A Grid Current-Controlling Shunt Active Power Filter

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ABSTRACT

In this paper, the implementation of a three-phase shunt active power filter is presented. The filter is essentially three independent single-phase current-controlled voltage source inverters (CC-VSI) with a common DC bus. The CC-VSI is operated to directly control the AC grid current to be sinusoidal and in phase with the grid voltage without detecting the load currents. The APF consists of a current control loop, which shapes the grid currents to be sinusoidal and a voltage control loop, which regulates the active power balance of the system. The experimental results indicate that the active filter is able to handle predominantly the harmonics, as well as the unbalance and reactive power, so that the grid currents are sinusoidal, in phase with the grid voltages and symmetrical.

Keywords: Active power filter, Harmonics, Power quality

1. Introduction

Non linear loads, especially power electronic loads, generate harmonic currents and voltages in power systems. They cause a low power factor, increase the losses and reduce the efficiency of the power system, and lead to voltage distortion. Passive LC filters can be used to eliminate harmonic currents. However, bulk passive

components, series and parallel resonance, a fixed compensation characteristic are the main disadvantages of passive filters. To overcome passive filter problems, for many years, various active power filters (APF) have been developed [1][2][3].

Conventionally, the power inverter as a shunt APF is controlled in such a way as to inject equal-but-opposite harmonic and reactive compensation currents based on calculated reference currents. Hence, the current sensors are installed on the load side. Then, their output signals will be processed to construct the reference or desired currents, which consist of harmonic and reactive components as well as negative- and zero-sequence components for unbalance compensation. Once the desired reference currents have been established, the currents must be injected into the grid accurately using the power inverter with a current control

mechanism. The actual inverter currents must attempt to follow the harmonic-rich reference currents.

Among numerous active power filters, filtering at the fundamental frequency and instantaneous power compensation are the common methods to create the reference currents. The application of a notch filter (or band-pass filter for indirect computation)[4][5] is considered the first filtering method to obtain the reference signals. The load current (I_L) is detected, and the reference current signal is obtained using a 50 or 60Hz filter. The transformation of non-sinusoidal currents in the *a-b-c* reference frame to the synchronously rotating *d-q* reference frame is useful in facilitating the separation process of fundamental components from the harmonic components[6][7]. Equivalent to this method is the transformation to a stationary reference frame with a notch filter [8], which allows for faster calculation. If the filter-based transformation is combined with a linear current control, cross coupling usually exists in the *d-q* current control loops. By introducing a decoupled control [9], i_d and i_q can be controlled independently. A recent attempt has been made to apply the neural network technique [10] for separating the fundamental components and the unwanted components. This method may be suitable for steady state condition. For instantaneous power compensation (IPC), the most popular theory in obtaining the reference currents is the *p-q* theory introduced by Akagi [11]. This theory has been expanded to other theories such as the cross-vector theory [12] and *p-q-r* theory [13]. Alternative approaches to implement IPC are a synchronous detection method [14][15] and application of symmetrical component transformation[16]. These methods are based on the calculation of the per-phase power to obtain the total three-phase average power.

However, the construction of a reference current waveform will introduce distortion or inaccuracies due to the filter and extensive calculations with inherent delays and errors. Furthermore, load or power system changes take time to be included by the reference current waveforms. Hence, the reference current created for the inverter current will have not only significant steady-state error, but also transient error. Controlling the inverter currents also leads to a problem. Even if a CC-VSI is completely successful in generating a current exactly matching a harmonic-rich reference current, the injection of that current will result in a

different harmonic composition of the voltage at the PCC. Hence, it changes the harmonic content of the load current and the resulting harmonic content of the grid current. This condition becomes worse if the load harmonic voltage source is present because it affects the harmonic voltage at the PCC.

The distortion and inaccuracies can be significantly reduced if these computational, filtering and control problems are avoided. Therefore, in this paper, the idea of directly controlling the grid/source current to track a three-phase balanced sinusoidal reference current rather than the inverter current to follow the harmonic-rich reference current using a current controller will be presented.

2. Active Power Filter Configuration

The three-phase shunt active power filter is a three-phase four-wire current-controlled voltage-source inverter (CC-VSI) with a mid-point earthed split capacitor (C_1 and C_2) in the DC bus and inductors (L_{inv}) in the AC output. The APF consists of two control loops, namely a current control loop and a voltage control loop. The current control loop is a polarized ramptime current control (PRCC) that shapes the grid currents to be sinusoidal by generating a certain pattern of PWM for continuous switching of the inverter switches. The voltage control loop is a simple Proportional Integral (PI) control to keep the DC-bus voltage constant and to provide the magnitude of reference current signals. Fig. 1 describes the shunt active power filter configuration.

2.1 Series Inductance

Another component of this system is a series inductance L_L, in which the value of the reactance X_L is comparable to the effective grid impedance, Z_g [17][18]. Basically, the inductor provides the required voltage decoupling between load harmonic voltage sources and the grid. It also enhances the controllability of the current controller by reducing the current slope of the loads.

Without a series inductor, the point of common coupling (PCC) is tied to the load harmonic voltage source. The load harmonic voltage considerably characterizes the harmonic voltage at the PCC. As a result, there would still be harmonic voltages across the grid impedance, which would

continue to produce harmonic currents and could not be compensated for by a shunt APF. Currents from the shunt APF do not significantly change the harmonic voltage at the loads.

With a series inductor, for a sinusoidal grid current, the CC-VSI output current is equal-but-opposite to the unwanted load current. These two currents generate identical harmonic voltages across the series inductance and the inverter inductance (in relative proportion to the inductances). In doing so, the CC-VSI generates the output harmonic voltage, which is equivalent to the load harmonic voltage. For perfect filtering, when no harmonic current flows through the grid impedance, a combination of the inverter and the load will be seen as infinite impedance for the grid harmonic voltages. The circuit equivalent from the harmonic point of view is shown in Fig. 2.

If a fundamental grid current component flows through the grid impedance, the voltage across the grid impedance will also be a fundamental component. The voltage across the grid impedance is represented by the $jI_{g-1}X_g$ phasor (assuming the resistance is negligible). With the V_{g-1} (the fundamental component of the grid voltage) fixed, the grid harmonic voltage V_{g-h} is represented in vector form by a circular region added to V_{g-1}. The voltage at the PCC (V_{pcc}) can be illustrated in Fig. 3. Hence, any harmonic voltage at the PCC actually mirrors the grid harmonic voltage. For a harmonic-free grid voltage, the voltage at the PCC only contains a fundamental component.
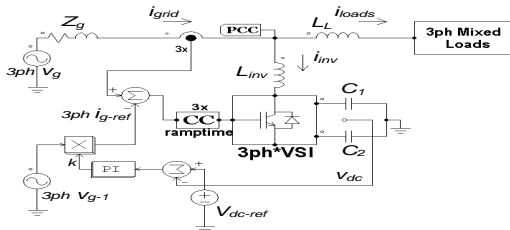

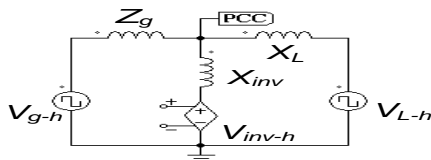Fig. 1.   Shunt active power filter configuration.

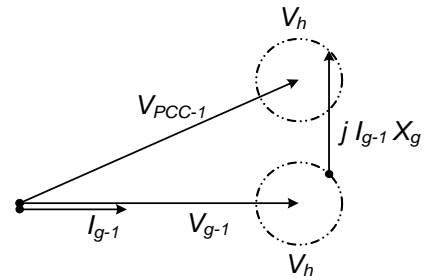Fig. 2.   Circuit equivalent for harmonics.

Fig. 3.   Phasor diagram of voltages at the PCC for successful Compensation.

2.2 Direct Control of the Grid Current

As seen from Fig. 1, a node, which is a point of common coupling (PCC), is created with three connections, one each to the load, the grid and the inverter. Accordingly, all three currents − i_L, i_g, and i_{inv} − (for three or four wires) are potentially accessible to be directly controlled by the CC-VSI, following the basic current summation rule:

$$i_g = i_{inv} + i_L \qquad (1)$$

Thus, for the CC-VSI operated to directly control the grid current, the current sensors are located on the grid side. The grid current is sensed and directly controlled to follow a symmetrical sinusoidal reference signal, which is in phase with the grid voltage. For perfect tracking, the shunt APF automatically provides the harmonic, reactive, negative- and zero-sequence currents for the load according to (1) without measuring and determining the unwanted load current components. Hence, the shunt APF has also the ability to balance the asymmetrical currents.

Moreover, the controllability of the grid current can be achieved using bipolar PWM switching. The upper and lower power switches of each half-bridge are switched on a complementary basis. As a result, the inverter output current, as well as the grid current, can always be controlled to ramp up and down continuously. Therefore, the direct control of the grid current is feasible because the switching action will have a direct, immediate and predictable effect on the AC grid current, and hence provide controllability.

By directly controlling the grid currents, the shunt APF can provide complete compensation for many loads at the PCC instead of compensating for each load individually.

The system is simple and efficient because only one current sensor per phase is required, located on the grid side.

In addition, controlling the grid current rather than the inverter current allows us to create a sinusoidal current reference (for the grid current), rather than having to create a harmonic- and transient-rich current reference (for the inverter current). The idea to obtain the desired grid current waveform instantaneously without calculation is easily fulfilled by using an active power balanced technique. The active power maintains balance among the grid, the load and the DC bus of the power inverter by regulating the DC-bus voltage.

3. The Current Control Loop

In the current control loop, the current sensors on the grid side detect the grid currents. The outputs of the sensors are compared to the reference signals. The current error signals, which are the differences between the actual currents (grid currents – i_g) and the reference signals – $i_{g\text{-}ref}$, are processed using polarized ramptime current control (PRCC) to generate PWM signals. The pulse signals drive the switches so that the VSI produces currents for compensation.

The PRCC technique based on ZACE (zero average current error) has been established and is described in the literature [19][20][21][22]. The PRCC is chosen for the shunt APF because it is simple and does not generate additional low order harmonics that deteriorate the performance of the filter.

3.1. Operating condition requirements

Neglecting the losses in the inverter, the output current for each phase of the inverter through the inductance L_{inv} can be expressed in a switching function (s) as:

$$\frac{di_{inv}}{dt} = \frac{1}{L_{inv}}(v_{pcc} - s\,v_{C1} - (s-1)\,v_{C2}) \tag{2}$$

$s = 1$ if the upper switch is closed, and $s = 0$ if the upper switch is open. It must be assumed that the voltage at the PCC (v_{pcc}), and the DC-capacitor voltages (v_{C1} and v_{C2}) are constant over the switching period. Values of v_{C1} and v_{C2} are always positive. For $\dfrac{di_{inv}}{dt} > 0$, then

$$v_{pcc} - s\,v_{C1} - (s-1)\,v_{C2} > 0 \tag{3}$$

To satisfy this condition, the relationship between v_{C1}, v_{C2} and v_{pcc} in terms of the switching function is given by:

$$\begin{aligned} &\text{If } s = 1, \text{ then } v_{C1} < v_{pcc} \\ &\text{If } s = 0, \text{ then } -v_{C2} < v_{pcc} \end{aligned} \tag{4}$$

For $s = 1$, the system does not work during the negative half-cycle of v_{pcc}. For $s = 0$, any value of v_{C2} will satisfy (4) during the positive half-cycle of v_{pcc}. For the negative half-cycle of v_{pcc}, the inverter functions well, as long as

$|v_{C2}| > |v_{pcc}|$. For $\dfrac{di_{inv}}{dt} < 0$, then

$$v_{PCC} - s\,v_{C1} - (s-1)\,v_{C2} < 0 \tag{5}$$

To satisfy (5), the relationship between v_{C1}, v_{C2} and v_{pcc} in terms of the switching function is given by:

$$\begin{aligned} &\text{If } s = 1, \text{ then } v_{C1} > v_{pcc} \\ &\text{If } s = 0, \text{ then } -v_{C2} > v_{pcc} \end{aligned} \tag{6}$$

For $s = 0$, the system is unlikely to be operated during the positive half-cycle of v_{pcc}. For $s = 1$, any value of v_{C1} will satisfy (6) during the negative half-cycle of v_{pcc}. During the positive half-cycle of v_{pcc}, the inverter functions well as long as $|v_{C1}| > |v_{pcc}|$.

Therefore, for both cases, the inverter always generates currents as long as the magnitude of both DC-capacitor voltages (v_C) is greater than the peak value of the PCC voltage ($v_{pcc\text{-}peak}$). If this condition is not achieved, then the required operating condition for the system is not provided, and the compensation fails completely.

3.2 Controllability condition

The PRCC has characteristics similar to a sliding mode control [19][23]. To control the grid current directly, the current error signal ε, which is a controlled parameter, can be defined as a sliding surface.

$$\varepsilon = i_g - i_{g\text{-}ref} \tag{7}$$

To ensure that the system can remain on the sliding surface and maintain perfect tracking, the following condition must be satisfied:

$$\varepsilon \, \dot{\varepsilon} \le 0 \tag{8}$$

where $\dot{\varepsilon}$ is derived from (7):

$$\frac{d\varepsilon}{dt} = \frac{di_g}{dt} - \frac{di_{g-ref}}{dt} \tag{9}$$

From the switching operation implementation, the $\dot{\varepsilon}$ is able to be controlled such that a positive value of the error signal produces a negative derivative of the error signal $(\dot{\varepsilon} < 0)$, and a negative value of the error signal produces a positive derivative of the error signal $(\dot{\varepsilon} > 0)$. Controlling the sign of $\dot{\varepsilon}$ is associated with controlling the sign of di_g /dt as well as di_{inv}/dt to be positive or negative.

Combining (1) and (9), $d\varepsilon/dt$ can be expressed as:

$$\frac{d\varepsilon}{dt} = \frac{di_L}{dt} + \frac{di_{inv}}{dt} - \frac{di_{g-ref}}{dt} \tag{10}$$

Since the sign of di_{inv} /dt and di_g /dt match, perfect tracking can be achieved when:

$$\left| \frac{di_{inv}}{dt} \right| > \left| \frac{di_L}{dt} + \frac{di_{g-ref}}{dt} \right| \tag{11}$$

As long as equation (11) is not satisfied, then the system is moving away from the sliding surface, and the CC-VSI loses its controllability. This means that zero crossing of the current error signal will not occur at the end of a half-switching period, since by definition, the system is controllable if there exists a (piecewise continuous) control signal that will take the state of the system from any initial state to any desired final state in a finite time interval [24]. Refer to (2), the value of di_{inv} /dt is normally determined by L_{inv} dan capacitor voltages.

4. The Voltage Control Loop

In order to satisfy the operating condition requirements of the current control loop, the DC-capacitor voltages have to be forced greater than $v_{pcc-peak}$ as well as to be kept constant by regulating the active power balance of the system. The voltage control loop employs a Proportional Integral (PI) controller to maintain the desired DC-bus voltage level.

4.1 Power flow

Power flowing in the grid, the load and the inverter is expressed in terms of real power p, imaginary power q, and zero sequence power p_0 [11][25][26], which consist of an average value and an oscillating value.

Considering a non-sinusoidal and unbalanced system, the load power can be decomposed into:

$$\begin{aligned} p_L &= \bar{p}_L + \tilde{p}_L \\ q_L &= \bar{q}_L + \tilde{q}_L \\ p_{L-0} &= \bar{p}_{L-0} + \tilde{p}_{L-0} \end{aligned} \tag{12}$$

Due to successful compensation, the grid currents will be sinusoidal, balanced and in-phase with the grid voltages. As a result, if the grid voltage is non-sinusoidal and/or unbalanced, the powers p_g, q_g and p_{g-0} generated from the grid become:

$$\begin{aligned} p_g &= \bar{p}_g + \tilde{p}_g \\ q_g &= \tilde{q}_g \\ p_{g-0} &= 0 \end{aligned} \tag{13}$$

The power developed by the inverter is calculated by subtracting the power supplied by the grid and the power consumed by the load, given by:

$$\begin{bmatrix} p_{inv} \\ q_{inv} \\ p_{inv-0} \end{bmatrix} = \begin{bmatrix} \bar{p}_g - \bar{p}_L \\ -\bar{q}_L \\ -\bar{p}_{L-0} \end{bmatrix} + \begin{bmatrix} \tilde{p}_g - \tilde{p}_L \\ \tilde{q}_g - \tilde{q}_L \\ -\tilde{p}_{L-0} \end{bmatrix} \tag{14}$$

From (14), the inverter controls the whole imaginary power associated with both the load $\bar{q}_L + \tilde{q}_L$ and the grid $\tilde{q}_g$ (in a small value). The DC bus does not contain imaginary power. Thus, the CC-VSI generates q_{inv} but it does not flow out of or into the DC-bus capacitors. According to Watanabe[25] and Peng[26], the imaginary power circulates among the phases due to the switching of

the inverter. In other words, instantaneously, the imaginary power required by one phase can be supplied by the other phase.

The inverter supplies $\tilde{p}_L$ as well as $\tilde{p}_{L-0}$ and consumes $\tilde{p}_g$ (in a small value) using DC capacitors as an energy storage element. The DC capacitors absorb (release) energy when $\tilde{p}$ is positive (negative). This power does not affect the DC-bus voltage level since its mean value is equal to zero. However, it will appear in the DC-bus voltage as a ripple. The ripple becomes small if the value of the DC capacitors is high.

For the average value $\bar{p}$ of the real power, the inverter supplies the zero sequence average (active) power $\bar{p}_{L-0}$ needed by the load. To supply the load zero sequence active power, the inverter has to take an active power from the grid because the inverter has no DC source. Neglecting the losses in the power converter, in steady state, the active power in the system is balanced if the active power consumed by the load is equal to the active power supplied by the grid; and the net active power flowing to the inverter is zero. Hence, active power balance according to (14) can be stated as:

$$\bar{p}_{inv} + \bar{p}_{inv-0} = \bar{p}_g - \bar{p}_L - \bar{p}_{L-0} = 0 \tag{15}$$

Thus, the active power taken from the grid by the inverter, which is used to support the zero sequence power delivered to the load, is: $\bar{p}_{inv} = \bar{p}_g - \bar{p}_L = \bar{p}_{L-0}$. Additional active power consumption is required to compensate for the losses, so that $\bar{p}_{inv} = \bar{p}_{L-0} + \bar{p}_{loss}$.

It can be concluded that the active power in the system has to be controlled because it flows to the DC capacitors and affects the DC-bus voltage level. The voltage control loop will regulate the active power balance of the system by retaining the DC-bus voltage around its reference level.

4.2 DC-bus voltage control system

For successful compensation, the grid current is the same as its reference. To obtain the reference signal, a three-phase symmetrical sinusoidal waveform is generated using a phase lock loop (PLL) circuit. Only the magnitude of the grid current needs to be determined.

As mentioned above, in steady state and ignoring the losses, the active power consumed by the load is equal to the active power supplied by the grid, and $\bar{p}_{inv}$ will be zero. As a result, the average DC-bus voltage can be maintained at the reference voltage level.

When a load variation occurs, the active power balance between the load and the grid will cease to be maintained. The inverter immediately supplies (absorbs) the active power mismatch between the grid and the load, since the voltage control loop cannot respond instantaneously to provide the appropriate grid reference current magnitude. This yields a DC-bus voltage deviation (ΔV_{dc}).

Due to active power balance, the amplitude of grid active currents must be adjusted appropriately to compensate for the active power charged/discharged from DC capacitors of the inverter. The required change in grid currents will come as soon as the voltage control loop responds to change (increase or decrease) in the magnitude of the grid currents. The output of the PI controller, which is a gain k, can determine the amount of ΔV_{dc} that corresponds to the grid current amplitude. The total active power flowing to the inverter will go to zero when the grid current amplitude approaches its final value. The average DC bus voltage is then recovered and stays at the reference voltage. Finally, the active power supplied from the grid is matched to that consumed by the load. A new steady state has been achieved with a new grid current amplitude and the active power balance according to (15) occurs. Hence, the sinusoidal grid current reference signal is given by:

$$i_{g\text{-}ref} = k\, v_{grid\text{-}1} \tag{16}$$

where $v_{grid\text{-}1}$ is the fundamental component of the grid voltage, and the value of k is the output of the simple PI controller.
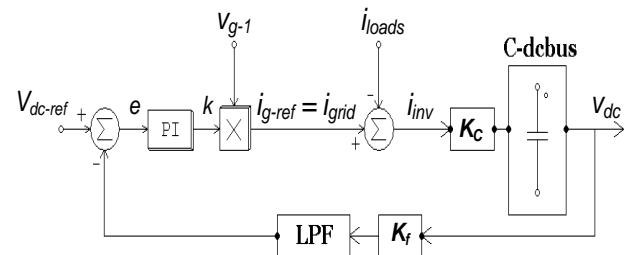

Fig. 4.   Voltage control loop.

The voltage control loop block diagram is shown in Fig. 4. Considering a perfect tracking current control loop, the grid current is the same as its reference. The inverter DC-bus voltage is detected and reduced by a gain K_f to the level of a signal. Since the DC-bus voltage contains ripples, a first-order low-pass filter (LPF) is added to the feedback loop to obtain a smooth gain k. The grid current reference waveform is yielded by multiplying the gain k with v_{g-1}, which is the fundamental component of the grid voltage obtained from a PLL circuit. The inverter currents will flow through the switches to the DC capacitors to develop the DC-bus voltage. K_C is a power conversion factor between the AC side and the DC side of the power converter.

Table 1   Parameter values for the system under study

Symbol	Description	Value
v_g	AC grid voltage, line-line, *rms*	207 V
f	AC line/grid frequency	50 Hz
L_L	Series inductor	0.92 mH
V_{dc}	DC-bus voltage of the inverter	480 V
$C_1 = C_2$	DC Capacitors, electrolytic type	4000 µF
L_{inv}	Inverter inductor	1.52 mH
C_{ac}	AC filter capacitor	2 µF
f_{sw}	Target switching frequency	15.6 kHz

Table 2   Parameter values of the mixed loads

Single-phase diode Rectifier with R-C load connected in phase B and C	Three-phase diode Rectifier with R-L load	Linear load
$C_{dc (ph B)} = 660\mu F$ $R_{L (ph B)} = 137\Omega$ $C_{dc (ph C)} = 660\mu F$ $R_{L (ph C)} = 149\Omega$	$L_{dc} = 0.25H$ $R_L = 97\Omega$	$R_{1 (ph A)} = 60\Omega$ $L_{1 (ph A)} = 0.145H$ $R_{2 (ph B)} = 60\Omega$ $L_{2 (ph B)} = 0.145H$ $R_{3 (ph C)} = 53\Omega$

5. The Three-Phase shunt active power filter for missed loads

The system in Fig. 1 is tested using laboratory experiments to verify the shunt APF concepts. Table 1 describes the parameter values for the system. The three-phase grid voltages contain harmonics (THD$_V$ = 3.9%), and the mixed loads consist of single- and three-phase linear and non-linear loads (Table 2). The linear loads are resistive and inductive loads, while the non-linear loads are a rectifier type of loads. The loads represent the distributed linear and non-linear loads, which exist in a typical electrical distribution system such as in commercial buildings. The three-phase current waveforms along with their harmonic spectrums of the mixed loads, as well as the neutral current from the laboratory experiments, are shown in Fig. 5. It shows clearly that the currents are not sinusoidal. The load phase-currents are also unbalanced and contain reactive components. The significant third-harmonic current flows in the neutral wire.

Fig. 6 demonstrates the steady-state performance of the compensation results. It can be seen that the shunt APF is successfully able to compensate for the total mixed loads. Although the grid voltage contains harmonics, it does not distort the grid currents. The PRCC can force the grid currents to follow accurately the sinusoidal reference waveforms without additional low order harmonics. The grid currents become both sinusoidal and in phase with the grid voltages (with insignificant phase leading by approximately 5° due to AC filter capacitors (C_{ac}) – in Fig. 7, only phase A of the grid voltage is shown). The amplitude is determined by the active power required by the system. The PRCC-VSI is capable of controlling the low order harmonics due to ZACE with a fixed switching frequency. However, it produces a high frequency switching current ripple. To avoid the current ripple flowing to the grid, small AC filter capacitors (C_{ac}) are installed on the grid side.
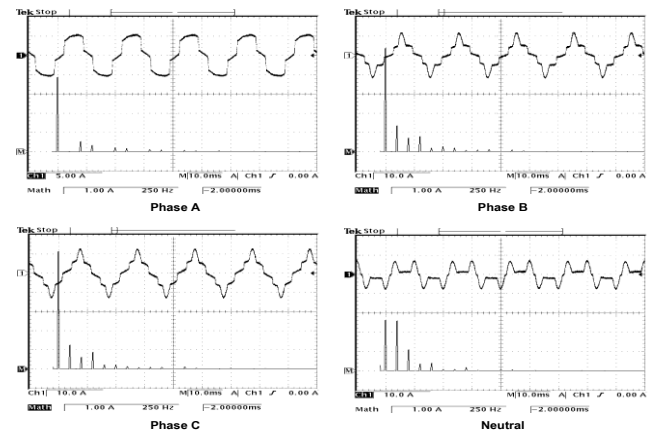

Fig. 5.   Phase and neutral currents for mixed loads.

After compensation, the grid currents are also symmetrical both in magnitude and phase. As a result, the neutral current at the grid is reduced to zero. The grid currents are balanced because the CC-VSI is able to force the grid currents to follow a three-phase balanced sinusoidal reference signal. Then, the inverter creates the inverse of the negative- and zero sequence currents automatically to balance the unbalanced loads, without measuring and determining the negative- and zero sequence components. From Fig. 8, it is obvious that the CC-VSI is able to generate three different currents for each phase as well as the neutral current. Hence, the inverter not only eliminates the load harmonics but also provides balancing to create the symmetrical grid currents.

6. Comparison with the *P-Q* theory

To evaluate the compensation effectiveness, the proposed direct grid current-controlling shunt APF is compared to the *p-q* theory. The *p-q* theory was chosen because it has been used extensively. The block diagram of the controller is given in Figure 9. Comparison focuses on THD-I performance and is based on computer simulation results using PSIM® .

In this case, the *p-q* theory is applied to the same system with the same mixed loads. Then the reference current for the CC-VSI is injected into the system using the same polarized ramptime current control (PRCC). The expected result is sinusoidal grid currents, instead of a constant source power. Hence, the system voltages are pre-processed with a PLL circuit. The system needs six current sensors. Three current sensors detect the load currents for reference current calculation, while the other three are for current control operation.

From computer simulation results, the reference CC-VSI currents for phases A, B and C are calculated and shown in Fig. 10. Using PRCC, the inverter output currents can follow the reference currents accurately, as seen in Fig. 11. After compensation, the grid currents and the spectrum are given in Fig. 12 and 13. The high-frequency grid current ripple has been filtered using AC filter capacitors.

The simulation results of the grid current-controlling method are illustrated in Fig. 14 and 15, which show the

grid currents and the spectrum. Compared with the *p-q* theory, the proposed method generates a lower THD as seen in Table 3. Thus, the proposed shunt APF is able to compensate more accurately and gives a better result.
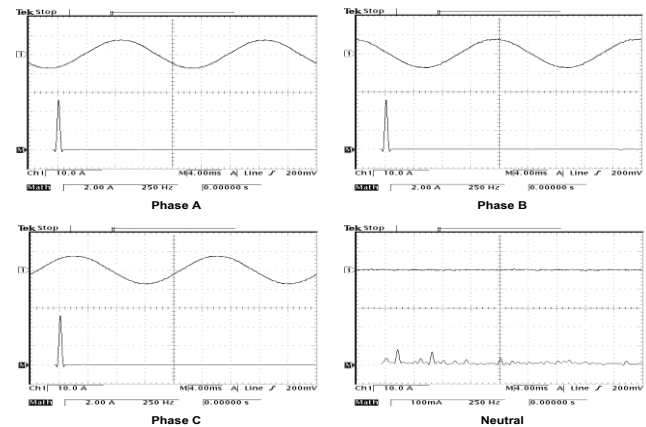

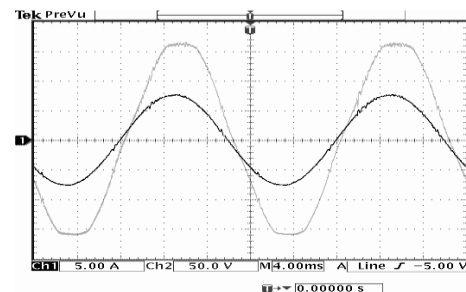Fig. 6.   Phase and neutral currents of the grid after compensation.

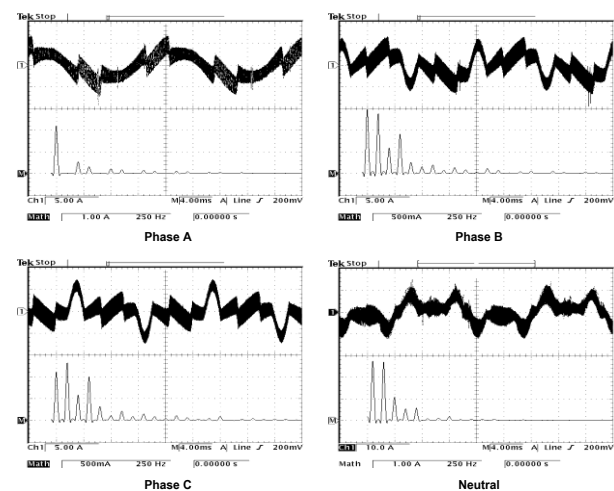Fig. 7.   Phase-A grid voltage and current after compensation.

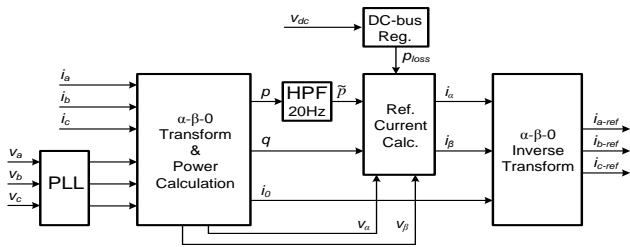Fig. 8.   Phase and neutral currents of the CC-VSI.
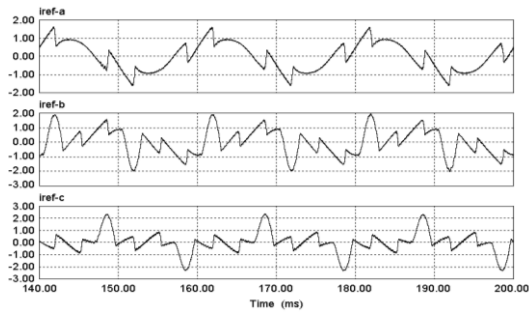
Fig. 9. Control diagram of the *p-q* theory.

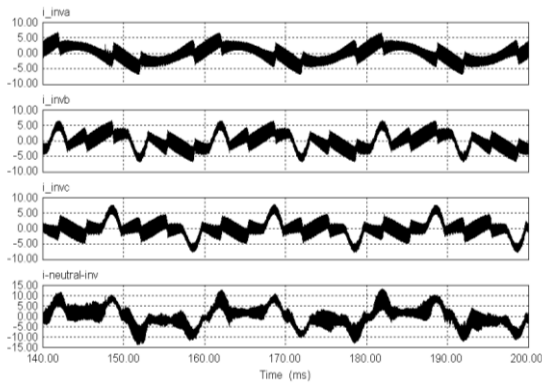Fig. 10.   CC-VSI reference currents.
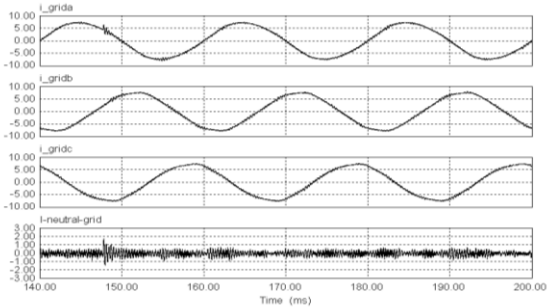

Fig. 11.   CC-VSI output currents.

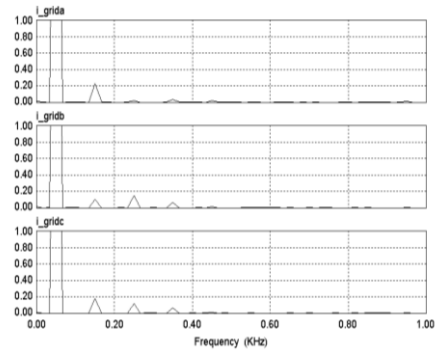Fig. 12.   Grid and neutral currents (*p-q* theory).

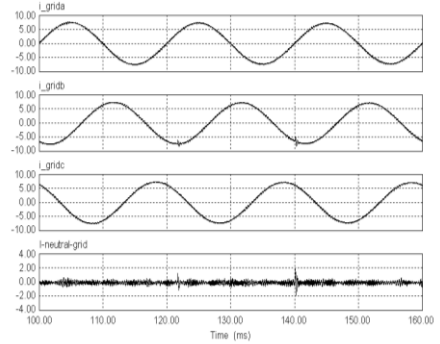Fig. 13.   Spectrum of grid currents (*p-q* theory).

Fig. 14.   Grid and neutral currents (proposed APF).
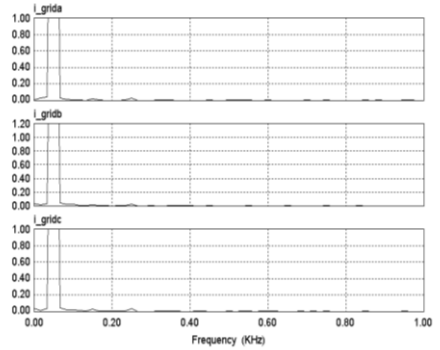

Fig. 15.   Spectrum of grid currents (proposed APF).

Table 3 Comparison results

	Proposed APF	*p-q* theory
THD-I_{phA} (%)	1.9	4.1
THD-I_{phB} (%)	1.9	4.7
THD-I_{phC} (%)	1.7	4.9

7. Conclusions

This paper explains the implementation of a three-phase four-wire shunt active power filter (APF) operated to directly control the AC grid current to be sinusoidal and in phase with the grid voltage. By doing this, the three-phase shunt APF automatically provides compensation for harmonics, reactive power and unbalance without measuring/sensing the load currents. Computational, filtering and control problems can be avoided so that distortion and inaccuracy problems can be significantly minimized. The experimental results prove the validity of the concept.

There are many advantages to directly controlling the grid current. Firstly, it is easy to create a simple sinusoidal reference for the grid current using the active power balance method. The reference current is an appropriate reference to minimize the grid harmonic currents. Secondly, the grid currents produced will be sinusoidal, balanced and in phase with the grid voltages regardless of grid voltage conditions. Thus, it prevents (more) pollution of the electrical system from non-linear loads. Moreover, the control mechanism becomes very simple and effective. Only three current sensors located on the grid side are needed rather than six current sensors for a conventional shunt APF.

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