 https://doi.org/10.1051/itmconf/20225003002

Observer-Based Quadrature Signal Generator for UPQC in a Single-Phase Distribution System

Kandukuri Pradeep
Research Scholar, Department of Electrical and Electronics Engineering, Chaitanya (Deemed to be University), Telangana, INDIA.
pradeepkv56@gmail.com

Dr.K. Vinay Kumar
Associate Professor, Department of Electrical and Electronics Engineering, Chaitanya (Deemed to be University), Telangana, INDIA.
kvinaykr1@gmail.com

Abstract - This paper presents a control algorithm for generation of reference voltage and current based on Observer-based QSG (Quadrature Signal Generator) for UPQC (Unified Power Quality Conditioner) in a Single-Phase Distribution System. The proposed UPQC is a combination of DSTATCOM and DVR used for load and source compensation such as voltage sag and swell, voltage and current harmonics etc. The proposed control algorithm is capable of generating reference signals from the distorted voltages and currents. In this paper, an improved OQSG-based PLL (Phase-Locked Loop) is utilized over OQSG to enable and operate with increased bandwidths that will improve the dynamic response, tracking accuracy and faster detection of reference signal under all varying load and grid conditions. The control algorithm is tested and evaluated using MATLAB / Simulink.

Keywords— Quadrature Signal Generator (QSG), Observer QSG (OQSG), Phase - Locked Loop (PLL), Power Quality (PQ), and Unified Power Quality Conditioner (UPQC).

I. INTRODUCTION

Today's interest is towards the renewable energy sources to produce electrical power. In this regard, single-phase photovoltaic (PV) power generation is increasing widely for residential applications. But, these are creating severe power quality (PQ) issues to the distribution system while connecting to the grid. Power electronic loads such as rectifiers, arc furnaces and fluorescent lamps etc are causing PQ problems such as harmonics, flickering, and excessive reactive power demand and sudden switching of loads at the point of common coupling (PCC) are also causing voltage related problems [1-4]. 92% of interruptions are due to voltage sags and to be compensated within 3 cycles. Voltage swells are less frequent; but, these swells are producing electromagnetic stress in power transformers due to flux saturation [5]. Voltage flicker is generally caused by the lightning intensity. It is described as voltage fluctuation by *IEEE 1159-2009*. Normally the voltage ranges in between 0.95 and 1.05p.u. Nearly 48% of power quality problems are due to voltage sags/swells and 22% are due to harmonics [6].

A UPQC is a combination of DVR and DSTATCOM and provides single solution for both voltage and current related problems such as harmonics, sag, swell and power factor improvement. It consists of two voltage source converters (VSC's) connected back to back with a common DC link capacitor at the DC bus.

Single-phase power generation is increasing widely based on PV system interfaced with a grid-tied inverter. Therefore, study of UPQC for single-phase applications has a prominent role to avoid both voltage and current related problems.

Different UPQC topologies are explained in the literature Multi variable regulator (MVR), Neural Network etc. [7]-[11]. Control algorithms based on single-phase UPQC are investigated in [12]-[13]. Control algorithms based on park transformation [14]-[15] and PQ theory (Instantaneous Active and Reactive Power) [16] are most popular and widely used techniques. In [17], three control algorithms such as UVT (Unit Voltage Template), DQ Theory and theory based on Fourier analysis are compared for single-phase applications.

In general, UPQC based compensation mainly depends on reference voltage and current generation that should be injected into the system by controlling of VSI. The performance of the UPQC depends on the tracking accuracy, speed and control method that was employed.

Since the subject of the paper represents an improved QSG, the following is the list of the conventionally applied QSG algorithms: transfer delay-based (TD-QSG), including the non frequency-dependent [18], enhanced [19], and adaptive [20] TD-QSG, (2) inverse Park-based QSG [21], (3) generalized integrator (GI)-based QSG, including the standard second-order GI (SOGI), fxed-frequency SOGI, and SOGI with diferent types of QSG input DC ofset compensation [22–25], (4) all-pass filters (APF)-based QSG [26], (5) derivative- based QSG [27], (6) sliding discrete Fourier transform-based SDFT QSG [28], and (7) observer-based QSG (OQSG) [29]. When compared to the most commonly used SOGI based QSG, OQSG enables the operation with increased bandwidths and response speeds, which was, however, not used by the OQSG parameter tuning procedure in [29] and was utilized by the OQSG novel parameter tuning procedure proposed in [30]. In order to overcome the shortcomings of these QSG's, an improved observer-based QSG parameter tuning procedure is proposed in this paper, which enables increased QSG bandwidths to be achieved while reducing the high-frequency components amplification when compared to derivative OSG and modified APF (MAPF), by introducing a modified observer QSG parameter tuning algorithm.

In this paper, Improved Observer Based Quadrature Signal Generator based control algorithm for UPQC in a single-phase distribution system is implemented for Voltage

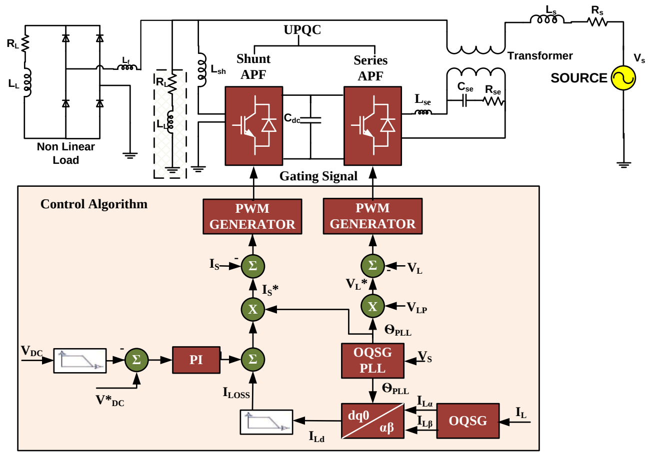

Fig. 1 Line-Diagram of UPQC with Improved OQSG Control

sag/swell compensation and load harmonic compensation. A single-phase OQSG is used for better estimation and accuracy of sinusoidal signal with wide range of frequencies.

However, this implementation for a single-phase UPQC is reported less in the literature. Simulations are carried out using MATLAB / Simulink, simpower systems block set.

II. Proposed Configuration and Control Algorithm

The UPQC shown in **Fig. 1** consists of two VSC's comprising of 4 IGBT switches in each converter feeding Linear/Nonlinear loads. The UPQC is a combination of Series and Shunt Active Filters connected in between the source and load. A ripple filter is connected to reduce any high frequency noises that are produced by the UPQC. The proposed controller for UPQC is capable of maintaining the total harmonic distortion (THD %) of voltage and current within the IEEE 519-1992 limits and load voltage is maintained at 1 p.u. even under sag and swell conditions. The proposed control algorithm has peak amplitude extraction for both voltage and current, unit template generation using OQSG-PLL and reference load voltage generation and reference source current generation and PWM generator to generate gating pulses for both VSC's.

A. OQSG-PLL

In Fig. 2, the observer-based QSG is outlined, which represents a basic QSG observer proposed in [29] with DC offset compensation. In the figure, Vi represents the QSG input signal, V_o the output that represents the direct component of the V_i signal, V_α the output signal that represents the quadrature component of the input signal, ω_n the input signal angular frequency, and K_1, K_2 and K_3 the observer parameters.

Based on the observer QSG outlined in Fig. 2, the following transfer functions (1) and (2) are obtained.

$$G_\alpha(s) = \frac{V_\alpha(s)}{V_g(s)} = \frac{k_2\hat{W}_n s^2 + k_3\hat{W}_n^2 s}{s^3 + (k_1+k_2)\hat{W}_n s^2 + (k_3+1)\hat{W}_n^2 s + k_1\hat{W}^3} \quad (1)$$

$$G_\beta(s) = \frac{V_\beta(s)}{V_g(s)} = \frac{-k_3\hat{W}_n s^2 + k_2\hat{W}_n^2 s}{s^3 + (k_1+k_2)\hat{W}_n s^2 + (k_3+1)\hat{W}_n^2 s + k_1\hat{W}^3} \quad (2)$$

By analyzing the transfer functions (1) and (2), the following conclusions can be made:

- By using parameters K_1, K_2 and K_3, the observer pole values can be set to any desired value.
- For $s = j\omega_n$ the OQSG outputs are $V_\alpha(j\omega_n) = V_g(j\omega_n)$, and $V_\beta(j\omega_n) = V_i(j\omega_n)/j$, which means that V_α represents the direct and V_β the quadrature input signal V_i component.
- The problem related to transfer functions (3) and (4) is that their zeros $z_{V\alpha} = -k_3\omega_n/k_2$ and $z_{V\beta} = k_2\omega_n/k_3$ cannot be tuned independently to the observer poles. This may in some cases result in $G_{V\alpha}(j\omega)$ and $G_{V\beta}(j\omega)$ frequency responses in which the higher frequency inputs signal components are significantly amplified.

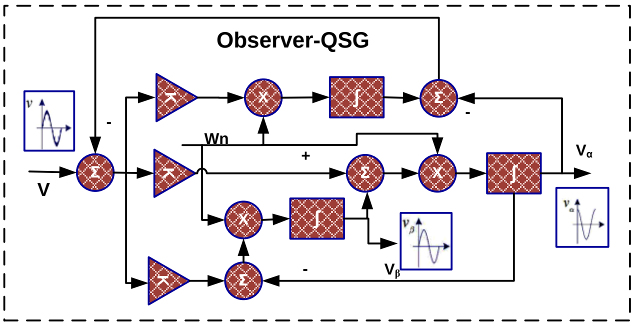

Fig. 2. Observer-based Quadrature Signal Generator.

The outputs from the orthogonal QSG are fed to the transformation block to convert into dq frame. Park transformation is used to convert αβ to dq.

$$T = \begin{bmatrix} \cos\hat{\theta} & \sin\hat{\theta} \\ -\sin\hat{\theta} & \cos\hat{\theta} \end{bmatrix} \quad \textbf{(3)}$$

The transformation output V_d is used to eliminate high frequency noises by passing it through a Loop Filter (LF) and the estimated phase angle $\hat{\theta}$ is generated by adding fundamental frequency (W). The bandwidth response is tuned for various gains k1, k2, k3 and implemented as shown in **Fig. 3.**

B. Estimation of Unit Template

Fig.3 shows the closed loop block diagram of OQSG-PLL. Single-phase OQSG-PLL is used for source voltage (V_s) and load current (I_L) to generate in-phase and quadrature templates. The output phase angles (Sin (θ), Cos (θ)) that are generated from the OQSG-PLL are considered as unit templates. In OQSG-PLL, in-phase and quadrature signals are

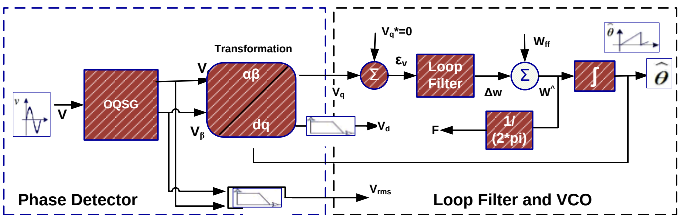

Fig.3 OQSG-based Phase-Locked Loop

generated and supplied it to park's transformation to convert into d-q signals. Either d or q are fed to loop filter based on the requirement (d in this case) to generate error in angular frequency and then added to the nominal frequency to obtain actual angular frequency and then supplied to voltage controlled oscillator to produce phase angle (θ_{PLL}). This phase angle converted to sine angle acts as unit template (U_{PLL}).

C. Reference Source Current Generation

The peak amplitude of active component of current is estimated as shown in Fig. 1. Then I_P is passed through low-pass filter to eliminate ripples produced from the OQSG and

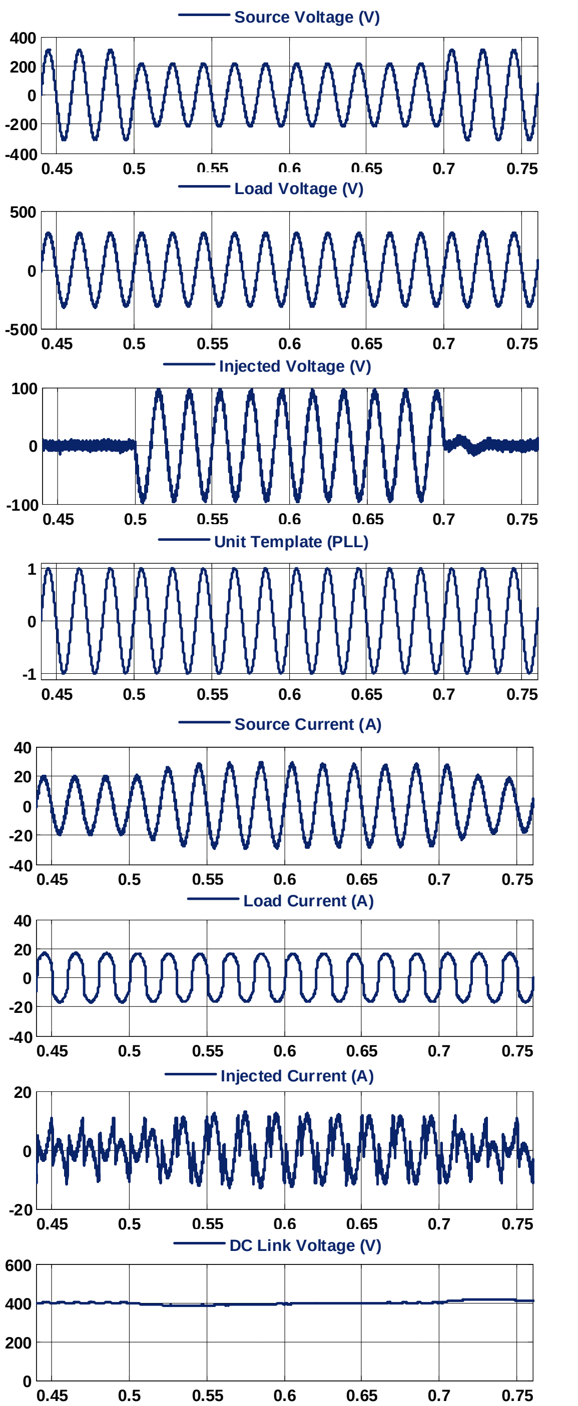

Fig.4 Operation of UPQC under Voltage Sag (30%)

to produce a reference magnitude of current (I_{LP}). Then it is added to I_{LOSS} component. The measured voltage (V_{dc}) across DC capacitor is compared with reference DC bus voltage (V_{dc}^*). The error of the signal at n^{th} sampling instant is given by:

$$V_d(n) = V^*_{dc}(n) - V_{dc}(n) \quad (4)$$

The voltage error $V_d(n)$ is then supplied to Proportional-Integral controller to regulate the DC bus voltage of Shunt APF to produce I_{LOSS} component. At n^{th} sampling instant, the output of the PI controller is as:

$$I_{LOSS}(n)=I_{Loss}(n-1)+k_p\{V_{dcer}(n)-V_{dcer}(n-1)\}+k_iV_{dcer}(n) \quad (5)$$

Where, K_p and K_i are proportional gain and integral gains of the PI controller. $V_{dcer}(n)$ and $V_{dcer}(n-1)$ are DC bus voltage errors in n^{th} and $(n-1)^{th}$ instant and $I_{Loss}(n)$ and $I_{Loss}(n-1)$ are the amplitudes of active component of currents at the fundamental reference current in n^{th} and $(n-1)^{th}$ instant.

The average magnitude of current (I_{LP}) and the output of the PI controller (I_{Loss}) are summed up and multiplied with the unit templates that are generated by the grid voltage to generate reference source current. The estimated reference source currents (i_s^*) is compared with the sensed source current at the point of common coupling (i_s) and supplied to a PWM generator to generate gating pulses for Shunt APF as shown in Fig. 1.

$$i^*_{sa} = (I_{LP}+I_{Loss}) * U_{PLL} \quad (6)$$

D. Reference Load Voltage Generation

The peak value amplitude of reference load voltage is generated by using unit template (U_{PLL}) generated by OQSG as shown in **Fig.1.** The magnitude of load voltage is multiplied with the U_{PLL} to obtain estimated load voltage and then subtracted with the actual load voltage measured across the load and then supplied to the PWM generator to generate gating pulses to the Series APF.

III. Simulation Results and Discussion

In this section, OQSG was proposed in the control algorithm for reference voltage generation and it is tested and evaluated using MATLAB/Simulink on a single-phase distribution system. Fixed time step of 10µs with ode1 (Euler) solver is chosen for simulation. Source Voltage (V_S), Source Currents (I_S), Load Currents (I_L), Load Voltage (V_L) and DC link Voltage (V_{dc}) are observed.

Some of the test cases are chosen in the simulation.

1. Steady State Condition under Non-Linear Load.
   A diode bridge rectifier load is applied to test the performance of UPQC at time t=0s to 2s. The source current is maintained sinusoidal even under non-linear load condition.
2. 30 % of Voltage Sag is introduced in source voltage.
   A voltage sag is introduced into the supply system and still the load voltage is maintained constant as shown in Fig. 7 from time t=0.5s to 0.7s.
3. 30 % of Voltage Swell is introduced in source voltage. A voltage swell is introduced into the supply system and

the load voltage is maintained constant as shown in Fig. 8 from time t=1s to 1.2s.

4. 5th and 7th harmonics are injected into source voltage.
   5th and 7th harmonics are injected into the source voltage at time t=1.5s to 1.7s. At this condition, the UPQC is performing well and the load voltage is maintained constant and pure sinusoidal.
5. Sudden increase in Non-Linear load.
   There is a sudden increase in Non-Linear load to test the dynamic performance of the system from time t=2s to 2.2s.

All these cases are tested and evaluated using MATLAB / Simulink and the results found satisfactory. Below table shows the total harmonic distortion (THD %) with the above mentioned test cases. In all the cases both Shunt and Series APF are working together and satisfying the IEEE limits.

THD (%) of Test Cases (Table-I)

Fig No.	V_s	V_L	I_s	I_L
6	0.7	3.2	3.8	24.17
7	1.02	3.24	2.94	24.09
8	0.58	3.49	4.37	24.25
9	25.03	3.51	3.95	24.25
10	0.72	3.15	2.65	29.21

IV. CONCLUSION

In this paper, a simple and effective control algorithm based on Observer QSG for single-phase UPQC has been analyzed, presented and validated using MATLAB/Simulink. This theory is adopted to work in sinusoidal and non-sinusoidal grid voltages such as sag, swell and harmonics and load conditions such as harmonics and increase in load. The source current is maintained within IEEE 519-1992 limits. The control algorithm is very promising and easy to implement than the conventional controllers proposed in the literature because of its simple structure and accuracy. The reactive current and harmonic compensation is effectively done under steady-state and dynamic conditions.

APPENDIX

AC supply source & Frequency	Single-Phase, 230 V, 50Hz
Source Impedance	Rs=0.1 Ω, Ls =50uH
Linear Load	R=45 Ω, R_L=20 Ω, L=250mH
Rating of Transformer	5 KVA, 1:1 ratio
Switching frequency	8kHz
Reference dc bus voltage	400V
Interfacing inductor	Ls=4.5mH
Gains of PI controller for dc bus	*kp* =0.4, *ki*=5

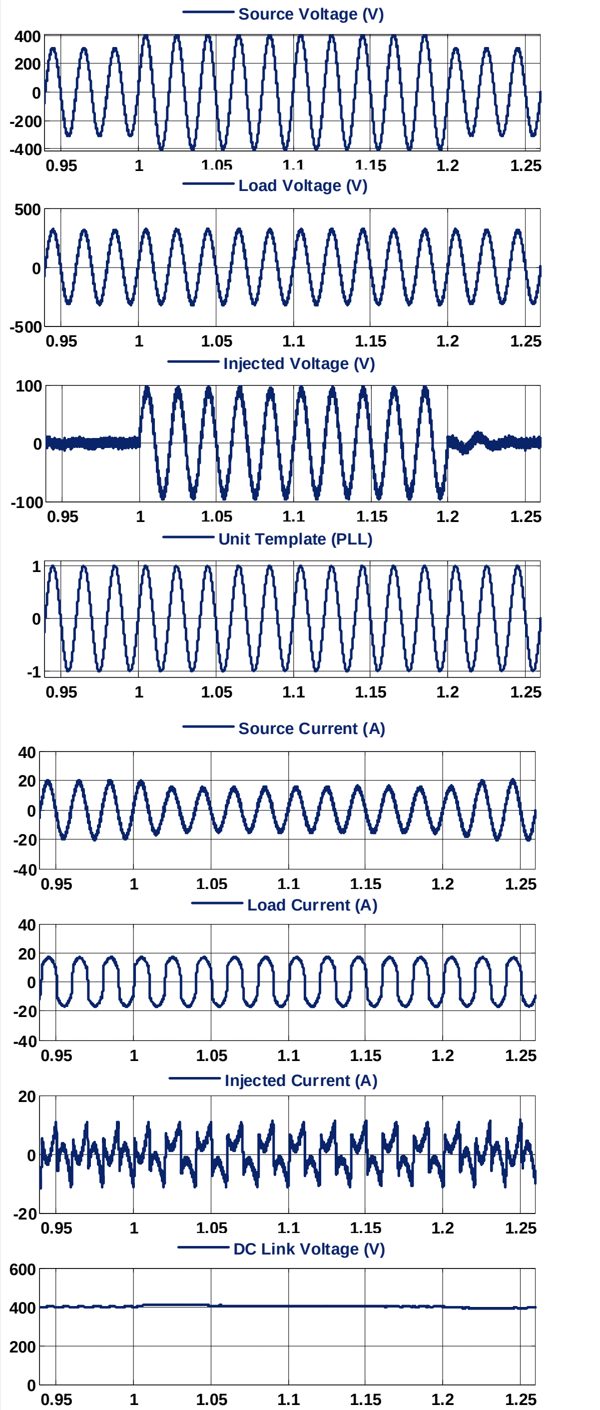

Fig.5 Operation of UPQC under Voltage Swell (30%)

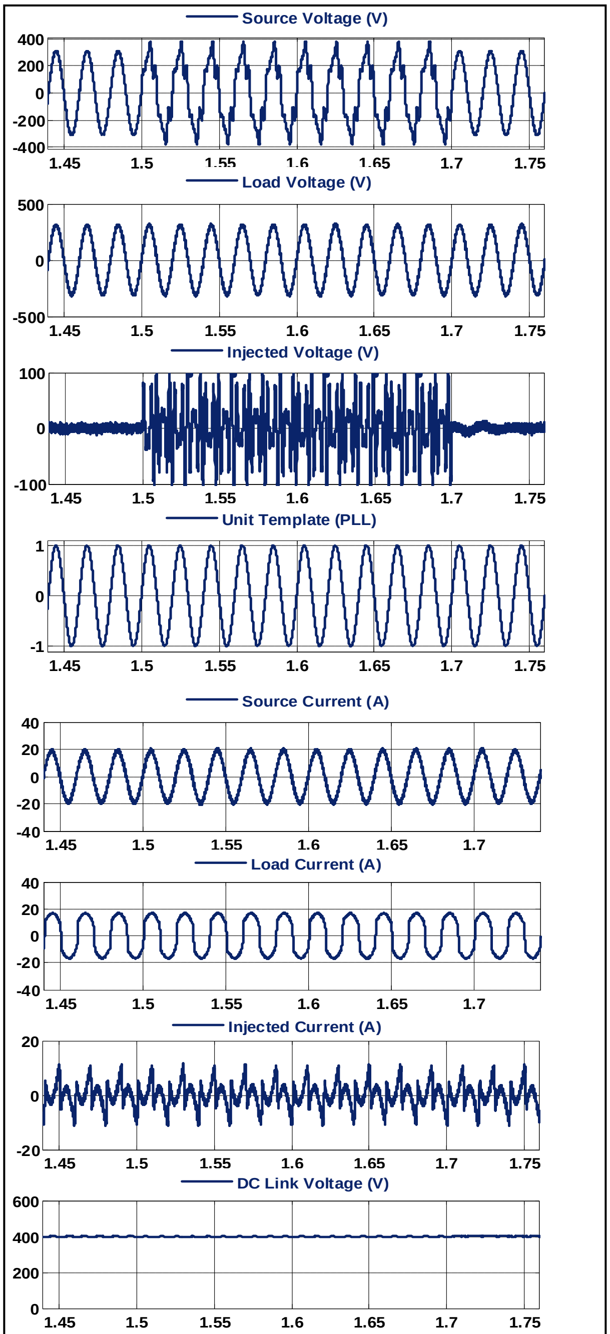

Fig.6 Operation of UPQC under Voltage Harmonics (5th & 7th)

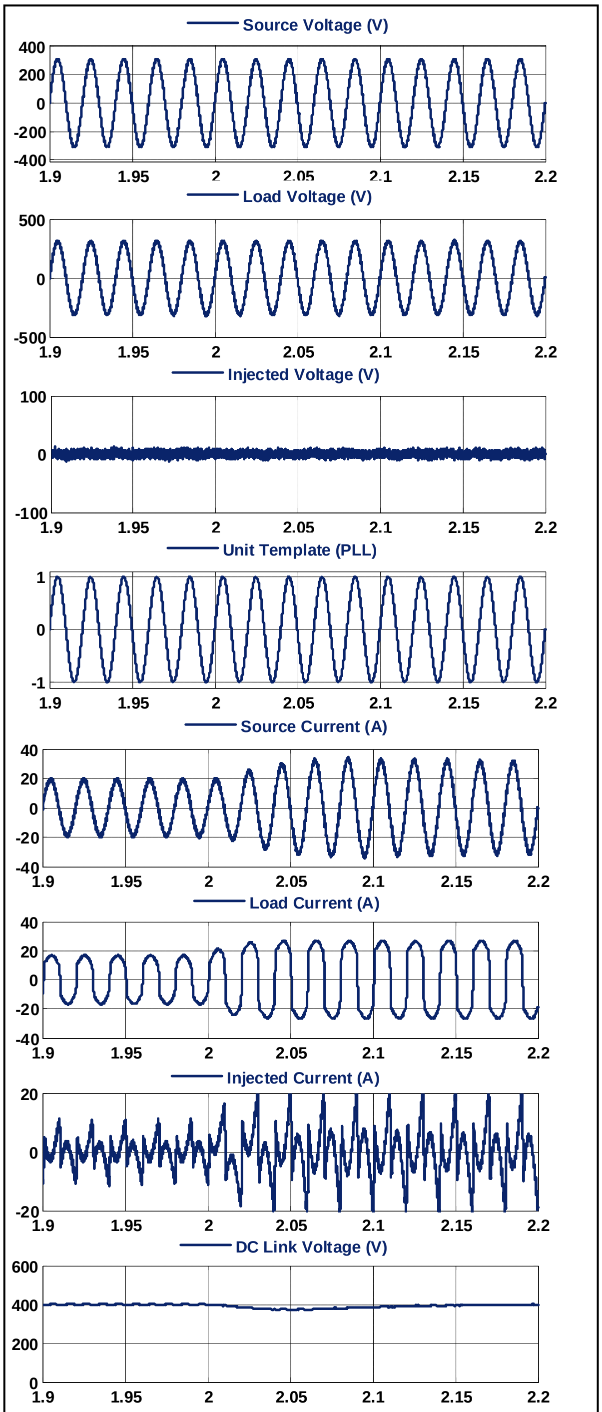

Fig.7 Operation of UPQC with Increase in Non-Linear Load

References

[1] F. F. Ewald and A. S.M.Mohammad, *Power Quality in Power Systems and Electrical Machines*. London, U.K.: Elsevier Academic Press, 2008.

[2] G. Arindam and L. Gerard, *Power Quality Enhancement using Custom Power Devices*, Springer International Edition ed. Delhi, India: Springer, 2009.

[3] C. Sankaran, *Power Quality*. Boca Raton, FL: CRC, 2001.

[4] *IEEE Recommended Practices and requirement for Harmonic Control on electric power System*, IEEE Standard 519, 1992.

[5] Bollen. M. "*Understanding power quality problems voltage sag and interruption*" (IEEE Press, Piscataway, NJ, 1999).

[6] Baggini A."Handbook of power quality" (John Wiley & Sons Ltd, 2008).

[7] M. Aredes, K. Heumann, and E. H. Walandble, "An universal active power line conditioner," *IEEE Trans. Power Del.*, vol. 13, no. 2, pp. 545–551, Apr. 1998.

[8] H. Fujita and H. Akagi, "The unified power quality conditioner: the integration of series and shunt-active filters," *IEEE Trans. Power Electron.*, vol. 13, no. 2, pp. 315–322, Mar. 1998.

[9] B. Han, B. Bae, H. Kim, and S. Baek, "Combined operation of unified power-quality conditioner with distributed generation," *IEEE Trans. Power Del.*, vol. 21, no. 1, pp. 330–338, Jan. 2006.

[10] K.H.Kwan, P.L. So and Y.C. Chu, "*A harmonic selective unified power quality conditioner using MVR with Kalman filters*," Proud. Int. Conf. IPEC 2007, pp.332-337, 2007.

[11] L. Chunwen ,R. Yuanjie ,C. Lingzhi and Z. Xuesheng, "*Adaptive Control for Single-Phase Unified Power Quality Conditioner Using Neural Networks*," Procd. Int. Conf. BIC-TA 2007.pp.146-150, 2007.
[12] Kolhatkar Y. Y. and Das S. P., "*Experimental Investigation of a SinglePhase UPQC With Minimum VA Loading"*, IEEE Trans. Power Delivery, vo1.22, no.I, pp. 373-380, Jan. 2007.
[13] Rong Y., Li C., Tang H. and Zheng X., "*Output Feedback Control of Single-Phase UPQC Based on a Novel Model"*, IEEE Trans. on Power Delivery, vol. 24, no. 3, pp. 1586-1597, July 2009.
[14] Bhattacharya S. and Divan D., "*Synchronous frame based controller implementation for a hybrid series active filter system"*, in Proc. IEEE Industry Applications Conference, 1995, vol. 3, pp. 253 1-2540.
[15] Vinod Khadkikar, Ambrish Chandra., *"Control of Single-Phase UQPC in Synchronous D-Q Reference Frame"*, in Proc. 2012 IEEE 15th Conference on Harmonics and Quality of Power, June, 2012.
[16] Akagi H., Kanazawad Y. and Nabae A., "*Instantaneous reactive power compensators comprising switching devices without energy storage components,"* IEEE Trans. Ind. Appl., vol. 20, no.3, pp. 625-630, May/June 1984.
[17] Yash pal, A.Swarup, Bhim Singh., "*Comparison of three control algorithms for Single-Phase UPQC*" in Proc. 2011 International conference on Energy, Automation and Signal, Dec, 2011.
[18] Ciobotaru M, Teodorescu R, F. Blaabjerg (2005) Improved PLL structures for single-phase grid inverters. In: Proceedings of international conference PELINCEC, pp 1–6.
[19] Golestan S, Guerrero JM, Vidal A, Yepes AG, Doval-Gandoy J, Freijedo FD (2016) Small-signal modeling, stability analysis and design optimization of single-phase delay-based PLLs. IEEE Trans Power Electron 31:3517–3527. https://doi.org/10.1109/tpel.2015.2462082
[20] Golestan S, Guerrero JM, Abusorrah A, Al-Hindawi MM, AlTurki Y (2017) An adaptive quadrature signal generation-based single-phase phase-locked loop for grid-connected applications. IEEE Trans Ind Electro 64:2848–2854. https://doi.org/10.1109/tie.2016.2555280
[21] Golestan S, Monfared M, Freijedo FD, Guerrero JM (2013) Dynamics assessment of advanced single-phase PLL structures. IEEE Trans Ind Electron 60:2167–2177. https://doi.org/10.1109/tie.2012.2193863
[22] Ciobotaru M, Teodorescu R, Blaabjerg F (2006) A new singlephase PLL structure based on second order generalized integrator. In: Power electronics specialists conference PESC'06 37th. IEEE, pp 1–6. https://doi.org/10.1109/pesc.2006.1711988
[23] Xiao F, Dong L, Li L, Liao X (2017) A frequency-fxed SOGIbased PLL for single-phase grid-connected converters. IEEE Trans Power Electron 32:1713–1719. https://doi.org/10.1109/tpel.2016.2606623
[24] Guan Q, Zhang Y, Kang Y, Guerrero JM (2017) Single-phase phase-locked loop based on derivative elements. IEEE Trans Power Electron 32:4411–4420. https://doi.org/10.1109/tpel.2016.2602229
[25] Ciobotaru M, Teodorescu R, Agelidis VG (2008) Ofset rejection for PLL based synchronization in grid-connected converters. In: Applied power electronics conference and exposition APEC 23rd annual. IEEE, pp 1611–1617. https://doi.org/10.1109/apec.2008.4522940
[26] Choi J-W, Kim Y-K, Kim H-G (2006) Digital PLL control for single-phase photovoltaic system. IEE Proc Electric Power Appl 153:40–46. https://doi.org/10.1049/ip-epa:20045225
[27] Galkin I, Vorobyov M (2015) Optimizing of sampling in a lowcost single-phase instantaneous AC-grid synchronization unit with discrete calculation of derivative function. In: Industrial electronics society IECON 41st annual conference of the IEEE, pp 4538–4543. https://doi.org/10.1109/iecon.2015.7392807
[28] Sumathi P, Janakiraman P (2011) Phase locking scheme based on look-up-table-assisted sliding discrete Fourier transform for low-frequency power and acoustic signals. IET Circuits Devices Syst 5:494–504. https://doi.org/10.1049/iet-cds.2010.0323
[29] Park Y, Kim H-S, Sul S-K (2017) Frequency-adaptive observer to extract AC-coupled signals for grid synchronization. IEEE Trans Ind Appl 53:273–282. https://doi.org/10.1109/tia.2016.2604299