Ramptime Current -Controlled APF for Harmonic Mitigation, Power Factor Correction and Load Balancing

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Abstract - This paper presents a simulation for a shunt active power filter aimed at mitigation of harmonics, power factor correction and balancing of unbalanced three-phase system. The system consists of load fed though a six pulse bridge rectifier. The active power filter consists of a three-phase current-controlled voltage source inverter (CC-VSI) with a filter inductance at the ac output and a dc-bus capacitor. The CC-VSI is operated to directly control the ac source current to be sinusoidal and in phase with the ac source voltage. The inverter switching is controlled using ramptime current control being based on the concept of zero average current error (ZACE). The active power filter reference currents are generated using perfect harmonic cancellation (PHC) control method. The proposed filter successfully succeeded in reducing the total harmonic distortion (THD) to less than unity, correcting power factor to unity and balancing of unbalanced currents under sinusoidal and distorted supply voltages. The dynamic performance of the proposed filter is so fast to meet the dynamic load conditions.

Index Terms – Active power filter, Harmonic mitigation, Ramptime current control, Power factor correction, Load balancing.

I. Introduction

Non-linear loads, especially power electronic loads, create harmonic currents and voltages in the power systems. These harmonics cause increase of losses, decrease of power factor and reduction of system efficiency. Passive LC filters can eliminate harmonics using bulk passive components. Series and parallel resonances are the main disadvantages of passive filters. Various active power filters (APF) have been developed to overcome passive filter problems [1]. Active power filters can suppress the harmonics, compensate for reactive power and balance three-phase unbalanced loads. Some reports [2, 3] appeared to achieve reactive power compensation and others have been made for reactive power compensation and harmonic elimination [3]. Some attempts [4, 5] have been made for reactive power compensation, harmonic elimination and balance three-phase unbalance nonlinear loads. However, the value of the current THD is high (4.2%), even it is within the standard limits, and the power factor is less than unity and the filter is tested under sinusoidal supply voltage only [4, 5].

The shunt type APF acts to eliminate the reactive power and harmonic currents produced by non-linear loads from the source current by injecting compensating currents which result in sinusoidal supply current with unity power factor [6]. This filter has been proven to be effective in compensating harmonic current sources, but it cannot properly compensate for harmonic voltage sources [7]. Many electronic appliances, such as switch mode power supplies and electronic ballasts, are harmonic voltage sources. A voltage sourcing series active power filter is suitable for controlling harmonic voltage sources, but it cannot properly compensate for harmonic current sources.

In many cases, non-linear loads consist of combinations of harmonic voltage sources and harmonic current sources and may contain significant load unbalance (ex. single phase loads on a three phase system). To compensate for these mixed non-linear loads, which generate harmonic voltages and harmonic currents, a combined system of a shunt APF and a series APF can be effective [7]. The power inverter of active power filter is controlled to generate a compensation current, which is equal but opposite to the harmonics current and to feed the load with the required reactive power so the supply current is sinusoidal and in phase with supply voltages.

The control of the APF is divided into two stages, the first stage is to generate the reference currents (i_{ar}, i_{br}, i_{cr}). The second stage is to generate the inverter switching signals.

Many control techniques such as instantaneous reactive power theory (p-q theory) [8, 9] and instantaneous active and reactive current (i_{a},i_{q}) controls [10] have been used to generate the APF reference currents. In ref. [3, 4], the DC side capacitor voltage was adjusted against a reference value where the error signal is fed to a PI regulator. The output of the PI regulator is multiplied by unit sin vectors in phase with source voltages to obtain the references current. An improved (i_{a},i_{q})
control was reported [5] to enhance the performance of the active power filter.

The p–q theory and id–iq control are widely used in APF control circuitry to calculate the desired compensation current. However, they are very sensitive to distortion and imbalance that may occur in the voltage at the point of common coupling (PCC) [11]. The p-q and id–iq strategies balance three-phase unbalanced loads on the expense of distorting the source current [12, 13]. The unity power factor (UPF) control method does not work well in presence of zero sequence voltage components. Also, it didn't correct the power factor to unity when the load currents are unbalanced [12, 13]. The use of DC side capacitor voltage to generate the reference APF current does not work at all the conditions. Ref [4] reported that if the DC capacitor voltage is less than the peak value of the point of common coupling (PCC) voltage, then the compensation fails completely. Also, ref. [4] reported that the CC-VSI loses its controllability if a certain condition is not satisfied.

Perfect harmonic cancellation method (PHC) is the best control method to eliminate harmonics, correct power factor and balance three-phase unbalanced currents for all operation conditions [12]. Therefore, the use of PHC provides a robust control strategy working at all the loading conditions on the expense of extra cost when compared with the use of PI loop only.

In order to generate the inverter switching signals PWM current control [5], hysteresis current control [7, 8, 11] or ramptime current control can be used. The zero average current control technique (ZACE) [14, 15] could be used with hysteresis or ramptime current controls. Ramtime like hysteresis current control where the switching instants are continuously generated so as to push the current error signal back towards zero. Like hysteresis current control, the current error signal spends roughly equivalent amounts of time on each side of zero within each switching period, resulting in zero average current error as shown in Fig. (1), where isr is the reference current and iL is the actual inductor current.

Unlike hysteresis current control, switching instants are chosen with the intention of producing a fixed switching frequency which is missed in hysteresis current control. Ramtime current control achieves ZACE with significantly improved control over the switching frequency when compared to hysteresis current control [16]. The performance and the effectiveness of the filter are enhanced by the use of the ramtime current control technique to control the CC-VSI.

In this paper, a shunt active power filter is introduced to eliminate harmonics, improve the power factor to unity and balance three-phase unbalanced loads under sinusoidal and distorted supply voltage. Ramtime current (RT) control and perfect harmonic cancellation (PHC) methodology are used. Also, the dynamic performance of the proposed filter has been tested.

II. Active Power Filter Operation

Figure (2) shows basic active power filter block diagram including non-linear three phase load (uncontrolled rectifier with series inductance L and shunt capacitance C for suppress harmonics fed to the resistive load R). The shunt active power filter is operated as a current source parallel with the non-linear load. The APF in general consists of a three phase current-controlled voltage source inverter (CC-VSI), smoothing inductor Ls, a DC capacitor Cc and control circuit.

![Active Filter Configuration](image)

III. APF Control Method

A Description of the First Control Stage

The PHC method is used here to generate the reference currents for the active power filter. This method is used before in harmonic mitigation in conventional and advanced aircraft electric power system [17]. Figure (3) Show the complete PHC method to generate the reference currents. Assume the voltages at the point of common coupling PCC are va, vb, vc, and loading currents are iLa, iLb, iLc, the instantaneous power of the load is given by [18]:

\[ p_L = v_a i_La + v_b i_Lb + v_c i_Lc \]  

(1)

This power has mean and oscillating values.

\[ p_L = \bar{p}_L + \tilde{p}_L \]  

(2)

The capacitor voltage Vdc is kept constant through controlling the switch power loss in the inverter using PI controller which regulates DC capacitor voltage. The total active power fed by the source is the sum of the inverter switching loss Psw and the active power needed by the load pL. The reference source current is given by:

\[ i_{sr} = K v^+ \]  

(3)

Where \( v^+ \) is the PCC voltage space vector with a single fundamental positive sequence component obtained from the phase-locked loop (PLL) circuit. The power delivered by the source will be:

\[ p_s = v i_{sr} = K v^2 \]  

(4)
To extract the average (mean) power, a low pass filter (LPF) is needed. The average load power is divided by the summation of the squared of the positive sequence component of the voltages to get parameter $K$.

$$K = \frac{\bar{P}}{v_a^2 + v_b^2 + v_c^2}$$

Once the parameter $K$ is obtained, the source reference currents are calculated by multiplying it by the positive sequence component of the voltage.

$$\begin{align*}
\bar{i}_{a'} &= K v_a^+ \\
\bar{i}_{b'} &= K v_b^+ \\
\bar{i}_{c'} &= K v_c^+
\end{align*}$$

Once the reference currents are obtained the error is obtained, which express as:

$$Error = i_L - i_r$$

### B Description of the Second Control Stage

Ramptime used to cause the current in the inductance $L_f$ of the active power filter to precisely follow a desired reference current signal. This is accomplished with only the zero crossing instants of the current error signal. Ramptime attempts to maintain a constant switching frequency based not on determining a hysteresis band, or using a clock, but on the choice of switching instant relative to the zero crossing times of the current error signal.

In this application, the current error signal is the difference between the actual load current and the desired/reference supply current waveform. The ramptime control produces switching instants, which make the current error signal crossing zero at intervals of half the desired switching period. Hence the current error signal spends half of the time on alternate sides of zero, resulting in an average value of zero, a close following of the reference signal, and a switching period (and hence switching frequency) very close to the desired value.

Figure (4) shows the how the switching signals are generated for the CC-VSI. The input to the ramp time (RT) current control is the error signal which is the difference between $i_i$ and $i_r$.

The selection of the switching frequency is based on the overall system performance. It is desirable to use high switching frequency as possible, except for one significant drawback, the switching losses in the inverter switches increase proportionally with the switching frequency $f_s$. Therefore, the switching is selected to be less than 6 KHz in most applications [19]. The switching frequency is chosen in order to minimize switching losses and achieve the optimal performance on the overall system. A switching frequency $f_s=5$ kHz has been chosen for the proposal application.

In practice, the IGBT switches are not ideal, so they do not turn on or off instantaneously. Therefore, it is necessary to include a dead time as shown if Fig. (5) to avoid a short circuit that may happen when switches in the same leg conduct simultaneously.
Fig. 5. IGBT switch pulse with and without dead time.

This time is included in the control signals and it is called 'dead time'. For two switch in the same leg, the switch that is on is turn off. Then there is a fixed time delay to allow the turn-off to be completed successfully. After the delay, the opposite switch is turned on as shown in Fig. (5).

IV. Simulation Results

The PSIM software program was used for filter simulation under balanced and distorted supply voltages.

A Balanced Mains Voltage

A. Six Pulses Rectifier as a Nonlinear DC Load

The PSIM software program is used for simulation of nonlinear loads, such as three-phase bridge rectifier as shown in Fig (2). Figure (6) shows the load current, which is non-sinusoidal. The THD value of the load current is 29.7% which is higher than the IEEE standard limits. In this case the filter tested under balanced supply voltages.

Fig. 6. Waveform of load current

Figure (7-a) shows the supply current and supply voltage and fig. (7-b) show the filter injected current. The APF made the supply current sinusoidal and fed the nonlinear load with its reactive power (i.e. the power factor improved to unity). The harmonic spectrum of the load and supply currents is shown in fig. (8). In the present simulation, the THD value of the supply current is 0.88%, which is within the standard limits. For the same non-linear load, the THD value was 3.7% and power factor was less than unity [3]. This confirms how the present simulation is better than that reported in [3].

Fig. 7 (a) Supply voltage and supply current, (b) Filter injected current for constant load current.

Fig. 8 Harmonic spectrum of the load and supply currents

Fig. 9 Load current

Fig. 10 (a) Supply voltage and supply current, (b) Filter injected current for varying load current.
In order to evaluate the dynamic performance of the proposed filter the load is increased during the operation by connecting more parallel resistors to load side, Fig. 9. The supply current is purely sinusoidal and in phase with the supply voltage irrespective of the value of load current as shown in Fig. 10. This confirms that the dynamic performance of the filter is satisfactory.

A. 2. Composite DC and AC Loads

In the second case of loading, AC load is added in parallel with the six pulse bridge rectifier as shown in Fig. (11). The load power factor is chosen 0.5 lag. Figure (12) shows the load current, supply current and supply voltage. The THD values of the load and supply currents are 18.5% and 0.92%, respectively and the power factor is improved to unity.

A. 3. Unbalanced Mixed loads

In the third case, a single phase load is added to the six pulse bridge rectifier load. This causes the phases currents to be unbalanced as shown in Fig. (13).

Figure (14) shows how the phases current are not sinusoidal, not balanced and contain reactive components (i.e., the power factor less than unity). The THD of phases load current a, b, c are 18.201%, 21.01% and 16.754% respectively, which exceeds the IEEE standard limits.

It can be seen from fig. (15) that the shunt active power filter is successful in elimination harmonics, correcting the power factor to unity and balancing load currents, which can
not be done using passive filters. The phases supply current THD is 1.12%, which match the IEEE standard limits.

B Distorted Mains Voltage

Supply voltages are distorted by adding different levels of 3rd through 11th harmonics, Fig. 16.

![Fig.16 Supply voltage](image)

Figure (17) shows that the APF succeeded in mitigation of harmonic currents and correct the power factor to unity under distorted supply voltage. The THD values of the load and supply currents are 28.31% and 1.9% respectively. The design specification and essential parameters of the system used in the simulation are indicated in Table 1. Comparison between the proposed filter with perfect harmonic cancellation technique and PI control loop alone is indicated in Table 2.

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<thead>
<tr>
<th>Table 1 System parameters</th>
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<tbody>
<tr>
<td>Parameter</td>
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<tr>
<td>V (rms/phase) (V)</td>
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<tr>
<td>f (Hz)</td>
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<tr>
<td>Lf (mH)</td>
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<td>Cf (µF)</td>
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<td>Ls (mH)</td>
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<th>Table 2 THD levels by different approach</th>
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<tr>
<td>Operation Condition</td>
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<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Balanced main Voltages and currents</td>
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<tr>
<td>Distorted main voltages</td>
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<tr>
<td>Balanced main voltages and unbalanced currents</td>
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<td>Phases current THD</td>
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Conclussion

The shunt active power filter (APF) is successfully used to mitigate the harmonic, feed the load with its required reactive power and balance unbalanced three-phase load currents under sinusoidal and distorted supply voltage. Subsequently, the supply current is pure sinusoidal with unity power factor. The dynamic performance of the proposed APF is fast under any load variation. The perfect harmonic cancellation method is suitable to control the APF in AC supply circuits. Ramp-time (RT) current control is very effective to shape the supply current to be sinusoidal without additional low order harmonics due to the concept of zero average current error (ZACE) with fixed switching frequency. Therefore, it is suitable for the supply current-controlling shunt active power filter.

References


