Performance Analysis of Current Injection Techniques for Shunt Active Power Filter

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Abstract. Shunt Active Power Filter (SAPF) can be used for compensation of current harmonics generated by non-linear loads. The process involves an injection of equal but opposite current to mitigate the distortion current supplied back by nonlinear load to the voltage supply. Thus, the injected current will shape the supply current to a sinusoidal. SAPF consists of signal processing part and injection part. Processing part generates reference current wave and the injection part injects the reference current parallel to the load. In this paper a comparison is made between three different control strategies for current injection in three-phase three-wire shunt active power filter. The current injection is performed by generating gate pulses pattern for the voltage source inverter using a suitable controller. In this paper three control techniques are compared including Hysteresis Current Control (HCC), Delta Modulation Control (DMC) and One Cycle Control (OCC). The performance of these techniques is evaluated by the accuracy of the injected current in parallel to the load by comparing the required current to be injected and the measured value of the injected current. The performance is also evaluated by measuring Total Harmonic Distortion (THD) of the source current before and after compensation. The results are evaluated and compared using Matlab/Simulink.

1. Introduction

With the advancement of technology, the dependency on the electrical energy has been increased greatly. The performance efficiency of different electric apparatus is directly affected by power quality. The power-quality problem is identified by a distortion in the voltage waveform of the power source from a sine wave, or in the amplitude from an established reference level [1]. Different types of disturbances that affect the power quality are voltage fluctuations, voltage sags, voltage unbalance, transients and harmonics [2].

Harmonics is known to be a major issue out of all power quality problems [3]. Harmonics in the power system are increasing rapidly due to the large scale use of power electronics equipment. Harmonics can be defined as currents or voltages which are integer multiples of fundamental frequency [4]. Harmonic currents are caused by nonlinear loads connected with the distribution system. These current harmonics will be responsible for power factor reduction, power system voltage fluctuations, decrease in efficiency and interference during communications. The Harmonic currents are increasing dramatically in all residential, commercial, and industrial installations as the nonlinear loads are increasing rapidly over the past few years. Different methods [5] like K-rated transformers, separate neutral conductors, zigzag autotransformers, phase shifting, series line inductors and harmonic filters are employed for mitigation of harmonics.
Active power filters (APF) have been used for harmonics suppression and reactive power compensation in order to enhance the power quality. Gyugi and Strycula [6] were the first to introduce the concept of Active Power Filters. Due to significant growth in power electronics, the use of APF has become the dynamic solution for reduction of harmonics because of having unique advantages as compared to passive filter devices [7]. The Shunt Active Power Filter connected in parallel with the load is used for mitigation of current harmonics. The process involves detection of harmonic component, generation of reference current and generation of the gate pulses for the power circuit to inject the reference current. The power circuit consists of AC to DC converter with a DC link capacitor and DC to AC voltage inverter. An active power filter cancels out the current harmonics introduced by the nonlinear load by injecting reference current in parallel to the load, thus making the current waveform supplied through the source, sinusoidal. The basic structure of Shunt Active Power Filter is shown in figure 1. The source voltage $V_s$ is supposed pure sinusoidal. The load current is represented by $I_L$. The reference current generation block detects the harmonic current waveform and generates the reference current $I_R$ which is anti-phase to the harmonic current. The current injection controller produces the switching pulses for voltage source inverter in order to inject $I_R$ at the point of common coupling (PCC). The injected current with addition to load current will make the source current very near to pure sinusoid. The parameter used to evaluate the performance of APF is Total Harmonic Distortion (THD). A THD value of the source current close to zero proves a very good performance of APF in terms of harmonics mitigation.

Reference current can be extracted using either time domain techniques like Instantaneous Reactive Power (p-q) theory, Synchronous Reference Frame (d-q) theory and perfect harmonic cancellation or frequency domain techniques like Discrete Fourier Transform (DFT) [8] and sine multiplication method. DC link voltage control is one of the important issues in voltage source inverter. PI control is used to regulate the DC link voltage. Different controllers are used to inject the reference current at the point of common coupling like Hysteresis Current Controller, Deadbeat Controller, Delta Modulation Controller, One Cycle Controller Predictive Controller and Sliding Mode Controller.

2. Reference Current Generation Techniques
Reference current generation is an important part of active power filter. Reference current is actually 180 degree out of phase with the harmonics current. The reference current added to the load current will make the source current sinusoidal. Many techniques are used for reference current generation but in this paper Instantaneous Reactive Power theory which is also known as p-q theory is used due to its simplicity and accuracy.

2.1. Instantaneous Reactive Power (p-q) Theory
This concept is very popular and useful for Active Power Filter application, and principally consists of a variable transformation from \( a, b, c \), reference frame of the instantaneous power, voltage, and current signals to \( \alpha, \beta \) reference frame [9].

Most APFs have been designed on the basis of p-q theory to calculate the desired reference currents. In this theory, instantaneous three phase current and voltages are transformed from \( a - b - c \) coordinates to \( \alpha - \beta - 0 \) co-ordinates [10] as shown in equation (1) and (2).

\[
\begin{bmatrix}
  v_0 \\
  v_a \\
  v_\beta
\end{bmatrix} = \sqrt{3} \begin{bmatrix}
  1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\
  1 & -1/2 & 1/2 \\
  0 & \sqrt{3}/2 & -\sqrt{3}/2
\end{bmatrix} \begin{bmatrix}
  v_a \\
  v_\beta \\
  v_c
\end{bmatrix}
\]

(1)

\[
\begin{bmatrix}
  i_0 \\
  i_a \\
  i_\beta
\end{bmatrix} = \sqrt{3} \begin{bmatrix}
  1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\
  1 & -1/2 & 1/2 \\
  0 & \sqrt{3}/2 & -\sqrt{3}/2
\end{bmatrix} \begin{bmatrix}
  i_a \\
  i_\beta \\
  i_c
\end{bmatrix}
\]

(2)

The source currents and phase neutral voltages are used to calculate the instantaneous real and imaginary power components as given in equation (3).

\[
\begin{bmatrix}
  p \\
  q
\end{bmatrix} = \begin{bmatrix}
  v_0 & 0 & 0 \\
  0 & v_a & v_\beta \\
  0 & -v_\beta & v_a
\end{bmatrix} \begin{bmatrix}
  i_0 \\
  i_a \\
  i_\beta
\end{bmatrix}
\]

(3)

The reference current in \( \alpha - \beta \) co-ordinates is given by (4).

\[
\begin{bmatrix}
  i_\alpha * \\
  i_\beta *
\end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix}
  v_\alpha & v_\beta \\
  -v_\beta & v_\alpha
\end{bmatrix} \begin{bmatrix}
  p \\
  q
\end{bmatrix}
\]

(4)

The reference current in \( a-b-c \) co-ordinates is given by (5).

\[
\begin{bmatrix}
  i_\alpha * \\
  i_\beta * \\
  i_c *
\end{bmatrix} = \sqrt{3} \begin{bmatrix}
  1 & 0 & 1/\sqrt{2} \\
  -1/2 & \sqrt{3}/2 & 1/\sqrt{2} \\
  -1/2 & -\sqrt{3}/2 & 1/\sqrt{2}
\end{bmatrix} \begin{bmatrix}
  i_0 * \\
  i_\alpha *
\end{bmatrix}
\]

(5)

3. Current Injection Techniques

The reference current generated must be injected in parallel to the load with high accuracy in order to make the source current sinusoidal. In this paper three different current injection techniques are implemented to evaluate the performance of active power filter. The techniques analyzed are Hysteresis Current Control (HCC), Delta Modulation Control (DMC) and One Cycle Control (OCC).

3.1. Hysteresis Current Control

In hysteresis current controller a fixed hysteresis band is set and is compared with a current error signal to generate the switching pulses of inverter. It is a closed loop system which senses the current error and generates the switching pulses of IGBT when the error exceeds an assigned band. This technique has the advantages of simplicity, good accuracy, robustness and fast dynamic response. The switching pattern of hysteresis current control is shown in figure 2(a) in which the hysteresis band is set with a lower and upper limit [11]. When the compensating current reaches the upper or lower limit, the controller increases or decreases the compensating current so that it follows the reference current[12]. The schematic diagram of HCC is shown in figure 2(b) where \( I_\alpha, I_\beta \) and \( I_c \)
are compensating currents and $I_{ca^*}$, $I_{cb^*}$ and $I_{cc^*}$ are reference currents. These currents are compared to generate the six switching pulses from $g_1$ to $g_6$. These pulses are used for switching of IGBTs.

![Diagram](attachment:image1.png)

**Figure 2.** Hysteresis Current Control (a) Switching pattern, (b) Schematic diagram.

### 3.2. Delta Modulation Control

The Delta Modulation Control (DMC) is also based on a nonlinear control [13] as shown in ‘figure 3(a)’. The switching signals of six IGBTs are generated by applying limit comparators and D-type flip-flops. The main advantage of delta modulation current control technique is that it is simple and easy to implement. $I_{ca}$, $I_{cb}$ and $I_{cc}$ are the compensating currents and $I_{ca^*}$, $I_{cb^*}$ and $I_{cc^*}$ are the reference currents for three phases. If $I_{ca}$ is over than $I_{ca^*}$, the output of comparator (y1) is 0. In contrast, if $I_{ca}$ is less than $I_{ca^*}$ then y1 is 1. The output of comparator is applied to D-type flip flop for producing the switching pulses. The clock signal is used to determine the output of D-type flip flop. The output Q is set equal to the output of comparator y1 upon transition of the clock signal from 0 to 1, thus generating the gate pulse $g_1$ and output Q generates the gate pulse $g_2$. The gate pulses $g_3$ to $g_6$ for the other two phases are generated in the same manner.

![Diagram](attachment:image2.png)

**Figure 3.** (a) DMC schematic, (b) OCC schematic

### 3.3. One Cycle Control

One-cycle control is a nonlinear control method which has fast transient response and good tracking performance [14]. This technique is implemented to control the duty ratio of the switch in real time. The input voltage perturbations are rejected by One-Cycle Control method in only one switching
cycle and follows the control reference very quickly. This new control method is very common and directly applicable to all switching converters. This method takes advantage of the pulsed and nonlinear nature of switching converters and attains instantaneous control of the average value of the chopped voltage or current [15].

The block diagram of OCC is shown in ‘figure 3(b)’ where \( i_{a*}, i_{b*}, \) and \( i_{c*} \) are the reference currents and \( V_a, V_b \) and \( V_c \) are the source voltages. \( R_c \) is the current sensing resistor. A key feature of the OCC control method is the fact that the ramp generated by the integrator circuit is reset at the end of each switching cycle and the ramp starts again from zero at the beginning of the subsequent cycle. Consequently, this method is termed, OCC, or “One Cycle Control”.

4. Simulation Results
The simulation results for all the three techniques have been obtained by using Matlab/Simulink. For the purpose of simulation a three phase three wire system with balanced load has been considered. The reference current is generated using p-q theory and initially in order to check its accuracy this current is added to the load current which becomes sinusoidal giving a THD of 0.9%. In the next step this reference current is injected using three control strategies. The performance of the three techniques is analyzed by calculating the THD of the source current and computing the error between the reference current wave and injected current wave. Table1 shows the Source parameters used for simulation.

| Parameter | Line-line RMS voltage | Source frequency | Source resistance | Line inductance | Line resistance |
|-----------|-----------------------|------------------|-------------------|----------------|----------------|
| Value     | 380 V                 | 50 Hz            | 0.001 Ω           | 1 μH           | 0.01 Ω         |

4.1. Results of HCC:
The Shunt Active Power Filter is simulated first by using Hysteresis current controller for current injection. The load current waveform is shown in Fig7 and its corresponding THD is shown in Fig8 which shows that THD is 29.89%. Fig9 shows the waveform of the reference current generated using p-q theory.

![Figure 4. (a) Load current, (b) Reference current](attachment:image)

The injected current waveform using HCC is shown in Fig10. The injected current waveform is subtracted from the reference current waveform thus producing an error as shown in Fig11. The minimum possible error proves the accuracy of current injection technique.
4.2. Results of DMC:
The Shunt Active Power Filter is simulated again by using Delta Modulation controller for current injection. The current injected using DMC is shown in Fig13 and its corresponding error is shown in Fig14. It can be seen that difference in error between HCC and DMC technique is very small but DMC error plot also contains some spikes at regular intervals. The source current waveform after compensation is shown in Fig15.

4.3. Results of OCC:
The last simulation of SAPF is carried out using One Cycle Control for current injection. The injected current waveform is shown in Fig16 and the error between reference current and injected current is shown in Fig17. It can be seen that this error is larger than the other techniques. Fig18 shows the compensated source current. Table 2 shows the performance of the techniques used for current injection by measuring THD of the source current before and after compensation. It also shows the amplitude of error between injected current and reference current.

| Table 2. THD of source current |
|-------------------------------|
| Control Technique  | HCC | DMC | OCC |
| THD before compensation | 29.89% | 29.89% | 29.89% |
| THD after compensation  | 1.55%  | 1.83%  | 2.9%  |
| Error Amplitude        | 0.755 | 0.789 | 1.38 |

5. Conclusion
In this paper three different control strategies used for current injection in shunt active power filters are analyzed. The three techniques considered are Hysteresis Current Control (HCC), Delta Modulation Control (DMC) and One Cycle Control (OCC). A three-phase three-wire system with a non-linear load is simulated to evaluate the performance of these techniques. The parameters used for performance evaluation are THD and error calculation between reference current and injected current. After comparing the results it is concluded that HCC is able to inject the reference current with good accuracy and minimum error as compared to DMC and OCC. Also THD of the source current is reduced to a lower value by using HCC.

6. References
[1] Singh, Bhim, Kamal Al-Haddad, and Ambrish Chandra. "A review of active filters for power quality improvement." IEEE transactions on industrial electronics 46.5 (1999): 960-971.
[2] Moravek, Jan, et al. "Power quality issues related to power flow control in systems with renewable energy micro sources." Electric Power Engineering (EPE), 2016 17th International Scientific Conference on. IEEE, 2016.
[3] Pandey, Shubham, Maneesh K. Tiwari, and Dileep K. Shukla. "Harmonic mitigation techniques in modern power system: A Review."Global Journal of Multidisciplinary Studies, Vol. 5, Issue-9, August-2016.
[4] Pejovic, Predrag. Three-phase diode rectifiers with low harmonics: current injection methods.
Anju Jacob, Babitha T Abraham, Nisha Prakash and Riya Philip. "A review of active power filters in power system applications." *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, Vol. 3, Issue 6, June 2014.

L. Gyugyi, E. C. Strycula, “Active ac power filters”, in *Proc. IEEE/IAS Annu. Meeting*, 1976, pp. 81-87.

Swain, Sushree Diptimayee, Pravat Kumar Ray, and Kanungo Barada Mohanty. "Improvement of power quality using a robust hybrid series active power filter." *IEEE Transactions on Power Electronics* 32.5 (2017): 3490-3498.

Chauhan, Siddharthsingh K., et al. "Analysis, design and digital implementation of a shunt active power filter with different schemes of reference current generation." *IET Power Electronics* 7.3 (2013): 627-639.

H. Akagi, Y. Kanazawa, and A. Nabae. "Generalized theory of the instantaneous reactive power in three-phase circuits." in *Proc. IEEJ Int. Power Electronics Conf. (IPEC-Tokyo)*, 2004, pp. 1375-1386.

Willems, Jacques L. "A new interpretation of the Akagi-Nabae power components for nonsinusoidal three-phase situations." *IEEE Transactions on Instrumentation and Measurement* 41.4 (1992): 523-527.

Belonkar, A., and M. Salodkar. "Performance Analysis of Shunt Active Power Filter with Different Switching Signal Generation Techniques." *Presented at Recent Advances and Applications of Electrical Engineering: Proceedings of the 9th WSEAS International Conference on Applications of Electrical Engineering (AEE'10), Penang, Malaysia*. 2013.

Bhople, Satish U., and Santhosh Kumar Rayarao. "Comparison of Various Reference Current Generation Techniques for Performance Analysis of Shunt Active Power Filter using MATLAB Simulation." *International Journal of Current Engineering and Technology* 6.2 (2016): 606-611.

Alargt, Farag S., Ahmed S. Ashur, and Ahmad H. Kharaz. "Novel adaptive delta modulation controller for Interleaved Boost DC-DC converters." In *Systems and Control (ICSC), 2016 5th International Conference on*, pp. 20-25. IEEE, 2016.

Ramani Kannan, Lokesh N. Khairul Nisak Md Hasan and Aravind CV. "Implementation of One cycle Controller for Single phase Bi-directional." *International Journal of Applied Engineering Research*. 12, no. 6 (2017): 804-812.

Sreeraj, E. S., et al. “An active harmonic filter based on one-cycle control.” *IEEE Transactions on Industrial Electronics* 61.8 (2014): 3799-3809.