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Experimental Results of a Developed Single-Phase Thyristor Switched Capacitor

Bruno Exposto, Nuno Manuel, J. G. Pinto, Vitor Monteiro, Delfim Pedrosa, João L. Afonso
Centro Algoritmi – University of Minho
Guimarães, Portugal

bexposto@dei.uminho.pt, a48172@alunos.uminho.pt, gpinto@dei.uminho.pt, vmonteiro@dei.uminho.pt, dpedrosa@dei.uminho.pt, jla@dei.uminho.pt

Abstract— **In this paper are presented simulation and experimental results of a developed single-phase Thyristor Switched Capacitor (TSC), when it is compensating the power factor at the fundamental frequency (displacement power factor) of an electrical system with distorted voltage. The developed single-phase TSC can produce reactive capacitive power with 3 different values. The Thyristor Switched Capacitor is a type of equipment capable of compensating inductive reactive power at the fundamental frequency, without causing voltage and current transients when it is turned-on. However, it can be observed in this paper that in situations where the voltage is distorted, the TSC produces harmonic currents, which is extremely harmful to the electrical system. The capacitor banks used in industries for power factor correction presents the same problem when voltages are distorted.**

Keywords - Thyristor Switched Capacitor (TSC); Power Factor Correction; Reactive Poower Compensation; Harmonics; Power Quality.

I. INTRODUCTION

The reactive power compensation in the electrical system is an important issue due to the necessity of maximize the energy transmission capacity of lines and transformers. Besides this it is necessary maximize the energy efficiency of the electrical system. Regarding the industrial consumer, the reactive power compensation is a suitable way of reducing costs.

The most common equipments for reactive power compensation are Capacitors Banks. However, the reactive power compensation based only on Capacitors Banks can cause Power Quality Problems, namely voltage and current transients.

The Thyristor Switched Capacitor is a type of Flexible AC Transmission Systems (FACTS) equipment capable to compensate inductive reactive power without causing voltage and current transients. In this paper it is shown a developed Thyristor Switched Capacitor (TSC) with three levels of compensation/modules. Studies were carried out in order to improve the dynamic response of the equipment and to mitigate the inrush current that occurs when the capacitors are switched to the mains.

The implemented control system measures the voltage and current in the electrical system and calculates the active power, power factor and reactive power needed to compensate the power factor to unit or to above 0.93, that is the Portuguese reference value for payment of reactive power.

Low power factor can present several problems to an electrical installation. Usually main problem associated with low power factor is inefficiency and reduction of the energy transmission capability of the electrical grid. Accordingly with [1] the compensation of power factor in EU25 reduces the energy losses in the transmission and distribution networks and in the customers’ networks of the industry and service sectors by 48 TWh per annum, and reduces the power to be transmitted in the transmission and distribution networks by 15%.

The correction of low power factor can be done using several types of devices, e.g.: Capacitor Banks, Synchronous Compensators, Shunt Active Filters and Thyristor Switched Capacitors, Static VAR compensators (SVC), and Static Synchronous Compensator (STATCOM) [2] [3].

II. CAPACITORS AND POWER QUALITY PROBLEMS

Power factor compensation, when is done using conventional Capacitor Banks can cause Power Quality problems, mainly transient overvoltages and resonances.

The transient overvoltages (Fig. 1) can happen during the capacitor banks switching, in normal operation to compensate power factor [4]. These transient overvoltages are usually in the range of 1.3-1.4 p.u. voltage [4]. If there is a non-protected sensitive load in the same circuit, it can be damaged by this Power Quality problem.

Resonances (Fig. 2) are also one of the Power Quality problems that can be originated by capacitor banks [5]. A resonance can produce several damages in an electrical installation.

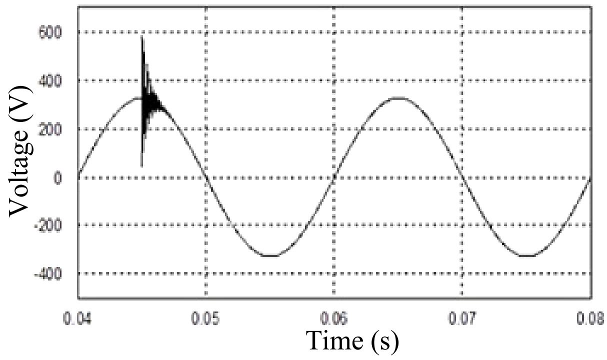

Fig. 1: Capacitor bank switching overvoltage.

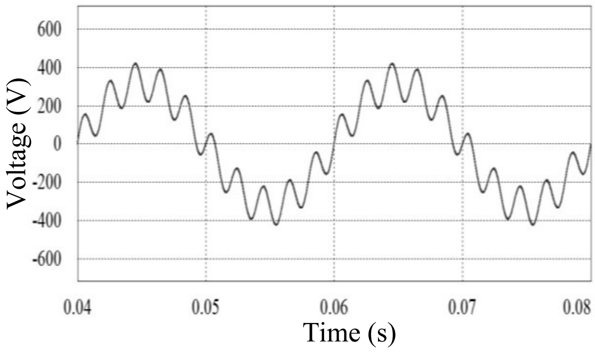

Fig. 2. Resonance voltage waveform

III. Capacitors and Voltage Harmonics

Capacitors that are placed usually for power factor correction in an electrical installation that has nonlinear loads are a low impedance path for harmonics. The placement of capacitor in harmonic rich environment can pose two problems: current overload of capacitors and parallel resonance of capacitances with inductances in their electrical proximity [6]. So is always necessary study the electrical environment in where will be placed the capacitor banks for power factor correction.

To minimize the effect of the distorted voltages in the capacitor it can be added a detuning reactor in series with the capacitor bank [6]. The added reactor impedance rises with the frequency, so although the capacitor impedance diminishes. This strategy is a good solution to deal with the harmonics in the capacitor, nevertheless the selection of the appropriate inductor requires several calculations.

IV. Developed Thyristorized Switched Capacitor

To better assess the behavior of capacitors in environments with harmonics it was simulated and developed a laboratory prototype of a Thyristor Switched Capacitor (TSC). The developed TSC is composed by three modules each one with one capacitor and two thyristors. The TSC measures the system voltage and the load current, and calculates the reactive power Q, and the power factor. At the same time it detects the voltage zero crossing. When the power factor is less than 0.93, and the reactive power (inductive) is bigger than 50 VAr the TSC control connects to the electrical grid the first module. The other modules can be connected too, depending of the value of the measured power factor and reactive power. If the load reactive power is capacitive, the TSC doesn't operate.

A. Laboratory Prototype

The developed laboratory prototype is divided in two parts, the power hardware and the digital control system. As referred before, the power hardware is composed by thyristors and capacitors, grouped in order to form three separate modules (each one with two thyristors and one capacitor).

On the other hand, the developed digital control system, shown in Fig. 4, is composed by several circuits, mainly the, the microcontroller (PIC32MX360F512L), the signal conditioning circuit to adjust the voltage and current signals from the power hardware to the voltage range of the ADCs, and the thyristors drivers. The control system is isolated from the power system through optocouplers.

The system current is measured with a LEM Hall effect sensor. The voltage is measured using a LEM voltage sensor.

B. TSC Switching Strategies

There are two switching strategies that can be used in TSC: the first ensures that the thyristor switching is done when the voltage in the capacitor is equal to zero; the second insures that the thyristor switching is done when the capacitor voltage is equal to the peak voltage of the system [7].

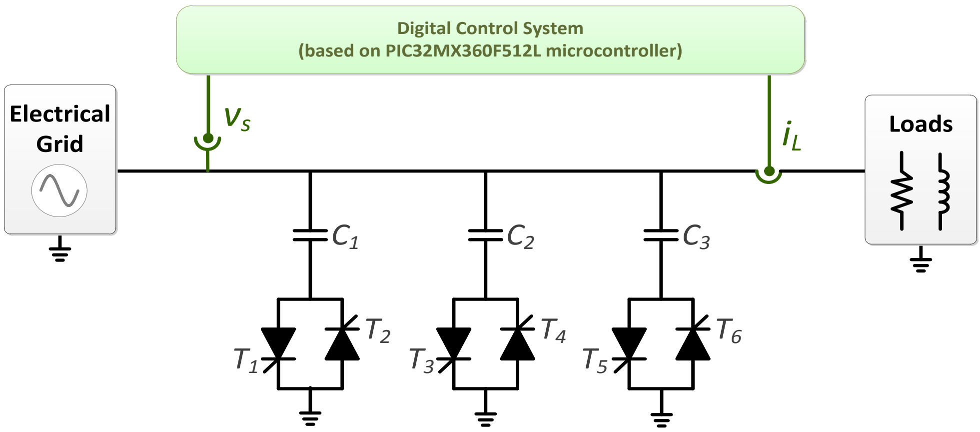

Fig. 3. Schematic of the developed single-phase Thyristor Switched Capacitor.

To perform the first strategy is necessary that the capacitors are discharged when they are disconnected from the grid, ensuring that the capacitor voltage is lower that the grid voltage. The second strategy implies a pre-charge of the capacitor so that its voltage has the same value of the peak voltage.

The connection of each module to the electrical grid is done respecting always the implemented TSC switching strategy.

Thus, this TSC switching strategy has the purpose of limit the transients that occur when the thyristors are turned on, so that the integrity of the device is not compromised and the Power Quality of the electrical installation is minimally affected.

V. Simulations of the Developed TSC

In order to understand the behavior of a TSC when the electrical grid voltage has harmonics, was recorded the voltage at Power Electronics Laboratory at the University of Minho, during a normal day, and that waveform was applied to the simulation model of the TSC. The line impedance of the simulation model is 5% of the nominal impedance. Aiming to analyze the TSC performances through computer simulations were used some resistive-inductive loads that emulate low power factor loads.

As it can be seen in Fig. 5, before the compensation the source current (i_s), it is lagging in relation with the system voltage (v_s). This indicates that the load has a low power factor. As referred before, the voltage waveform is distorted has is the voltage in a common day at University of Minho. As result of this, taking into account that the resistive-inductive load is a linear load, it's possible to see in Fig. 5 that the current is slightly distorted.

After the source current (i_s) compensation (Fig. 6) it is possible to see that the current (i_s) is almost in phase with the system voltage (v_s). Although this, the source current presents a higher harmonic distortion than before (Table 1). This distortion is caused by the distorted system voltage, and as result of that the current harmonic content increases dramatically.

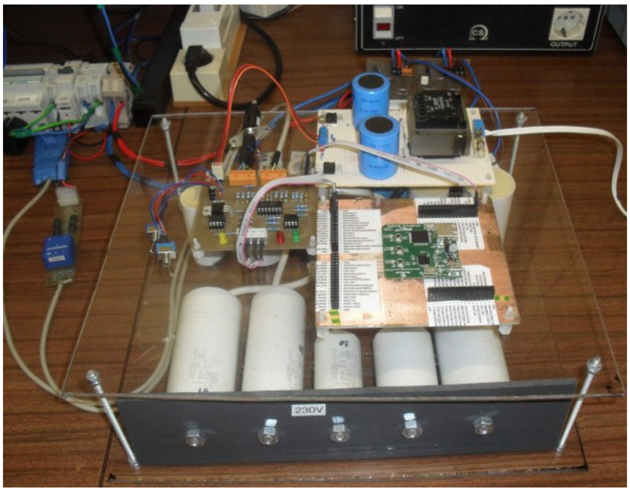

Fig. 4. Implemented single-phase Thyristor-Switched Capacitor

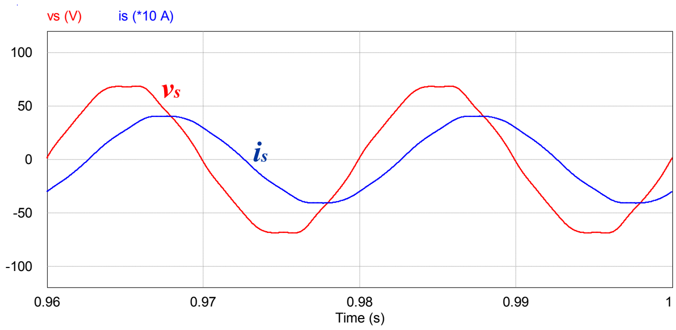

Fig. 5. Simulation results: Source voltage (v_s) and load current (i_s) before the power factor compensation made by the TSC.

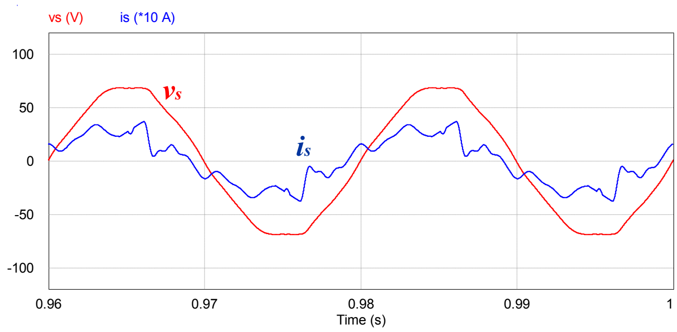

Fig. 6. Simulation results: Source voltage (v_s) and load current (i_s) after the power factor compensation made by the TSC.

TABLE I. Current and Voltage THD Before and After the Compensation

Before the Compensation			**After the Compensation**		
Total Power Factor	**Voltage THD**	**Current THD**	**Total Power Factor**	**Voltage THD**	**Current THD**
0.59	2.4%	1.6%	0.96	2.6%	27.2%

VI. Experimental Results

To assess the behavior of the TSC in real operation, the developed laboratory prototype was connected to the electrical grid, in order to compensate the power factor of a resistive-inductive load, in the same in the same condition that in the simulations.

In Fig. 7 is possible to see that as in the simulations the source current (i_s) is lagging in relation with the system voltage (e_s). The current is result of a resistive-inductive load and this is clearly a low power factor load. The system voltage (e_s) presents the normal distortion that results of the nonlinear loads present in the electrical facilities of the University of Minho.

After the power factor compensation (Fig. 8) it is possible to see that source current (i_s) is in phase with the system voltage (e_s). This indicates that the developed TSC is performing properly the correction of the low power factor at the fundamental frequency.

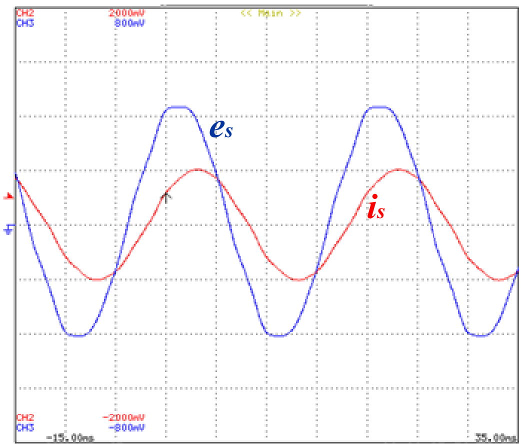

Fig. 7. Experimental results: source voltage (e_s) and current (i_s) when the electrical grid is feeding a resistive inductive load before the compensation.

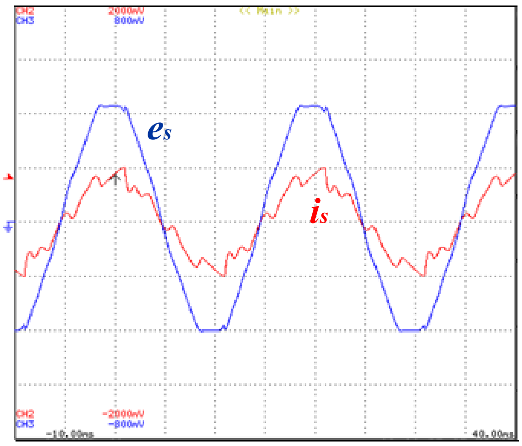

Fig. 8. Experimental results source voltage (e_s) and current (i_s) when the TSC is compensating the resistive-inductive load.

In the experimental results, the source current (i_s), as was seen in the simulation results, presents high harmonic distortion after the compensation (Table 2). As referred before, this distortion is a result of the operation of the TSC with the distorted system voltages (e_s). This indicates that the use of capacitors to correct low power factor, with distorted voltages, can increase substantially the current harmonics, and create several problems to the electrical grid.

TABLE II. CURRENT AND VOLTAGE THD BEFORE AND AFTER THE COMPENSATION

Before the Compensation			After the Compensation		
Total Power Factor	**Voltage THD**	**Current THD**	**Total Power Factor**	**Voltage THD**	**Current THD**
0.59	2.6%	1.9%	0.96	3%	15.2%

VII. CONCLUSIONS

The implemented single-phase Thyristor Switched Capacitor performs well when compensating the low power factor at the fundamental frequency, as can be seen both in the simulations and in the experimental results. However, the experimental and simulation results show that after the compensation the source current becomes highly distorted. This is related with the distortion of the system voltage, originated by nonlinear loads connected to the electrical installation (in the case of a University there are nonlinear loads almost everywhere: in the illumination systems, office equipment, computers, etc).

The compensation of reactive power in an electrical installation with distorted voltages through the use of capacitor banks, originate the distortion of the installation currents, since the capacitors consume harmonic currents in this condition of operation. With this in mind, it is necessary to take care of this problem, and should be adopted current harmonics mitigation techniques when the compensation of the low power factor is done using capacitors. Another solution consists in replacing the capacitor banks by Shunt Active Power Filters [8][9].

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REFERENCES

[1] J. S. Ronald Hänßler, Peter Knoll, "Position Paper on the Green Paper on Energy Efficiency 'Improving Energy Efficiency by Power Factor Correction'."ZVEI - Zentralverband Elektrotechnik und Elektronikindustrie e.V., 2006.

[2] J. Afonso, C. Couto, and J. Martins, "Active Filters with Control Based on the p-q Theory," IEEE Industrial Electronics Society newsletter, vol. 47, pp. 5-10, 2000.

[3] M. A. Edson H. Watanabe, "Teoria de Potência Ativa e Reativa Instantânea e Aplicações — Filtros Ativos e FACTS —," Tutorial in the CBA'98 (XII Brazilian Automatic Control Conference), pp. 1-21, 1998.

[4] M. F. M. Surya Santoso, H. Wayne Beaty, Roger C. Dugan, Electrical Power Systems Quality. McGraw-Hill Prof Med/Tech, 2002.

[5] A. Baggini, Ed., Handbook of Power Quality. 2008.

[6] S. Fassbinder, "Harmonics - Capacitors in Harmonic-Rich Environments," Leonardo Energy, 2004.

[7] R. K. V. R.M. Marhur, Thyristo-Based FACTS Controllers for Electrical Transmission Systems. John Wiley & Sons, Inc., 2002.

[8] J. G. Pinto, P. Neves, D. Goncalves, and J. L. Afonso, "Field results on developed three-phase four-wire Shunt Active Power Filters," in Industrial Electronics, 2009. IECON '09. 35th Annual Conference of IEEE, 2009, pp. 480 - 485.

[9] E. H. W. João L. Afonso, Júlio S. Martins, Maurício Aredes, "Filtro Activo Paralelo com Controle Digital de Baixo Custo," in IV SBQEE - V Seminário Brasileiro sobre Qualidade da Energia Eléctrica, 2001.