AN EVALUATION OF TECHNIQUES FOR DETERMINING ACTIVE FILTER COMPENSATING CURRENTS IN UNBALANCED SYSTEMS

S.D. Round and D.M.E. Ingram

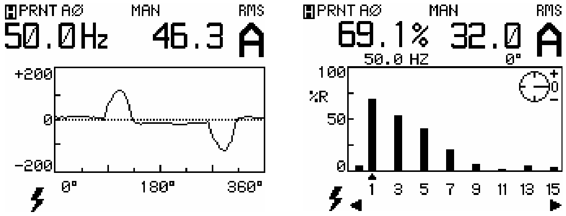
University of Canterbury, New Zealand

Abstract. An active filter is used to eliminate current harmonics produced at a consumer's site. This paper evaluates five different methods of determining the compensating current for an active filter that compensates unbalanced three-phase loads. The methods compared are notch filtering, Instantaneous Reactive Power Theory, Synchronous Reference Frame, sinusoidal subtraction and the Fast Fourier Transform. Simulation results have determined that the Fast Fourier Transform method provides good steady state and transient responses for active filters in unbalanced systems.

Keywords. Active filtering, harmonic elimination, digital signal processing.

INTRODUCTION

Traditionally, the majority of power consumption has been drawn by linear loads such as incandescent lighting and ac motors. This situation is rapidly changing as modern loads typically contain power electronic devices. The current drawn by these modern loads is non-sinusoidal and therefore contains harmonics. A common example of a load drawing non-sinusoidal current is the switching power supply. Figure 1 illustrates that a personal computer power supply draws current in pulses. If the current in Figure 1(a) was sinusoidal the only line in the bar graph would be for "1", the fundamental current. From Figure 1(b) it can be seen that there are significant levels of 3rd, 5th and 7th harmonic currents — there is almost as much 3rd harmonic current as there is fundamental.



(a) (b)

Figure 1: Current drawn by single-phase computer power supplies in (a) the time and (b) the discrete frequency domain.

In industry, harmonics cause excess heating in motors and transformers and can lead to overloading of neutral conductors in power lines [1]. This is because harmonics that are a multiple of three (the *triplens*) will add, rather than cancel, in the neutral wire. The neutral current will only be zero if the three phases are each carrying exactly the same current (ie. the phases are balanced) and there are no triplens. Having the three phases balanced is unusual for light industrial and commercial loads where each of the three phases are treated as independent supplies.

Shunt active filters were initially proposed in 1971 by Sasaki and Machida [2] as a means of removing current harmonics. Recent advances in semiconductor technology have produced high-speed, high-power devices suitable for constructing active filters [3].

In the active filter a controller determines the harmonics that are to be eliminated. A three-phase inverter is then used to inject the compensating currents, I_C, into the power line. Figure 2 illustrates the connection of an active filter. There are a variety of methods for implementing the detection of harmonic currents and the aim of this paper is to quantitatively determine the optimal method for a three-phase system with unbalanced loads.

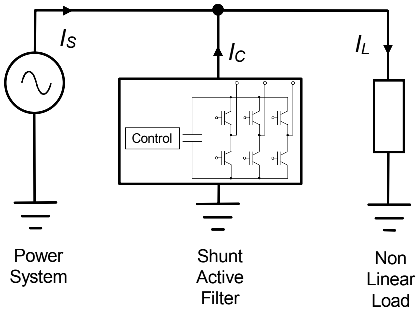


Figure 2: System diagram of an active filter. I_L is the current drawn by the non-linear load, I_C is the compensating current injected by the active filter and I_S is the resulting current supplied by the power system.

HARMONIC DETERMINATION METHODS

A number of methods exist for determining the harmonic content of a current waveform. Two common methods are notch filtering of the fundamental [4] and Instantaneous Reactive Power Theory [5]. Less common methods include the Synchronous Reference Frame [6], Fast Fourier Transforms (FFTs) and a novel method using the subtraction of a synthetic fundamental from the load current [3]. Each of these methods is described with attention to the case of unbalanced load currents. The effectiveness of each method was quantitatively determined by calculating the Total Harmonic Distortion (THD) of the resulting supply current and response of the controller to step changes in load. An expression for THD is given in Eqn. (1), where $I_{n(rms)}$ is the root-mean-square current of the n^{th} harmonic.

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_{n(rms)}^{2}}}{I_{1(rms)}} \times 100\% \tag{1}$$

Notch Filtering

The load current is filtered by a notch filter, which removes the fundamental while leaving the harmonic components. A single notch filter with a bandwidth of 5Hz has good isolating characteristics. The filter can significantly reduce the output THD and can recover from a step change transient in 10 fundamental cycles. An active filter which uses a notch filter on each of the three phases to determine the compensating current can cope with unbalanced three-phase loads [4].

Figure 3 shows the block diagram for an active power filter that uses a notch filter. The load current is filtered to leave the harmonics. The harmonic currents are subtracted from the load current by injecting into the power line with a 180° phase shift.

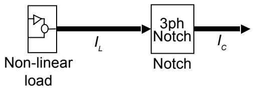


Figure 3: Block diagram for notch filter based active power filter.

Instantaneous Reactive Power Theory

Instantaneous Reactive Power Theory (IRPT) uses the Park Transform, given in Eqn. (2), to generate two orthogonal rotating vectors (α and β) from the three phase vectors (a, b and c). This transform is applied to the voltage and current and so the symbol x is used to represent v or i. IRPT assumes balanced three phase loads and does not use the x_0 term.

$$\begin{bmatrix} x_0 \\ x_\alpha \\ x_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{2}$$

By looking at instantaneous powers, the harmonic content can be visualised as a ripple upon a DC offset representing the fundamental power. By removing the DC offset and performing the Inverse Park Transform the harmonic current can be determined [5].

Figure 4 shows the block diagram for an active power filter based on Instantaneous Reactive Power Theory. The supply voltage and load current are transformed into αβ quantities. The instantaneous active and reactive powers p and q are calculated fom the transformed voltage and current as given in Eqn. (3).

$$\begin{bmatrix} p = \bar{p} + \tilde{p} \\ q = \bar{q} + \tilde{q} \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3}$$

The instantaneous active and reactive powers are filtered to leave the AC components. The compensating currents are determined by taking the inverse of Eqn. (3) as given in Eqn. (4).

$$\begin{bmatrix} i_\alpha' \\ i_\beta' \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \tag{4}$$

The inverse Park transform is applied to i_α' and i_β' and this gives the harmonic currents in standard three-phase form, shown in Eqn. (5).

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha' \\ i_\beta' \end{bmatrix} \tag{5}$$

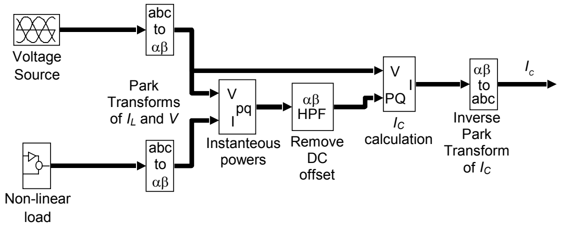


Figure 4: Block diagram for an active power filter controller using Instantaneous Reactive Power Theory.

Synchronous Reference Frame

Bhattacharya et al. [6] proposed the DQ transform, given in Eqn. (6), which changes the three conventional rotating phase vectors into direct (D), quadrature (Q) and zero (0) vectors. The fundamental component for each is now a dc value with harmonics appearing as ripple.

$$\begin{bmatrix} x_0 \\ x_d \\ x_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \cos(\omega t) & \cos(\omega t - \frac{2}{3}\pi) & \cos(\omega t + \frac{2}{3}\pi) \\ -\sin(\omega t) & -\sin(\omega t - \frac{2}{3}\pi) & -\sin(\omega t + \frac{2}{3}\pi) \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{6}$$

Harmonic isolation of the DQ transformed signal is achieved by removing the DC offset. This is accomplished with a high pass filter. Figure 5 illustrates the block diagram of the DQ active power filter. There is no need to supply voltage information for an SRF based controller.

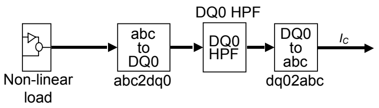


Figure 5: Block diagram for the DQ based active power filter.

As with the IRPT method, DQ based filtering cannot cope with load imbalances. If the load is unbalanced there will be a ripple of 100Hz on the D, Q and 0 terms when there are no harmonics in the current. A 100Hz ripple is also present if third harmonic currents are present (the 150Hz is translated down to 100Hz). There is no way of determining the source of the ripple should the load current contain triplens and be unbalanced.

Sinusoidal Subtraction

This method artificially synthesises a sinusoid of the same magnitude and phase as the load current fundamental. This synthetic sinusoid is subtracted from the load current, isolating the harmonics. Figure 6 illustrates the block diagram of the notch filtering method.

The load current is low-pass filtered to yield the magnitude of the 50Hz component which is peak detected every half cycle, but with a phase shift. This indicates the magnitude of a sinewave to be subtracted during the next half cycle. A band-pass filter is used to detmermine the phase of the non-linear load but this signal has a slow transient response and is not suitable for changing the magnitude of the synthetic sinewave. It is not possible to have a fast transient response, good harmonic rejection and no phase shift from a single filter and so the two complimentary filters have been used. A phase locked loop is used by the synthesizer to generate the sinewave from a ROM lookup table.

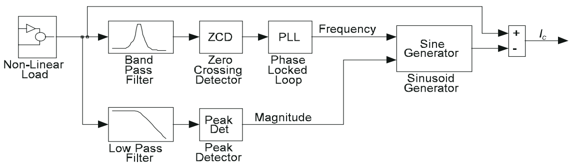
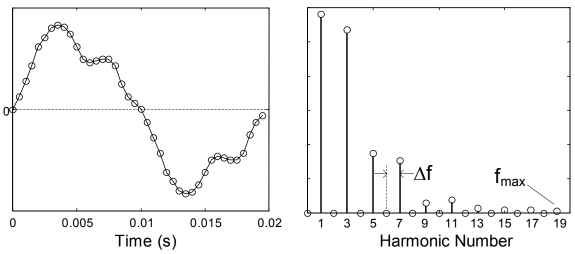


Figure 6: Block diagram of the sinusoidal harmonic isolation method.

Fast Fourier Transform

The Fast Fourier Transform (FFT) takes the sampled load current for one period and calculates the magnitude and phase of the frequency components. Figure 7(a) shows the time domain sample used as the input to the FFT and Figure 7(b) shows the FFT output.



(a) (b)

Figure 7: (a) shows the input waveform with 40 samples. The total length of the sample is 20ms and this gives a Δf of 1/20ms=50Hz in (b).

Each element in the frequency plot is a harmonic since the spacing is 50Hz. The number of harmonics that can be resolved is given by half the number of samples used. Therefore the higher the number of samples in each cycle of current, the higher the value of f_{max}.

Removal of the fundamental from the input current is easily performed by setting the frequency component for 50Hz to zero and then performing the Inverse Fast Fourier Transform (IFFT). The IFFT recreates a time domain signal based on the magnitude and phase information of each harmonic. These calculations are performed on each cycle of mains current. It is important to ensure that a FFT is calculated on a complete cycle to prevent distortion due to spectral leakage [1]. Any changes in the load current that distort the waveform will cause errors in the output of the FFT and this leads to an incorrect compensating current signal for a short time. The algorithm used for performing the FFT based harmonic detection detects step changes in load current and generates a zero compensating current for one cycle. This prevents the injection of erroneous compensating currents.

A frequency domain based harmonic isolation method has some advantages. The magnitude of the load harmonics is known from the FFT and this allows selective harmonic cancellation to be performed. By manipulating the harmonic magnitudes it is possible to prevent the cancellation of certain harmonics or reduce the level of cancellation of selected harmonics.

SIMULATION OF HARMONIC DETERMINATION METHODS

To simulate the performance of the harmonic determination methods the system-modelling package of Matlab/Simulink was used. Each of the five harmonic isolation techniques was simulated in a computer model of an active power filter. Exactly the same input current waveform was fed into each controller and the quality of compensation and transient response was determined.

TABLE 1 – Summary of the harmonic isolation methods. Shaded techniques are those that warrant further investigation.

	Notch	IRPT	SRF	Sine Subtraction	FFT
Steady-state Quality	Good	Poor	Good	Excel.	Excel.
Transient Response Speed	Good	Excel.	Good	Good	Excel.
Transient Response Quality	Good	Good	Good	Poor	Poor
Requires Voltages	No	Yes	No	No	No
Requires Balanced 3 Phase	No	Yes	Yes	No	No
Number of Filter Stages	3	2	3	3	0

Transient Response Time and Quality of Compensation

The transient response to step change in load was was determined, both in magnitude and harmonic content. Initially the load current was characteristic of fluorescent lighitng and had a large amount of the third harmonic. A step change added the current drawn by a variable frequency drive which had a large amount of the fifth harmonic. The load current with the transient applied and the resulting supply currents for each of the five methods is shown in Figure 8. The effectiveness of the active power filtering methods was gauged by measuring the THD of the resulting supply currents. Figure 9 compares the THDs for each of the methods.

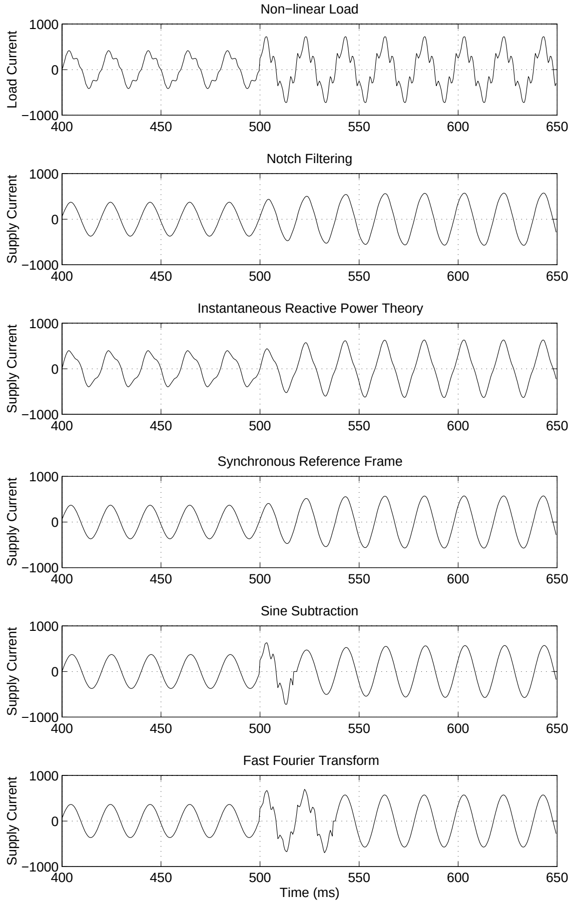

Non−linear Load
Notch Filtering
Instantaneous Reactive Power Theory
Synchronous Reference Frame
Sine Subtraction
Fast Fourier Transform

Figure 8: Transient response in the time domain for each of the methods examined.

TABLE 1 summarises the results of simulation of the five harmonic isolation methods examined for use within an active power filter. The shaded techniques are those that warrant further experimental investigation. IRPT failed to compensate completely due to the presence of third harmonic currents. Steady-state compensation quality was determined by the THD of the supply current with no load changes. The transient response speed is the ability of the controller to change the magnitude of the compensating current rapidly when the load current changes. Deviation from correct compensation during a load change is assesed by the transient response quality.

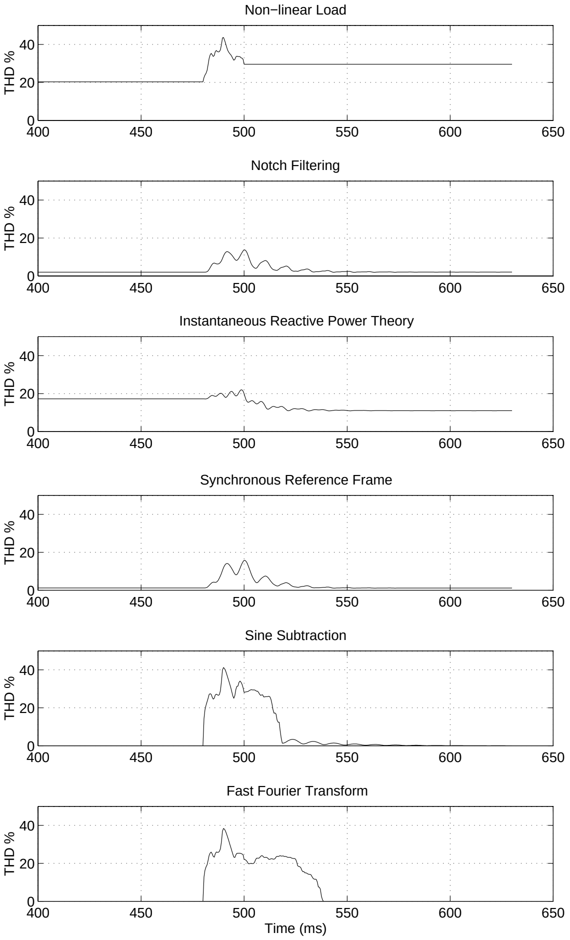

Non−linear Load
Notch Filtering
Instantaneous Reactive Power Theory
Synchronous Reference Frame
Sine Subtraction
Fast Fourier Transform

Figure 9: In steady state, the output THD for each method is generally less than 5%. The two techniques that have the best steady state performance, FFT and Sine Subtraction, give the worst transient errors.

Operation with Unbalanced Loads

The active power filter being developed must be able to compensate unbalanced three phase loads, particularly those found in commercial and light industrial situations. One characteristic of these loads is the presence of triplen harmonics caused by independent single phase loads, for example switching power supplies. A Fluke 41 Power Harmonics Analyser was used to sample the current drawn by personal computers. These waveforms were used in Figure 1 to illustrate currents with a high harmonic content. This current was used to generate the load current for simulation in Matlab. The load currents were artificially unbalanced; Phase A = 100%, Phase B = 50% and Phase C = 150%. In the following figures Phase A is a solid line, Phase B is dashed and Phase C is dotted,

The three single phase harmonic determination methods, notch filtering, sinusoidal subtraction and FFT, each performed correctly as these do not make any assumptions about the three-phase currents. The IRPT and SRF methods failed to correctly compensate for the harmonics that were present. Figure 10 shows the load current (I_L in Figure 2) drawn and the resulting supply currents (I_S in Figure 2) for the IRPT, SRF and FFT methods.

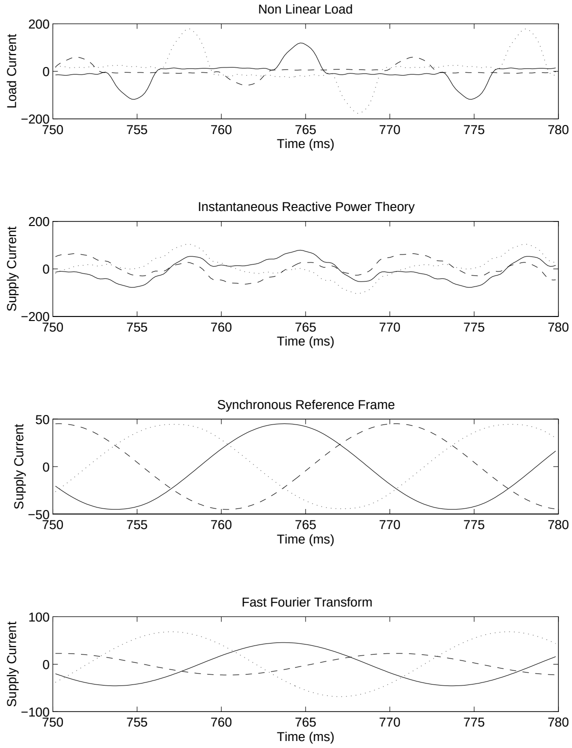


Figure 10: Comparison of steady-state currents for three harmonic determination methods.

The errors introduced by the imbalance in the SRF method lead to unwanted load balancing and would require an inverter with a larger power rating. The IRPT method has a large third harmonic component left in the supply current. Further simulation has shown that if the load is balanced and no triplen harmonics are present this method provides very good compensation with excellent transient response. The FFT method has correctly compensated the three phases and has preserved the relative magnitudes of the currents. Figure 11 shows the resulting supply currents when an IRPT based controller is used with four different line current characteristics. It can be seen from Eqn. (2) that the Park transform produces a zero sequence term. Instantaneous Reactive Power Theory does not use the zero term in its calculations and so some information has been lost. This results in the IRPT method effectively being unable to correctly compensate when neutral currents are present.

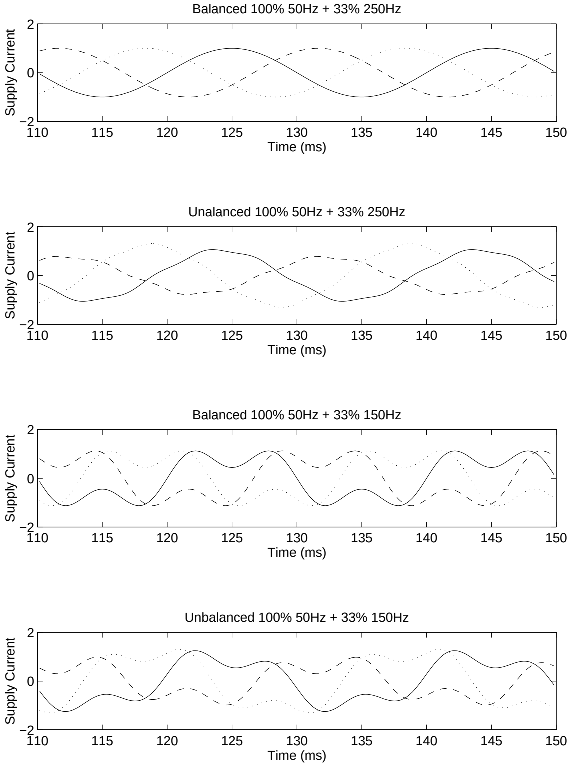


Figure 11: The four possible load current types and the response of the IRPT based controller. From the top these are: balanced with no triplens, unbalanced with triplens, balanced with triplens and unbalanced with triplens.

HARDWARE IMPLEMENTATION

An active power filter controller has been implemented with a digital signal processor (DSP). A low power inverter has been developed for initial testing of the controller while a 60kVA inverter is constructed.

Test Inverter

The structure of the inverter used for testing the digital controller is shown in Figure 12. The full DC bus voltage is 60V and 800V, 8A IGBTs are used [7]. A novel digital hysteresis current control method has been implemented for this inverter and is discussed in more detail by Ingram and Round [8]. This digital controller interfaces directly with the DSP active filter controller.

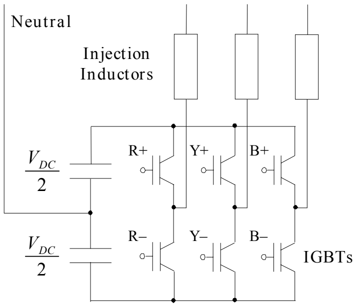


Figure 12: Small-scale test inverter.

System Block Diagram

The inverter controller interfaces the digital signal processor to the three-phase inverter. Figure 13 shows the system with the active filter controller, the power inverter and current feedback. The digital inverter controller is resistant to high levels electromagnetic interference and is extremely flexible in its operation [8].

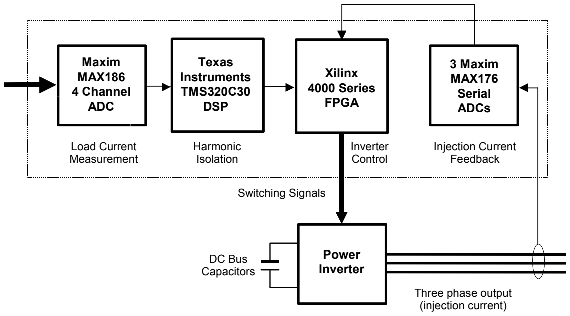


Figure 13: System diagram of the inverter and controller.

CONCLUSION

Industrial and commercial loads are typically unbalanced and contain harmonic currents. This paper evaluated five different methods of determining the active filter compensating current for these unbalanced loads. The three single-phase methods, notch filtering, sinusoidal subtraction and Fast Fourier Transform, provide good steady-state compensation of the harmonic currents. The simplest method is notch filtering although it has a slow transient response. The FFT method has a good transient response by being able to compensate for changes in the load current within two fundamental cycles. Implementation of the FFT method is possible with modern DSP controllers. The IRPT method is unable to compensate for the triplen harmonic components and provides unsatisfactorily performance. The SRF method also assumes balanced loads and is unable to distinguish between load imbalances and third harmonic components. This results in the SRF method performing load balancing and therefore a larger VA inverter rating is required compared to the four other methods. Simulation results have determined that the Synchronous Reference Frame and the Fast Fourier Transform methods provide good steady state and transient response for active filters in balanced and unbalanced systems respectively.

Acknowledgments

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Address of the Authors

Department of Electrical and Electronic Engineering, University of Canterbury, Private Bag 4800, Christchurch, New Zealand.