Combined system for reactive power control in wind farms

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Abstract **- Operation of wind turbine installations may affect the steady-state voltage in the connected network. The voltage fluctuations imposed by the wind farm will depend on the characteristics of the grid. 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 in wind farms with a generation of harmonic currents very reduced. The electrical analysis and filtering characteristics are discussed theoretically and several situations are simulated.**

I. INTRODUCTION

Wind power is starting to play (contribute in) an important role in the electric generation in several countries. In EU the wind generation capacity exceeded 17 500 MW by the end of 2001 (with an annual growing in the year 2001 over 35%). In Spain, more than 3600 MW were in operation by this time, with an annual growing in the year 2001 near of the 50%.

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.

In particular, the operation of a wind turbine installation may affect the steady-state voltage in the connected network. The voltage fluctuations imposed by the wind turbine will depend on the characteristics of the grid. Voltage regulation problems arise in the power system as a consequence of grids being made dependent on wind power, a matter of growing concern as wind power gets more important in the power balance. Load-flow analyses must be done to assess this effect and to ensure that the wind turbine operation does not bring the magnitude of the voltage outside the required limits.

Until now, wind generation has not been considered for providing voltage support. The dominating kind of wind power generators are asynchronous, because of its robustness and cost effectiveness. Induction generators, however, do not contribute to regulation of grid voltage nor frequency, and they are substantial absorbers of reactive power. Ideally, they need to be connected to very stiff grids in order not to decrease power quality in a detrimental way. In weak grids, the megawatts of wind generation are limited due to this effect.

In a certain degree, voltage control problems caused by deficit of reactive power in the grid can be, and it is, reduced by installation of fixed or mechanically switched shunt capacitors. This will not help on voltage fluctuations, however, caused by varying output of wind generators.

Beside, in a philosophical point of view, in a deregulated market where all generation is considered equal, wind generation must account for the same performance as other generators in the system or make provisions to be comparable.

II. 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]. Voltage support maintains grid voltage close to a nominal value by injecting or absorbing VARs in the system. Dynamic compensation can mitigate voltage fluctuations and flicker caused by wind farms and management of reactive power helps to preserve or restore dynamic voltage stability of the system with fault situations in the grid, fast arising overvoltages caused by sudden islanding, and potential voltage collapses due to cumulating deficit of reactive power. [11,12].

The reactive output power (capacitive or inductive) of the compensator can be varied to control the voltage at given terminals of the transmission network so as to maintain the desired power flow under possible system disturbances and contingencies. The best location of the reactive power compensation is not necessarily in the farm.

The simplest possibility to inject reactive power 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. It is the case of the thyristor-switched capacitors systems (TSC), in which several capacitors in parallel are connected or disconnected with a switch or with bi-directional thyristors valve. (A damping reactor serves to de-tune the circuit to avoid parallel resonance with the network. 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. The magnitude of the 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.

III. THYRISTOR CONTROLLED REACTOR (TCR)

A TCR consists of a fixed reactor in series with a bi-directional thyristor valve. 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. Usually TCR reactors are of air core type, glass fibre insulated, epoxy resin impregnated. A single-phase TCR is shown in figure 1..

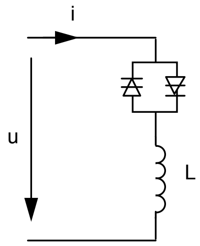

Fig. 1. TCR model.

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

$$i_L(t) = \frac{U_m}{wL}(\cos\alpha - \cos wt) \quad \alpha < wt < 2\pi - \alpha \tag{1}$$

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

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

$$I_1 = \frac{\sigma - \operatorname{sen}\sigma}{\pi \; wL} U \tag{2}$$

In a wind farm, a TCR-FC can help to maintain voltage in limits and to absorb or inject reactive power following

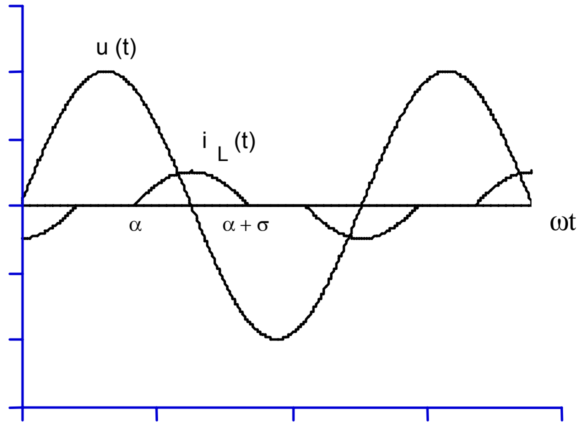

Fig. 2. Waveforms of voltage and current in a TCR

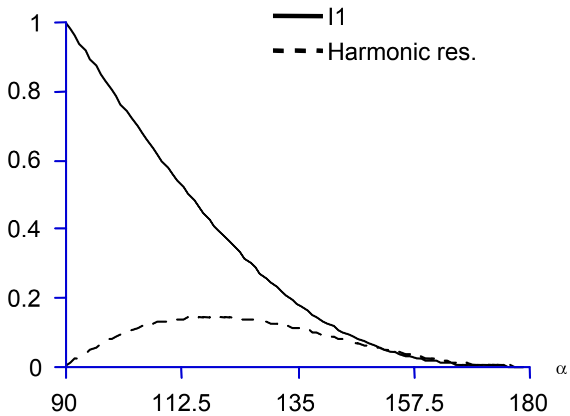

Fig. 3. Fundamental component and harmonic residue in the current of a TCR

the requirements of the utility or following economic consigns. Nevertheless, this mode of operation results obviously in a non-sinusoidal current waveform as it is shown in figure 3.

IV. HARMONIC DISTORTION GENERATED BY A TCR

A wind turbine with an induction generator directly connected to the electricity system (i.e. without a power electronic converter) is not expected to cause any significant harmonic distortion. For a wind turbine with a power electronic converter, the applicable limits for emission of harmonics should be found by applying the guidance given in IEC 61000-3-6. [10,11].

But, as has been shown, 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

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

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.

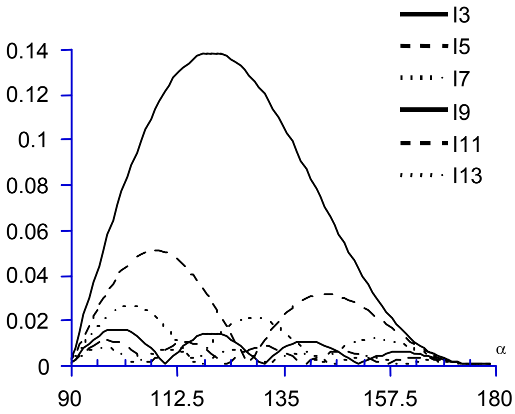

Fig. 4. RMS value of some harmonics in the current of a TCR

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. (and it is difficult to meet the requirements for total symmetry).

Therefore, reduction of harmonic currents is required. 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 has serious shortcomings. The 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.

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 characterised by high cost. The converter VA rating determines the cost, electromagnetic interference, and switching losses.

In the present, as well as in the foreseeable 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]

V. HYBRID CONFIGURATION FC-TCR-AF AND PRINCIPLE OF OPERATION

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

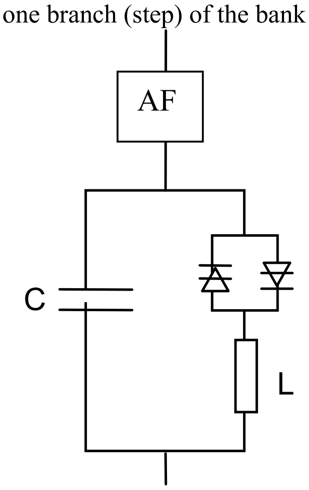

Fig. 5. Hybrid configuration FC-TCR-AF

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

$$vc = K\, ish, \qquad (4)$$

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 6

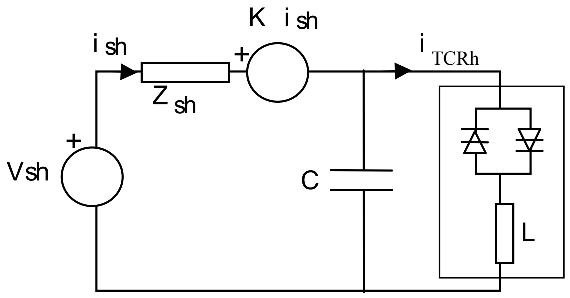

Fig. 6. Equivalent electrical circuit.

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.

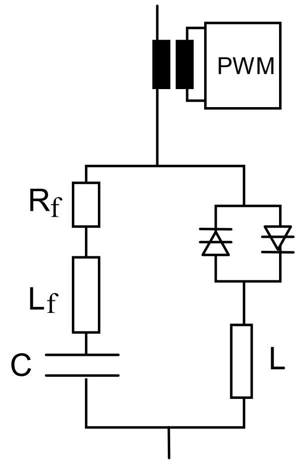

Fig. 7. Configuration proposed with tuned filter.

From an easy analysis of the circuit, (neglecting the harmonic content of the current generated by the wind generator) the expressions for the filtering characteristics are

$$Is_h = \frac{1}{Zs_h + K + Z_{fh}} Vs_h + \frac{Z_{fh}}{Zs_h + K + Z_{fh}} I_{TCRh} \qquad (5)$$

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; Zsh is the harmonic impedance of the power system; K is the gain of the active filter, and Zfh is the harmonic impedance of the passive branch, passive filter or capacitor

$$Z_{fh} = R_{fh} + j(h\omega L_f - \frac{1}{h\omega C}) \qquad (6)$$

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

$$\frac{Is_h}{I_{TCRh}} = \frac{Z_{fh}}{Zs_h + K + Z_{fh}} \qquad (7)$$

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

$$v_{pcch} = - \underline{Z}_f \underline{I}_{TCRh} \qquad (8)$$

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

$$v_{fh} = \underline{Z}_f \underline{I}_{TCRh} + \underline{V}_{sh} \qquad (9)$$

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.

VI. 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 in a 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).

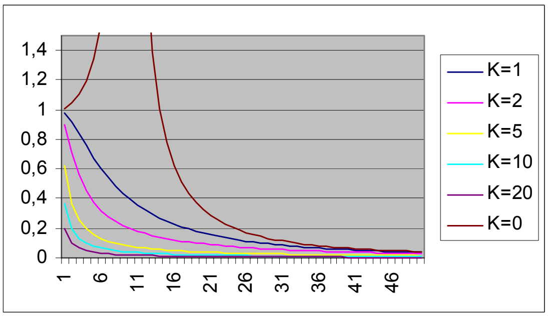

Fig. 8. Multiplicative factor as a function of K

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 to a 110% of its normal value, 134% the fifth, 199% the 7th, 568% the 9th, 431% the 11th, 138% the 13th and so on, as can be seen in figure 9. Note the differences between figure 9 and figure 4. Fortunately, in a three-phase system, triplen hamonics are cancelled.

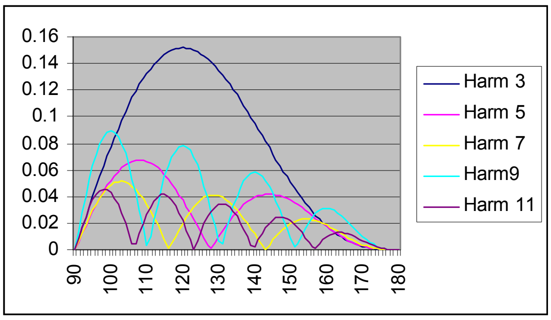

Fig. 9. Harmonic currents absorbed by the TCR due to harmonic amplification

In figure 10 is shown, as an example, the magnitude of the 7th harmonic with and without the combined system presented. Zth = 0 represents the ideal situation, neglecting the harmonic impedance of the grid. K=0 represents the situation with harmonic impedance of the network and without the actuation of the active filter, so the harmonic resonance is excited. The actuation of the active part reduces the amplitude of the harmonic, avoiding the resonance. In figure 8 is also shown that with the hybrid system, all the harmonics are attenuated (factors below unity).

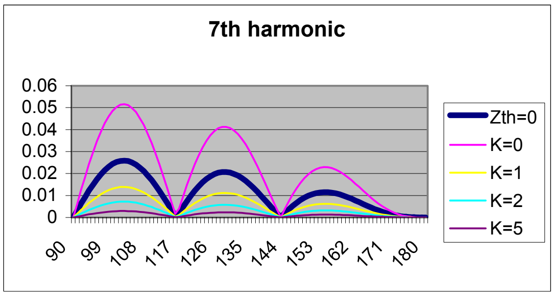

Fig. 10. Amplitude of the 7th harmonic current in the TCR

If we tuned the fixed capacitor at the fifth 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 shown in figure 11.

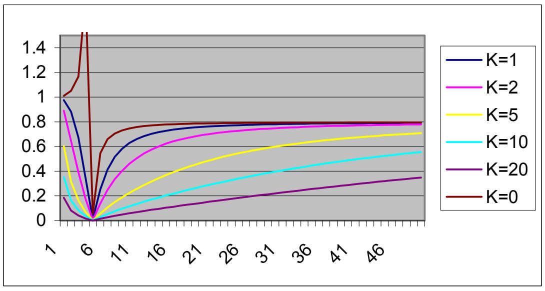

Fig. 11. Multiplicative factors with passive filter tuned at fifth harmonic.

In this case, if only the passive filter is installed, K=0, (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 also solved with the hybrid configuration proposed. With the passive filter, the active part can be designed with a small size.

VII. CONCLUSION

A combined system of a capacitor and a thyristor controlled reactor (TCR) used for a fine reactive power compensation or regulation and a small-rated active filter (PWM-VSI) reducing the harmonic content of the currents and avoiding the possibilities of resonances. The size of the active filter can be reduced even more if the capacitor is tuned at the first predominant harmonic. The combined system can help to mitigate voltage fluctuations and flicker caused by wind farms to preserve or restore dynamic voltage stability of the system.

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