The GTO-Controlled Series Capacitor Applied to Half-Wave Length Transmission-Lines

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***Abstract* – This article discusses the possibility of using FACTS devices to control the power flow in very long transmission lines. The concerned lines are a little longer (about 2 700 km at 60 Hz) than half of the wavelength with respect of the power system's frequency. These long lines basically do not need reactive power compensation to function properly, and if they are not compensated, they present, in several important aspects, much better behaviour than long lines with a length above 300 km and with conventional reactive compensation (series capacitors and/or shunt reactors). Therefore, small series compensation can be used to control large quantities of active power transmitted by half-wave length transmission lines. A FACTS device, the GCSC – GTO-Controlled Series Capacitor – is used as a series compensator to control the power flow of the line. A new control strategy is presented for the GCSC, which proves to be efficient, simple and robust. Results of computer simulations are shown to confirm the theoretical principles.**

Keywords – FACTS devices, GCSC, Half-Wave Length Transmission-Lines, Series Compensation.

I. INTRODUCTION

Brazil has suffered a severe energy crisis in the last couple of years, which has caused huge monetary losses. One of the solutions for this crisis will be the utilisation of the potential energy (based on hydro-electric units) at the Amazon Region, which is still unexplored. According to studies [1], the average potential energy reaches near to 105 GW, which is approximately 170% of the generation potential of the whole country at the end of the year 2000. It is a great challenge to transport this energy to the consumer centres, since the average distance between generation and consumption is more than 2000 km. Some publications [2-4] deal on this topics and discuss about the use of AC transmission-lines that are a little longer than half of the wavelength for the system frequency (hereafter denominated as Half-wave Length Transmission-Line). Leaving the conventional techniques of compensation which reduce the electric length of a long line through the use of capacitive series- and/or inductive shunt-compensation, and using the concepts of half-wave length transmission-line, will result in designs with low cost per unit length.

This article discusses the possibility of using FACTS devices to control the power flow in half-wave length transmission-lines. The focus is on the analysis of the GCSC (GTO-Controlled Series Capacitor) [5], of which the authors think of it, based on its simplicity and efficiency, as a device with a prosperous future. A new control strategy is presented for the GCSC, which proves to be efficient, simple and robust.

II. HALF-WAVE LENGTH TRANSMISSION PRINCIPLES

Long transmission lines that are a little longer than half of the wavelength with respect to the frequency of the power system, present some particular characteristics if they are compared to "short" lines (maximum length of a quarter of the wavelength) [2]. Conventional techniques of reducing the equivalent electric length of long transmission lines (also known as reactive compensation) to values much shorter than a quarter of the wavelength, produce innumerable severe consequences caused by multiple resonance conditions. Besides, it significantly elevates the total cost of the line. Hence, for long transmission lines, but still shorter than half of the wavelength, an interesting solution might be the dual compensation, that is, series reactors and shunt capacitors, in order to increase the equivalent electric length up to a little longer than half of the wavelength.

Consider a transmission line with reactive series- and/or shunt-compensation, uniformly distributed along the line at relatively short distances with respect to a quarter of the wavelength at the highest frequency of interest. Here, α and β are defined as in [4], that is, as series- and shunt-factors of the compensated line in relation to the line without compensation, respectively. Thus, $\alpha = 1$ and $\beta = 1$ for an uncompensated line, and, for example, in a line with 30% capacitive longitudinal (series) compensation and 60% of inductive transversal (shunt) compensation, α = 0.70 and β = 0.40. Note, that the factor $\alpha > 1$ for series inductive compensation, and $\beta > 1$ for shunt capacitive compensation.

The series- and shunt-compensation has as effect in relation to a non-compensated line [2]:

- Multiplication of the characteristic power P_C with a factor ($\sqrt{\beta/\alpha}$), where,

$$P_C = V_0^2 / Z_C \, , \tag{1}$$

- Multiplication of the electric angle between two points of the line (in particular between two extremities) with a factor ($\sqrt{\alpha\beta}$).

Therefore, in case of a necessity to reduce the electric length of a very long line (2000 until 3000 km) to a length much shorter than a quarter of the wavelength, implicates a high level of reactive power compensation. This results in high costs for this compensated line.

For long distances, according to [3], it is sensible to use lines with electric length, θ, a little longer than half of the wavelength π (2475 km, for 60 Hz, for phase speed v, 0.99 times the speed of light in vacuum). A reasonable approximation, in accordance with [3], is to choose the electric length between 1.05 π e 1.10 π (circa 2599 and 2722 km, respectively, for 60Hz). These lines do not need any reactive power compensation for operation, and can be energised at once. However, these lines need to be operated with a limited transmitted power, up to the characteristic power P_C. By passing this limit, the reactive consumption will be too high, and the voltage at the middle of the line will exceed the terminal voltage. In [4] it is demonstrated that the voltage at the middle of the line is proportional to the transmitted power. Nevertheless, in case of point to point transmission, voltage variations between 0 and V_0 at the middle of the line may not represent a major problem.

Several advantages of the use of very long lines with respect to short lines are presented in [3]. For instance, the cost of transmission per unit length of a line for a 2800 km line, 60 Hz, is lower than for a 400 km line. Further, overvoltages caused by switching of a 2800 km line without compensation are lower or equal to overvoltages of a 300 km line with normal compensation. Moreover, very long lines can be energised without the necessity of compensators, and present a better cost-effectiveness when series- or shunt-compensation is used, which is demonstrated in the following section. Thus, AC transmission lines with a little more than half of the wavelength is a viable solution, as long as costs of converters in HVDC systems are not reduced and a small HVDC tap has not been developed in practice [4].

III. Series Compensation of Transmission Lines

The basic principle of power-flow control in short transmission lines is well known and applied. For a transmission line with arbitrary length and for a series-factor α and shunt-factor β as defined before, neglecting losses, the well-known equation that determines the power flow through the line becomes:

$$P = \frac{|V_1||V_2|}{X_{eq}} \sin\delta \tag{2}$$

where,

$$X_{eq} = Z_C \sqrt{\frac{\alpha}{\beta}} \sin\left(\sqrt{\alpha\beta}\cdot\theta\right), \tag{3}$$

$$V_2 = V_0 \quad \text{and} \quad V_1 = V_0 e^{j\delta}, \tag{4}$$

V_1 is the voltage at terminal #1 (generation), V_2 is the voltage at terminal #2 (load), and δ is the angle between the two terminals.

The fundaments of FACTS (Flexible AC Transmission Systems) consist in controlling *in real time* at least one variable of the power flow, as in equation (2). In other words, the FACTS device should control the terminal voltages, the series reactance of the line, and/or the phase shift between the terminal voltages.

Fig. 1 shows the transmitted normalised active-power, P/P_c, as a function of δ, for six lines with different lengths, without losses, and without compensation for 60 Hz [4]: a) $\theta = 0.05\pi$ (approximately 124km); b) 0.10π (approximately 248km); c) 0.90π (approximately 2228km); d) 0.95π (approximately 2351km); e) 1.05π (approximately 2599km); f) 1.10π (approximately 2722km).

Lines **a** and **b** are relatively short, with "common" electric length. These lines are operated at the region with δ close to zero (see Fig. 1). Lines **c** and **d** are very long lines, with electric lengths a little shorter than π. These lines have to be operated at the region with δ close to π. However, the derivative of the power is negative in this region, as shown at Fig. 1. Therefore, this region does not contain the natural effect of stabilisation as it has for the positive derivative, which is one of the causes that make AC-systems naturally stable. Thus, lines with an electric length between a quarter of the wavelength and half of the wavelength (π/2 ≤ θ ≤ π) are not adequate for conventional operation.

Lines **e** and **f** have a length that is a little longer than half of the wavelength. These lines have to be operated at the region with δ close to π (see Fig. 1), where the derivative of the power is positive, which provokes the natural stabilisation. Near $\delta = \pi$, the behaviour of the transmission line, seen by its terminals, for a transferred power P in the range of $-P_C \leq P \leq P_C$, is similar to the behaviour of a "short" line near $\delta = 0$ [4].

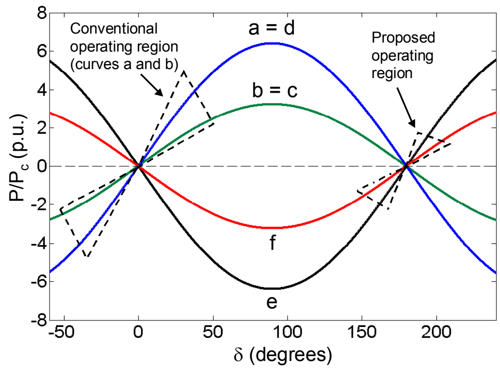

Fig. 1 Normalised transmitted power as a function of δ for different line lengths.

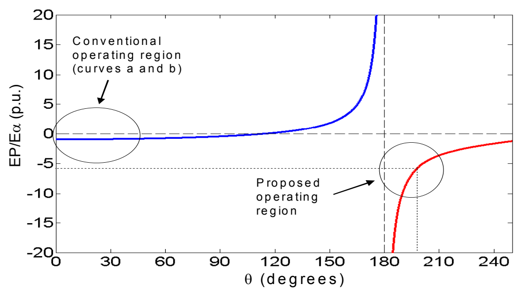

Fig. 2 Elasticity of transmitted power versus the line length θ, for active series compensation.

Fig. 2 shows the elasticity of P as function of α, $EP/E\alpha$, as a function of the electric length θ of the line where,

$$EP/E\alpha = \alpha/P \cdot \partial P/\partial\alpha \ . \quad (5)$$

It can be observed that for short lines, the elasticity of P is approximately equal to –1. In other words, for every 1% of reactive series-compensation, a control over 1% of the power flow is obtained. Whereas, for example, for a line with electric length equal to 1.10π (2722 km, for 60 Hz), an elasticity of P approximately equal to –5.82 is obtained. In this case, for every 1% of reactive series-compensation in this line, a control over 5.82% of the power flow is obtained. In this way, small series compensators can control large quantities of active power. The behaviour of reactive shunt compensation is similar, but a little less efficient [2].

As shown in the previous section, the transmission system with a little more than half wavelength, as proposed in [3], may be an interesting solution for long distance, point-to-point power transfer. The operating conditions of this transmission system can be improved with a kind of small controller, based on power electronics. This controller can be synthesised, based on FACTS concepts [6-8]. Under FACTS conceptions, there are series-, shunt-, and combined series/shunt-compensators. Various different circuit topologies synthesise shunt- or series-FACTS compensators [8]. Nevertheless, as mentioned before, reactive series-compensation appears to be more efficient in the example conditions than reactive shunt-compensation for the control of active power flow in half-wave length transmission lines. Hence, this article is only focused on series compensators.

The principal series compensators in the concepts of FACTS devices are the TSSC (thyristor switched series capacitor); TCSC (thyristor controlled series capacitor); SSSC (static synchronous series compensator); GCSC (GTO-controlled series capacitor). The first two compensators are based on thyristors. The TSSC does not permit an accurate compensation control; only a variation in degrees. The TCSC is a robust device and permits variation in the equivalent series compensating impedance by varying the firing angle of the thyristors. However, this variation is not continuous, since there is a prohibitive range of firing angle where resonance occurs. The last two compensators are based on fast commutating switches, which permit a higher degree of controllability with respect to thyristor devices. The SSSC is based on forced-commuted, voltage-source converters (VSC) and with a "minimum" energy storage element on the dc side of the converter. This device presents a fast and accurate control, and a continuous equivalent-impedance, which can be inductive as well as capacitive. Its problems still seem to be the relative high cost and lack of large previous experience in real operating conditions. Finally, the GCSC is elected as a good alternative and is discussed in the next section.

IV. The GTO-Controlled Series Capacitor

The GTO-Controlled Series Capacitor – GCSC – is a very simple device with probably the simplest configuration among all FACTS devices. It consists of a main capacitor and two GTOs connected in anti-parallel. It is inserted in series with the power transmission line. Fig. 3 shows the principal components of the GCSC.

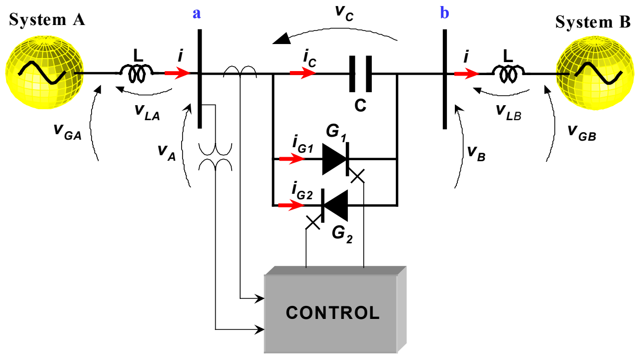

Fig. 3 The GCSC – GTO Controlled Series Capacitor.

The operation principle of the GCSC is quite simple. It is controlled by varying the extinction angle γ of the GTOs. The GCSC is a zero-voltage switching (ZVS) equipment, that is, the GTOs always fire and block at zero voltage, which reduces significantly the switching losses. Fig. 4 shows the principal current- and voltage-waveforms for the GCSC. It is assumed that the transmission-line current, i, is sinusoidal. If the GTOs are kept turned-on all the time, the capacitor C is bypassed and it does not realize any compensation effect. On the other hand, if the positive- (G_1 in Fig. 3) and the negative-GTO (G_2 in Fig. 3) turn off once per cycle, at a given blocking angle γ counted from the zero-crossings of the line current, the main capacitor C charges and discharges with alternate polarity. Hence, a voltage v_C appears in series with the transmission line, which has a controllable fundamental component that is orthogonal (lagging) to the line current.

Fig. 4 shows that the control signal for G_2 can be made as the complement of G_1. In this case, although the gate pulse duration is 180º, the positive-GTO start to conduct the line current only when the capacitor voltage (v_C) returns to zero and tries to cross the zero voltage level with positive slope. The same occurs with the negative-GTO, but when the voltage is crossing zero with negative slope.

It should be pointed out that the waveforms of i and v_C in Fig. 4 are the dual of those in a Shunt Thyristor Controlled Reactor (TCR) unity, that is often called Static var Compensator (SVC) if in parallel with capacitor banks.

It is possible to see in Fig. 4 that the GCSC capacitor stays permanently inserted if γ = 90º. This corresponds to the maximum series compensation, given by the capacitor's reactance at the fundamental frequency. Contrarily, the capacitor stays permanently bypassed if γ = 180º. An analytical expression for the equivalent series reactance, $X_l(\gamma)$, at the fundamental frequency, as a function of the extinction angle γ can be found, which is,

$$X_l(\gamma) = \frac{X_C}{\pi}\left[2\gamma - 2\pi - \sin 2\gamma\right] , \quad (6)$$

where X_C is the full series reactance at the fundamental frequency.

A simple controller has been developed for the digital model of GCSC. Basically, it consists of two control parts: a synchronising circuit (PLL) and a modified extinction-

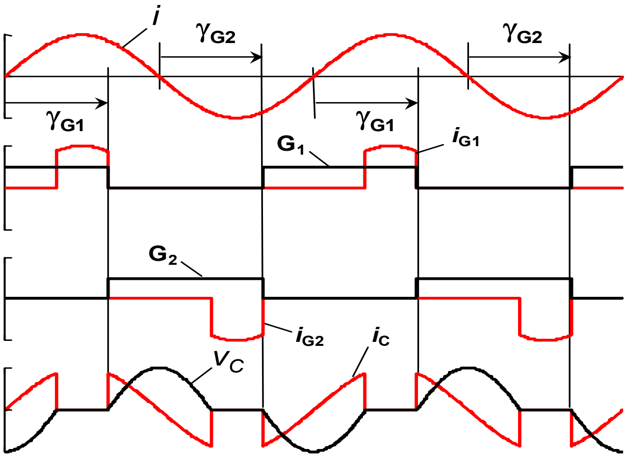

Fig. 4 Voltage, current and control signals of the GCSC.

angle (γ'), as shown in Fig. 5. The synchronising circuit locks the control signal ωt at the same frequency as the line current, and with a phase angle such that sin(ωt) is orthogonal (leading 90°) to the fundamental positive-sequence component of the line current. This type of PLL is presented with more details in [9], where it is shown to be robust and appropriated to deal with input voltages or currents containing high degree of unbalance and/or harmonic distortions.

In Fig. 4, one sees that the pulse G_1 for the positive-GTO would lead the line current by 90° if γ_{G1} is set equal to 90°. The pulse G_2 for the negative-GTO is the complement of pulse G_1. On the other hand, it is shown in [9] that the PLL circuit has only one stable point of operation, that is, sin(ωt) leads 90° in respect of the fundamental positive-sequence component of the input current (line current). This is the reason why the modified extinction angle γ' of the GCSC controller (Fig. 5) is limited in the range $0 \le \gamma' \le 90°$, which forces the effective extinction angle be in the range $90 \le \gamma_{G1} \le 180°$.

High-power application normally needs to have series-connected switches to produce high-voltage valves. However, because of the high-speed switching, the connection of large numbers of power semiconductor devices in series has been a serious problem. Fortunately, the GCSC is a type of Zero Voltage Switching (ZVS) equipment, i.e., it blocks and fires the GTOs always at zero voltage. Therefore, the series configuration of switches for very high-power GCSC-applications is much easier than in hard-switching converters [10].

The effects concerning harmonics excited by the series compensating voltage V_C of the GCSC were addressed in [10]. In order to achieve higher levels of line compensation with acceptable harmonic distortion, some arrangements of GCSC were investigated. The conclusion is, that the configuration in multi-modules is preferred, instead of multi-pulse configuration. If series compensation from inductive to capacitive is necessary, a reactor can be put in series with the GCSC of Fig. 3, and still have continuous range of operation ($90 \le \gamma_{G1} \le 180°$), but now from capacitive to inductive equivalent series impedance. This is a great advantage, if compared with the TCSC mentioned before.

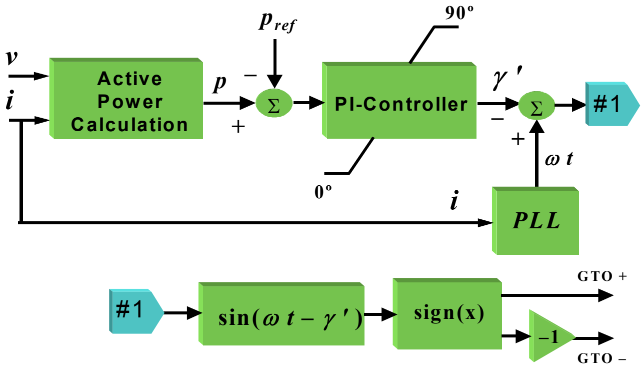

Fig. 5 The GCSC Controller.

V. System Description

Fig. 6 shows the system, which was simulated with PSCAD/EMTDC. It contains two sub systems, A and B, that are connected by two parallel half-wave length transmission lines. They are identical, they have a length of 2722 km, and are ideally transposed. One line is controlled by the GCSC and the other is not controlled. The GCSC is designed to series compensate the line and allow a control of about 20% of the rated power with no more than 3.17% of series reactance compensation.

Systems A and B are composed by ideal voltage sources behind equivalent impedances and have the following characteristics.

- System A: line-to-line voltage of 750 kV, angle 0°; 60 Hz; Impedance: 18 Ω (87°); Load at bus "a" is composed of a shunt resistor (R_1) and a R_2L-branch, both in star-connection, being $R_1 = 2000\ \Omega$, $R_2 = 724.9\ \Omega$ and L = 2.550 H.
- System B: line-to-line voltage of 825 kV, angle -191.4°; 60 Hz; Impedance: 28 Ω (87°); Load at bus "b" is composed of a shunt resistor (R_1) and a R_2L-branch, both in star-connection, being $R_1 = 250.0\ \Omega$, $R_2 = 173.6\ \Omega$ and L = 0.3054 H.

Fig. 7 shows a schematic representation of the line configuration. Although the line design has not been optimised for the use in very long distances, this does not interfere with the validation of the presented concepts. The distance between the parallel lines is considered sufficiently large, so that mutual inductances between lines can be neglected. The lines were simulated with the frequency-dependent phase model of the PSCAD/EMTDC. For 60 Hz, it gives:

$Z_{c(pos)} = 265.27 - j\,3.9455\ \Omega$

$Z_{(pos)} = 0.010174 + j0.34195\ \Omega/km$

$P_c = 2.12$ GW (750 kV);

The GCSC capacitance is C = 90 µF ($X_{C(max)}$ = 29.473 Ω, for 60 Hz); control gain of the PLL's PI (kp = 30 and ki = 3000); gain of the extinction-angle control's PI (kp = 30 and ki = 1667).

VI. Simulation Results

The design optimisation of the half-wave length transmission line is still in progress. This section shows preliminary results obtained with the line design that is shown in

Fig. 7. Hitherto, simulation results have confirmed the feasibility of the proposed approach of GCSC for controlling power flow through half-wave length transmission lines.

Fig. 8 and Fig. 9 show the phase-to-ground voltages at the sending and receiving ends of the half-wave length transmission line, for the worst case of open-line energising and with the GCSC by-passed. The one-phase circuit breakers are forced to close at different instants, close to the peak value of each phase voltage and keeping a time delay between the first and the last closing breaker no longer than 8 ms. Moreover, there are no shunt reactors, neither at the receiving end, nor at the sending end, and the breakers are not equipped with pre-insertion resistors. The maximum over-voltages for the phase-to-earth voltage, and phase-to-phase voltage, respectively, are 1.97 p.u. and 1.904 p.u. (voltage bases are 433 kV and 750 kV, respectively). The ratio between receiving-end voltage and sending-end voltage is 1.067 at the non-loaded line. Thus, this line induces lower over-voltages than those typical values observed in short lines.

Fig. 10 shows a case that starts with a quasi stationary state, with the Z-constant loads connected with bus "a" and "b" (see Fig. 6). It also shows the unblocking of the GCSC at 0.5 s; a step change in the power order of the controlled transmission line from 0.8 p.u. to 1 p.u. at 1 s, another step change from 1 to 0.85 p.u. at 3 s, and finally the blocking of the GCSC at 5 s. The active power reference is determined as 1 p.u. (1.89 GW), as for the power at the output of the transmission line (bus "b"), when the input power (bus "a") is equal to the line's characteristic power, $P_1 = P_C = 2.12$ GW. Fig. 10 shows the transmitted active powers through both lines, Transmission Line #1 (TL#1, controlled line) and Transmission Line #2 (TL#2, uncontrolled line), and the power reference. Fig. 11 shows the GTOs' extinction angle, γ_{G1}, for the same simulation.

A small compensation of just 0.0316 p.u. of series reactance for the line allows a control range of 0.20 p.u. in the transmitted power. This represents an approximated average elasticity, $EP/E\alpha$, of 6.33, which coincides with the theoretical curves shown in Fig. 2.

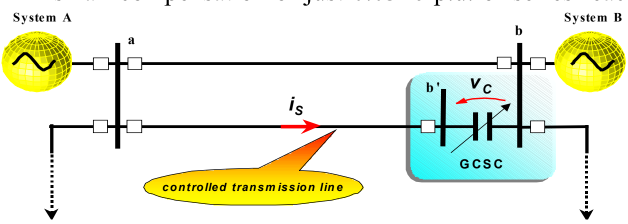

Fig. 6 Power system configuration.

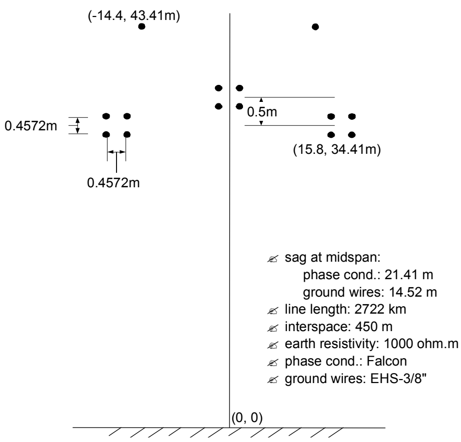

Fig. 7 Schematic representation of line configuration.

Fig. 12 shows, for $1.0\ \text{s} \le t \le 1.5\ \text{s}$, the *a*-phase capacitor-voltage [kV] of the GCSC and the *a*-phase line-current [kA] (this current was multiplied by 50, for a better viewing in the same scale of the voltage). It can be observed, that the current rises as the compensation by the GCSC increases (increasing the GCSC compensating voltage).

For the same time interval as in Fig. 12, Fig. 13 shows the time evolution of continuously calculated 3^{rd}, 5^{th} and 7^{th} voltage harmonics expressed in effective values. Note that the harmonics have maximum values at different values of blocking angles. The maximum THD_V is 5.50 kV effectively and occurs approximately at $t = 1.212$s, when $\gamma \approx 113°$.

VII. Conclusions

The concept of half-wave length transmission-lines discussed in the paper is viable to transmit large amount of energy over very long distances. The use of a type of FACTS device, the GTO-Controlled Series Capacitor (GCSC) proved to be very effective in controlling such lines and presented fast response, comparable with those obtained with dc-transmission systems (HVDC systems).

Long transmission lines, which are a little longer than half of the wavelength with respect to the system frequency, are very convenient from the compensation point of view. Its operation constraints are comparable to those applied to 300 km lines with conventional compensation.

A relatively small series compensator has been employed to control the power flow in a range of about 20% of rated power. It is expected that it is possible to increase this range without a significant increment in the rated power of the GCSC. The developed GCSC controller has proved to be robust and very simple to be implemented. The GCSC has a very fast response and can be used to improve system transient stability, with advantages if compared to the performance of others series compensators like TCSC, based on thyristor valves, or SSSC, based on voltage-source converters.

Recently, the authors are working on the use of non-conventional designs of transmission lines, optimised for very long distance interconnections and investigating the possibility of draining power through an "HVAC Tap".

Acknowledgments

The authors are grateful to CNPq, Conselho Nacional de Desenvolvimento Científico e Tecnológico, Brazil, which supported this work.

References

[1] Eletrobrás, "SIPOT, Information System on Brazilian Hydro–Electric Potential (in Portuguese)," Brazil, 1999.

[2] C. Portela, M. Tavares, G. Moreno, "Basic Constraints of Very Long Distance Transmission (in Portuguese)," *XII SNPTEE, National Seminar of Production and Transmission of Electric En-*

ergy, 6p., Recife, Brazil, 1993.
[3] C. Portela, S. Gomes, "Analysis and Optimization of Non Conventional Transmission Trunks, Considering New Technological Possibilities" *VI SEPOPE - Symposium of Specialists in Electric Operational and Expansion Planning*, Salvador, Brazil, 1998.
[4] E. H. Watanabe, M. Aredes, C. M. Portela, "Electric Energy and Environment: Some Technological Challenges in Brazil – chapter of book Energy and Environment – Technological Challenges for the Future", Edit. Y. H. Mori, K. Ohnishi - Springer -ISBN 4-431-70293-8 Springer-Verlag, pp. 10-40, Tokyo, Japan, 2001
[5] G. G. Karady, T. H. Ortmeyer, B. R. Pilvelait, D. Maratukulam, "Continuously Regulated Series Capacitor," *IEEE Trans. Power Delivery*, Vol. 8 (3), pp. 1348-1355, July 1993.
[6] N.G. Hingorani, "Power electronics in electric utilities: role of power electronics in future power systems", *Proc. of the IEEE*, Vol. 76, no. 4, pp. 481-482, April 1988.
[7] N.G. Hingorani, "Flexible AC transmission," *IEEE Spectrum*, vol. 30 (4), pp. 40-45, April 1993.
[8] N.G. Hingorani, L Gyugyi, "*Understanding FACTS: concepts and technology of flexible AC transmission systems*," IEEE Press, New York, 1999.
[9] M. Aredes, G. Santos Jr., "A Robust Voltage Control for Multi-pulse STATCOMs," *in IPEC 2000 - International Power Electronics Conference*, Vol. 4, pp. 2163-2168, Japan, April 2000.
[10] L.F.W de Souza, E.H. Watanabe, M. Aredes, "GTO Controlled Series Capacitors: Multi-module and Multi-pulse Arrangements," *IEEE Trans. Power Delivery*, Vol. 15 (2), pp.725-731, 2000.

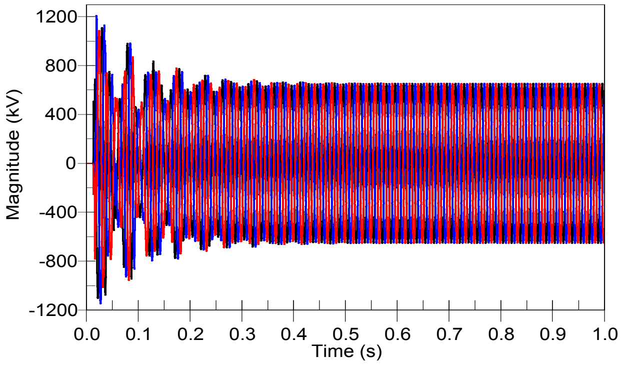

Fig. 8 Receiving-end (bus b) phase voltages during open-line energising.

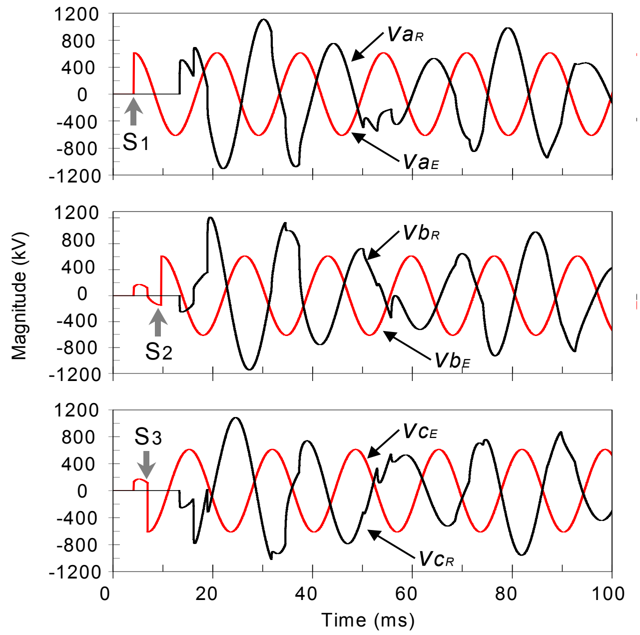

Fig. 9 Sending-end phase voltages (index E) and receiving-end phase voltages (index R). S1 until S3 indicates the distinct closing instants of the one-phase circuit breakers.

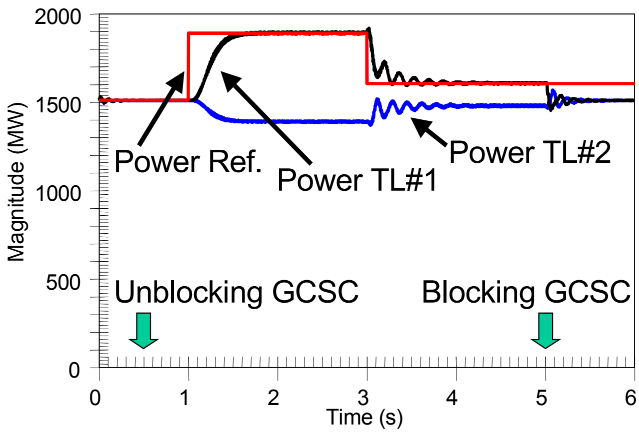

Fig. 10 Power flow through the parallel lines and the power order for the line controlled by the GCSC.

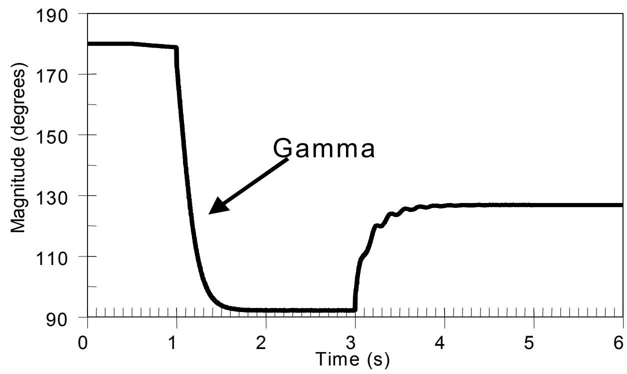

Fig. 11 The GTOs' extinction angle, γ_{G1}.

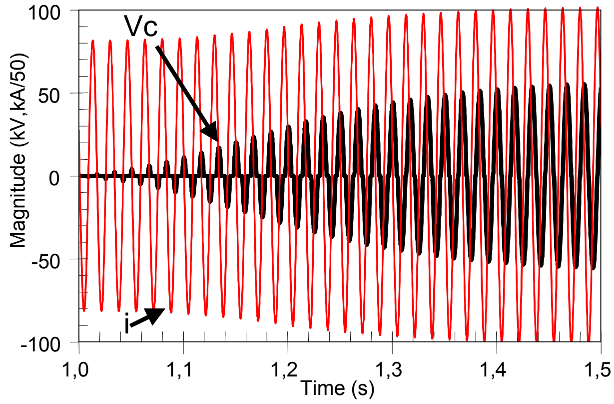

Fig. 12 Capacitor voltage v_c and current i, of the GCSC.

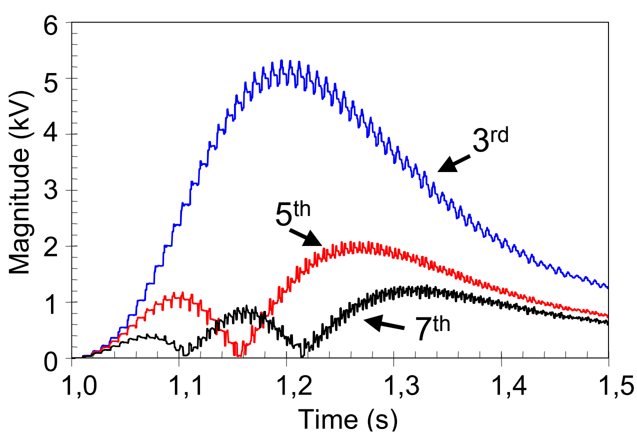

Fig. 13 The 3rd, 5th and 7th order voltage-harmonics in the GCSC.