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Performance analysis of shunt active filter for harmonic compensation under various non-linear loads

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Abstract: This paper shows the motivation towards the development of a dq-Proportional Resonant (PR) control strategy in shunt active power filter design for eliminations of distortions in source currents for different loading conditions. The switching signals for the inverter of shunt active power filter (APF) have been generated by the hysteresis current control scheme. The controller performance has been verified by using different types of loads such as non-linear balanced, unbalanced and variable etc., with the system in MATLAB/Simulink environment. An experimental prototype has also been developed in the laboratory and results are analyzed to validate the efficacy of the proposed controller.

Keywords: dq-PR control technique; harmonic compensation; hysteresis current control; SAF, shunt active filter; THD, total harmonic distortion.

1 Introduction

In a modern and dynamic power system the loads keep on increasing and solid-state devices like uninterruptible power supplies (UPS), adjustable speed drives (ASD), and arc furnaces, etc., demand compensation of the disturbances caused for them. The power semiconductor devices develop harmonics and simultaneously increase the reactive power requirement in the system. These

power semiconductor devices are treated as loads with non-linearity character [1]. They also cause problems like inefficient utilization of distribution system, voltage distortion and poor power quality from AC mains thereby drawing excessive neutral current from the unbalance created resulting in low system efficiency and poor power factor. The harmonics introduced by the non-linear loads cause interference with communication lines and also disturbance to other consumers [2]. Initially passive filters [1–4] were used for harmonic suppression and reactive power compensation and capacitors for power factor improvement. But due to the demerits related with the passive filters like the series resonance, fixed compensation, and large size, the new type of filters has been introduced known as the active power filters [5, 6]. These have been proved to be better in comparison with the passive filters due to their small size and weight, easy to design and tune. Many control strategies [7, 8] have been developed for achieving better performance from active filters and for meeting various compensation requirements. The total harmonics distortion (THD) before compensation result can be achieved using new techniques. Though several control techniques [13–15] are implemented in various filters such as shunt active filter, series active Filter and Hybrid Filter to compensate the harmonics content present in the signal by generating the reference current, different types of approach for generation of reference current [11, 14–16] is discussed. But still there is scope to develop various control algorithms to obtain proper reference signals. The implementation of control technique in a designed filter has important role for reduction of harmonics. This paper presents the implementation of dq-PR control technique for the proposed shunt active filter and focuses on harmonic suppression and improvement of power factor. The performance of the proposed filter is verified by connecting different types of load with different conditions.

The paper is organized as follows, Section 2 and Section 3 present the proposed shunt active filter and the control techniques implementation respectively. Results and analysis are presented in Section 4. Experimental analysis with results discussed in Section 5 and the paper is concluded in Section 6.

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Figure 1: Schematic diagram of the proposed filter.

2 Proposed shunt active filter

The proposed shunt active power filter (SAPF) consists of two different control blocks. They are the active filter controller and the hysteresis controller. A dc capacitor is kept to maintain a constant voltage of the converter. As the system is three phases, a three-phase non-linear load which is a diode rectifier is connected to the system along with RL combination and this can be treated as the non-linear load. The power converter is controlled to generate compensation currents which are equal in magnitude and opposite in phase with the harmonic currents. The performance of the proposed filter with the proposed control technique is investigated and verified by different conditions. The schematic diagram of the proposed filter is shown in Figure 1.

3 Proposed control techniques implementation

In the proposed work, dq-PR Control Technique along hysteresis current controller is implemented for proper operation and generation of switching signal for the shunt active power filter. The systematic approach of the control technique implementation is discussed below

3.1 dq-PR control strategy

In this method, the fundamental positive and negative sequence component of the instantaneous currents i_d , i_q is separated by transforming the abc stationary reference frame into the dq synchronous reference frame. The “d-q theory” with dq-PR controller-based control algorithm is shown in Figure 2

Figure 2: dq-PR based controller algorithm block diagram.

The transformation matrix is used to translate load currents from the abc phases to the dq frame and It is given in Eq. 1

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \times \begin{bmatrix} i_a^{ref} \\ i_b^{ref} \\ i_c^{ref} \end{bmatrix} \quad (1)$$

The angular position of the dq synchronous reference frame is represented by a time variant synchronization angle ($\theta = \omega t$). To maintain synchronization with three phase voltage, this frame is always rotating at constant speed. A Phase Locked Loop (PLL) is used to detect θ from grid voltage V_{abc} . The i_α and i_β components are compared with i_{dd}^* and zero (0) respectively and then passes through PR controller to get a controlled signal in order to control the dc voltage V_{dc} that is influenced by the active power balance, a dc-voltage controller is typically used, whose output i_{dd}^* is added to the d-current reference and also subtract i_{dd}^* . The resultant vector of three phase grid current needs to be equal to i_d for unity power factor operation of grid. To achieve this condition i_q is compared to 0. The transfer function of PR controller [9] is given as follows:

$$G_{PR} = K_p + K_i * \frac{2\omega_c s}{(s^2 + 2\omega_c s + \omega_r^2)} \quad (2)$$

where K_p = Proportional gain, K_i = Integral gain of the controller, ω_r = Resonance frequency and ω_c = Cut off

frequency. A harmonic compensator (HC) block is designed in parallel with the main PR controller, which gives more robustness to this control scheme. The equation of HC is extracted from [10]

$$G_{HC} = \sum_{h=3,5,7} \frac{2K_{ih}s}{s^2 + (\omega h)^2} \quad (3)$$

where h : harmonic order. K_{ih} : Individual resonance gain ($h = 3, 5, 7$). Here HC block used to control 3rd, 5th, and 7th order source current harmonic component. The inverse transformation to transfer currents from the dq frame to the abc frame is given by:

$$\begin{bmatrix} i_a^{ref} \\ i_b^{ref} \\ i_c^{ref} \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} * \begin{bmatrix} \cos \theta & -\sin \theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (4)$$

A hysteresis current controller is used to produce reference current for the VSI using this controlled i_{abc} . The generated reference current i_{abc}^{ref} and sensed source current are fed to hysteresis current controller for the generation of desired gate pulses for the shunt inverter, which generates compensation current for harmonics and reactive power compensation.

A PR controller is used for reference tracking in stationary which introduces an infinite gain at particular resonant frequency to reduce steady state error. Here resonant frequency is 314 rad/s and cutoff frequency is 10 rad/s. An additional harmonics compensator block is used in this control approach which helps to control particular harmonics frequency and provide more robustness to the controller.

3.2 Hysteresis current control strategy

To get accurate current control, the instantaneous currents are sensed quickly. For this reason, hysteresis current control is chosen for the generation of switching signals for the inverter. The advantage of the hysteresis control over other current control techniques is the quick controllability and easy implementation. Figure 3 shows the hysteresis control scheme used for the current control of active filter along with the switching pattern. The switching frequency is not constant throughout the power frequency cycle. It keeps changing in time with the operating point. The hysteresis band regulates the switching pattern of the active filter.

Figure 3: Hysteresis current control and generation of switching pattern.

4 Results and discussion

The proposed filter model is designed and simulated waveforms are extracted using MATLAB SIMULINK. In this work, simulations are carried out for balanced, unbalanced non-linear loads, balanced variable non-linear load and unbalanced variable load.

4.1 Case 1: balanced non-linear load

A balanced non-linear load is fed to the system and the quantity of harmonics contents present in the Signal is measured in terms THD. The proposed filter injects a signal which suppresses the harmonics content and the quantity of harmonics contents present after compensation is mentioned below. The simulated waveform of all the necessary parameters which is analyzed such as source current, load current and filtering current is presented in Figure 4. The Corresponding FFT analysis before and after mitigation is presented in Figure 5 and Figure 6, It is observed from the Fast Fourier Transform (FFT) analysis that before mitigation the harmonic distortion level was 24.04% and after mitigation it comes

Figure 4: a) Mains current b) Load current c) Compensation current waveform for balanced non-linear load.

Figure 5: Fast fourier transform (FFT) analysis of the simulated source current waveform before compensation.

to 2.95%. Details of THD in each harmonics component is presented in Table I and the results obtained comes under IEEE 519 standard.

Figure 6: Fast fourier transform (FFT) analysis of the simulated source current waveform after compensation.

Table I: THD of individual harmonics components of balanced load.

Individual harmonics component	THD in percentage before compensation	THD in percentage after compensation
<i>Fundamental</i>	100	100
<i>3rd</i>	32.03	0.35
<i>5th</i>	19.15	0.10
<i>7th</i>	13.58	0.02
<i>9th</i>	10.46	0.14
<i>11th</i>	8.45	0.19
<i>13th</i>	7.05	0.15

THD, Total harmonics distortion.

4.2 Case 2: non-linear load with unbalanced condition

A non-linear load with unbalance condition is developed through addition of different resistors and it is fed to the system. The quantity of harmonics contents present in the signal is measured in terms of THD. The simulated waveform of all the necessary parameters which is analyzed such as source current, load current and filtering current is presented in Figure 7. The corresponding FFT analysis before and after mitigation is presented in Figure 8 and Figure 9. The harmonic spectrum of source current waveform is measured. It is observed from the FFT analysis before mitigation the harmonic distortion level was 24.04% and after mitigation it comes to 3.08%. In this case it is observed that the harmonics contents before compensation is more in comparison to balance linear load. The percentage of reduction of THD is more and it is 3.08%. Details of THD in each harmonics component are presented in Table II and the result obtained comes under IEEE 519 standard.

Figure 7: a) Mains current b) Load current c) Compensation current waveform for balanced non-linear load.

Figure 8: Fast Fourier Transform (FFT) analysis of the simulated source current waveform before compensation.

4.3 Case 3: balanced variable non-linear load condition

In general, the loads present in the electrical power system are dynamic in nature which means the load is not fixed, for this reason a case of variable load is considered to check whether THD is limited even after an extra load is added to the system. Another diode rectifier load is connected through a circuit breaker with switching period as [0.2, 0.3]. Initially the C.B is kept open. The simulated waveform of all

Figure 9: Fast Fourier Transform (FFT) analysis of the simulated source current waveform after compensation.

Table II: THD of individual harmonics components of unbalanced load.

Individual harmonics component	THD in percentage before compensation	THD in percentage after compensation
Fundamental	100	100
3rd	30.71	0.35
5th	18.23	0.12
7th	12.79	0.24
9th	9.71	0.25
11th	7.70	0.18
13th	6.28	0.12

THD, Total harmonics distortion.

the necessary parameters which is analyzed such as source current, load current and filtering current is presented in Figure 10. The FFT analysis is presented in Figure 11. The harmonic spectrum of source current waveform is measured. The THD is 2.06% of the fundamental signal. Details of THD in each harmonics component are presented in Table III and the result obtained comes under IEEE 519. When additional load is added there will be a rise in the value of the current. In Figure 10 (a) it is observed that there is a sudden spike on addition of load and later it got stabilized. Filter current before and after addition of at 0.2 s is shown in Figure 10 (c).

4.4 Unbalanced variable load

Another diode rectifier load is connected through a circuit breaker with switching period as [0.2, 0.3]. Initially the C.B is kept open. The simulated waveform of all the necessary parameters which is analyzed such as source current, load current and filtering current is presented in Figure 12. The FFT analysis of source current after compensation is shown

Figure 10: a) Mains current b) Load current c) Compensation current waveform for balanced non-linear load.

Figure 11: Fast fourier transform (FFT) analysis of the simulated waveform with APF for balanced variable non-linear load.

in Figure 13. The THD is 2.30% of the fundamental signal. Details of THD in each harmonics component are presented in Table IV and the result obtained comes under IEEE 519 standard. The average THD for all the four cases for better understanding described above are presented with HCR in Table V.

Table III: THD of individual harmonics components with balanced variable load.

Individual harmonics component	THD in percentage before compensation	THD in percentage after compensation
<i>Fundamental</i>	100	100
<i>3rd</i>	31.69	0.60
<i>5th</i>	18.85	0.91
<i>7th</i>	13.27	0.84
<i>9th</i>	10.12	0.80
<i>11th</i>	8.07	0.84
<i>13th</i>	6.63	0.85

THD, Total harmonics distortion.

Figure 12: a) Mains current b) Load current c) Compensation current waveform for balanced non-linear load.

5 Experimental validation

The verification of the dq-PR control strategy has been carried out by experimental analysis using dSPACE 1104. The effectiveness of the proposed filter with different load condition is presented. The experimental analysis is easily understood from the block diagram as shown in Figure 14. The experimental setup is presented in Figure 15.

Figure 13: FFT analysis of the simulated waveform with APF for unbalanced variable non-linear load.

Table IV: THD of individual harmonics components with unbalanced variable load.

Individual harmonics component	THD in percentage before compensation	THD in percentage after compensation
Fundamental	100	100
3rd	30.71	1.56
5th	18.23	0.86
7th	12.79	0.62
9th	9.71	0.53
11th	7.70	0.63
13th	6.28	0.53

THD, Total harmonics distortion.

Table V: THD before and after compensation with HCR percentage.

Type of load	THD in percentage before compensation	THD in percentage after compensation	HCR percentage
Balanced	22.4	2.95	13.1
Unbalanced	43.92	3.08	7.01
Balanced	31.69	2.06	8.20
Variable			
Unbalanced	30.71	2.30	7.48
Variable			

THD, Total harmonics distortion.

Rectifier with serial port no. SQL100A1600V, capacitor of 470 V and a rheostat is used as a non-linear load. Two different conditions such as balanced and unbalanced condition is set up for verification of the simulation results. Variable voltage is obtained through an auto transformer. The proposed filter is a SEMIKRON based inverter and it is placed between source and load at the point of PCC along with H ferrite core-based inductor. Two legs out of three legs of the inverter are utilized in the experiment. SKHI 22 AR and SKM 75 GB 123 D drivers and switches used in the Insulated Gate Bipolar Transistor respectively. Source

Figure 14: Block diagram of experimental setup.

Figure 15: Laboratory experimental setup.

Figure 16: Source voltages, source current, load current and filter current from top to bottom.

voltage and voltage across the capacitor is sensed through two voltage sensors and in the same way desired current and actual current is sensed through two current sensors. LV 25-P and LA 55-P is the used voltage and current sensors in the work. dSPACE 1104 control board receives the output signals from both the sensors and accordingly pulses are fed to the input of the driver with amplified signal. Waveforms are extracted from oscilloscope with the help of digital to analog port of the dspace 1104. The dq-PR controller based proposed filter model is implemented using dSPACE 1104 platform which allows real time controller implementation in MATLAB/Simulink [11, 12]. The real time workshop of dSPACE 1104 is used to convert the Simulink file in a C-Code file automatically and the developed C-Code file treated as the source of the Real Time Interface of the system. The machine code is generated with the help of C Compiler.

5.1 Case A: balanced non-linear load

The experiment is carried out as per the procedure mentioned above. Balanced non-linear load is connected, by observing the voltage and current sensor parameters dSPACE 1104 starts functioning and accordingly the source voltage, source current, load current and filter current are captured as shown in Figure 16.

5.2 Case B: non-linear load with unbalanced condition

In this case unbalanced condition is developed and then the load is connected. The dSPACE 1104 receives the parameters of both voltage sensors and current sensors and accordingly the switching action carried out. The results obtained from the mentioned cases are presented in Figure 17.

Figure 17: Source voltages, source current, load current and filter current from top to bottom.

6 Conclusions

This paper demonstrates the validity of dq-PR control algorithm implementation in the proposed shunt active filter. Four cases such as non-linear, non-linear unbalanced, balanced variable, unbalanced variable loads are considered for verification of the proposed algorithm. The simulated waveforms of the four cases are presented with corresponding FFT analysis. In every case, the source current THD is obtained and it is found to be suitable as it comes under IEEE 519 standard. The percentage of reduction of harmonics is less and very encouraging. The effectiveness of the proposed control algorithm is verified through real time analysis using dSPACE 1104 platform for balanced and unbalanced conditions. The obtained waveforms are presented and from the obtained wave forms it can be easily understood that the source current is sinusoidal in nature which proves the effectiveness of the proposed filter.

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