An Exponential Composition Algorithm Based UPQC for Power Quality Enhancement

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Abstract

Power quality is a major concern nowadays due to extensive use of smart controllers based power system equipment. These controlled load behaves with nonlinear characteristics. It introduces distortions in source voltage and source current at the point of common coupling (PCC). The distortions are propagated throughout the system and affects performance characteristics of all other loads connected to the same point of common coupling. Hence mitigation of power quality issues is essential to maintain good power quality at the point of common coupling. This paper deals with implementation of unified power quality conditioner (UPQC) to compensate for power quality issues voltage sag, voltage harmonics and current harmonics. UPQC is controlled by an exponential composition algorithm (ECA), which is proposed by the author. The performance of UPQC is examined with a nonlinear load and simulation studies using MATLAB/Simulink verify the satisfactory performance of UPQC.

Keywords: Current distortion; Power quality; Reactive compensation; Unified Power Quality Conditioner (UPQC); Voltage distortion.

1. Introduction

Present day developments in automation and energy conservation has led to extensive use of solid state power electronics devices for smooth and efficient control of power system apparatus. These nonlinear loads introduce voltage distortion, current harmonics, sag, swell, flicker [1, 2] leading to poor power quality. Traditionally, passive filters are used for harmonic mitigation. But they have many limitations such as fixed compensation, detuning, and bulky size and may also cause resonance also [3]. As an improved solution, active filters [4, 5] and hybrid filters [6, 7] are developed. In addition to complex and expensive control circuit, they provide partial voltage or current
compensation to improve power quality. So as an effective dynamic solution for mitigation of distortions at PCC, the concept of custom power devices such as Dynamic Voltage Restorer (DVR) [8], STATCOM and UPQC is developed. These devices improve the quality of the power delivered to the customers.

UPQC [9, 10] is a hybrid topology of series and shunt active filter connected back to back by a common DC link capacitor. UPQC has two components, a series compensator and a shunt compensator. The series compensator of UPQC is used to mitigate voltage sag, voltage distortions and shunt compensator compensates for harmonic current to specifically protect highly sensitive loads at the PCC. The shunt filter effectively reduces the source current harmonics and provides reactive power compensation while the series filter ensures a distortion free, balanced and regulated voltage at PCC. UPQC is capable of compensating in steady state as well as in dynamic conditions.

The performance of UPQC depends on the control algorithm used. Different algorithms such as dq0 transformation [11], synchronous reference frame theory [12], unit vector template generation [13], and Icosφ algorithm [14] to generate reference signals for voltage and current compensation are developed. The dq0 and synchronous reference theories use low pass or high pass filters for dc signal extraction, but the cut off frequencies of these filters has a negative impact on the dynamic performance of the controllers. The synchronous reference frame theory does not work well with unbalanced supply voltages. The algorithm requires complex PLL as frequency synthesizer to generate unit vector template. Icosφ algorithm [14, 15] requires accurate and precise zero crossing detection of phase voltage to extract the real component of fundamental current. Hence, it is difficult to implement using digital controllers. This paper presents an Exponential Composition Algorithm (ECA) which is easier to implement using digital circuits. The Section 2 of the paper explains the development of ECA. The section 3 discusses the simulation model on which the algorithm is tested. Simulation Results are discussed in section 4. Conclusions are summarized in section 5.

1.1. Control Strategy of UPQC

An UPQC has a series active filter and a shunt active filter. The series active filter compensates for voltage sag, swell and harmonics. The shunt active filter compensates reactive and harmonic current. Both are fed from a common DC bus through inverters. These inverters are switched based on control strategy. Fig. 1. depicts a system with non-linear load and UPQC connected as compensators.

![Fig.1. Model of a System with UPQC](image-url)
1.2. Exponential Composition Algorithm for Shunt Active Filter

The Exponential Composition Algorithm (ECA) is developed on the fact that the energy source has to supply only the real power component of load current, while the reactive and harmonic components are provided by the shunt active filter. Let the three phase balanced source voltages are expressed as

\[ v_a = V_m \sin(\omega t); v_b = V_m \sin(\omega t - 2\pi / 3); v_c = V_m \sin(\omega t + 2\pi / 3) \]  

The three phase nonlinear load currents, composition of fundamental and harmonics are given as

\[ i_{La} = \sum_{h=1}^{\infty} I_{La,h} \sin(\omega_h t - \phi_{ah}); i_{Lb} = \sum_{h=1}^{\infty} I_{Lb,h} \sin(\omega_h t - \phi_{bh} - 2\pi / 3); i_{Lc} = \sum_{h=1}^{\infty} I_{Lc,h} \sin(\omega_h t - \phi_{ch} + 2\pi / 3) \]  

The real and reactive components of the sensed load currents are separated with a second order biquad filter, which has three portions - low pass filter, high pass filter and a band pass filter. The fundamental component is extracted using the low pass filter with cut off frequency of 50Hz. It has an inherent phase delay in each phase of 90°. The currents obtained from the low pass filter are given as

\[ i_{La(LP)} = I_{La} \sin(\omega t - \phi_a - 90°) = -I_{La} \cos(\omega t - \phi_a) \]
\[ i_{Lb(LP)} = I_{Lb} \sin(\omega t - 2\pi / 3 - \phi_b - 90°) = -I_{Lb} \cos(\omega t - 2\pi / 3 - \phi_b) \]
\[ i_{Lc(LP)} = I_{Lc} \sin(\omega t + 2\pi / 3 - \phi_c - 90°) = -I_{Lc} \cos(\omega t + 2\pi / 3 - \phi_c) \]  

The low pass filter output currents are inverted to extract real part of fundamental component of load current. The output of band pass filter with cut off frequencies of 49.9Hz and 50.1 Hz is the reactive part of fundamental component of load current and expressed as

\[ i_{La(BPF)} = I_{La} \sin(\omega t - \phi_a); i_{Lb(BPF)} = I_{Lb} \sin(\omega t - 2\pi / 3 - \phi_b); i_{Lc(BPF)} = I_{Lc} \sin(\omega t + 2\pi / 3 - \phi_c) \]  

The instantaneous fundamental current components are formulated as follows

\[ i_{La} = I_{La} \cos(\omega t - \phi_a) + jI_{La} \sin(\omega t - \phi_a) = \left| I_{La} \right| e^{j(\omega t - \phi_a)} \]
\[ i_{Lb} = I_{Lb} \cos(\omega t - 2\pi / 3 - \phi_b) + jI_{Lb} \sin(\omega t - 2\pi / 3 - \phi_b) = \left| I_{Lb} \right| e^{j(\omega t + 2\pi / 3 - \phi_b)} \]
\[ i_{Lc} = I_{Lc} \cos(\omega t + 2\pi / 3 - \phi_c) + jI_{Lc} \sin(\omega t + 2\pi / 3 - \phi_c) = \left| I_{Lc} \right| e^{j(\omega t + 2\pi / 3 - \phi_c)} \]  

The load currents are passed through a peak detector. The magnitude of fundamental peak load currents is multiplied with the unit sine wave generated (6) to obtain \( |I_{La}|u_a, |I_{Lb}|u_b \) and \( |I_{Lc}|u_c \). 

\[ u_a = \sin(\omega t); u_b = \sin(\omega t - 2\pi / 3); u_c = \sin(\omega t + 2\pi / 3) \]  

The displacement angle is extracted from the fundamental component of load current by the instantaneous division of composite current with the template waveform in phase with source voltage with amplitude as peak value of fundamental component of load current. The template waveform is passed through a low pass filter of cut off frequency 50Hz and bandpass filters with cut off frequency between 49.9Hz and 50.1Hz. The outputs of low pass filter and band pass filter are added and expressed in the complex exponential form as

\[ i_{La(Temp)} = \left| I_{La} \right| e^{j\omega t}; i_{Lb(Temp)} = \left| I_{Lb} \right| e^{j(\omega t - 2\pi / 3)}; i_{Lc(Temp)} = \left| I_{Lc} \right| e^{j(\omega t + 2\pi / 3)} \]
On dividing the instantaneous fundamental current of each phase in equation (5) by each phase in equation (7), exponential components and are extracted.

\[
\begin{align*}
    e^{-j\phi_a} &= \frac{|I_{la}|e^{j(\omega t - \phi_a)}}{|I_{la}|e^{j\omega t}}; e^{-j\phi_b} = \frac{|I_{lb}|e^{j(\omega t - \frac{2\pi}{3} - \phi_b)}}{|I_{lb}|e^{j(\omega t - \frac{2\pi}{3})}}; e^{-j\phi_c} = \frac{|I_{lc}|e^{j(\omega t + \frac{2\pi}{3} - \phi_c)}}{|I_{lc}|e^{j(\omega t + \frac{2\pi}{3})}}.
\end{align*}
\] (8)

To maintain balanced source currents, displacement power factor and peak value of reference source currents are obtained as average values of three phases as shown in (9) and (10).

\[
\begin{align*}
    \cos \phi_a &= \frac{e^{j\phi_a} + e^{-j\phi_a}}{2}; \cos \phi_b = \frac{e^{j\phi_b} + e^{-j\phi_b}}{2}; \cos \phi_c = \frac{e^{j\phi_c} + e^{-j\phi_c}}{2} \\
    \cos \phi &= \frac{\cos \phi_a + \cos \phi_b + \cos \phi_c}{3}.
\end{align*}
\] (9)

The control block diagram of the exponential composition algorithm is as shown in Fig. 2.

The average of the load current of each phase is taken so as to compensate for any unbalance in any of the phases and is expressed as

\[
I_{Lavg} = \frac{I_{la} + I_{lb} + I_{lc}}{3}
\] (10)

![Fig. 2. Block diagram of Exponential Composition Algorithm of Phase a](image)

The magnitude of the desired source current is expressed as

\[
I_{sref} = I_{Lavg} \cos \phi
\] (11)

The reference source currents for each phase is given as

\[
I_{sa(ref)} = |I_{sref}|u_a; I_{sb(ref)} = |I_{sref}|u_b; I_{sc(ref)} = |I_{sref}|u_c
\] (12)

The compensation currents are the difference between the actual load current and the source reference currents i.e.
The inverter losses are also met with active power drawn from AC mains. The error signal obtained by comparing the actual capacitor voltage with a reference dc value is processed using a PI controller. The required main currents is obtained with the help of PI Controller. The loss component of mains current is obtained as the output of the PI controller $i_{swl}$ multiplied by the unit sine wave obtained in equation (6). The compensation currents to meet switching losses are calculated as

$$i_{abc(comp)} = i_{Labc} - i_{subc(ref)}$$

(13)

The reference currents generated using an exponential composition algorithm are obtained as

$$i_{ref\_abc} = i_{abc(comp)} - i_{abc(sw)}$$

(14)

The switching pulses for the shunt filter are obtained by comparing the reference and actual filter currents in a hysteresis controller. The simulation results of the exponential algorithm for phase a is shown in Fig. 3.

![Fig. 3. Simulation results of various stages in Exponential Composition Algorithm (Phase a)](image)

1.3 Control for Series Active Filter

The distorted terminal voltages at PCC are sensed and passed through a band pass filter to obtain the fundamental voltage as given as

$$v_{L_a(BPF)} = V_{La} \sin(\omega t)$$

$$v_{L_b(BPF)} = V_{Lb} \sin(\omega t - 2\pi / 3)$$

$$v_{L_c(BPF)} = V_{Lc} \sin(\omega t + 2\pi / 3)$$

(16)

The terminal voltage is sent through the peak estimator to obtain the peak voltage. The fundamental of terminal voltages in equation (16) is divided by the peak voltages to obtain unit sine waves. The Hysteresis controller is used to generate the switching pulses for the series filter to get fast response. The reference voltage is obtained using a PID controller and this is multiplied by the unit sine wave to obtain the instantaneous terminal voltages. The reference voltages and the actual terminal voltages are compared using hysteresis controller to obtain the switching pulses for the active power filter

2. Verification of ECA by Simulation

A Test System is used to verify the effectiveness of the control algorithm. It consists of a three phase sinusoidal source feeding power to a three phase induction motor through a line. The rating of induction motor and line
impedance is shown in Table 1. The speed of induction motor is controlled by phase controlled technique using AC Voltage Regulator.

Fig. 4. Block diagram for series active filter control

2.1 Simulation Model without UPQC

The simulation of the system has been carried out using MATLAB/Simulink. The results tabulated in Table 1 show the harmonic analysis of a system at PCC with an induction motor fed through an AC Voltage Regulator for different firing angles. The induction motor is running at 80% of the rated torque with the required speed control for all set of readings. The speed control of induction motor is done by varying the stator voltage by changing the firing angle of the AC Voltage controller.

Table 1. Harmonic Analysis and Power Parameters of Test System for a Source Voltage of 400V

| Voltage at PCC | Current |
|---------------|---------|
| α | Effect. Volt (V) | Fund. Volt (V) | THD (%) | Load Current (A) | Line Current(A) | TH D (%) | φ | P (kW) | Q (kVAR) | S (kVA) | D (kVAD) | Disp. Pf | Dist.p f | pf |
|---|-----------------|----------------|---------|--------------|---------------|-------------|-----|-------|---------|--------|---------|----------|----------|-----|
| 10 | 67.88 | 60.9 | 49.25 | 5.46 | 5.38 | 18.3 | -18.5 | 0.53 | 0.18 | 0.64 | 0.304 | 0.94 | 0.882 | 0.83 |
| 20 | 88.20 | 80.3 | 45.45 | 5.15 | 5.04 | 21.1 | -24.4 | 0.63 | 0.29 | 0.78 | 0.356 | 0.91 | 0.890 | 0.80 |
| 30 | 110.4 | 102.8 | 39.21 | 4.76 | 4.58 | 28.7 | -32.0 | 0.69 | 0.43 | 0.91 | 0.407 | 0.84 | 0.894 | 0.76 |
| 40 | 131.7 | 125 | 33.12 | 4.25 | 4.04 | 33.2 | -39.7 | 0.67 | 0.56 | 0.97 | 0.421 | 0.76 | 0.900 | 0.69 |
| 50 | 150.3 | 144.9 | 27.67 | 3.62 | 3.38 | 38.9 | -47.7 | 0.57 | 0.63 | 0.94 | 0.416 | 0.67 | 0.898 | 0.6s |
| 60 | 166.8 | 161.9 | 24.98 | 2.94 | 2.66 | 47.5 | -55.3 | 0.42 | 0.62 | 0.85 | 0.410 | 0.56 | 0.876 | 0.49 |
| 70 | 185.5 | 180.9 | 22.70 | 2.58 | 2.20 | 61.9 | -64.0 | 0.26 | 0.61 | 0.69 | 0.313 | 0.43 | 0.829 | 0.36 |

The current and voltage at PCC are distorted due to the non-linear nature of induction motor drive. With the increase in the firing angle of AC voltage regulator, the reactive power consumption of the load has increased considerably. The power factor is also decreasing with the increase in firing angle.

2.2 Simulation Model with UPQC

The test system mentioned in Fig. 1 is installed with an ECA based UPQC to mitigate the voltage and current quality issues in the nonlinear system. Based on the exponential composition algorithm, a control circuit for the shunt active filter is simulated using Simulink and a hysteresis controller for series active filler. The simulation results in Fig. 5 shows that the distortions in the current and voltage are compensated using UPQC.
simulation results, it is seen that the source current harmonics and voltage at PCC are reduced with UPQC. The source current is almost in phase with the source voltage, thus making the power factor unity.

![Fig. 5. Simulation results of a) Load Voltage; b) Load Current; c) Shunt filter current; d) Series Filter voltage; e) Voltage with UPQC at PCC; f) Source Current after compensation for a triggering angle of 60°](image)

3. Results and Discussion

Tables 2 show simulation result obtained with compensation. When UPQC is compensating, both voltage and current THD is considerably reduced and power factor is close to unity as shown in Fig. 6. The current drawn from the source have only fundamental component and is reduced as firing angle increases with smooth control possible. So the proposed algorithm works well.

Table 2. Harmonic Analysis and Power Parameters with UPQC for various triggering angles for a Source Voltage of 400V

| Voltage at PCC | Current |
|----------------|---------|
| **α** | Effect. Volt(V) | Fund. Volt (V) | THD (%) | Load Current (A) | THD (%) | Line Current (A) | P (kW) | Q (kVAR) | S (kVA) | D (kVAD) | Disp Pr | Dist. pf | pf |
| 10 | 226.5 | 226.5 | 0.08 | 5.541 | 5.54 | 0.09 | -0.01 | 2.17 | 0.0037 | 2.17 | 0 | 0.99 | 0.99 | 0.998 |
| 20 | 226.9 | 226.9 | 0.08 | 5.041 | 5.04 | 1.19 | -0.02 | 1.98 | 0.0059 | 1.98 | 0 | 0.99 | 0.99 | 0.998 |
| 30 | 227.4 | 227.4 | 0.09 | 4.391 | 4.39 | 1.75 | -0.02 | 1.73 | 0.0059 | 1.73 | 0 | 0.99 | 0.99 | 0.998 |
| 40 | 228 | 228 | 0.09 | 3.631 | 3.63 | 2.10 | -0.03 | 1.43 | 0.0075 | 1.43 | 0 | 0.99 | 0.99 | 0.998 |
| 50 | 228.7 | 228.7 | 0.09 | 2.791 | 2.79 | 2.45 | -0.04 | 1.10 | 0.0077 | 1.10 | 0 | 0.99 | 0.99 | 0.998 |
| 60 | 229.4 | 229.4 | 0.09 | 2.031 | 2.03 | 3.09 | -0.07 | 0.81 | 0.0077 | 0.81 | 0 | 0.99 | 0.99 | 0.998 |
| 70 | 229.8 | 229.8 | 0.09 | 1.411 | 1.41 | 4.26 | -0.08 | 0.56 | 0.0078 | 0.56 | 0 | 0.99 | 0.99 | 0.998 |
Fig. 6. (a) Harmonic Analysis with and without UPQC; (b) Reactive Power and Power factor comparison with and without UPQC

The graphical analysis of the harmonic analysis and power parameters are shown in Fig. 6. From the analysis of simulation results with UPQC, it can be seen that there is an improvement in all the parameters at all firing angles. The source meets only the real power demand of the load while the reactive power and harmonic demands and voltage sag are met by the UPQC.

4. Conclusion

In this paper, a Novel Exponential Composition Algorithm for controlling unified power quality conditioner is proposed by the author. The algorithm involves simple mathematical process and easy to implement using digital controller. The performance of the controller is verified with MATLAB/Simulink for nonlinear load conditions. The source current harmonics and load voltage at PCC is found to be within the IEEE Standard limits.

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