A SINGLE-PHASE POWER SERIES COMPENSATOR FOR VOLTAGE DISTORTION

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Abstract. The purpose of this paper is to describe the work that is being done in the design and implementation of a single-phase series power compensator for electrical power quality purposes. This system is able to compensate several voltage related problems in the power grid, namely: voltage distortion due to harmonics, voltage flicker (sub harmonics) and over or under voltages. The power circuit of the series compensator is described in this paper, and some experimental results are presented.

1 INTRODUCTION

Voltage distortion is caused by several factors. Nearby non linear loads and some types of voltage sources (renewable energy sources, for example), are very common causes. Power quality problems origin instantaneous and long term effects on electrical equipment. The short term effects are malfunctioning, interferences and degradation of the performance of devices or equipments. Effects in the long run are, basically, overheating and premature aging of the electric devices.

If non linear loads are connected to the electrical grid, even if the mains voltage is undistorted, the current harmonics will cause voltage distortions in the line impedances, and the voltage at the load terminals will also be distorted. Figure 1 illustrates this fact. The harmonics in the line-current (i_s) produce a non-linear voltage drop (Δv) in the line impedance, which distorts the load voltage (v_L). Since load voltage is distorted, even the current at the linear load (i_{L1}) becomes non-sinusoidal.

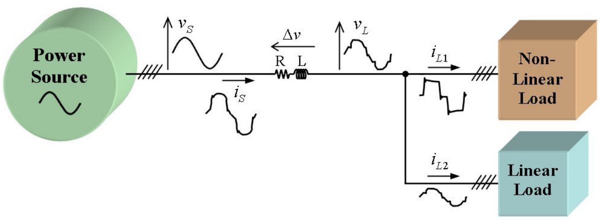

Figure 1: Voltage distortion due to the presence of a nearby non linear load.

Passive filters can be used to compensate some of the mentioned problems, but they have some limitations, namely: they only filter the frequencies for which they have been previously tuned, its operation cannot be limited to a certain load or circuit, resonances can occur, and the electrical system can start to operate with capacitive power factor.

2 ACTIVE POWER FILTERS

Active power filters have several advantages over passive ones: compensation is automatic, there is no risk of resonances, unity power factor (or any other value) can be achieved permanently and without disturbing the electrical network, they can compensate for phase unbalance in three-phase electrical systems. They can also be combined with passive filters (which may be already installed) in hybrid topologies, in order to diminish their rated power.

There are basically two types of active power filters: the shunt active filter, presented in figure 2, which is designed to filter line currents; and the series active filter, shown in figure 3, designed to filter mains voltages. It is also possible to combine both topologies to provide both current and voltage filtering.

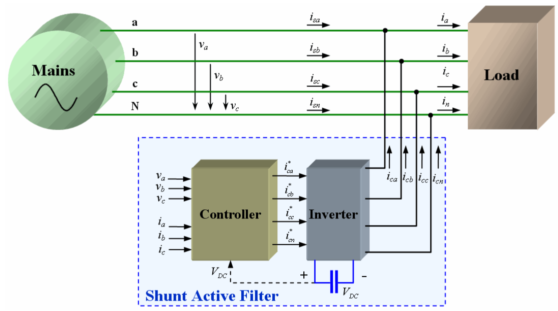

Figure 2: Shunt active power filter.

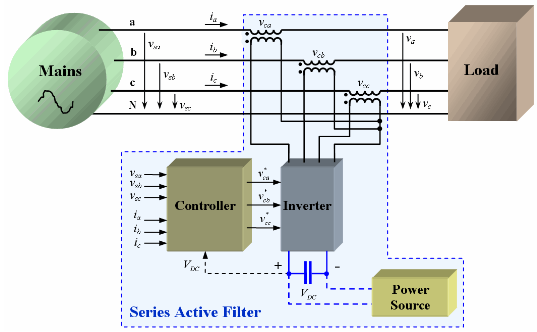

Figure 3: Series active power filter.

The control system for active power filters is usually implemented on a microcontroller or on a digital signal processor (DSP). There are many control algorithms, providing good results: for instance, the control algorithms based on the p-q theory may be easily and efficiently used for controlling active power filters. The calculations are done in the time domain, with instantaneous values of voltages and currents, and are relatively simple [1-5].

3 THE PROPOSED COMPENSATOR

The block diagram of the proposed single phase active series compensator for voltage distortion is shown in figure 4, at the end of this paper.

The system's power compensator is constituted by an IGBT single-phase full-bridge inverter, with an inductive and capacitive filter on the output. This passive filter feeds an isolation transformer which adds the compensating voltage to the mains voltage, providing an ideally non-distorted voltage to the linear load. The existence of snubber circuits associated to each IGBT is essential, because the inverter load is highly inductive, causing very high voltage glitches in the semiconductors when they turn off.

The inverter's power source is a full-bridge diode rectifier with filtering capacitor. Although there is also an isolation transformer feeding the rectifier, the presence of this transformer is not mandatory. If it is necessary to do some voltage level transformation, an auto-transformer may be used, reducing price and weight.

The main goal of the variable non-linear load in the experimental layout is to provide an adjustable non-linear voltage drop on the (exaggerated) line impedance, causing a changeable voltage distortion on the emulated "mains". There is also a bypass switch which connects the linear load directly to the "mains" or trough the series compensator.

The control system of this series compensator is implemented on a personal computer (PC) with a general purpose multifunction data acquisition board included in the PCI bus. The major advantages of this approach are the relative low cost of the equipment, the high processing capabilities of the personal computer processor, and its versatility. The personal computer used has a *733MHz Intel Pentium III* processor with *512MByte* memory. The data acquisition board is the model *PCI-MIO-16E-4* manufactured by *National Instruments*.

The control of a series active filter is a type of application which requires a fast controller, which does not lose samples, and where all the maximum allowed deadlines must be met each and every time. These characteristics imply that this application needs a hard real-time control system.

A PC implemented controller presents some difficulties. The main problems are related to the standard multitasking operating systems, and can only be solved by very skilled programmers. Another problem is the slow data input/output system. These boards are connected to the PCI bus and do not take advantage of the full processor speed. They are usually designed to acquire data for monitoring purposes or process control. Thus, they are very limited when performing hard real-time control.

Another limitation of these standard multifunction boards concerns the analogue inputs, since the several channels usually available are multiplexed and share the same digital to analogue converter, which causes the acquisition process to take a major period of time.

The reference voltage for voltage compensation is always known. Exploring this fact, it is possible to generate a reference signal and use a proportional and integral control algorithm. In this case, the load voltage is acquired and compared with the reference (desired voltage) and a voltage error is generated. Then, the control system uses the symmetric value of the voltage error as compensating voltage to be generated by the filter's power converter. The reference signal is synchronized with the mains voltage and it is generated by the personal computer, intended to obtain a 48.0 V RMS voltage applied to the linear load. It is also necessary to continuously adjust the controller's gain to compensate for the voltage drop on the inverter's direct current voltage source, because it is unregulated. Further information about the personal computer based control system and control algorithms, may be found on given references [6-8].

4 EXPERIMENTAL RESULTS

Figure 5 shows a picture with the developed system operating. The inverter is on the left, the loads are on the centre and a digital oscilloscope is on the right.

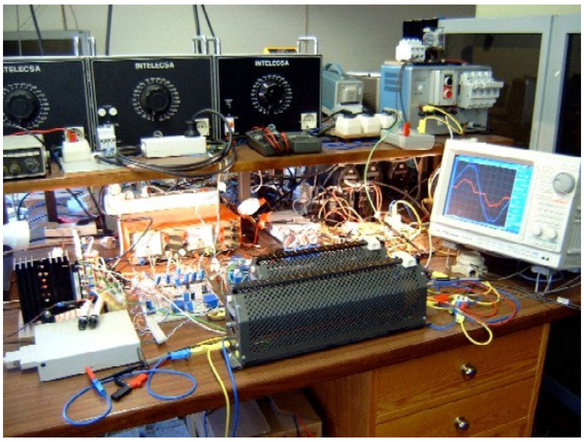

Figure 5: Developed series compensator operating.

Some tests were made to evaluate the series compensator performance. First, the non-linear load was adjusted to provide a desired voltage distortion, and the voltage waveforms and output voltage spectrum were recorded. Then, the series compensator was connected trough the bypass switch, and the new output voltage waveforms and spectrum were also recorded. Pictures 6 to 14 show the most important registered waveforms and output voltage spectrums, before and after voltage compensation. The waveforms colours means: brown - distorted mains voltage; red - compensating voltage; green - reference signal; blue - compensated load voltage.

First Test: The non-linear load was adjusted to create a small distortion on the "mains" voltage, causing the voltage to drop to 46.4 V RMS, presenting a total harmonic distortion (THD) of 4.5 %. Figure 6 shows the waveforms, figure 7 shows the voltage spectrum before compensation, and figure 8 shows the voltage spectrum after compensation. As can be seen, when the bypass switch connects the series compensator, the voltage amplitude rises to 48.2 V and the THD decreases to 1.3 %. Note that reference signals and output voltages are almost coincident.

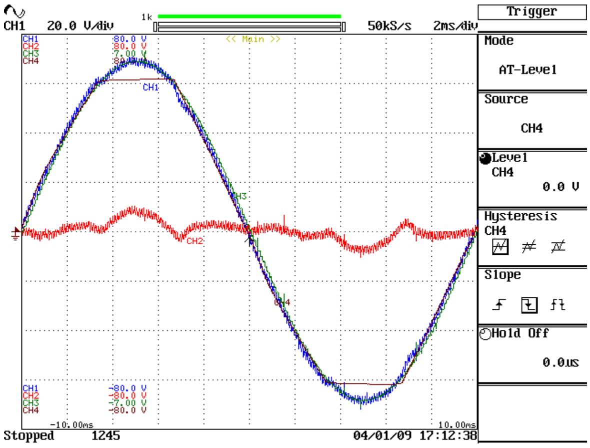

Figure 6: Most important voltage waveforms for "small voltage distortion".

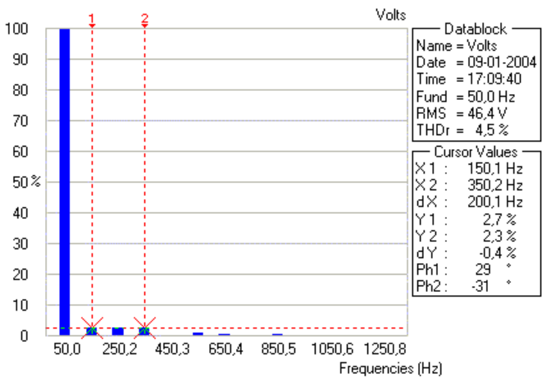

Figure 7: Output voltage spectrum for "small voltage distortion", before compensation.

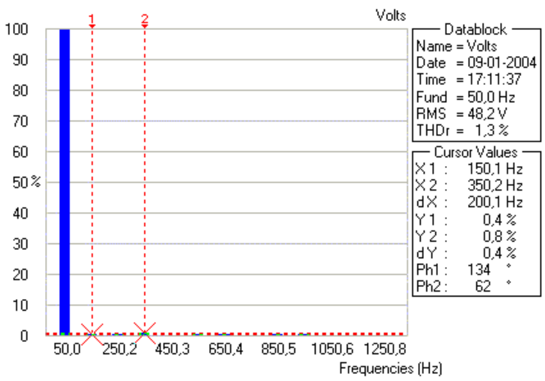

Figure 8: Output voltage spectrum for "small voltage distortion", after compensation.

Second test: In this case the non-linear load was adjusted to create a large distortion on the "mains" voltage, causing the voltage to drop to 37.2 V RMS, which represents a 22.5% voltage drop. The "mains" voltage also presents a very high level of THD: 13.2 %. Figure 9 shows the waveforms, figures 10 and 11 show the voltages spectrums.

Now, when the series compensator is connected, the voltage amplitude rises to 48.2 V and the THD decreases to 1.8 %.

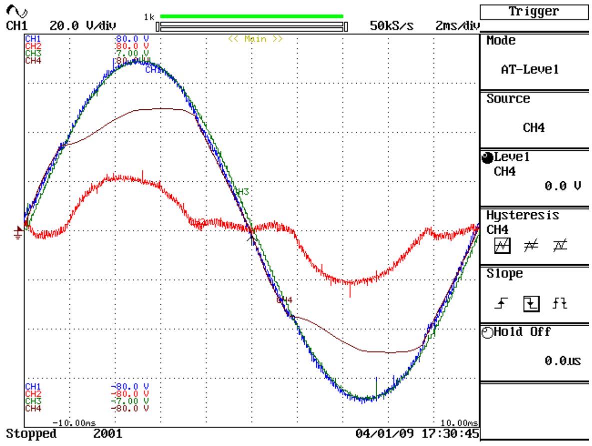

Figure 9: Most important voltage waveforms for "large voltage distortion".

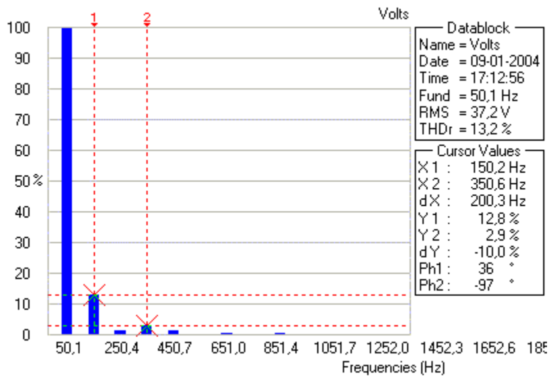

Figure 10: Output voltage spectrum for "large voltage distortion", before compensation.

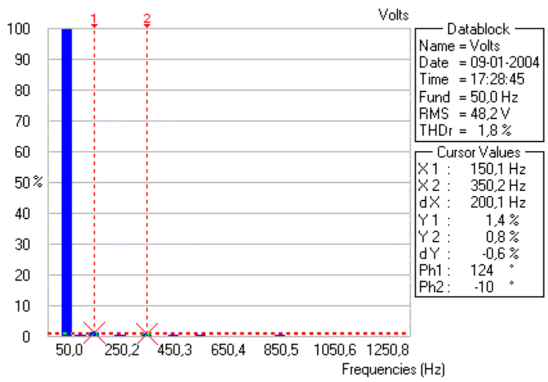

Figure 11: Output voltage spectrum for "large voltage distortion", after compensation.

Third Test: The non-linear load and the line impedance (see figure 4) were disconnected and the system was tested to compensate for the voltage distortion present on the "real" mains. The voltage THD on the laboratory where the tests were performed varies a little along the day, but it is always around 3 %. This voltage distortion can be easily seen with an oscilloscope. Figure 12 shows the voltage waveforms (colour brown - mains voltage), figure 13 shows the voltage spectrum before compensation, and figure 14 shows the voltage spectrum after compensation.

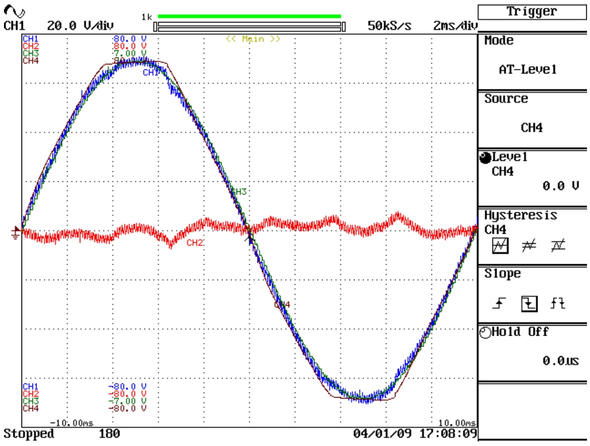

Figure 12: Most important voltage waveforms for "line voltage distortion".

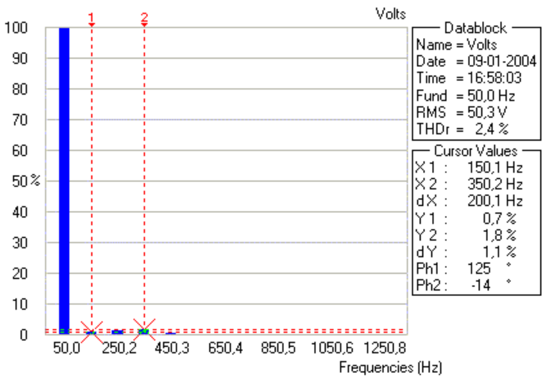

Figure 13: Output voltage spectrum for "line voltage distortion", before compensation.

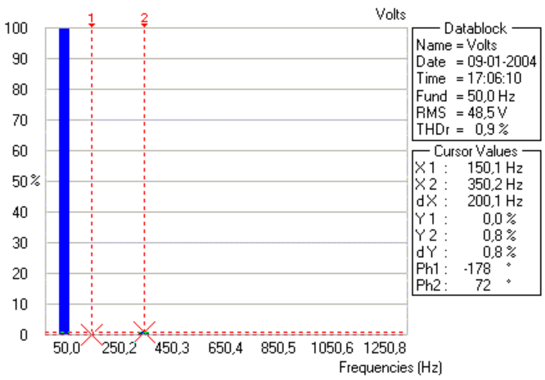

Figure 14: Output voltage spectrum for "line voltage distortion", after compensation.

At the time this test was made, the mains RMS voltage on the secondary of the step down transformer was 50.3 V and the THD was 2.4 %. This was the voltage applied to the linear load when the series compensator was disconnected.

Connecting the series compensator, trough the bypass switch, the voltage applied to the linear load becomes 48.5 V RMS (a value closer to the desired value of 48.0 V) and the THD decreases to 0.9 %.

As it can be seen in pictures 12 to 14, the proposed series compensator is able to provide a better voltage waveform than the one available on the power grid, increasing power quality.

5 CONCLUSION

The p-q theory is very effective and simple to use when controlling three-phase shunt active power filters, because the reference signals (desired currents) are not known and load dependent. Very often, the mains voltages may be considered non-distorted, simplifying even more the controller calculations, because it is not necessary to determine the voltages fundamental positive sequence.

The previous assumption is almost always not true when it concerns to a series active power filter. If the p-q theory is to be used when compensating voltage distortion, it is necessary to determine the line currents fundamental positive sequence. However, the reference signals (desired voltages) are known, allowing the use of a simple classical controller (proportional plus integral, for example).

The proposed single phase series compensator for voltage distortion reduces effectively the voltage total harmonic distortion, providing better power quality than it is available on the mains. Within certain limits, it is also capable of correcting fundamental voltage amplitude.

Although the tested series compensator was a single phase version, it may be easily adapted to a three-phase system. For this purpose it will be necessary to implement two more single-phase inverters, sharing the same DC power source.

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REFERENCES

[1] H. Akagi, Y. Kanazawa, A. Nabae, Generalized Theory of the Instantaneous Reactive Power in Three Phase Circuits, IPEC'83 - Int. Power Electronics Conf., Tokyo, Japan, pp. 1375-1386, 1983.

[2] E. H. Watanabe, R. M. Stephan, M. Aredes, “New Concepts of Instantaneous Active and Reactive Power in Electrical Systems with Generic Loads”, IEEE Transactions on Power Delivery, Vol. 8, nº. 2, April 1993.

[3] J. L. Afonso, H. R. Silva and J. S. Martins, “Active Filters for Power Quality Improvement”, IEEE Porto Power Tech’2001, Porto, Portugal, 10-13 Sept. 2001.

[4] João Luiz Afonso, “Filtro Ativo Paralelo com Controlo Digital para a Melhoria da Qualidade de Energia Eléctrica”, PhD Thesis, University of Minho, 2000.

[5] João L. Afonso, M. João Sepúlveda Freitas, Júlio S. Martins, “p-q Theory Power Components Calculations”, IEEE International Symposium on Industrial Electronics (ISIE’03), Rio de Janeiro, Brazil, 9-11 June 2003.

[6] M. João Sepúlveda, João L. Afonso and Júlio S. Martins, “A Series Active Filter Controlled by Personal Computer”, International Conference on Renewable Energy and Power Quality (ICREPQ’03), Vigo, Spain, 9-12 April 2003.

[7] M. João Sepúlveda Freitas, João L. Afonso, Adriano Tavares, Júlio S. Martins, “A Personal Computer Based Controller for an Active Power Filter”, International Symposium on Industrial Electronics (ISIE’03), Rio de Janeiro, Brazil, 9-11 June 2003.

[8] Manuel João Sepúlveda Mesquita de Freitas, “Implementação de um Filtro Activo de Potência para Optimização da Interface entre a Rede e outros Sistemas Eléctricos”, PhD Thesis, University of Minho, December 2004.

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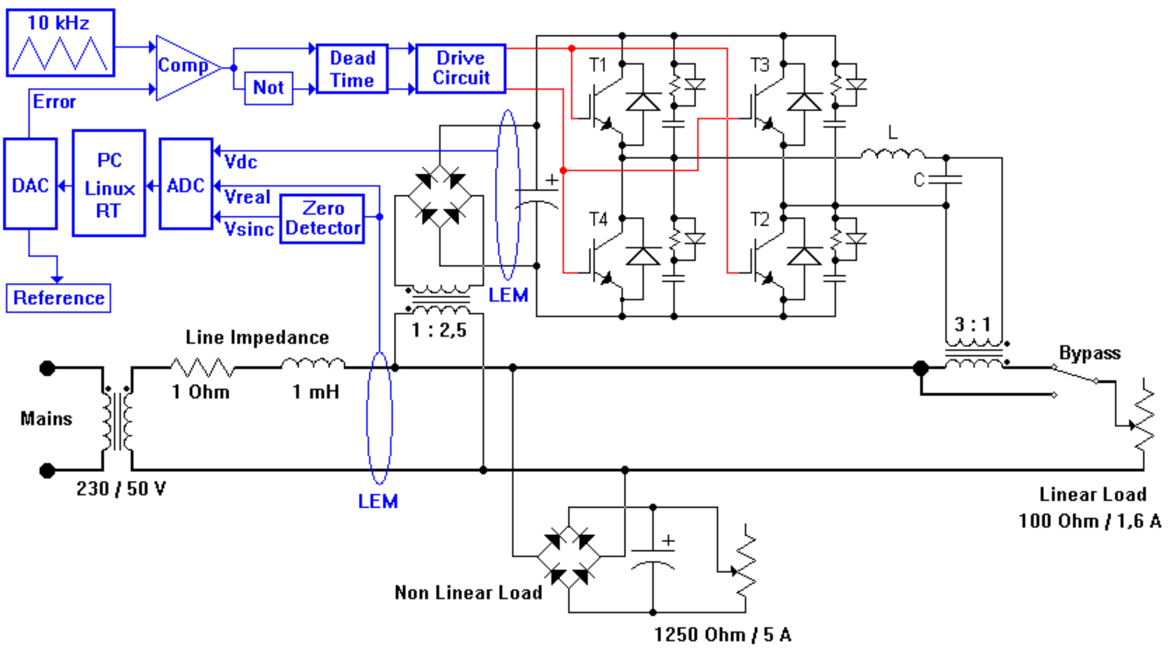

Figure 4: Block diagram of the proposed single phase active series compensator.