A Load-Current Sensorless Shunt Active Power Filter

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Abstract: In this paper, the implementation of a shunt Active Power Filter (APF) for a three-phase system is presented. The system consists of mixed non-linear loads with reactive and unbalanced components. The filter consists of a three-phase current-controlled voltage source inverter (CC-VSI) with a filter inductance at the AC output and a split capacitor at the DC-bus. The CC-VSI is operated to directly control the AC grid current to be symmetrical, sinusoidal and in phase with the grid voltage. The switching is controlled using ramptime current control, which is based on the concept of zero average current error (ZACE). The simulation results indicate that the active filter is able to handle predominantly the harmonic sources, as well as the unbalanced and reactive component, so that the grid currents are sinusoidal, in phase with the grid voltages and symmetrical.

Keywords: active power filter, harmonics

1. INTRODUCTION

Non-linear loads, especially power electronic loads, create harmonic currents and voltages in power systems. For many years, various active power filters (APF) have been developed to suppress harmonic currents, as well as compensate for reactive power, so that the source/grid will supply sinusoidal voltage and current with unity power factor [1-3].

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 a current control mechanism. The actual inverter currents must attempt to follow the reference currents with high bandwidth. In addition, the DC bus voltage has to be kept constant to compensate for the inverter losses. A typical block diagram of a shunt APF is shown in Figure 1.

However, the construction of a reference current waveform will introduce distortion or inaccuracies due to 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.

The distortion and inaccuracies can be significantly reduced if these computational, filtering and control problems could be avoided. Therefore, in this paper, the idea of directly controlling the grid/source current rather than the inverter (power converter) current is investigated. Figure 2 shows the proposed filter configuration.

2. SHUNT ACTIVE POWER FILTER CONFIGURATION

The three-phase shunt active power filter is a three-phase 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. Thus, it is essentially three independent single-phase inverters with a common dc bus.

The APF consists of two control loops, namely an inner control loop and an outer control loop. The inner control loop is a ramptime current control that shapes the grid currents to be sinusoidal by generating a certain pattern of PWM for continuous switching of

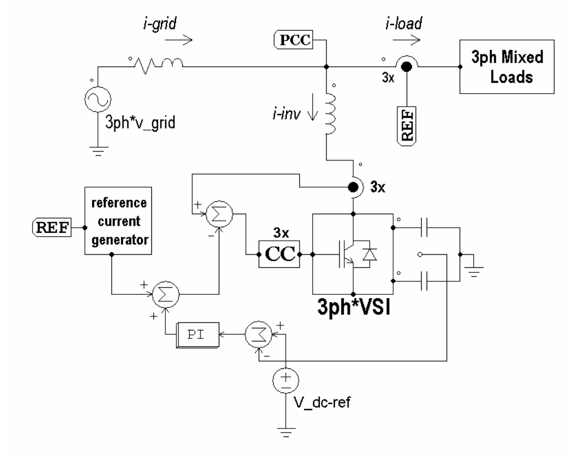

Figure 1 Typical block diagram of a shunt APF

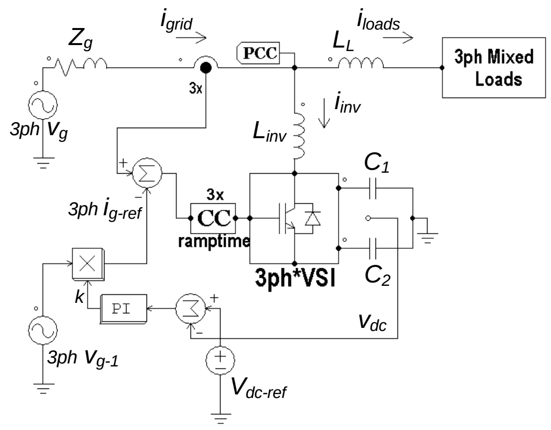

Figure 2 Block diagram of the proposed shunt APF

the inverter switches, while the outer 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.

The performance and effectiveness of the filter are enhanced by the use of the ramptime current control technique [4, 5] to control the inner loop of the CC-VSI. The ramptime current control has characteristics similar to a sliding mode control. The principle operation of the ramptime current control is based on ZACE (zero average current error). The current error signal is the difference between the actual current and the reference signal. This error signal is forced to have an average value equal to zero with a constant switching frequency. The ramptime current control maintains the area of positive current error signal excursions equal to the area of negative current error signal excursions, resulting in the average value of the current error signal being zero over a switching period. The switching period (or frequency) is also kept constant based on the choice of switching instants relative to the zero crossing times of the current error signal. The ramptime current control has a high bandwidth with a fast transient response that can quickly follow the rapid changes in non-linear loads.

Another important component of this system is the added series inductance L_L (see Figure 2). In this case, it could be considered as a part of the loads. The addition of a small series inductance is simple, effective and practical not only to provide the required voltage decoupling between voltage type of load harmonic sources and the point of common coupling (PCC) but also to reduce the bandwidth of the load harmonic currents.

3 DIRECT CONTROL OF THE GRID CURRENT [6, 7]

As seen from Figure 2, the VSI is connected in parallel with the grid, close to the non-linear loads. A node is created with three connections, one each to the load, the grid and the converter, so that all three currents (for three or four wires) are potentially available to be directly controlled by the converter. Hence, it would seem reasonable to control the grid current directly.

Moreover, the controllability of the grid current can be achieved using bipolar PWM switching. The upper and lower switches of each half-bridge are switched on a complementary basis. As a result, the output current of the inverter through the inductor, 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 the controllability.

Thus, for the CC-VSI operated to directly control the AC grid current, the grid current is sensed and directly controlled to follow symmetrical sinusoidal reference signals in phase with the grid voltage. Hence, by putting the current sensors on the grid side, the grid current is forced to behave as a sinusoidal current source and the grid appears as a high-impedance circuit for harmonics. By forcing the grid current to be sinusoidal, the APF automatically provides the harmonic, reactive, negative- and zero-sequence currents for the load, following the basic current summation rule:

$$i_{grid} = i_{inverter} + i_{loads} \quad (1)$$

The system may contain significant amounts of load unbalance as in commercial buildings with non-linear single-phase computer type loads. Such loads produce large negative- and zero-sequence and harmonic currents. Hence, the filter has to inject the inverse of the negative- and zero-sequence current to balance the unbalanced loads. The proposed shunt APF has also the ability to balance the asymmetrical current. This is because the CC-VSI is operated to directly control the AC grid current to follow a three-phase balanced sinusoidal reference signal without measuring and determining the negative- and zero-sequence component. Once the grid currents are able to follow the reference signal, the inverter creates the inverse of the negative- and zero-sequence current automatically. At the PCC, all three currents according to (1) are potentially accessible to be directly controlled by the CC-VSI.

By directly controlling the grid currents, a three-phase 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.

Controlling the grid current rather than the inverter (power converter) 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 AC-DC power balance technique to determine the magnitude of the sinusoidal reference current. The active power is maintained balanced among the grid, the load and the DC bus of the power inverter.

The sinusoidal grid current reference signal is given by:

$$i_{g\text{-}ref} = k\, v_{grid\text{-}1} \quad (2)$$

where $v_{grid\text{-}1}$ is the fundamental component of the grid voltage, and k is obtained from an outer control loop regulating the CC-VSI dc-bus voltage. This can be accomplished by a simple PI control loop, which will be explained in the next section.

3.1 Reference current determination

In this section, a detailed description of an AC-DC power balance method for a three-phase CC-VSI with a split capacitor at the DC bus is explained.

The shunt APF has to compensate for the reactive and harmonic currents from the load. If the compensation is successful, the grid currents will be sinusoidal, balanced and in phase with the grid voltages:

$$\begin{aligned} i_{g-a} &= \sqrt{2}\, I_{g-1} \sin(\omega t) \\ i_{g-b} &= \sqrt{2}\, I_{g-1} \sin(\omega t - 120^o) \\ i_{g-c} &= \sqrt{2}\, I_{g-1} \sin(\omega t + 120^o) \end{aligned} \quad (3)$$

To obtain the reference signals, only one phase of the three-phase grid voltage is detected as the reference phase. Then, a three-phase symmetrical sinusoidal waveform is generated using a phase lock loop (PLL) circuit. Only the magnitude of the grid current $I_{g\text{-}1}$ needs to be determined.

The use of a phase lock loop (PLL) circuit will provide advantages to this method by enhancing the compensation performance so that the grid current will be sinusoidal, balanced and in phase with the grid voltage. The PLL circuit continuously tracks the fundamental frequency component of the system voltage. The design of the PLL circuit should allow proper operation within highly distorted and unbalanced systems due to an interesting feature of the PLL circuit that is almost insensitive to imbalances and distortions. It does not require any reference frame (synchronous) transformation either.

The amplitude can be obtained using the principle of AC-DC average power balance through regulating the DC-bus voltage of the power converter. The DC bus consists of DC capacitors as an energy storage element. The active power flow can be represented as:

$$3V_{g-1}\, i_{g-1} = \bar{p}_L - \bar{p}_{inv} \quad (4)$$

where $\bar{p}_L$ is the active power consumed by the load, which can be expressed as $\bar{P}_L + \Delta\bar{P}_L$; and $\bar{p}_{inv}$ is the active power supplied from the inverter, which can be expressed as $\bar{P}_{inv} + \Delta\bar{P}_{inv}$. Thus, another expression for Equation (4) is:

$$3V_{g-1}(I_{g-1} + \Delta I_{g-1}) = (\bar{P}_L + \Delta\bar{P}_L) - (\bar{P}_{inv} + \Delta\bar{P}_{inv}) \quad (5)$$

Ignoring the losses in the inverter ($\bar{P}_{inv} = 0$), in steady state, the active power consumed by the load is equal to the active power supplied by the grid, and $\bar{p}_{inv}$ will be zero, so that $3V_{g-1}\, I_{g-1} = \bar{P}_L$. With no active power flow into the inverter, the average DC-bus voltage thus can be maintained at the reference voltage level.

When a load variation occurs ($\Delta\bar{P}_L$) the active power balance between the load and the grid will cease to be maintained. The power converter immediately supplies the active power mismatch between the grid and the load, since the outer control loop cannot respond instantaneously to provide the appropriate grid reference current magnitude.

The active power mismatch supplied by the inverter is indicated by $\Delta\bar{P}_{inv}$. The power is drawn from the DC-bus capacitors of the CC-VSI as an energy storage element. The DC capacitors of the inverter produce $v_{C1}\, i_{C1} + v_{C2}\, i_{C2}$. For the case where $v_{C1} = v_{C2} = v_{dc}/2$, and $C_1 = C_2 = C$, the active power taken from the DC capacitors is:

$$\Delta\bar{P}_{inv} = 2C\,\frac{v_{dc}}{2}\,\frac{d\,\frac{v_{dc}}{2}}{dt} = \tfrac{1}{2} C\, v_{dc}\,\frac{dv_{dc}}{dt} \quad (6)$$

The power mismatch drives the average voltage of the DC capacitor away from the reference value, $v_{dc} = V_{dc} + \Delta V_{dc}$. Noting that $x\, dx/dt = ½\, dx^2/dt$, then Equation (6) can be rearranged to become:

$$\Delta\bar{P}_{inv} = \tfrac{1}{4} C\,\frac{d(V_{dc} + \Delta V_{dc})^2}{dt} \quad (7)$$

and, because ΔV_{dc} is much smaller than V_{dc}, $\Delta\bar{P}_{inv}$ can be simplified to:

$$\Delta\bar{P}_{inv} = \tfrac{1}{2} C\, V_{dc}\,\frac{d\,\Delta V_{dc}}{dt} \quad (8)$$

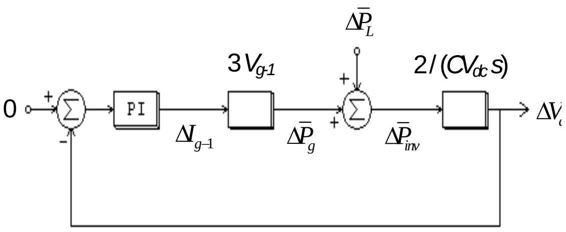

Figure 3 Block diagram of AC-DC power balance

After Laplace transformation is applied, the relationship between $\Delta V_{dc}(s)$ and $\Delta\overline{P}_{inv}(s)$ can be expressed as:

$$\frac{\Delta V_{dc}(s)}{\Delta\overline{P}_{inv}(s)} = \frac{1}{\frac{1}{2}C V_{dc}\, s} \tag{9}$$

The active power fluctuation drawn by the load directly causes an active power variation of the inverter, which yields a DC-bus voltage deviation. Due to active power balance, the amplitude of grid currents must be adjusted appropriately to compensate for the active power charged/discharged from DC capacitors of the power converter. The required change in grid currents will come as soon as the outer voltage control loop responds to change in the magnitude of the grid current. This condition is illustrated by Equation (10) that is written as:

$$3V_{g-1}\,\Delta I_{g-1} = \Delta\overline{P}_L - \Delta\overline{P}_{inv} \tag{10}$$

$\Delta\overline{P}_{inv}$ will go to zero when ΔI_{g-1} 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.

In conclusion, the amplitude of grid currents can be established by regulating the average DC capacitor voltage through a PI controller as shown in Figure 3. If the grid current amplitude is too large (or small), the average capacitor voltage must increase (or decrease) to absorb (or deliver) the excess (or deficit) active power delivered by the grid. 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.

A computer simulation using PSIM has been conducted to demonstrate the concept of AC-DC power balance in determining the reference grid currents. The results describe the relationships among the variations of the load, the changing of the DC-bus voltage and the responses of the PI controller. The simulation shows the results (Figure 4 and 5) for the case when the load increases. A similar process will occur when the load decreases.

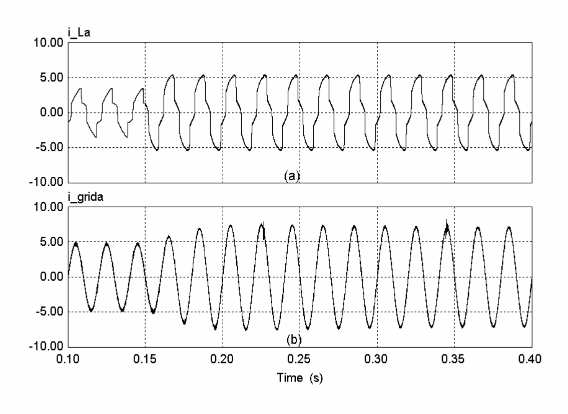

Figure 5 The load variation; (a) phase-A load current (b) phase-A grid current

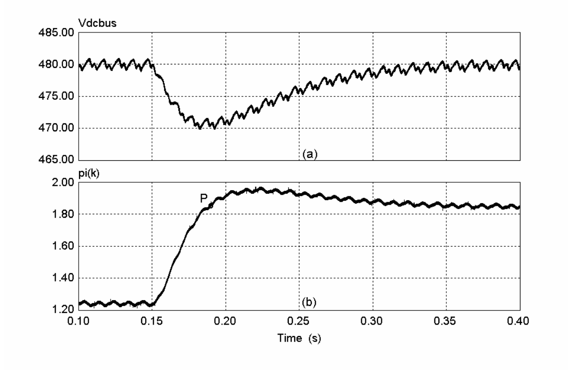

Figure 5 Power balance (simulation results); (a) DC-bus voltage (b) PI controller output

When the load changes, (in this case at t = 0.15sec – see Figure 4), the active power of the system becomes unbalanced. For clarity, a phase-A current is shown for illustration. The DC-bus capacitors supply the active power mismatch immediately. As a result, the DC-bus voltage decreases, since the DC capacitors discharge. In a short time, the PI controller starts to respond due to the voltage error signal, which is the difference between the DC-bus reference voltage and the DC-bus actual voltage. The output voltage of the PI controller will increase slowly to attain the required amplitude of the grid currents. It is obvious that the grid gradually supplies the active power to the system.

The DC-bus voltage stops decreasing when the output of the PI controller reaches a value around its balanced point ***P*** (Figure 5). At this moment, the instantaneous value of the active power from the grid is equivalent to the active power consumed by the load. The inverter stops supplying the active power.

Afterwards, the DC-bus voltage returns to the value according to the DC-bus reference voltage. The DC capacitors commence charging from the grid currents. It is evident that the output of the PI controller is overshot and the amplitude of the grid currents is a bit higher than the steady-state value. When DC-bus voltage is at the reference value, the new steady state has been achieved with a new grid current amplitude. The difference between the final and initial values of the PI controller output is equal to the delta amplitude of the grid currents. The final value of the PI controller output becomes a new value of the amplitude of the grid current reference signal according to Equation (2).

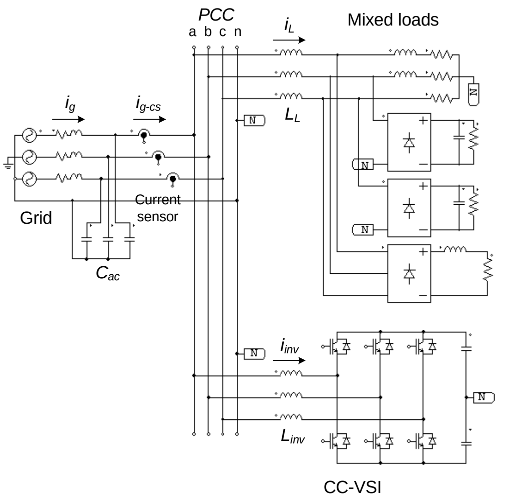

Figure 8 Circuit for computer simulation

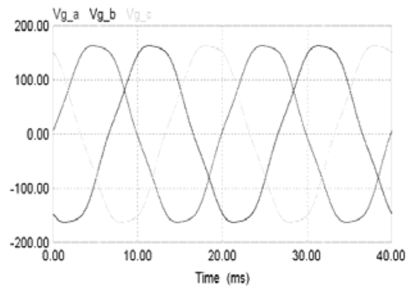

Figure 8 The grid voltages

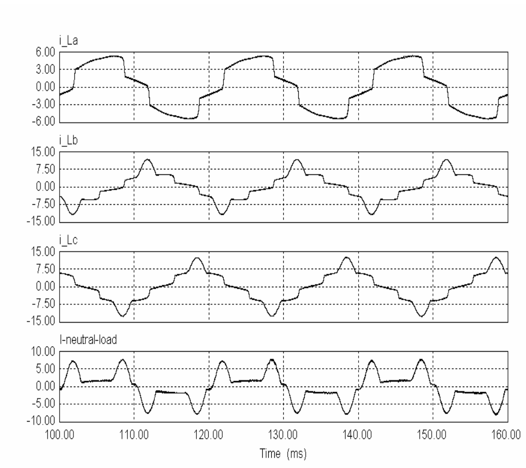

Figure 8 The phase and neutral currents of mixed loads

4. A THREE-PHASE SHUNT ACTIVE POWER FILTER FOR MIXED LOADS

The system in Figure 2 is tested using computer simulation (PSIM) to verify the shunt APF concepts. Figure 6 shows the circuit diagram for computer simulation. The three-phase grid voltages as seen in Figure 7 contain harmonics. The mixed 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 of the mixed loads, as well as the neutral current from the computer simulation, are shown in Figure 8. It shows clearly that the currents are not sinusoidal. The load currents are also unbalanced and contain reactive components.

Figures 9 and 10 demonstrate the steady-state performance of compensation results. It can be seen that the shunt APF is successfully able to compensate for the total mixed loads that produce harmonic, reactive and unbalanced currents. Although the grid voltage contains harmonics, it does not distort the grid currents. The ramptime current control 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 (in this graph, only phase A of the grid voltage is shown). The magnitude is determined by the active power required by the system.

After compensation, the grid currents are symmetrical both in magnitude and phase. As a result, the neutral current at the grid is also reduced to zero. The grid currents are balanced because the CC-VSI is operated to directly control the AC grid currents to follow a three-phase balanced sinusoidal reference signal. Once the grid currents are able to follow the reference signals, 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 Figure 11, 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 generates harmonics to eliminate the load harmonics but also provides balancing to create the symmetrical grid currents.

A PWM CC-VSI is capable of controlling the low order harmonics. 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. From the simulation, it is demonstrated that the grid currents contain insignificant switching ripples.

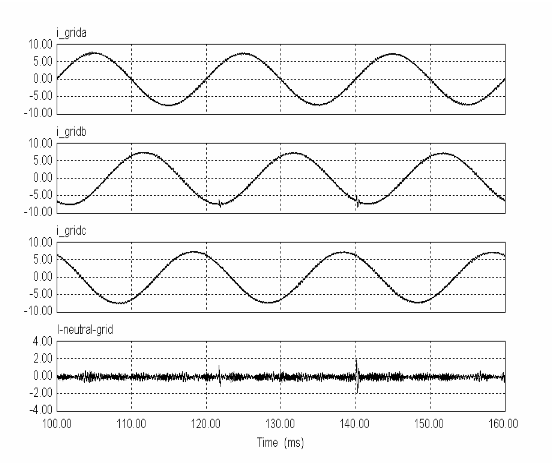

Figure 11 The phase and neutral currents of the grid after compensation

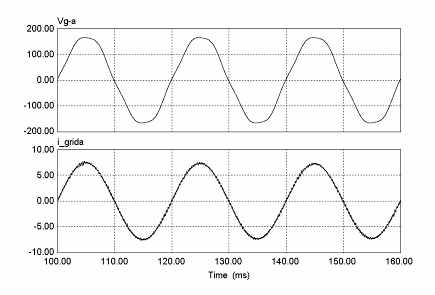

Figure 11 The grid current is in phase with the grid voltage (phase A)

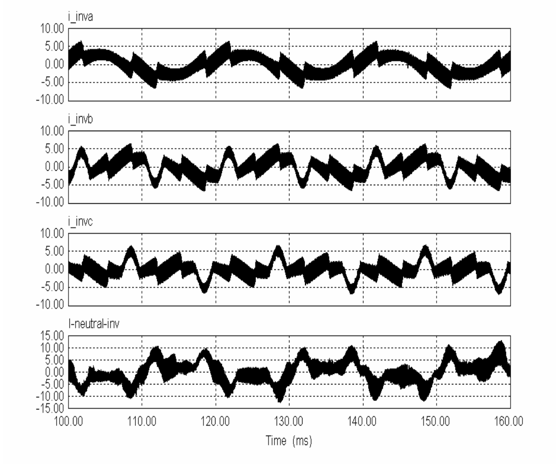

Figure 11 The phase and neutral currents of the CC-VSI in compensation for mixed loads

5. CONCLUSION

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. The simulation results prove the validity of the concept.

There are many advantages to directly control the grid current. Firstly, it is easy to create a simple sinusoidal reference for the grid current using the AC-DC 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 voltage regardless of grid voltage conditions. Thus, it prevents (more) pollution of the electrical system from non-linear loads. Moreover, there are three current sensors installed at the grid side instead of six current sensors in a conventional shunt APF. The control mechanism becomes very simple as well.

6. REFERENCES

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