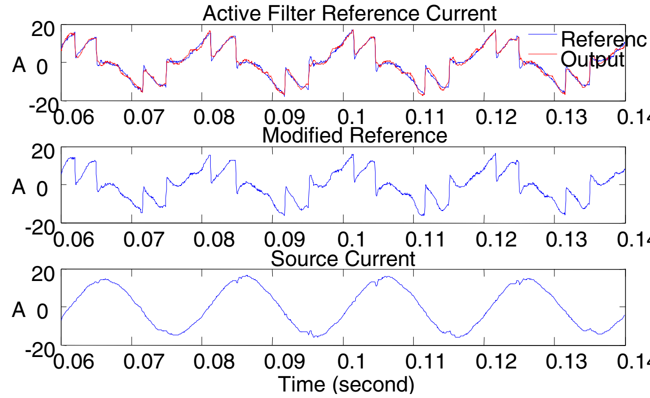

Fig.16. Reference Current, Compensating Current, Modified Reference Current, and the Resulting Compensated Current with Optimal UPQC

This voltage change in turn requires the OFC system to start over the optimization process that leads to new optimized results. The concept has carefully been described in [3].After some iterations, the OFC provides the final results. For all the simulations, a Proportional-Integral (PI) Controller is used to regulate the capacitive dc bus of the Inverter (K_p=10 and K_I=5) [1].

V. CONCLUSION

Impact of frequency domain limitations of the practical active power filters operating under distorted voltage conditions was studied. Through extensive simulation results carried out in MATLAB / SIMULINK environment, it was explored that how such limitations including bandwidth limitation and load voltage disturbance can deteriorate tracking performance of the Inverter based compensators. Several simple approaches including an adaptive phase and gain regulator for the Inverter to improve tracking ability of the OFC based APF system were suggested and investigated. Also, a novel system called OFC based UPQC was proposed and its superior performance was proved through simulation studies. The OFC based UPQC system besides removing the load voltage harmonics and unbalance, can significantly contribute in improving the shunt compensator's performance. Studies presented in the paper reinforce the overall superiority of the optimal active filters in not only compromising between power quality requirements, but also in intelligent dealing with some practical limitations. Other practical requirements such as dc bus voltage fluctuations and Inverter's conduction and switching loss can intelligently be optimized in OFC algorithm.

VI. REFERENCES

[1] S. Mohammad-Reza Rafiei, Hamid A. Toliyat, Reza Ghazi and Tilak Gopalarathnam, "An Optimal and Flexible Control Strategy for Active Filtering and Power Factor Correction Under Non-Sinusoidal Line Voltages," IEEE Trans. On. Power Delivery, Vol. 16, No. 2, April 2001, pp. 297-305

[2] S.M.R. Rafiei, R. Ghazi, and H.A. Toliyat, IEEE-519 Based Real Time and Optimal Control of Active Filters Under Non-

Sinusoidal Line Voltages Using Neural Networks," IEEE Transactions on Power Delivery, Vol. 17, No. 3, July 2002, pp 815-822.

[3] S.M.R. Rafiei and Reza Iravani, "Optimal and Adaptive Compensation of Voltage and Current Harmonics under Non Stiff Voltage Conditions" IEE Proceedings of Generation, Transmission, and Distribution. Vol. 152, Issue 5, September 2005 pp. 661 – 672

[4] Sincy George and Vivek Agarwal, "A Novel, DSP Based Algorithm for Optimizing the Harmonics and Reactive Power Under Non-Sinusoidal Supply Voltage Conditions, "IEEE Transactions on Power Delivery, Vol. 20, No. 4, October 2005, pp 2526-2534

[5] Gary W. Chang,, "A New Approach for Optimal Shunt Active Power Filter Control Considering Alternative Performance Indices, "IEEE Transactions on Power Delivery, Vol. 21, No. 1, January 2006, pp 406-413

[6] S. D. Round and R. M. Duke, "Real-time optimization of an active filter's performance," IEEE Trans. Ind. Electron., vol. 41, June 1994

[7] Gary W. Chang,, Chia-Ming Yeh, and Wei-Cheng Chen, " Meeting IEEE-519 Current Harmonics and Power Factor Constraints With a Three-Phase Three-Wire Active Power Filter Under Distorted Source Voltages," IEEE Transactions on Power Delivery, Vol. 21, No. 3, July 2006, pp 1648-1654

[8] Ting Qian, Anindita Bhattacharya, Brad Lehman, Herb Ginn, and Marshall Molen, "Adaptive Phase Adjustment Synchronization Method for Source Voltage Distortion in Electric Ship Application, "Proceedings of the 2005 IEEE Conference on Control Applications Toronto, Canada, pp. 1498-1503, August 28-31, 2005

[9] H. Fujita and H. Akagi, "The unified power quality conditioner: the integration of series and shunt-active filters, IEEE Trans. On Power Electronics, 1998, Vol. 13, No. , pp. 315–322

[10] E.H. Watanabe and M. Aredes, "Power quality considerations on shunt/series current and voltage'. 10th Int. Conf. Harmonics and Quality of Power, Oct. 2002, Vol. 2, pp. 595–600

[11] IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems, IEEE std 519-1992, New York, 1993

[12] A. Kawamura, T. Haneyoshi and R. G. Hoft, "Deadbeat controlled PWM inverter with parameter estimation using only voltage sensor", *IEEE Trans. on Power Electronics.*, Vol. 3, pp. 118-125, Apr. 1988

[13] Jung Shih-Liang and Tzou Ying-Yu, **"**Discrete sliding-mode control of a PWM inverter for sinusoidal output waveform synthesis with optimal sliding curve," IEEE Trans. On Power Electronics**,** Vol. 11, Issue 4, July 1996 pp.567 - 577

[14] S. Hara, Y. Yamamoto, T. Omata and M. Nakano, "Repetitive control system: A new type servo system for periodic exogenous signals", *IEEE* Trans. On Automatic. Control, vol. 33, Jul. 1988 pp. 659-667

[15] Y.Nishida and T. Haneyoshi, "Predictive instantaneous value controlled PWM inverter for UPS", *IEEE Power Electronics. Spec. Conf,* pp. 776-783

[16] H. A. Gründling, E. G. Carati and J. R. Pinheiro, "A robust model reference adaptive controller for UPS applications", *IEEE Ind. Electr. Conf.*, 1997, pp. 901-905

[17] Hiroshi Fujimoto, Yoichi Hori, and Seiji Kondo, "Perfect Tracking Control Based on Multi rate Feed forward Control and Applications to Motion Control and Power Electronics – A Simple Solution via Transfer Function Approach," Power Conversion Conference (PCC2002) , vol. 1, pp. 196--201, Osaka, 2002

[18] D. W. Clarke, "Adaptive Predictive Control", *Annual Review in Automatic Programmin*g, Vol. 20, pp. 83-94, 1996

[19] C. D. Schauder and R. Caddy, "Current Control of Voltage-Source Inverters for Fast Four-Quadrant Drive Performance," IEEE Trans. On Industry Applications, Vol. IA-18, No. 2, pp. 163-171, March/April 1982

[20] T. M. Rowan and R. J. Kerkman, "A New Synchronous Current Regulator and an Analysis of Current-Regulated PWM Inverters," IEEE Trans. on Industry Applications, Vol. IA-22, No. 4, pp. 678-690, March/April 1986

[21] S.M.R. Rafiei, "Neural Network Based Adaptive Phase and Amplitude Equalizer for Optimal and Robust Control of the Current Regulated PWM Inverters, "35th IEEE Southeastern Symposium on System Theory, USA, May 2003

VII. BIOGRAPHIES

Mohammadreza Rafiei (M'03-SM'04) was born in 1969 in Tehran, Iran. He received B.Sc. degree with honor from the Sistan and Baluchistan university, Zahedan, Iran, in 1991, M.Sc., and Ph.D degrees from the Ferdowsi University of Mashhad, Mashhad, Iran, in 1995 and 2000 respectively all in electrical engineering. He is currently with the Department of Electrical Engineering, Politecnico di Torino, Torino, Italy Dr. Rafiei is member of IEEE Control Systems, Power Electronics, and Power Engineering societies. His field of interests includes Control Systems, Power Electronics, and Power Quality

Reza Asadi was born in Kermanshah in Iran, on September 21, 1978. He graduated B.S. in electrical power engineering from Hormozgan University, Bandar Abbas and M.S. from Shahrood University, Iran.

His employment experience included H.V. in Niroo Consultant Engineers Company, Tehran and maintenance engineer in North Drilling Company and National Iranian Oil Company, Iran. His special fields of interest included power quality.