Design of Unified Power Quality Conditioner for Power Quality Improvement in Distribution Network

S. Biricik

***Abstract*—Unified Power Quality Conditioner (UPQC) is one of the most advanced Custom-Power-Devices in use today to improve the quality of Power (PQ) in the distribution network. UPQC compensates both voltage and current related PQ disturbances. Its control in unbalanced and distorted weak grid condition is of research interest. Also the performance of UPQC in the presence of unbalanced and non-linear harmonic loads is critical to maintain desirable PQ. In this work, a Self-Tuning Filter (STF) is implemented on the controller part to improve the performance of UPQC in the weak grid voltage along with current unbalance and distortion. The studied control structure gives an adequate voltage and current compensation for voltage sag with distorted voltage conditions, and also for unbalanced current conditions. A three-phase system is modelled in MATLAB/Simulink. The results of simulation study are presented to verify the effectiveness of the proposed control technique.**

Index Terms—**UPQC, Voltage Sag, Unbalanced Voltages, Voltage Harmonics, Current Harmonics, STF.**

I. Introduction

VOLTAGE distortions and fluctuations are frequently encountered in the weak grid network systems. The distorted load currents cause non-sinusoidal voltage drops and as a result the network voltages become distorted. On the other hand, voltage sag and swell problems are usually caused by short-circuit current flowing into a fault. Voltage sag and swell are defined as a sudden reduction or rise of grid voltages from its nominal value. Unified Power Quality Conditioner (UPQC) is one of the most advanced custom power devices to solve such power quality problems [1, 2]. UPQC is a combination of series active filter and shunt active power filters, connected back-to-back on a common DC link capacitor. The series part of the UPQC is liable for managing of the network side voltage disturbances: voltage unbalance, sags/swells, voltage flicker, and harmonics. It inserts voltages so as to maintain the load voltages at a desired level; balanced and distortion free. The shunt part is responsible for managing the current quality problems caused by the consumer: poor power factor, load harmonic currents, load unbalance etc. A 12-kVA DSP controlled laboratory prototype UPQC has been designed and installed at the DIT Lab to test all of the above mentioned quality [3].

S. BİRİCİK, is with Department of Electrical & Electronics Engineering, European University of Lefke, Northern Cyprus TR 10 Mersin, Turkey, (e-mail: sbiricik@eul.edu.tr)

Manuscript received July 9, 2017; accepted November 16, 2017.
DOI: 10.17694/bajece.402009

As the UPQC can compensate most of the existing PQ problems in the distribution grid, integration of a UPQC in the DG integrated network can be multipurpose. Different integration techniques with their pros and cons are discussed in [4]. Recently published article shows that UPQC can improve the power quality in microgrid system with their intelligent islanding and seamless reconnection techniques [5, 6].

The performance of the UPQC depends on the appropriate design of the components, generation of reference signals and selection of control strategy. As the UPQC is a back-to-back combination of series and shunt active power filter (SAPF) and is directly connected to a dc link capacitor, both the design and controlling mechanism of the APF in terms of the series and parallel connection are very important. Design parameters for both shunt and series part of APF are calculated from [7, 8].

Generation of appropriate switching patterns or gating signals with reference to command the compensating signals determines the control strategy of any compensating devices. It becomes challenging when the unbalance and distorted grid voltage/current are exist in the grid. Recent studies show that self-tuning filter (STF) is introduced in the control part for most of the compensating devices. It helps to filter out the harmonics from the signal and also calculate the balanced condition to create the precise reference waveform. Some of the examples of implementing STF can be found in [9-16]. STF is mostly used as a filter to extract current harmonics in the controller of SAPF [9-14] and hybrid active power filter [15]. It is also proposed in the control of dynamic voltage restorer (DVR) with dc linked storage to improve its performance in case of weak grid condition [16]. Its performance in DVR and shunt APF encourages to exploit its opportunity to improve the performance of UPQC and specially in the un-balanced and distorted grid condition. Therefore, STF is introduced in this study to improve the performance of the UPQC. The stimulating part of this study is to observe the performance of STF to generate the reference current precisely in the case of combination of shunt and series APF and connected back-to-back with a common dc-link capacitor. It is worth to mention that compare to DVR with separate energy storage, self-stored series APF in UPQC requires high fluctuation of source current in the event of voltage sag. The performance of UPQC is studied in the case of both non-ideal grid voltages and unbalanced voltage sag with current harmonics. Fig 1 gives the studied UPQC topology.

This paper has been organized as follows. The improved control method with STF for the control of UPQC is described in Section II. Based on the control method and design parameters, simulation results of a UPQC placed in a weak grid distribution network are discussed in Section III which is followed by concluding remarks in Section IV.

II. Control of The UPQC

First aim of the UPQC is to suppress the voltage harmonics, $\tilde{u}_s$, then regulation of the voltage amplitudes at the system frequency, $\bar{v}_s$ to obtain the pure sinusoidal voltage waveforms on the load terminal as

$$v_s(t) = \sqrt{2}.230\, sin(\omega t + \theta) \tag{1}$$

the STF is used in the studied control system . In this case, the sensed utility voltages (v_{sa}, v_{sb}, v_{sc}) are transformed first into two phase coordinate system using the Clarke (or α-β) transformation:

$$\begin{bmatrix} v_{s\alpha}(t) \\ v_{s\beta}(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{sa}(t) \\ v_{sb}(t) \\ v_{sc}(t) \end{bmatrix} \tag{2}$$

The obtained voltage waveforms by (2) are processed with (4) as described in [11].

$$\begin{aligned} \bar{v}_{s\alpha}(s) &= \frac{K_1}{s}[v_{s\alpha}(s) - \bar{v}_{s\alpha}(s)] - \frac{\omega}{s}\bar{v}_{s\beta}(s) \\ \bar{v}_{s\beta}(s) &= \frac{K_1}{s}[v_{s\beta}(s) - \bar{v}_{s\beta}(s)] + \frac{\omega}{s}\bar{v}_{s\alpha}(s) \end{aligned} \tag{3}$$

Then, the waveforms obtained in (3) is converted to the three phase system by using following Clarke transformation :

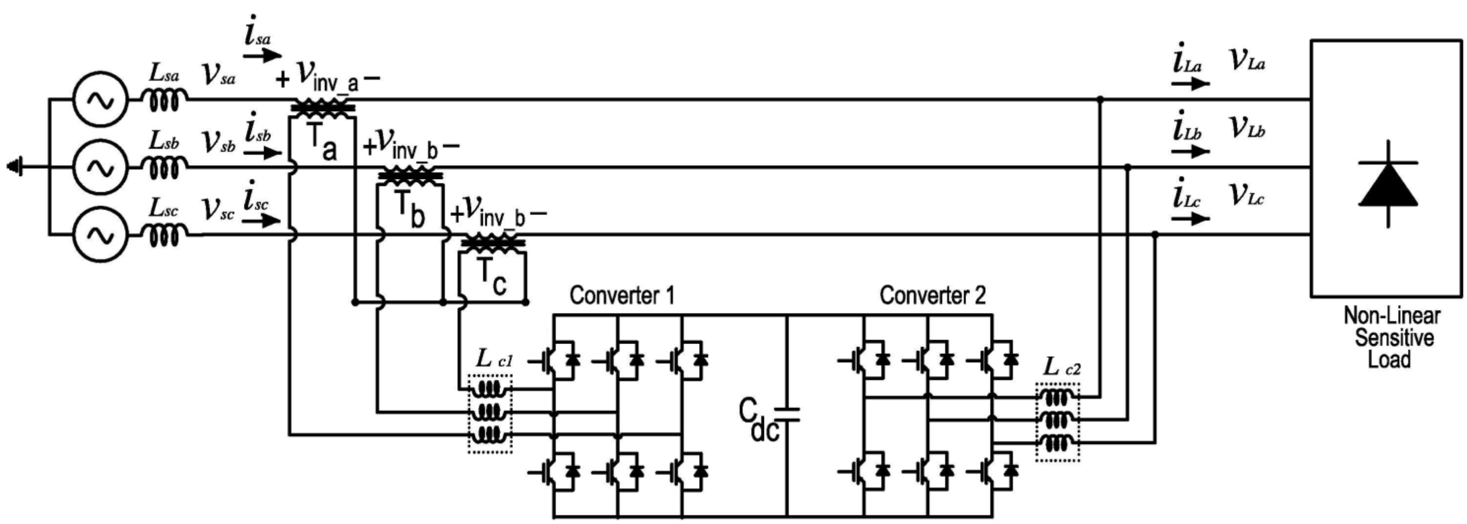
$$\begin{bmatrix} \bar{u}_{sa}(t) \\ \bar{u}_{sb}(t) \\ \bar{u}_{sc}(t) \end{bmatrix} = \sqrt{\frac{3}{2}} \begin{bmatrix} 0 & 1 \\ \frac{\sqrt{3}}{2} & -\frac{1}{2} \\ -\frac{\sqrt{3}}{2} & -\frac{1}{2} \end{bmatrix} \begin{bmatrix} \bar{u}_{s\alpha}(t) \\ \bar{u}_{s\beta}(t) \end{bmatrix} \tag{4}$$

The result of (4) are voltage waveforms at the 50 Hz. However, the obtained waveforms may have voltage sag or swell due to the network fluctuations. Therefore, these waveforms cannot be used as reference source signals. To obtain reference signals for each phase, first the amplitude of the determined voltages ($V_{sa}{}', V_{sb}{}', V_{sc}{}'$) from (4) are calculated, and then divided with the obtained waveforms for each phase from (5) as,

$$sin(\omega t + \theta) = \frac{\bar{v}_s(t)}{V_s{}'} \tag{5}$$

Eq. (5) can be used to obtain unity sine functions for each phase which will be vary between ±1V. Lastly, the reference source voltage waveforms can be determined by multiplying standard utility voltage peak (amplitude) level, U_s^*, which is $\sqrt{2}.230$. The reference source voltage, $u_s^*(t)$, is given by,

$$u_s^*(t) = \sqrt{2}.230\, sin(\omega t + \theta) \tag{6}$$



A. *Fig.1. Topology of the Studied Unified Power Quality Conditioner*

Then the expected reference voltages for compensation, $u_c^*(t)$, which are required to induce over the secondary side of the transformer, can be determined by subtracting it from the measured utility voltages, v_s, that is,

$$v_c^*(t) = v_s(t) - v_s^*(t) \tag{7}$$

Results of (7), under ideal condition mean that the source voltages are as described in (1) will be zero. Therefore, the Converter 1 will turn off. However, results of (7) during voltage sag and harmonic pollution on the source will be as

$$v_c^*(t) = v_{inv}(t) + \tilde{v}_s(t) \tag{8}$$

Therefore, the generated reference voltages are subtracted from the sensed induced voltages on the secondary sides of the coupling transformers (Converter 1 output) for each phases.

$$e(t) = v_c^*(t) - v_{sec}(t) \tag{9}$$

where $e(t)$ is the error signal. Finally, the obtained errors for the phases by (9) are used to drive Converter 1 by generating PWM pulses. In order to determine load current harmonics, the currents on the load terminal are converted to dq frame as

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} \sqrt{\frac{2}{3}} \begin{bmatrix} cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{10}$$

As well known that, the un-equal line currents are one of the most important power quality problem. This problem also may reduce compensation performance of APF controllers. Accordingly, the determined i_d and i_q current waveforms by (10) are also processed using second STF in the studied control structure in order to determine balanced current waveforms at the fundamental frequency.

$$\begin{aligned} \bar{i_d}(s) &= \frac{K_2}{s}\left(i_d(s) - \bar{i_d}(s)\right) - \frac{\omega}{s}.\bar{i_q}(s) \\ \bar{i_q}(s) &= \frac{K_2}{s}\left(i_q(s) - \bar{i_q}(s)\right) + \frac{\omega}{s}.\bar{i_d}(s) \end{aligned} \tag{11}$$

Then the instantaneous currents can be separated to fundamental harmonic current, reactive current and harmonic current harmonics by using (12),

$$\begin{aligned} \tilde{i}_d &= i_d - \bar{i_d} \\ \tilde{i}_q &= i_q \end{aligned} \tag{12}$$

In the most of the control techniques, high pass filters or low pass filters are used to extract harmonic currents from fundamental harmonic. However, there is no need for an additional filter in the studied control structure. Finally, the determined harmonic current waveform, from (12), are then re-converted to three phase reference currents using the inverse synchronous transform as given by,

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos\theta & -sin\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} \tilde{i}_d \\ \tilde{i}_q \end{bmatrix} \tag{13}$$

The schematic representation of the proposed method is shown in Fig. 2.

III. Simulation Results

In order to test performance of the studied system, a power system model has been implemented in MATLAB/Simulink. The system performance is verified under voltage sag (50%) condition. Moreover, linear and a non-linear load combinations were also used. Detailed of the system parameters for the study are given in Table1.

The first Load (*Load* $_1$) is used to consume only active current with reactive current. However, the second load (*Load* $_2$) consume both active and reactive current and injects harmonic current to the network. The simulation blocks of the power and control systems are presented in Figs 2 and 3.

The proposed system is tested for the following cases and conditions;

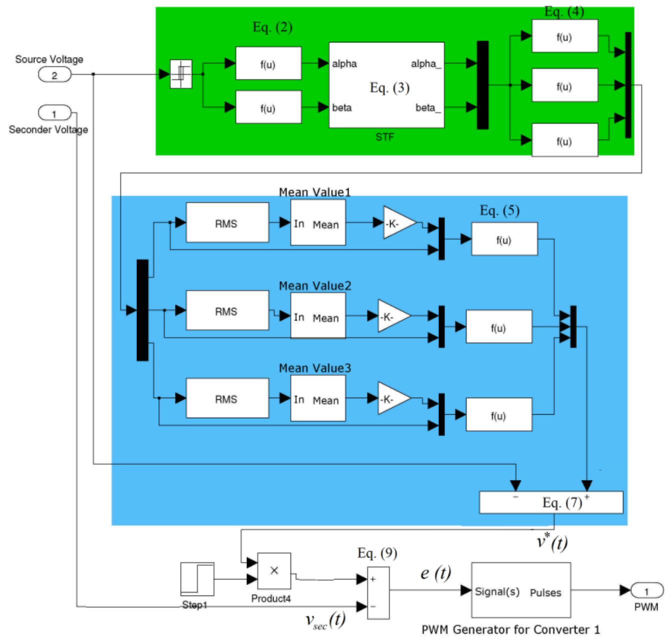


Fig.2. Simulink block diagram of the Converter 1 control

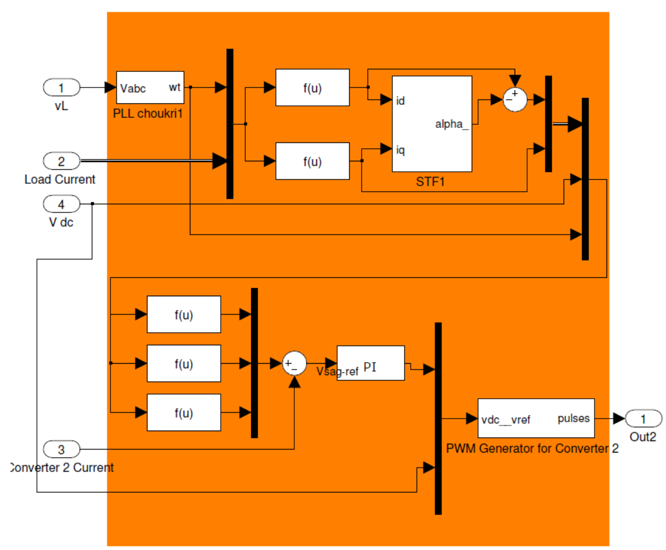


Fig.3. Simulink block diagram of the Converter 2 control

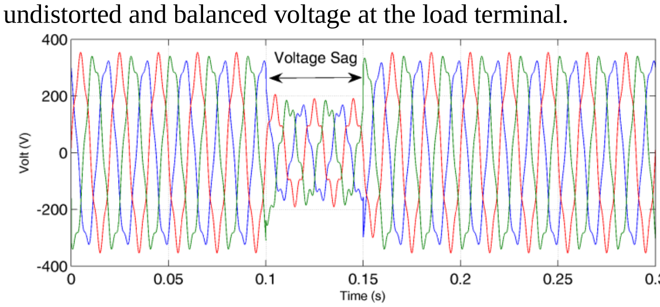
TABLE I
PARAMETERS OF THE STUDIED SYSTEM

Symbol	Quantity	Value
v_S	Ideal Grid L-N rms Voltage	230 V
f	Grid Frequency	50 Hz
$Load_1$	Linear Load Res. and Ind.	4Ω, 10 mH
$Load_2$	Non-Linear Load Res. and Ind.	24Ω, 20 mH
$Lc1$	Filter Inductor for Converter 1	0.3 mH
$Lc2$	Filter Inductor for Converter 1	2.5 mH
f_{s1}	Switching Freq. for Converter 1	10 kHz
f_{s2}	Switching Freq. for Converter 1	14 kHz
U_{dc}	DC-Link Source Voltage	750 V
C_{dc}	DC-Link Capacitor Size	2 mF
Kp	Proportional gain for DC link Cont.	0.89
Ki	Integral gain for DC link Cont.	78.96

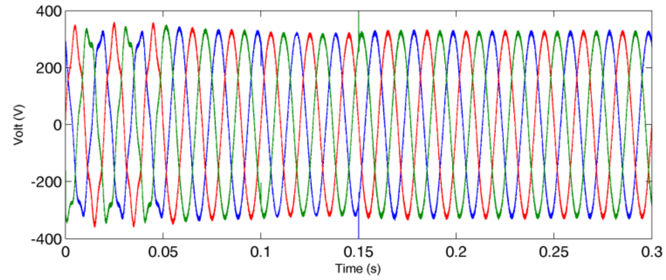
A. Unbalanced voltages and voltage harmonics on the grid side

The overall system is verified with the adverse grid voltage condition as shown in Fig 4(a). The harmonic distortion in each phases are measured as 9.06 % (229.4V rms) , 9.65 % (229.4V rms) and 7.39 % (231.9V rms), respectively. The system was simulated for 0.3 second and UPQC is activated after 0.05 sec. In order to test the system performance, the voltages are reduced 50 % (voltage sag) between 0.1 to 0.15 sec and voltages are reduced to 117 V at phase-a, 117 V at phase-b and 110.4 V at phase-c. The performance of the system is presented in Fig 4(b) where Converter 1 was immediately injected the required voltages to restore the voltage at the load terminal.

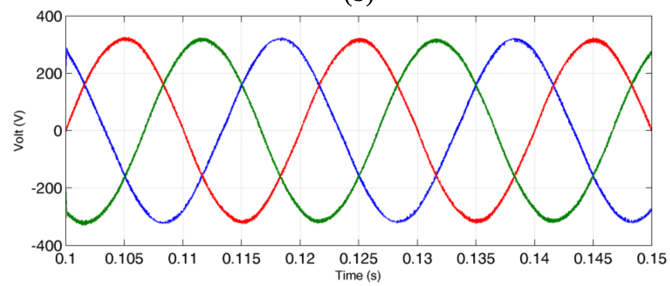
Fig. 4(b) shows the obtained pure sinusoidal voltage waveforms at the load side. With the proposed system, the load voltage harmonics are reduced from 10 % around to 2.10 %, 2.22 %, and 2.01% in each phase. RMS voltage levels are restored from 117 V to 225 V during voltage sag condition on the grid. Fig 4(c) shows the zoomed in load voltages between 0.1 to 0.15 sec during voltage sag on the grid voltages which confirms the balanced and linear voltages are obtained on the load terminal. Thus it shows that STF performs it task perfectly by precisely generating the reference signals and therefore, UPQC provides undistorted and balanced voltage at the load terminal.



(a)



(b)



(c)

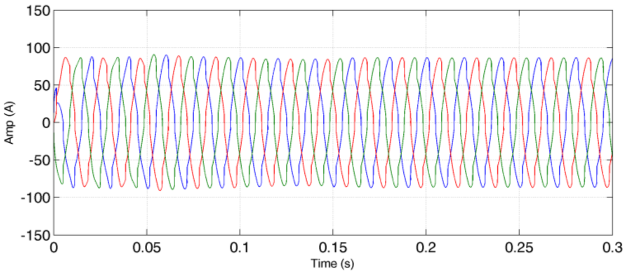
Fig 4. (a) Distorted and unbalanced grid voltages, b) un-distorted and balanced voltages at the load terminal. c) voltages at the load terminal during voltage sag (between 0.1 to 0.15 s)

B. Current harmonics on the load terminal

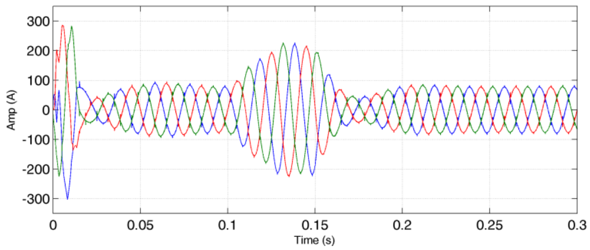
The load currents THD are found 8.99 %, 8.87 % and 9.02 % while the rms currents are 59.43 A, 59.51 A, 59.37 A., as shown in Fig 5(a). The shunt part of UPQC controls the injection of load harmonics to the grid and reactive power compensate by the UPQC. Thus the grid side only supply the fundamental active current required by the load and series APF of UPQC, as shown in Fig 5(b). This figure also confirms the performance of STF by generating the balanced reference current for the supply side during the voltage sag condition. Therefore, UPQC smoothly compensate the voltage sag, reactive and harmonic current at the same time as shown in Fig 4(b) and 5(b) during the period of 0.1 to 0.15 sec. Fig 5(c) shows the performance of the DC link capacitor by maintaining link voltage near to the reference.

C. Power flow analysis

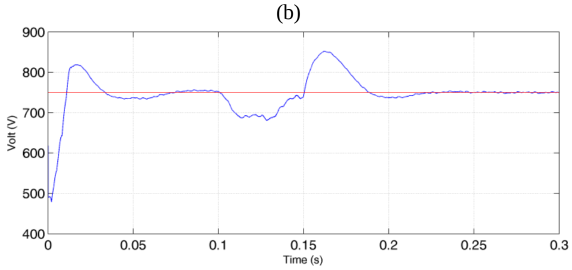
The precisely generated reference signal and the overall control of the UPQC also impact on the power flow within the converters of the UPQC. Fig 6(a) shows the power supply by the grid. During the performance of UPQC, grid only supplies the active power. Therefore, reactive power supplied by the grid is zero. Fig 6(b) shows the power flow within the UPQC. Shunt part of UPQC compensate the reactive and harmonics and therefore Q becomes constant during the operating time. Series APF consumes the active power from the grid to compensate the voltage sag and distortion and this also reflected in Fig 6(a, b). Therefore, load does not sense any disturbance by the grid and thus maintaining constant active and reactive power consumption as shown in Fig 6(c). Moreover, power factor of the system improved with the effective compensation of reactive power.



(a)

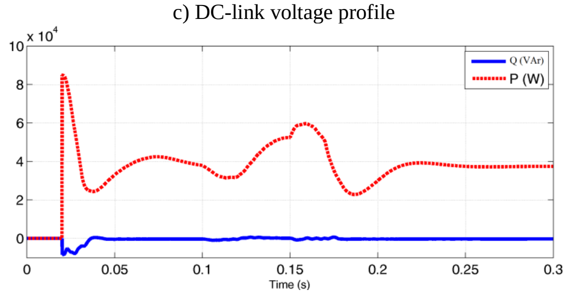


(b)

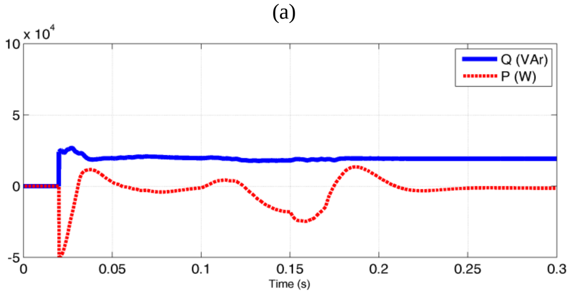


(c)

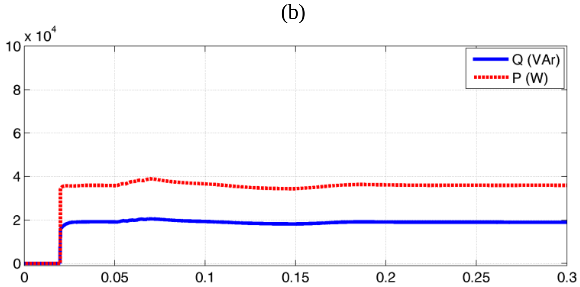
Fig 5. a) Three phase non-linear load currents, b) Grid currents after filtering; c) DC-link voltage profile



(a)



(b)



(c)

Fig 6. a) supplied powers by the grid; b) by the UPQC and c) consumed powers by the load.

IV. Conclusion

Unbalance and distorted voltage conditions are more common now-a-days in the distributed generation integrated network. Harmonic injection by the non-linear and energy efficient load is also increasing. Therefore, precise generation of reference signal for improved control of UPQC is a must. Simulation performance of the UPQC confirms that the inclusion of STF in the controller will add a degree of advantages for better performance of UPQC in distorted and unbalanced grid voltage condition.

References

[1] H Akagi, E H Watanabe and M Aredes, Instantaneous Power Theory and Applications to Power Conditioning. Piscataway, NJ: IEEE Press, 2007

[2] I Axente, M Basu, M F Conlon, A Control Approach for UPQC Connected to Weak Supply Point, UPEC 2007, p. 619-623.

[3] I Axente, J N Ganesh, M Basu, M F Conlon, K Gaughan, A 12-kVA DSP-Controlled Laboratory Prototype UPQC Capable of Mitigating Unbalance in Source Voltage and Load Current , IEEE Trans Power Electronics, Vol. 25(6), 2010, pp. 1471 - 1479

[4] S K. Khadem, M Basu, and M F Conlon, UPQC for power quality improvement in DG integrated smart grid network—A review, Int. J. Emerg. Electr. Power Syst., 2012, vol. 13(1), article 3.

[5] S K Khadem, M Basu, M F Conlon, Intelligent Islanding and Seamless Reconnection Technique for Microgrid With UPQC," Emerging and Selected Topics in Power Electronics, IEEE Journal of , 2015, vol.3(2), pp.483-492

[6] S K Khadem, M Basu, and M F Conlon, A new placement and integration method of UPQC to improve the power quality in DG network, UPEC 2013, vol. 1. pp. 1–6.

[7] S K Khadem, M Basu and M F Conlon, Harmonic power compensation capacity of shunt active power filter and its relationship with design parameters, IET Power Electron., 2013, vol. 7(2), pp. 418–430

[8] S.K. Khadem, "Power quality improvement of distributed generation integrated network with unified power quality conditioner", Ph.D. dissertation, Dept. Elect. Electron. Eng., Dublin Inst. Technol., Ireland, Europe, Jan. 2013.

[9] M. Abdusalam, P. Poure, S. Karimia, S. Saadate, New Digital Reference Current Generation for Shunt Active Power Filter under Distorted Voltage Conditions, Electric Power Systems Research, 2009, vol. 79, pp 759-76

[10] A. Ghamri , M. T. Benchouia, A. Golea Sliding-Mode Control Based Three-Phase Shunt Active Power Filter, Simulation and Experimentation, Electric Power Components and Systems, 2012, vol. 40, no. 4, pp. 383-398.

[11] S. Biricik, S. Redif, O.C.Ozerdem, M Basu, Control of the Shunt Active Power Filter under Non-Ideal Grid Voltage and Unbalanced Load Conditions, UPEC 2013, Dublin, Ireland.

[12] S S Patnaik, A K Panda, Real-Time Performance Analysis and Comparison of Various Control Schemes for Particle Swarm Optimization-Based Shunt Active Power Filters, Electrical Power and Energy Systems 52 (2013), pp. 185–197.

[13] S. Biricik, S. Redif, O.C.Ozerdem, S. K. Khadem, M Basu, Real-Time Control of Shunt Active Power Filter under Distorted Grid Voltage and Unbalanced Load Condition using Self Tuning Filter, IET Power Electronics (2014)

[14] S. Biricik, O.C.Ozerdem, S. Redif and M.O.I. Kmail, Performance Improvement of Active Power Filter under Distorted and Unbalanced Grid Voltage Conditions, Journal of Electronics and Electrical Engineering, 2013, Vol. 19, No.1, pp 35-39

[15] S.Biricik, O.C.Ozerdem, S.Redif and M.O.I.Kmail, Novel Hybrid Active Power Filter Structure To Compensate Harmonic Currents and Reactive Power, MELECON 2012, 25-28 Mart 2012, Tunisia.

[16] S. Biricik, S. K. Khadem, S. Redif, M Basu, Control of the Dynamic Voltage Restorer to Improve Voltage Quality, PEDG 2014, Galway, Ireland.

 ISSN: 2147-284X

BIOGRAPHIES

SAMET BİRİCİK received his B.Sc. and Ph.D. in electrical and electronic engineering in 2006 and 2013, respectively, from the Near East University, Nicosia, North Cyprus. He won the Best Paper Award from the IEEE 9th International Conference on Environment and Electrical Engineering in the Czech Re public. He was a founding member of the Energy Professionals Association (EPA) and a member of the Cyprus Turkish Chamber of Electrical Engineers. Between 2006 and 2017, he has worked in various industrial and commercial project engineers. He is currently a research fellow in the School of Electrical and Electronic Engineering of Dublin Institute of Technology in Ireland and a lecturer in the European University of Lefke. His research interests are the application of power electronics, power quality, electrical machines, and high-voltage engineering.