Hybrid Configuration for Reactive Power Management in Power Systems

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ABSTRACT
This paper presents a combined system of a capacitor, a thyristor controlled reactor (TCR) and a small-rated active filter (PWM-VSI) whose goal is to obtain a regulation of reactive power with a generation of harmonic currents very reduced. The electrical analysis and filtering characteristics (and size of the active unit) are discussed theoretically and several situations are simulated.

Keywords. Hybrid filters, Harmonics, Reactive Power compensation.

Introduction

Ideally, each equipment connected to the power system would absorb only active power, being the waveforms of the voltage and current purely sinusoidal and balanced. However, most of the electrical equipment absorb current distorted and/or with non-active components, which are due to the difference of phase or waveform between the current and the voltage.

Fundamental reactive power is a very important magnitude normally associated to high powers and that governs the voltage amplitude in the bus and it also affects the network stability and the power losses.

It is necessary to limit the non-active components of the power absorbed by the loads because they reduce the efficiency of the power systems and they cause a worst profit of the electrical installations, they deteriorate the power quality of the power systems and they produce extra heating and dielectric stress in power apparatus and systems, malfunctioning of control, protection and measurement equipment and degradation of the communications.

The goal of the compensation is to eliminate the components of power that do not contribute to the net transfer of energy from the source to the load. The ideal situation is that the waveforms of voltage and current in the line are both sinusoids, balanced in the case of multiphase systems and in phase. Of course, to obtain this situation at any cost is not justified.

The aim of some compensation systems such as capacitors and static var compensators (SVC) is to reduce the fundamental reactive power delivered by the power system to the load (and provide voltage control). Others, (active and passive filters) are designed to cancel the distortions.
But some compensation systems are themselves a source of distortion, being necessary the connection of passive filters, for instance, to cancel the distortion. This is the case of the SVC like the thyristor controlled reactors (TCR), that compensate for the fundamental reactive power but generate harmonic currents.

In the traditional approach to suppress harmonics in power systems, the use of shunt passive filters, filtering characteristics are determined by the impedance ratio of the source and the shunt passive filter. The source impedance is not accurately known and varies with the system configuration, affecting filtering characteristics. Parallel resonance between a source and a passive filter causes amplification of harmonic currents on the source side at specific frequencies. Besides, a passive filter may fall into series resonance with the source so that the distortion in the source voltage, vsh, produces excessive harmonic currents flowing into the passive filter. On the other hand, as the shunt passive filter acts as a current sink, is difficult to decouple the effects of one load from those of other lads connected to the line, and thus it is often necessary to oversize passive filters in order to avoid compensator failure.

A viable approach is to use active filters associated with passive ones and SVCs. Different structures have been proposed [6,7,8] on the basis of a combination of active filters (PWM voltage-source inverters) and passive elements obtaining a performance comparable to that of a conventional active filter while the active unit is much smaller in rating, thus resulting in a limitation of the overall cost.

Compensation of fundamental reactive power

Fundamental reactive power compensation can be used for power factor improvement, reduction of losses, increase of the steady-state transmittable power, voltage regulation (at intermediate points of a transmission line, or/and at the end of a line and transient and dynamic-stability improvements (to increase the first swing stability margin and provide power oscillation damping). [1].
The reactive output power (capacitive or inductive) of the compensator can be varied to control the voltage a given terminals of the transmission network so as to maintain the desired power flow under possible system disturbances and contingencies.
In load compensation, the requirements are usually to reduce or cancel the reactive Power demand of large and fluctuating industrial loads, such as electric arc furnaces, rolling mill, etc., and to balance the real power drawn from the ac supply lines. [9].

The simplest possibility is to use fixed shunt capacitors, but obviously it is no convenient if the reactive power has to be changed. Another possibility is to control the number of capacitors connected. Is the case of the thyristor-switched capacitor (TSC), in which several capacitors in parallel are connected or disconnected (with a switch or thyristors). Each capacitor conducts for an integral number of half-cycles.
The reactive power is therefore not continuously adjusted, but in steps. Besides, a resonant condition between the capacitor and the power system can be created at several capacitance values (so many as harmonic components of voltage exist). If a capacitor is shunt connected with a harmonic-producing load, a series and/or parallel resonance can occur, with amplification of harmonic voltages or currents. The magnitude of this amplification will be given by the quality factor of the resonance circuit, i.e. by the resistance connected to the circuit.
A much more fine regulation can be obtained with a Thyristor Controlled Reactor.

Thyristor Controlled Reactor (TCR)

In a Thyristor Controlled Reactor (TCR), the current can be controlled from maximum (total conduction of the thyristor valve) to zero (open circuit) by the method of firing delay angle control (the closure of the thyristor is delayed with respect to the peak of the applied voltage in each half-cycle, and thus the duration of the current conduction intervals is controlled.
A single-phase TCR is shown in figure 1.

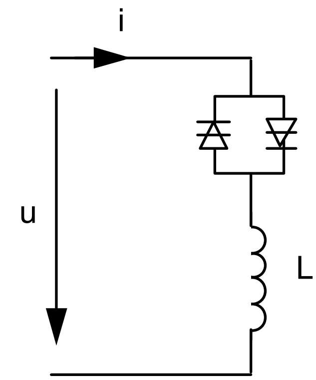

Figure 1.

When the gating of the valve is delayed by an angle alpha with respect to (the crest of) the zero pass of the voltage, the current in the reactor (in the ideal case of zero network impedance and voltage purely sinusoidal) can be expressed as

The current in the reactor can be varied.

$$i_L(t) = \frac{U_m}{wL}(\cos\alpha - \cos wt) \quad \alpha < wt < 2\pi - \alpha$$

$$i_L(t) = 0 \quad \alpha + \sigma < wt < \alpha + \pi$$

where σ is the conduction angle, $\alpha + \sigma/2 = \pi$

The adjustment of current can take place only once in each half-cycle.

The amplitude of the fundamental reactor current can be expressed as a function of alpha

$$I_1 = \frac{\sigma - \operatorname{sen} \sigma}{\pi \; wL} U$$

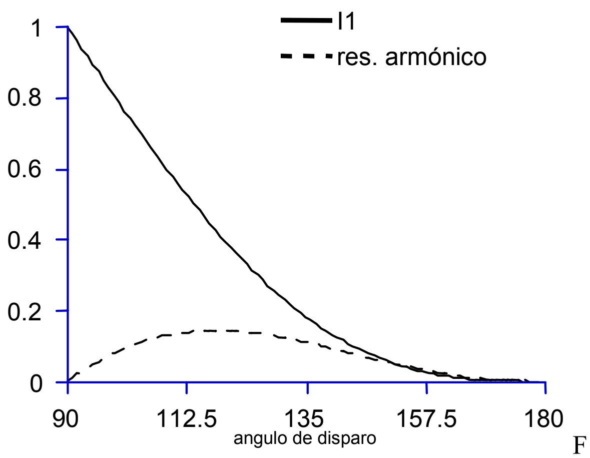

Figure2.

This mode of operation results obviously in a non-sinusoidal current waveform as it is shown in figure 2

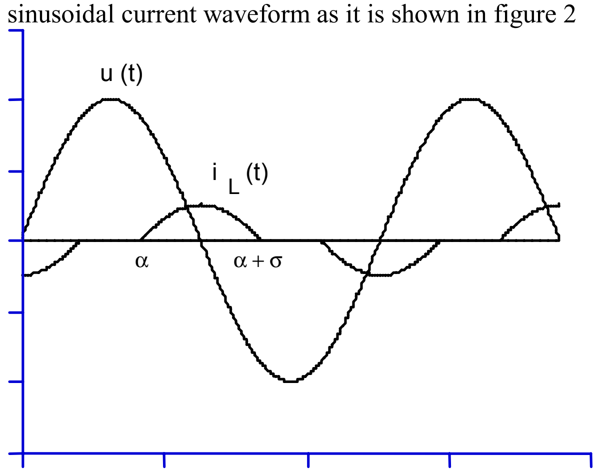

Figure 3

Therefore, the TCR, in addition to the required fundamental current, also generates harmonics. (for identical operation in positive and negative half cycles of the voltage, only odd harmonics are generated). The amplitudes of these are also a function of alpha, and can be expressed

$$I_n = \frac{4}{\pi}\frac{U}{X_L}\left(\frac{\text{sen}(n+1)\alpha}{2(n+1)} + \frac{\text{sen}(n-1)\alpha}{2(n-1)} - \cos\alpha\,\frac{\text{sen}\,n\alpha}{n}\right) \qquad n = 3,5,7....$$

The amplitude of these harmonics, expressed as percent of the maximum fundamental current, (in the ideal conditions) is shown plotted against alpha in figure 4

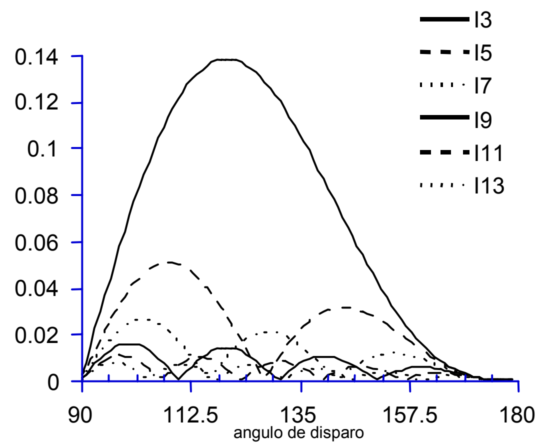

Figure 4

Harmonic currents drawn result in the distortion of the supply voltage waveforms at the point of common coupling due to the impedance of the power system. The phenomenon known as harmonic amplification, which is due to resonances between inductive and capacitive elements in the electric networks, causes an increase in the levels of distortion. Standards such as IEC 61000-3-6 and IEEE 519 have emerged with the aim of controlling those levels of harmonic distortion.

In a three-phase system, three single-phase TCR are used, usually in delta connection. Under balanced conditions, the triple- n harmonic currents (3rd, 9th, 15th, etc.) circulate in the delta and do not enter the power system.

It may not be adequate for use in an unbalanced system, since it requires an asymmetric controlling of firing angles, and then, there is a generation of third harmonic currents than enter the power system.
Further harmonic cancellation is possible higher pulse arrangements, with several phase shifted sets, but these configurations are much more complex and expensive. (Besides it is difficult to meet the requirements for symmetry)
Therefore, reduction of harmonic currents is required.

Compensation of the harmonic currents generated by the TCR

Shunt passive filters consisting of LC filters tuned at various dominant harmonic frequencies and/or high pass filters have traditionally been used to prevent harmonic currents from entering the power system because of their simplicity, low cost and high efficiency. In the case of a single-phase TCR, the predominant harmonic orders are 3, 5, 7, 11 and 13.

It has been widely recognised that the connection of shunt passive filters have serious shortcomings:
- filtering characteristics are determined by the impedance ratio of the source and the shunt passive filter and its performance is very sensitive to changes of the system impedance, usually not accurately known and variable with the system configuration;
- they are ineffective at all other frequencies different from the ones they are tuned;
- it exists the possibility of detuning of the filter;
- and, which is more important, a series or parallel resonance with the power system can result, worsening the problem of distortion both in the current and in the voltage, apart form exceeding the filter current rating.

Moreover, as the shunt passive filter acts as a current sink, it is difficult to decouple the effects of one load from those of other loads connected to the line, being often necessary to oversize the passive filters in order to avoid a compensator failure.

Active filters consisting of voltage- or current-source PWM inverters have been studied to overcome the above mentioned disadvantages inherent in passive filters. Active filters have been researched to compensate for reactive power, negative-sequence, harmonics, and/or flicker in industrial power systems since their basic compensation principles were proposed in the 1970's. However, their VA rating is very large, and unfortunately active filters are characterized by high cost. The converter VA rating determines the cost, electromagnetic interference, and switching losses.

In the present, as well as in the forseeable future, the cost of passive components will be less than that of the active components. The combined use of compensator of different rating an switching frequency can reduce the cost and improve the characteristics of compensation [3,4,5]

Hybrid configuration FC-TCR-FA and principle of operation

The hybrid compensation system proposed consists on a small active filter (FA), in series with a basic fundamental reactive compensation system: a TCR in parallel with one branch (step) of the bank of capacitors.

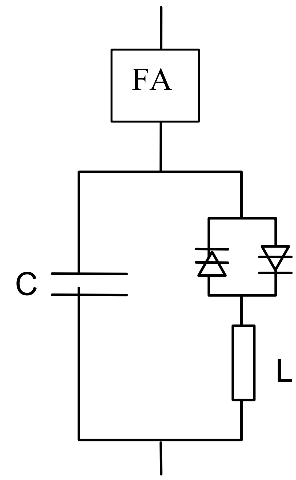

Figura 5

The active filter consists in a dc/ac converter, with a capacitor in the dc bus, whose output voltage is totally controlled by a PWM control (Pulse Width Modulated voltage-source inverter PWM-VSI)

In the figure a single phase configuration is shown. In three -phase systems it will be three single-phase inverters, with the same dc bus.

The active unit is controlled in such a way as to present an output voltage

$$vc = K\ ish,$$

where ish is the source harmonic current.

No fundamental voltage is applied to the active filter; this results in a great reduction of the voltage rating of the active filter. The function of the active filters in this topology is not to cancel directly the harmonics of the load, but to improve the filtering characteristics of the shunt passive branch and to solve the problems of the shunt passive branch used alone. The voltage-source PWM inverters are inserted in the system through current transformers. The purpose of the CT's in not only to isolate the PWM inverters from the power system, but also to match the voltage and current rating of the PWM inverters with that of the power system.

The equivalent electric circuit is shown in the figure

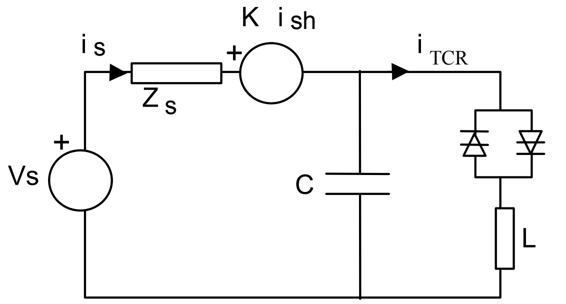

Figure 6

The passive branch can be a linear capacitor, but in a single-phase case it will be better a passive filter tuned at the third harmonic (figure 7), reducing the rating of the active filter.

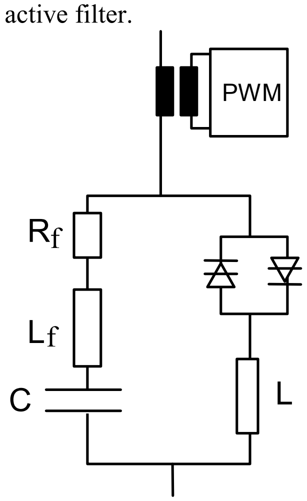

Figura 7

From an easy analysis of the circuit, the expressions for the filtering characteristics are

$$Is_h = \frac{1}{Zs_h + K + Z_{fh}} Vs_h + \frac{Z_{fh}}{Zs_h + K + Z_{fh}} I_{TCRh}$$

where I_{sh} is the harmonic component of order h of the current in the line; I_{TCRh} is the harmonic component of order h of the TCR current; V_{sh} is the harmonic component of order h of the distortion in the voltage present in the power system; Zs is the impedance of the power system; K is the gain of the active filter, and Zf is the impedance of the passive branch, passive filter or capacitor

$$Z_{fh} = R_{fh} + j(hwL_f - \frac{1}{hwC})$$

The active filter manages to regulate the amount of harmonics flowing in the passive link. The performance is very good in eliminate the resonances and the harmonic components in the current in the source.

$$\frac{Is_h}{I_{TCRh}} = \frac{Z_{fh}}{Zs_h + K + Z_{fh}}$$

The series active filter acts as a harmonic isolator between the source and the compensation system, eliminating the parallel resonance between the capacitor or shunt passive filter and the source impedance, and preventing the harmonic current produced by the source harmonic voltage from flowing into the shunt passive filter. If the resistance K is much larger than the source impedance, variations in the source impedance have no effect on the filtering characteristics of the shunt passive filter, thus reducing the source harmonic current to zero.
Under ideal control conditions, $K = \infty$ and

$$i_{sh} = 0$$

The harmonic component of order h of the voltage at the point of common coupling (pcc), V_{pcch}, is

$$v_{pcch} = - \underline{Z}_f \underline{I}_{TCRh}$$

The terminal harmonic voltage corresponds to a voltage drop across the passive filter. The source harmonic voltage does not appear on the load side because it applies across the series active filter.

The output voltage of the series active filter, is given by

$$v_{fh} = \underline{Z}_f \underline{I}_{TCRh} + \underline{V}_{sh}$$

If I_{TCRh} contains harmonic components having unspecified frequencies other than the tuned frequencies in the passive filter, a relatively large amount of harmonic voltage would occur on the bus.

The current flowing through the active filter is the fundamental compensation current of the TCR without harmonic components. The rating of the series active filter is given as a vector sum of a term which is inversely proportional to the quality factor of the shunt passive filter, and another one, which is equal to the source harmonic voltage.

Example

Let us go to consider a power system represented by its Thevenin equivalent, with the series impedance formed by a inductance (Ls = 0,1273 mH) and a resistance (Rs= 0,005Ω). The compensation system

consists ina TCR in parallel with a fixed capacitor of 810 µF.
With the hybrid system proposed in this paper (for several values of K), the harmonic currents that enter the power system are multiplied by the factor that it is shown in the next figure (harmonic order in abscissas).

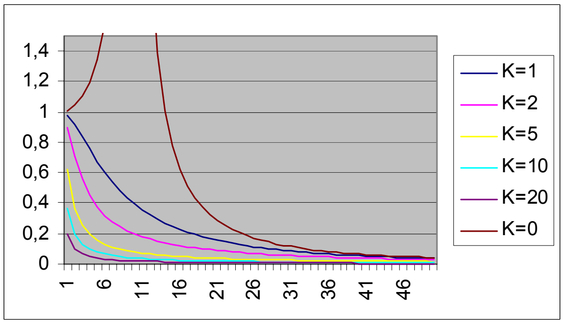

Figure 8

It can be seen that without the active filter (K=0) there is a resonance with the power system (at a frequency 9,9 times the fundamental), and the harmonics of low order generated by the TCR are amplified (in a first approximation, the order 3 is amplified a 10%, 34% the fifth, and so on). With the hybrid system, all the harmonics are attenuated (factors below unity).

If we tuned the fixed capacitor at the third harmonic (by adding a reactor in series as it is shown in figure 7, and supposing a quality factor Q of 14), the factors are

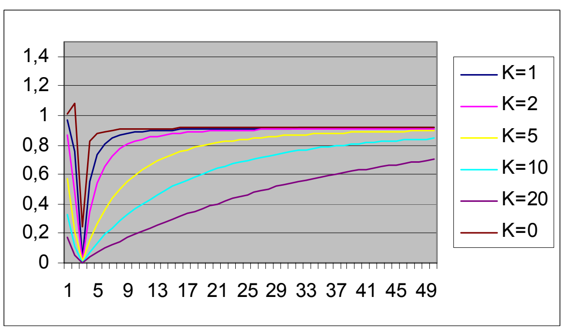

Figure 9

In a three-phase system, we can tune the capacitor to the fifth order. In this case (Q = 14) we obtain

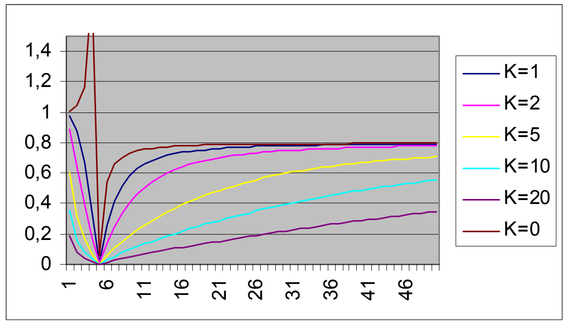

Figure 10

In this case, if only the passive filter is installed (as usual in three-phase systems), the third harmonic is amplified. So, if some unbalance is present (in the power system or in gating), the non-characteristic third harmonics can became important. This problem is solved with the hybrid configuration proposed.

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