

# Australian Journal

*by* Hanny Tumbelaka

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Papers should be related to the relevant field and will usually fall into one of the following categories:

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The expected length of acceptable contributions will vary considerably but 4000 to 5000 words or equivalent for papers would be the norm. Technical notes should not exceed 1500 words and contributions to discuss published papers should not exceed 500 words.



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## foreword

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The Australasian Universities Power Engineering Conference (AUPEC) 2004 was held at the University of Queensland in Brisbane. The theme of the conference was "Challenges and opportunities in the deregulated power industry". Blackouts are becoming more frequent and causing substantial losses to consumers. There is a need for security in the modern complex and interconnected power system. New techniques and solutions are required to manage and operate the deregulated electricity industry in a market environment.

AUPEC 2004 received over 235 digests/full papers from 17 countries. The prospective authors were academics, research higher degree students and power industry professionals. After a thorough review process 167 papers were accepted for presentation and discussion. Now out of these 167 papers we have selected the top 15 papers for presentation in this special issue of the Journal of Electrical and Electronics Engineering.

In 2005, the AUPEC 2005 will be hosted by the University of Tasmania in Hobart.



Akhtar Kalam  
Guest Editor



Tapan Saha  
Guest Editor

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## Analysis of a series inductance implementation on a three-phase shunt active power filter for various types of non-linear loads \*

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**SUMMARY:** In this paper, the implementation of a shunt active power filter with a small series inductor for a three-phase system is presented. The 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 series inductor is primarily used to handle the harmonic voltage source. The main concern is the size of the series inductance so that it is as small as possible but effective in compensating the harmonics. In order to select the proper value of the series inductance, the simulation is conducted to evaluate the value for different types of loads.

### 1 INTRODUCTION

Non-linear loads, especially power electronic loads, create harmonic currents and voltages in the power systems. 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) that creates negative and zero sequence components.

For many years, various active power filters (APF) have been developed to suppress the harmonics, as well as to compensate for reactive power, so that the utility grid will supply sinusoidal voltage and current with unity power factor.<sup>1,2</sup> Basically, the shunt type APF acts to eliminate the reactive and harmonic currents produced by non-linear loads from the grid current by injecting compensating currents intended to result in sinusoidal grid currents with unity power factor. This filter has been proven to be effective in compensating harmonic current sources, but it cannot properly compensate for harmonic voltage sources. With mixed non-linear loads, it has been proven that a modified three-phase line current forcing shunt APF combined with a series inductor installed at the Point of Common Coupling (PCC) is

effective in compensating harmonic current sources, as well as harmonic voltage sources.<sup>3</sup> The filter is able to handle the load unbalance as well. Figure 1 shows the filter configuration.

The addition of a small series inductance is simple, effective and practical not only to support the shunt APF to compensate the harmonic voltage source but also to improve the filtering process for other types of loads. However, the inductor size has to be selected properly, because it is related to the size of other filter components and to filtering characteristics. Therefore, in this paper, the selection and effectiveness of a series inductor are examined.

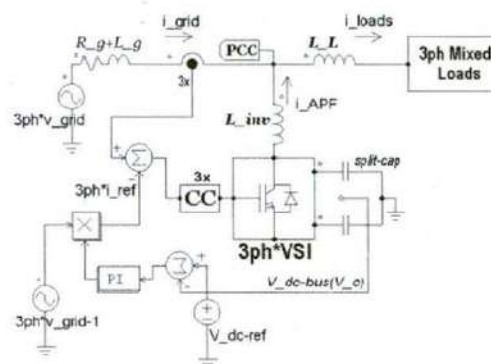


Figure 1: Active power filter configuration.

\* Paper presented at the Australasian Universities Power Engineering Conference, 2004



## 2 A THREE-PHASE SHUNT ACTIVE POWER FILTER OPERATION

### 2.1 Operation principle of a three-phase shunt active power filter

The three-phase shunt active power filter is a four-wire three-phase current controlled voltage-source inverter (CC-VSI) with a mid-point earthed, split capacitor in the dc bus and inductors in the ac output (It is essentially three independent single-phase inverters with a common dc bus).

In this scheme (Figure 1), the CC-VSI is operated to directly control the ac grid current rather than its own 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:

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

The sinusoidal grid current reference signal is given by:

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

where  $v_{grid-1}$  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. This is an effective way of determining the required magnitude of active current required, since any mismatch between the required load active current and that being forced by the CC-VSI would result in the necessary corrections to regulate the dc-bus voltage.

A key component of this system is the small-added series inductance  $L_L$ . Without this inductance, load harmonic voltage sources would produce harmonic currents through the grid impedance, which could not be compensated by a shunt APF. Currents from the APF do not significantly change the harmonic voltage at the loads. Therefore, there would still be harmonic voltages across the grid impedance, which would continue to produce harmonic currents. The inductance  $L_L$  provides the required voltage decoupling between load harmonic voltage sources and the grid (Figure 2).

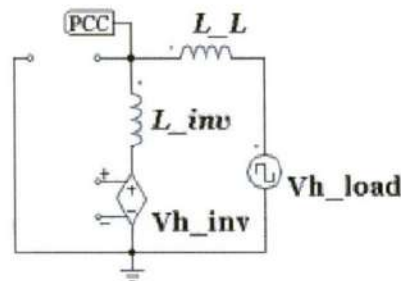


Figure 2: Equivalent circuit for low order harmonics.

### 2.2 Current control loop

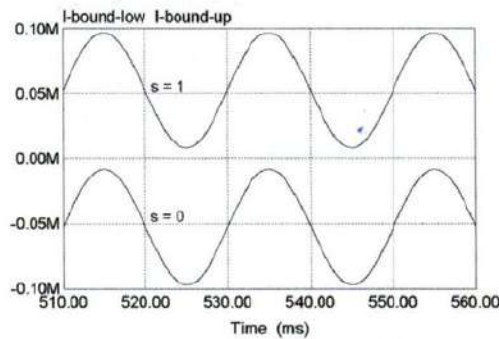
The current control loop employs the ramptime current control technique.<sup>4</sup> The principle operation of ramptime current control is based on the concept of zero average current error (ZACE) with a constant switching period (or frequency). In this application, the current error signal is the difference between the actual grid current and the desired/reference grid current waveform.

In this control loop, the output current ( $di_{APF}/dt$ ) of the inverter through  $L_{inv}$  (inverter output inductance) is expressed as

$$\frac{di_{APF}}{dt} = -\frac{v_{PCC}}{L_{inv}} + (2s - 1) \frac{v_c}{2L_{inv}} \quad (3)$$

$s = 1$  if the upper switch is closed, and  $s = 0$  if the upper switch is open. The switches are operated on a complementary basis. The voltage source inverter can always generate currents and the system is stable as long as  $v_c/2 > v_{PCCpk}$ . Hence, although  $v_c$  (dc bus voltage) contains ripple,  $v_c$  has to be sufficiently large so as to outweigh the fluctuation of  $v_{PCC}$  (voltage at PCC) and small perturbations.

Full controllability is achieved when  $di_{APF}/dt$  is greater than the  $di/dt$  of the loads. This provides the CC-VSI with complete control over the ac grid current. Therefore, equation (3) expresses the boundaries of controllability (pu), represented in Figure 3 for  $V_{PCC-rms} = 1$  pu,  $V_{C-de} = 3.333$  pu,  $X_{inv} = 1\%$ ,  $f = 50$  Hz with  $s = 1$  (upper curve) and  $s = 0$  (lower curve). As long as the  $di/dt$  of the loads is within the boundaries ( $di_{APF}/dt$ ), the current control will force the grid currents to track the reference signals perfectly. For this case, filter parameters must be chosen such that the  $di/dt$  of the loads never exceeds the upper and lower curves of the boundaries of controllability.



**Figure 3:** The boundaries of controllability ( $di_{AP}/dt - pu$ ) for  $V_{PCC-rms} = 1pu$ ,  $V_{C-dc} = 3.333 pu$ ,  $X_{inv} = 1\%$ ,  $f = 50Hz$ .

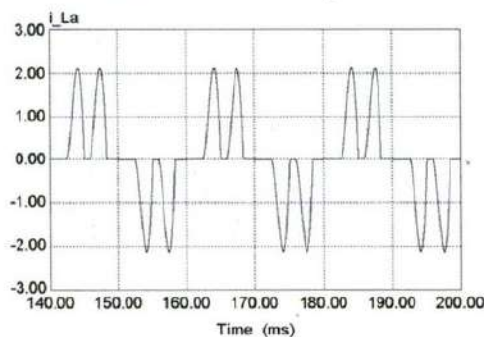
### 2.3 Voltage control loop

The outer voltage control loop uses a PI controller to adjust the gain  $k$  of the reference currents in order to regulate the desired dc bus voltage. The PI parameters,  $K_p$  and  $T_i$  must be determined so that the characteristic equation of the closed-loop transfer function has poles in the left-hand side of the  $s$  plane.  $T_i$  is chosen such that the speed of response of the voltage control loop is much slower than that of the current control loop. Hence, the inner current and outer voltage control loops are decoupled.

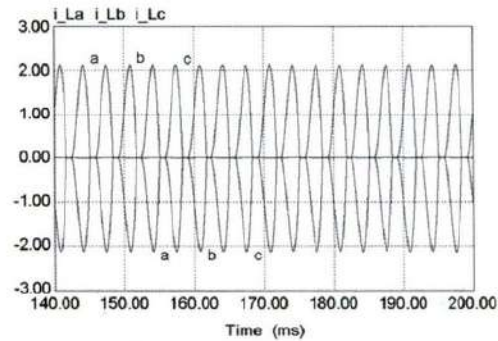
## 3 THE RELATIONSHIP BETWEEN A SERIES INDUCTANCE $L_L$ AND VARIOUS NON-LINEAR LOADS

### 3.1 Compensation for harmonic voltage sources

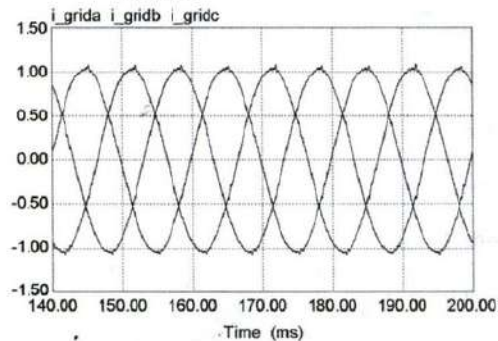
To show a compensation for harmonic voltage sources, a simulation was conducted based on a three-phase ac system with a grid voltage rms value of  $1pu$  ( $V_{base} \text{ phase-neutral} = 240V_{rms}$ ),  $X_{inv} = 1.96\%$ ,  $X_s = 0.8\%$ ,  $X_L = 0.8\%$ . The load is a three-phase diode rectifier with dc filter capacitor as a harmonic voltage source, with  $I_{load-rms} = 1pu$  ( $I_{base} = 10A_{rms}$ ). Computer simulation results are shown in Figures 4, 5 and 6.



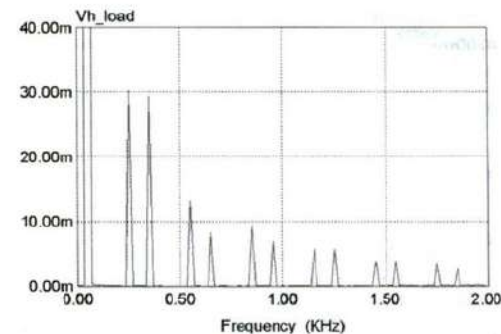
**Figure 4:** The load current (phase A – pu) for a three-phase harmonic voltage source.



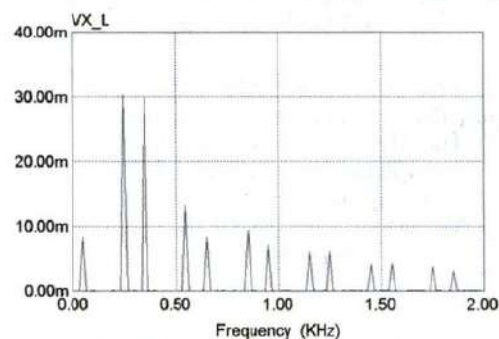
**Figure 5a:** The three-phase load currents (pu) for a three-phase harmonic voltage source.



**Figure 5b:** The three-phase grid currents (pu) after compensation.



**Figure 6a:** Harmonic spectrum of load harmonic voltage (peak value – pu).



**Figure 6b:** Harmonic spectrum of voltage across  $L_L$  (peak value – pu).



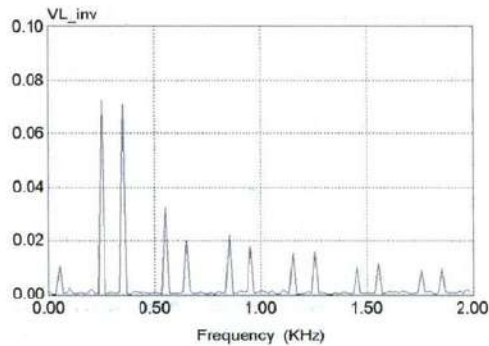


Figure 6c: Harmonic spectrum of voltage across  $L_{inv}$  (peak value – pu).

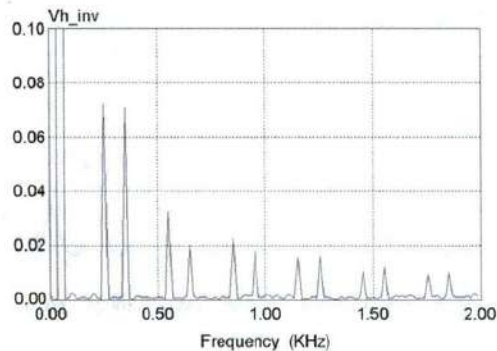


Figure 6d: Harmonic spectrum of CC-VSI output voltage (peak value – pu).

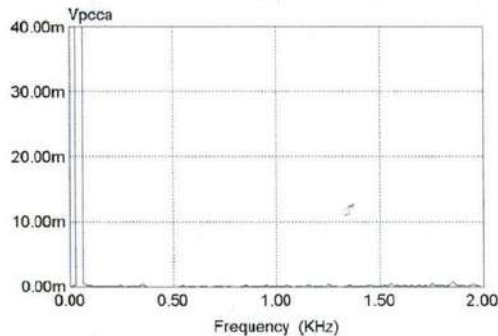


Figure 6e: Harmonic spectrum of voltage at PCC (peak value – pu).

The three-phase shunt APF successfully forces sinusoidal current from the grid, as shown in Figure 5(b). The APF combined with  $L_L$  forces the load harmonic voltage shown in Figure 6(a) (in spectral performance up to 2kHz) to appear across  $L_L$  in Figure 6(b). As previously described in figure 2, these same harmonic voltages appear (in relative proportion to

the inductances) in the inverter output voltage in Figure 6(d) and across the inverter inductance in Figure 6(c). Thus, the load harmonic voltages do not appear across  $Z_s$ , and load harmonic currents are not created through this grid impedance. Also, assuming the grid voltage harmonics are negligible, the ac grid voltage at the PCC will be sinusoidal (Figure 6(e)).

It is apparent that the CC-VSI generates harmonic voltages with the same characteristics as the load harmonic voltages. Moreover, the harmonic voltage of CC-VSI yields equal-but-opposite voltage on the inverter inductance ( $L_{inv}$ ) to keep harmonic voltage at the PCC close to zero. This result leads the output current of the active filter to match the harmonic components of  $i_{loads}$ .

### 3.2 The size of a series inductance $L_L$

There are several ways to determine the size of  $X_L$  that represents  $L_L$ . As suggested by Peng,<sup>5</sup> the minimum value of  $X_L$  is 6%. In Al-Zamil's paper,<sup>6</sup> the size of  $X_L$  depends on the maximum load current slope because the reactance is used specifically to reduce the current slope of harmonic current type loads. However, the practical value of  $L_L$  should be as small as possible to minimize cost.

If the APF can directly force the grid current to be sinusoidal, the voltage at the PCC will have similar characteristics to the grid voltage with a small sinusoidal voltage appearing across the grid impedance. While the intent of the APF is to improve the grid current, it is not expected that the APF should improve the current harmonics into the load, but only supply those harmonic currents rather than have the grid supply them. Conversely, the APF also should not increase the current harmonics into the load, since that may result in greater stress on the loads. Hence a rationale choice of decoupling inductance would be to choose a value, which results in the harmonic content of the load current being largely the same as it would have been without the APF in place.

Assuming a perfect sinusoidal (harmonic free) grid voltage source, the operation of the APF should result in a harmonic free voltage at the PCC. Hence, in order to make the loads operate in the similar operating point as if they were connected directly to the grid, then the size of  $X_L$  should be chosen close to  $Z_s \approx X_s$  in per-unit value (usually the resistance of the grid impedance is very small compared to its inductance). In other words, it is suggested to select  $L_L \approx L_g$ , so that the characteristics of the load current would be similar after and before installing the APF.



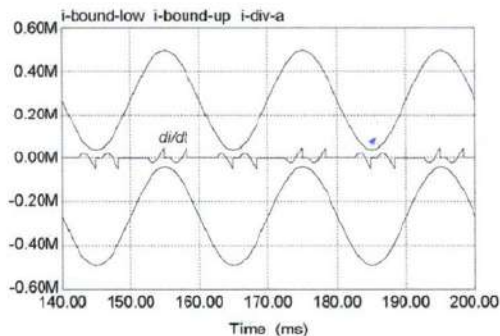


Figure 7: The  $di/dt$  of loads (pu) are inside the boundaries (case 1).

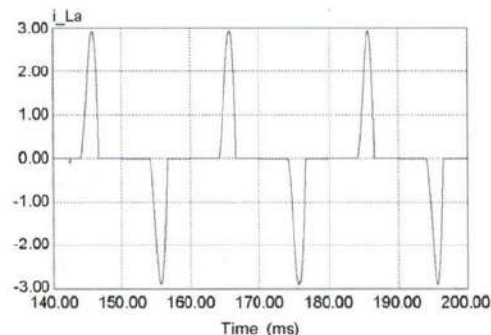


Figure 8: The load current (phase A – pu) for three single-phase harmonic voltage sources (case 2).

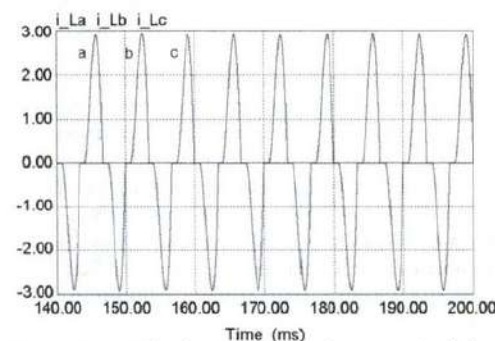


Figure 9a: The three-phase load currents (pu) for case 2.

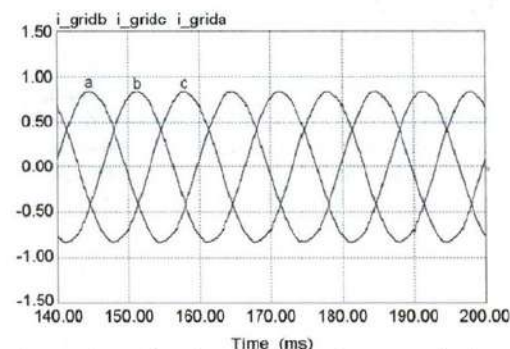


Figure 9b: The three-phase grid currents (pu) after compensation (case 2).

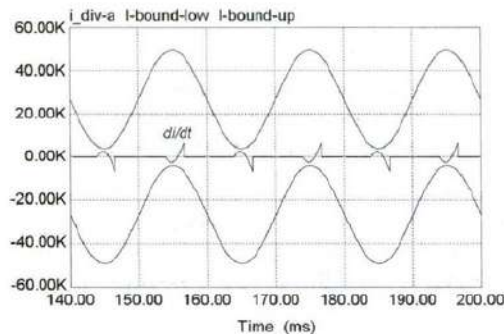


Figure 10: The  $di/dt$  of the loads (pu) are inside the boundaries (case 2).

In order to select the proper value of  $L_L$ , it is better to evaluate the value with three different types of loads. In this case, the circuit constants are  $V_{C-d} = 3.333$  pu,  $X_{mv} = 1.96\%$ , and  $X_s = 0.8\%$ .

### 3.2.1 Compensation for a three-phase diode rectifier as harmonic voltage sources (case 1)

From the previous section as shown in Figure 5, it is shown that for the  $X_L = 0.8\%$ , full controllability is achieved and the compensation is successful. Before compensation, the grid currents are the same as the load currents, which are 1 pu per-phase. After compensation, the grid currents are sinusoidal, and the rms values are reduced to 0.74 pu. The small series inductance  $L_L$ , which is close to  $L_s$  provides voltage decoupling between the load harmonic voltage and the grid. Moreover,  $L_L$  forces the  $di/dt$  of loads inside the boundaries of controllability as shown in Figure 7.

### 3.2.2 Compensation for a three single-phase diode rectifier as harmonic voltage sources (case 2)

To show a compensation for three per-phase single-phase diode rectifiers as harmonic voltage sources ( $I_{load-rms} = 1$  pu), a simulation was conducted using the same circuit constants, with  $X_L = 0.8\%$ . The load and grid currents can be seen in Figures 8 and 9.

From Figure 9, it is shown that with  $X_L = 0.8\%$ , full controllability is achieved. The compensation is successful and the grid currents are sinusoidal. The added series inductance  $L_L$  provides voltage decoupling between the load harmonic voltage and the grid. Moreover, for only  $L_L = L_s$  (neglecting the resistance of the line impedance), the requirement of controllability is satisfied, and the  $di_{load}/dt$  is inside the envelope of the boundaries of controllability, as shown in Figure 10.  $L_L$  could be smaller as long as sufficient voltage decoupling is provided and the  $di/dt$  of the loads is still inside the

boundaries of controllability.

### 3.2.3 Compensation for a three-phase thyristor controlled rectifier as harmonic current sources (case 3)

Basically, the shunt APF has been shown to be effective in compensating harmonic current sources. To show a compensation for harmonic current sources, a simulation was conducted using the same circuit constants.  $X_L = 0.8\%$ . The load and grid currents can be seen in Figure 11 and 12. The firing angle for the thyristor control circuit is chosen at  $60^\circ$ , and  $I_{load-rms} = 1pu$

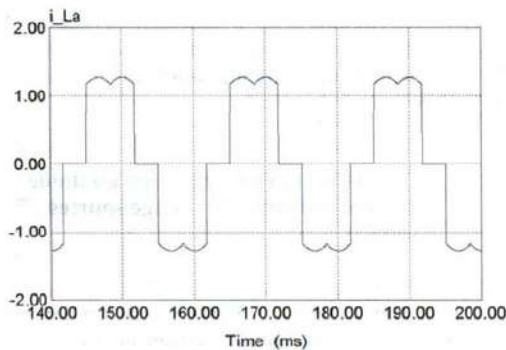


Figure 11: The load current (phase A – pu) for a three-phase harmonic current source.

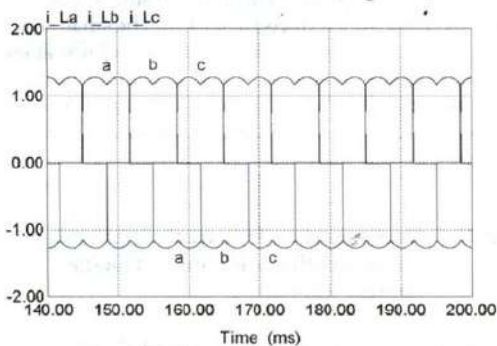


Figure 12a: The three-phase load currents (pu) for case 3.

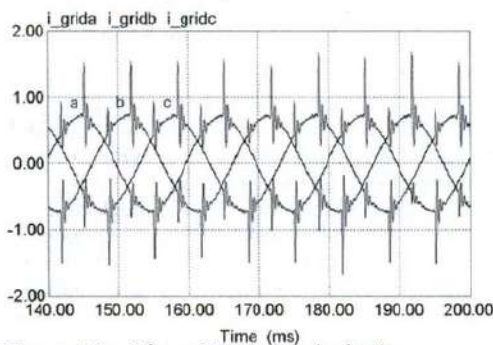


Figure 12b: The grid currents (pu) after compensation, for  $X_L = 0.8\%$  (case 3).

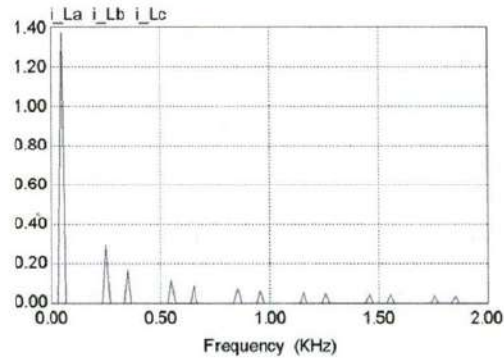


Figure 12c: Spectrum of the load currents (peak value – pu) for case 3.

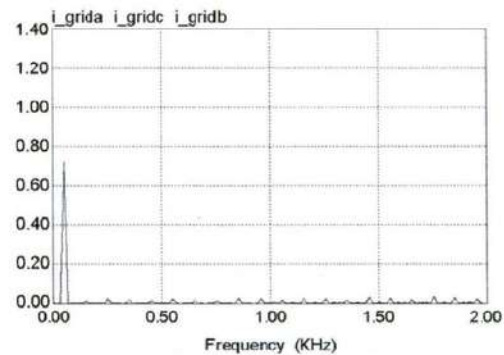


Figure 12d: Spectrum of the grid currents (peak value – pu), for  $X_L = 0.8\%$  (case 3).

From Figure 12, it can be seen that for  $X_L = 0.8\%$ , the compensation creates current spikes in the grid currents at the instant of current commutation. The APF is unable to eliminate these current spikes. The APF attempts to compensate for the larger current error, but at that moment the maximum  $di_{load}/dt$  exceed the boundaries, as shown in Figure 13. The maximum  $di/dt$  of non-linear loads supplied from a thyristor-based circuit during commutation is given as: <sup>7</sup>

$$\frac{di_{loads}}{dt} = \frac{\sqrt{2}\sqrt{3} v_{pcc}}{2L_L} \quad (4)$$

Strict controllability is lost during the commutation since the current error signal moves away from zero regardless of switch position. However, as soon as the commutation process has finished, the controllability is returned, and the APF is able to force the grid current to follow the reference value.



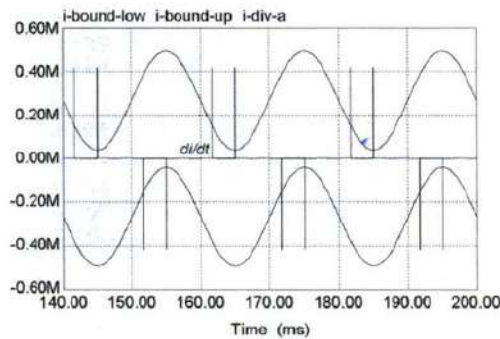


Figure 13: The  $di/dt$  of the loads (pu) exceeds the boundaries for  $X_L = 0.8\%$  (case 3).

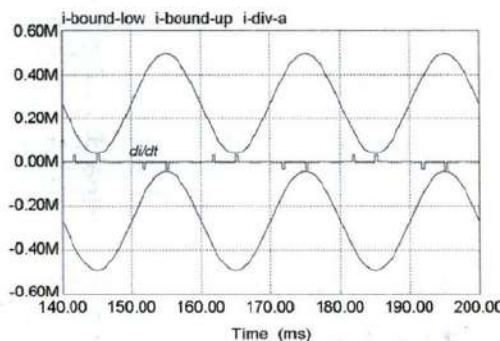


Figure 14: The  $di/dt$  of the loads (pu) are inside the boundaries for  $X_L = 11.13\%$  (case 3).

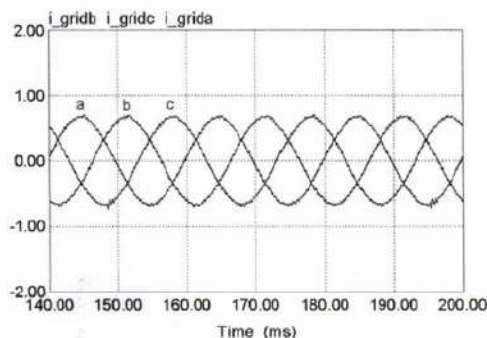


Figure 15: The grid currents (pu) after compensation for  $X_L = 11.13\%$  (case 3).

To reduce the spikes, either  $L_L$  must be increased in order to reduce the  $di/dt$  of the loads, or the boundaries of controllability of the inverter must be increased. The latter is undesirable due to device limitations. For  $di_{APF}/dt$  greater than  $di/dt$  of the loads, from (3) and (4), the value of  $L_L$  can be expressed as:

$$L_{inv} < L_L (0.4m - 1.155) \quad (5)$$

where  $m = V_C/V_{PCC-rms}$ . For  $V_{PCC-rms} = 1pu$  and  $V_C = 3.333pu$ ,  $L_L$  must be about six times larger than  $L_{inv}$ . By increasing  $X_L$  to 11.13%, with  $X_{inv} = 1.96\%$ , the

$di/dt$  of the load is between the upper and lower envelope of the controllable region (Figure 14). Then, full controllability is achieved, the compensation is successful, and the spikes of the grid currents are significantly attenuated (Figure 15).

Undeniably, for  $X_L = 0.8\%$ , it can be seen from the current spectrum (up to 2 kHz) in Figure 12d that the low order harmonics are reduced significantly. However, the THD of the grid currents is relatively high (17.6%) due to the spikes. By increasing  $L_L$  to a higher value, the  $di/dt$  of the loads is reduced. Consequently, controllability is improved, the spikes are attenuated, and the THD is reduced. For this case, the relationship between  $L_L$  (relative to  $L_{inv}$ ) and the THD of the grid currents is shown in Figure 16.

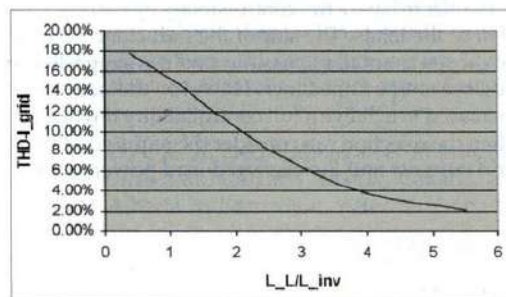


Figure 16: THD- $I_{grid}$  vs a series inductance  $L_L$  (case 3).

### 3.3 A series inductance $L_L$ and power factor of the loads.

As mentioned above,  $X_L$  should be selected close to  $X_s$  in per-unit value so that the load operates at a similar point before and after installing the APF. In other words, the existence of the APF and a series inductance  $L_L$  would not change the characteristics of the loads. A measure of this load characteristic is the true power factor. In Table 1, for voltage-harmonic producing loads (diode-capacitor rectifiers), it can be seen that the operation of the APF with increasing series inductance results in an increasing improvement in the load power factor.

Table 1: The load power factor due to  $L_L$

	With-out APF	With APF: $X_L$ (%)				
		0.8	1.96	5	7.85	11.13
1-ph Diode rectifier	0.602	0.603	0.664	0.722	0.748	0.766
3-ph Diode rectifier	0.711	0.711	0.795	0.906	0.923	0.929
3-ph Thyristor controlled rectifier	0.474	0.477	0.475	0.469	0.464	0.458



For the current-harmonic producing load (three-phase controlled rectifier with dc side inductance), the power factor is relatively constant with increasing series inductance. If the size of  $X_L$  is selected close to  $X_s$ , the power factor of both voltage-harmonic producing and current-harmonic producing loads is maintained unchanged after the installation of the APF.

#### 4 CONCLUSION

The series inductance  $L_s$  is an important component that supports the APF to compensate harmonics. The main role is to handle the problem of harmonic voltage sources. Moreover, it helps the current controller to have a full controllability by reducing the  $di/dt$  of the loads. The size of the inductance should be chosen as small as possible, and it is suggested to be close to line impedance. However, the size can be increased to achieve a full controllability if required. Then the selection can consider the required THD of grid currents and the preferred load power factor.

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