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DETAILED MODELING OF AN ACTUAL STATIC VAR COMPENSATOR FOR ELECTROMAGNETIC TRANSIENT STUDIES

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ABSTRACT

This paper presents a detailed model of an actual Static VAR Compensator for digital simulation of electromagnetic transients. It also demonstrates that this model is adequate to reproduce SVC transient behaviour as verified in TNA studies carried out with a replica of the SVC control system. The SVC control system is described, with emphasis on some special blocking schemes needed to meet particular requirements of the power system transient performance. Complete system and SVC data are also included.

KEYWORDS - Static VAR Compensator (SVC), Thyristor Controlled Reactor (TCR), Electromagnetic Transient Program (EMTP), Transient Network Analyser (TNA).

INTRODUCTION

Time domain simulation is the most important tool there is for power system analysis. Powerful, efficient programs now available, as the EMTP [1] enable simulation to the required level of detail of practically all transients of a power system. With such programs, sophisticated, detailed models of, for example, SVC control systems can be developed to investigate complex transients of a power system. Transient Network Analysers have also been used in the analysis of system transients. These may use physical models of power system components, as reactors, capacitors etc, or electronic models. They are not commonly available within utility companies, where digital programs are the usual tool for simulating power systems.

The simulation facilities and modeling potential that such digital programs provide have assuredly met the requirements of power systems made increasingly complex by equipment of new, sophisticated technology. Various types of SVCs, HVDC transmission and their control systems, for instance, cause new, complex phenomena that substantially modify system transients. Understanding the interrelated physical phenomena, and sorting the effects which should be taken into account from those which can be disregarded are prime requirements for modeling system equipment. The definition of the level of detail required by a specific phenomenon in the system demands familiarity with the equipment and with the characteristics of the system.

For synchronous machines, it has been possible to set up general guidelines for the level of detail required by models for various types of investigation [2]. Owing to differences of design concept and type between SVCs, however, guidelines for them have proved difficult to set up. Furthermore, interaction between the SVC and inherent system characteristics affects the modeling requirements [3]. False assumptions can lead to the suppression in the simulation of relevant, real effects or to the appearance of non-existing effects.

This paper presents the experience of modeling an actual SVC whose detail requirements are remarkably strict. It is made up of a thyristor-controlled reactor and a fixed capacitor. It operates in a regional subsystem that is part of the Northern-NorthEastern interconnected power system of Brazil, in the Fortaleza substation. Its Effective Short Circuit Ratio - ESCR is 1.67. As its rating is so high compared with the short-circuit power level of the connected bus, the SVC control system can be said to practically dictate the behaviour of system transients. Short-circuits and subsequent load rejections demand an effective, suitable SVC response, which is determined by the strategy and parameters of the SVC control system.

Studies to define, for example, the parameters of the control system of an SVC demand an appropriately detailed modeling of its control system, of its synchronising, and of its firing system.

In the present work, each section of the SVC structure is described in detail. Some special features of the SVC control system, as the Undervoltage Blocking Scheme (UBS) and the BOD Blocking Scheme (BBS) are commented on. Detailed modeling of the synchronising and firing systems for EMTP/TACS (Transient Analysis of Control Systems) is presented. Results of simulations with the EMTP compared with TNA simulations are also presented.

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2 - DESCRIPTION OF FORTALEZA SVC

2.1 - Power Circuit

Fortaleza SVC has two sections, each one with one capacitor bank and one TCR connected to the low voltage side of a 230/26/26kV step down transformer, as shown in Figure 1.

Power components of the SVC are represented with the conventional models available in the EMTP. Complete data of the SVC and transmission system studied, shown in Figure 4, are presented in the appendix.

2.2 - Control System

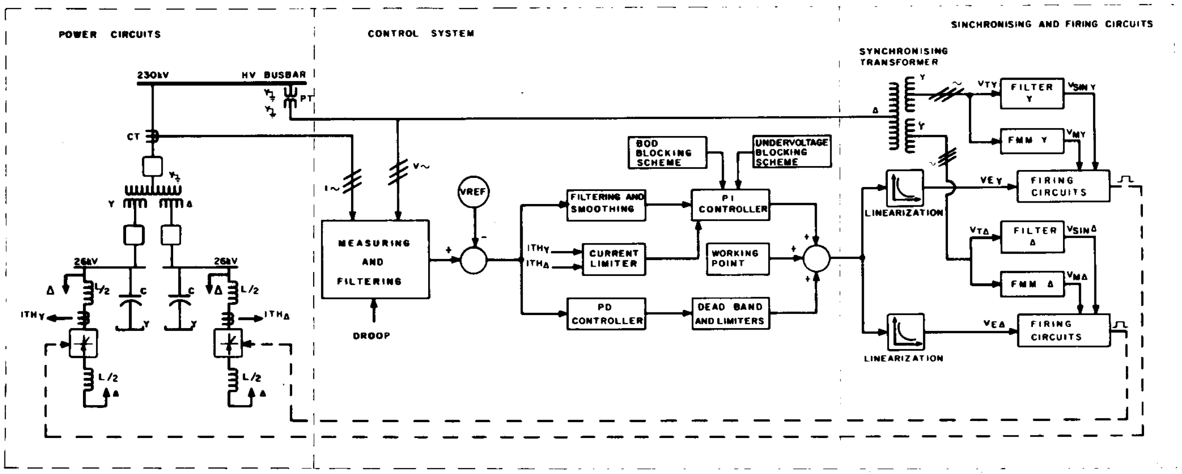

Figure 1 - Structure of the Fortaleza SVC

The SVC is dimensioned to be capable of drawing -140Mvar (inductive) to +200Mvar (capacitive) at high voltage bus, when operating with both sections in a twelve pulse mode or from -70Mvar to +100Mvar when operating with only one section, for any value of HV busbar voltage within the range 230kV ± 5%.

2.2.1 - Measuring and Regulators

Three phase voltages and currents measured by 230kV potential transformers (PTs) and current transformers (CTs) are used to evaluate w(t) = v(t) + ki(t), where k is the regulating droop, adjustable between 0 and 10%, as shown in Figure 2. These signals are

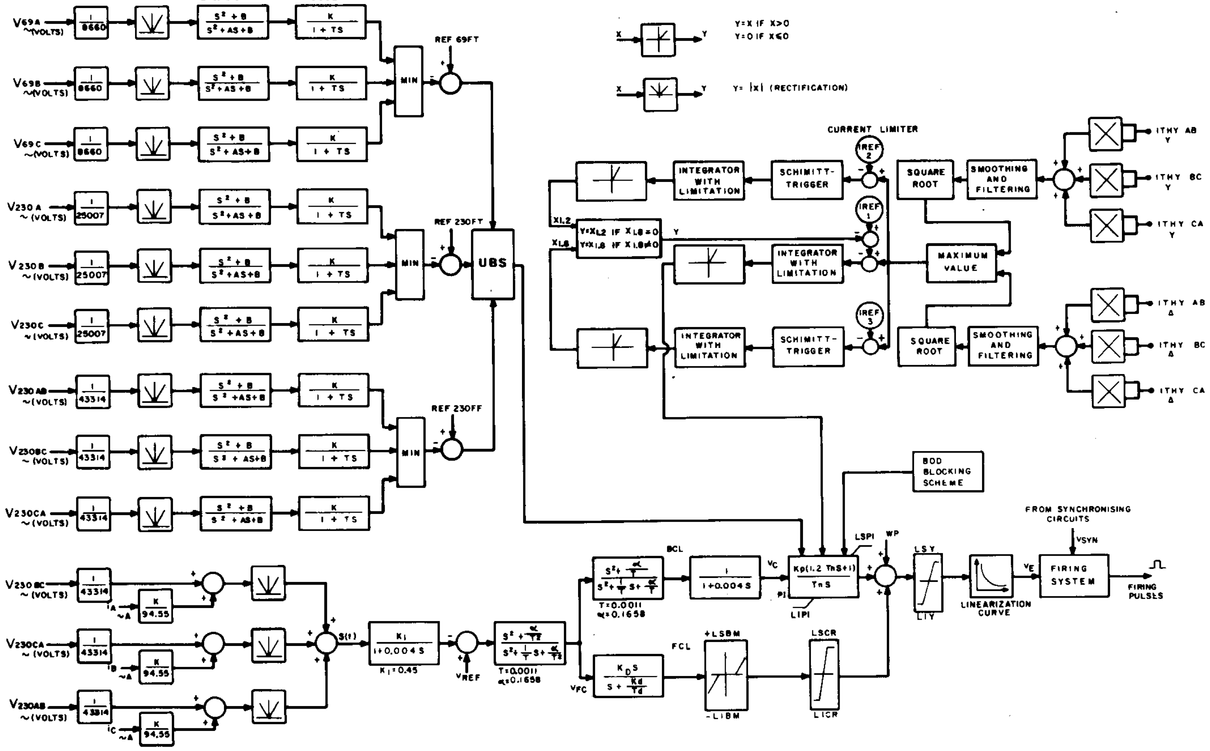

Figure 2 - Block diagram of the SVC control system

rectified, smoothed and summed to obtain U. U is then compared with the reference value to give the error signal E. The control action is determined by two control loops, known as Basic Control Loop (BCL) and Fast Control Loop (FCL), whose structures are shown in Figure 2. The BCL, which operates continuously, uses a PI regulator that is the main regulator. The FCL operates only for large disturbances due to the use of Dead-Band blocks. The magnitude of the FCL control action is also adequately limited.

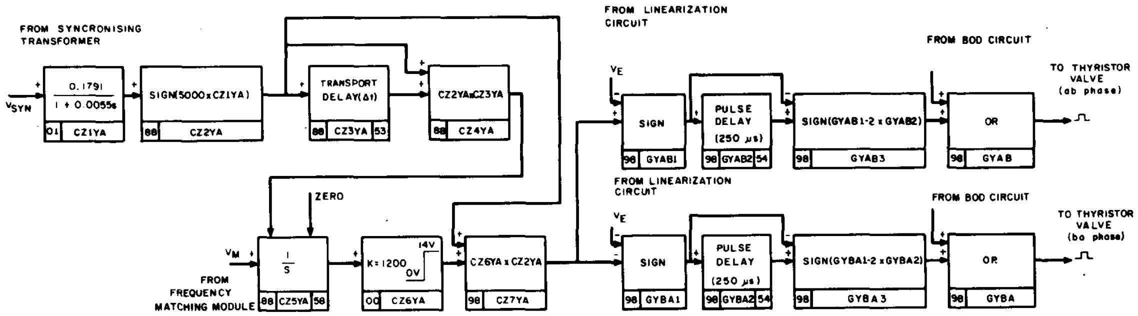

Figure 3 - Modeling of firing system in term of TACS/EMTP language

The total control UR is made up of two control loops plus a DC value (WP), so that 0 Volt input of the linearization curves gives zero Mvar at 230kV busbar, corresponding to a firing angle equal to 119°. UR is a voltage signal proportional to the SVC admittance (Y) for fundamental frequency; here, 60Hz.

The linearization curves needed to compensate the non-linear relationship between admittance and firing angle are tuned to produce the desired effect of admittance as seen from the 230kV busbar, as shown in Figure 2. Two exactly equal curves are provided, one for each SVC section Y and Δ. The output of the linearization curves are voltage signals proportional to the firing angle "α". The linearity between UR and the corresponding Y is tested on site during commissioning.

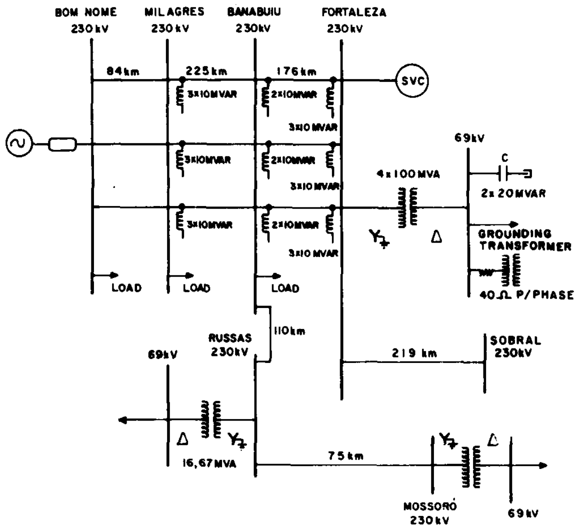

Figure 4 - Simplified one-line diagram of the subsystem as used in simulations.

2.2.2 - Undervoltage Blocking Scheme

During faults in the transmission system, for which the system voltages go down, the SVC voltage regulator would attempt to control the busbar voltage. This would take the SVC to the maximum capacitive operating point with disastrous results after fault clearing, especially when load rejection occurs. To avoid this, an Undervoltage Blocking Scheme (UBS) is provided, to force the SVC to zero Mvar operating point, whenever any of the 230kV phase-phase, 230kV phase-ground or 69kV phase-ground voltages drops below set values.

The UBS works by discharging the integrator of the PI regulator, blocking its output at zero until 10ms after the blocking conditions are removed. With the PI regulator blocked, the SVC operates around 0 Mvar. Such characteristics of the SVC control system can easily be modeled with TACS/EMTP special block facilities [1].

The UBS plays an essential role in SVC transient performance. Voltage control equipment that handles 340 Mvar in a system busbar with a power short-circuit equal to only 600Mvar must be appropriately intelligent and reliable.

2.2.3 - Current Limiter

In order to avoid thyristor valve current overloads, an additional current limiter control loop (CL) is provided.

The rms values of thyristor valve currents are measured in both sections of the SVC, for each phase. The highest value of the twelve measured currents is selected, filtered and smoothed, as shown in Figure 2. Comparing this signal with reference values enables the identification of an overload condition that requires CL control.

Under thyristor current overload, the CL reduces the inductive limit of the total regulator output.

2.2.4 - BOD Blocking Scheme

TNA simulations have shown that under some operating conditions, faults on the 69kV busbar with total load rejection may give rise to overvoltages on the thyristor valves high enough to cause BOD firing. In these cases, the transient thyristor valve currents are high enough to activate the current limiter (CL) control loop. The BOD Blocking Scheme (BBS) coordinates BOD firing with CL actuation. It operates as follows:

- When protective firing occurs, the BBS forces the PI regulator output to an adjustable value for 10ms. After 10ms, the PI is released to operate normally.

The TNA studies demonstrated that this BBS action prevents oscillations between CL and BOD. In simulations where BOD firing is likely to occur, the CL and BBS must therefore be adequately modeled.

2.3 - Synchronising and Firing Circuits

The synchronising circuit gives the firing system voltage signals that are in phase with the 26kV busbar voltages applied to the thyristor valves. These voltages are obtained from the 230kV busbar by means of a 230kV/115V potential transformer and by means of a special "synchronising transformer" (Fig. 1). The synchronising voltages are filtered by a low-pass, first-order filter that introduces a lag of 60°. The six voltage signals so obtained are free of harmonic distortion; a requisite condition for a precise firing.

The firing system is based on the zero-crossing technique, for which it uses the TCA 780 standard IC. The synchronising voltages and firing angle voltage signals are used by an electronic circuit called TRIGGER SET to emit the firing pulses. According to the TRIGGER SET characteristic, -2.3 V and 4.2V inputs correspond to 92.5° and 170° firing angle respectively. The firing pulses are treated by many other electronic circuits before they reach the thyristor gates. Such circuits, however, which have no effect on the functionality of the process, need not be modeled. Inaccuracies of firing can be guaranteed to be under 2°. In the present application, the firing angle is limited to the range of 92.5° to 170°.

In steady-state operation, the firing system uses a Phase-Locked-Loop (PLL), that has a firing error under 0.2°. When the PLL and zero-crossing system pulses present a shift equal to or greater than 2°, the firing system switches to the zero-crossing system. This can be caused by system transients, when abrupt phase shifts in the power system voltages are produced by short-circuits, line removal, load rejection etc. For digital simulation, the representation of the zero-crossing system process is sufficient. The synchronising and firing system modeling in term of TACS language is shown in Figure 3 for phase AB of section Y. A special circuit called Frequency Matching Module - FMM gives a signal to compensate eventual frequency deviation. In electromagnetic transient simulations the FMM was not considered, because frequency is assumed to be constant.

3 - SVC MODELING WITH THE EMTP

3.1 - General Comments

Fortaleza SVC, owing to its specific control schemes needed to meet important performance requirements, has a relatively complex control system.

Defining the level of detail required in modeling the SVC for electromagnetic transient studies demands a familiarity with the system, from the electronic equipment to the power system transient phenomena. Such work usually calls for people with different experience.

With a digital program as EMTP, practically all known controls can be adequately modeled. Yet obviously we can only model controls when they are fully known, and when we are sure of how they will operate under all actual system conditions. In our present case, the power supply for the SVC electronic circuits is obtained from normal auxiliary service. Accordingly, HV disturbances caused by a system fault will affect voltage supply. This means that the control system performance must be verified under fault conditions.

A replica of the Fortaleza SVC control system, purchased from the manufacturer of the SVC, was installed in the TNA of CEPEL, the Brazilian Electric Power Research Center in Rio de Janeiro. The simulation of severe contingencies was carried out with the SVC properly interfaced with the system in the TNA.

This SVC model was developed from the electronic circuits and with a judicious evaluation of their performance under actual condition.

It seems to us that experience with many simulations using a very detailed model, as here described, can lead to justifiable simplifications in later studies. This is important for the system under study, as two further SVCs are planned to come into operation close to Fortaleza SVC. Digital studies with such detailed representation of three SVCs would be computationally prohibitive.

3.2 - Initialization

In our case, a network resonance close to the second harmonic makes the start-transient excessively slow. Unbalanced, distorted 26kV busbar voltages in the initial instants result in wrong firing which, in turn, contributes to the generation of harmonics. This self-sustaining cycle leads to a long time transient. To accelerate the network transient, fictitious ideal voltage sources, whose voltage magnitude and angle are exactly equal to the corresponding steady-state value obtained from loadflow results, are connected to the 26kV busbar for 30ms.

The SVC control system would attempt to control terminal voltage during the network initialization transient. This would make this transient longer, especially if a high regulator gain is used. To avoid this, the PI regulator input is switched off and the SVC operates as in manual. The operating point corresponds to the PI initial condition.

The integration time step around 20 microseconds seems to be sufficient for most simulations.

The representation of the snubber circuits improves physical modeling. At the same time, it avoids numerical oscillations associated with the switching of inductive currents. As suggested by [4] the time step should be, at least 0.5Tsn, where Tsn is the snubber circuit time constant. Here Tsn = 216 microseconds.

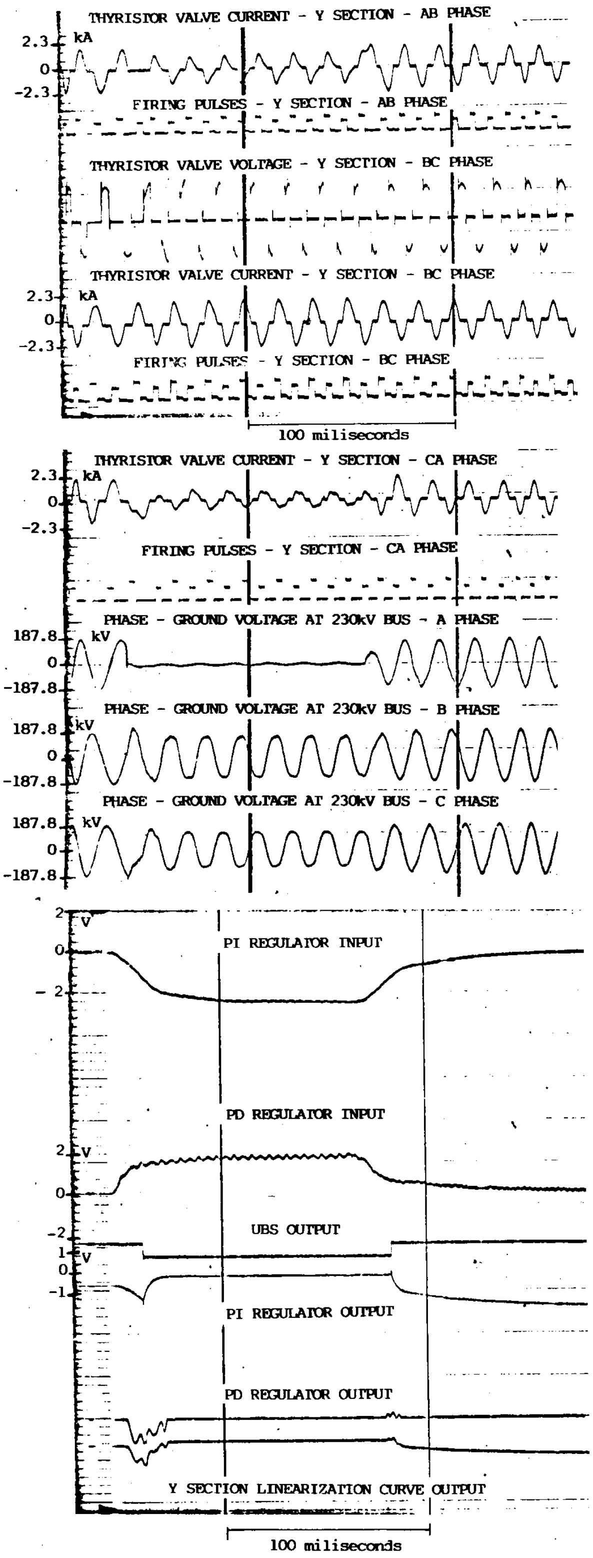

Figure 5a - Phase A - Ground fault at
Fortaleza 230kV - TNA simulation.

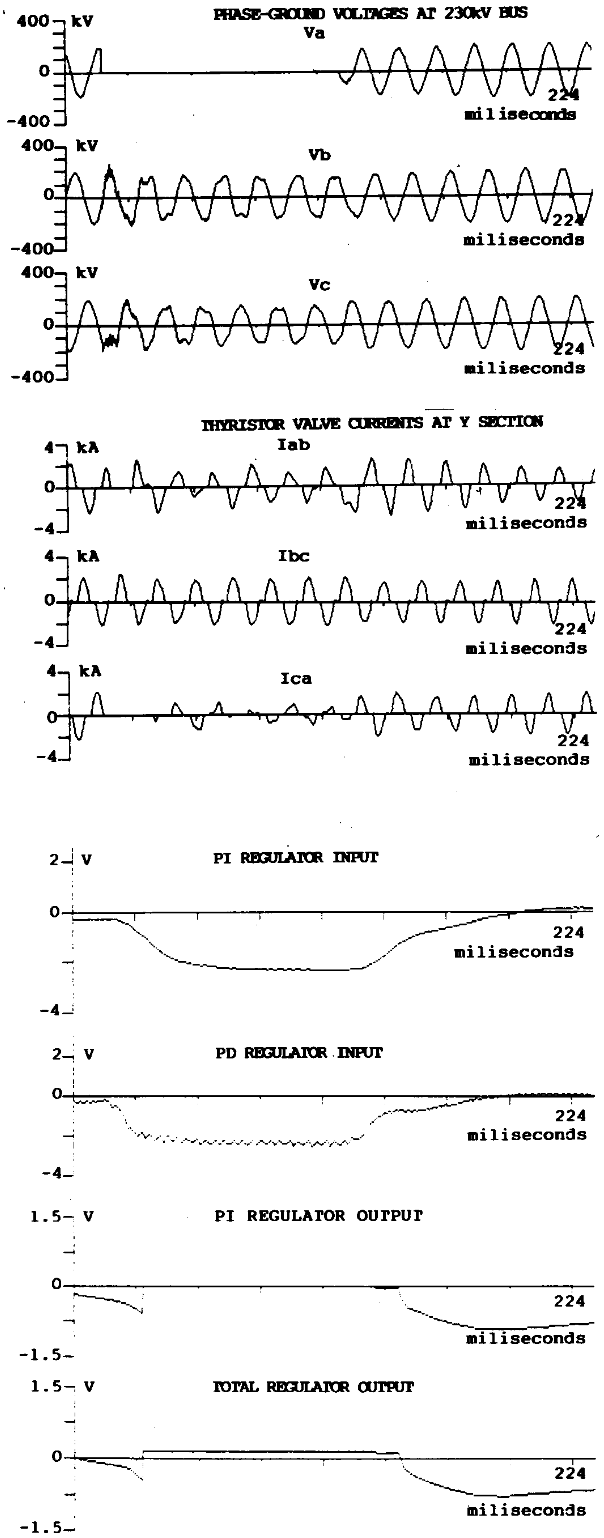

Figure 5b - Phase A - Ground fault at
Fortaleza 230kV - EMTP simulation.

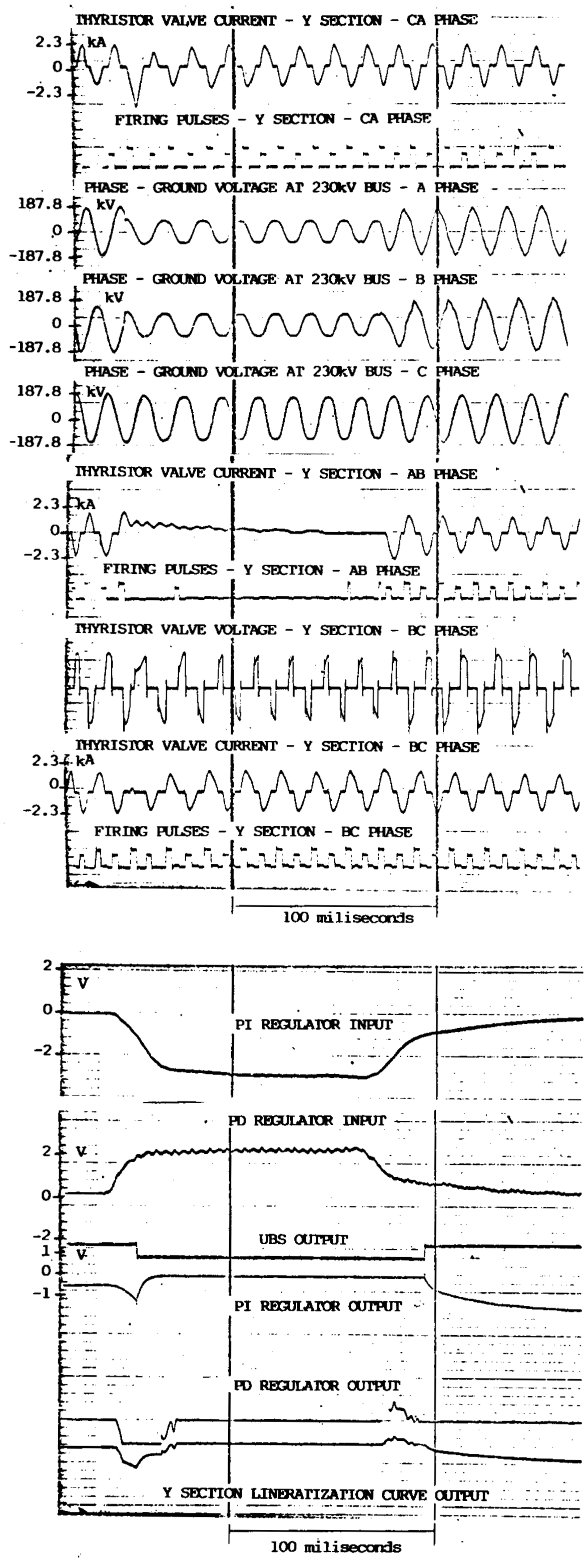

Figure 6a - Phase A-phase B fault at Fortaleza 230kV. TNA simulation.

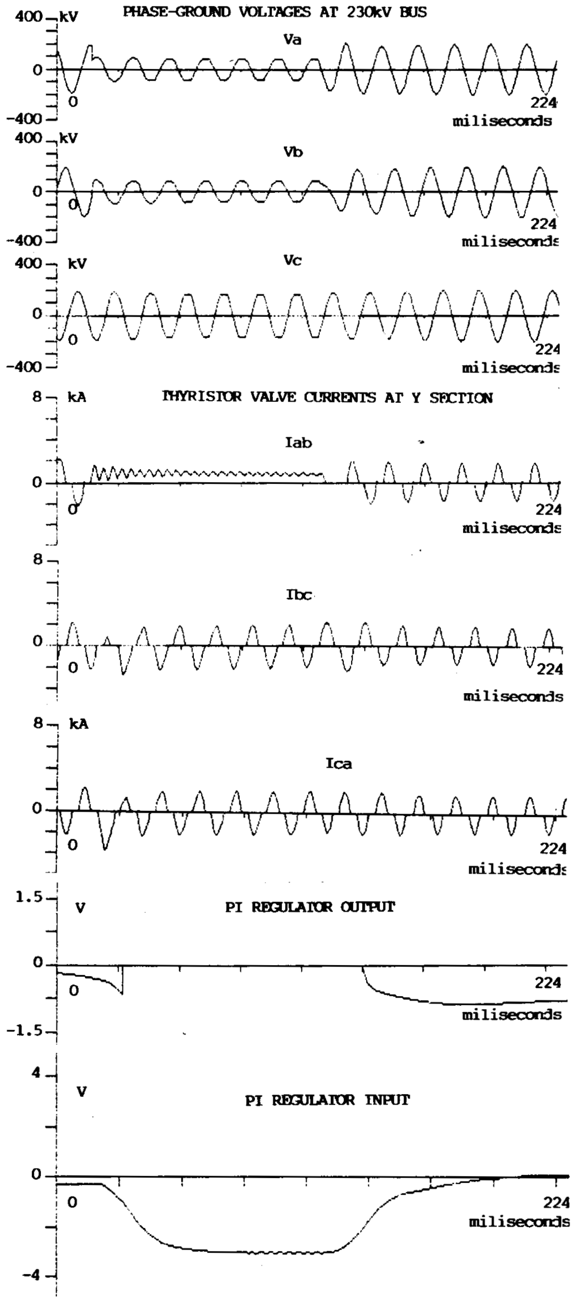

Figure 6b - Phase A-phase B fault at Fortaleza 230kV. EMTP simulation.

4. SIMULATION RESULTS WITH EMTP

Simulation results from EMTP were compared with those from the TNA study. Some differences between EMTP and TNA models merit prior consideration.

a - Transmission system

Real quality factors of reactors and transformers that can be modeled with EMTP are excessively low in TNA, which exaggerates damping.

While we can be sure of the same instant of fault initiation with both EMTP and TNA , they give different instants of fault clearing, owing to their different damping of fault current.

b - Control system and firing circuits.

Thyristor valves in TNA have resistance values disproportionately great, where as EMTP can model the real values. Owing to this, DC components of the TCR transient currents decay faster in TNA simulations.

In EMTP, the internal electronic transients need not be represented. For example, PI blocking is performed by jumping the capacitor of the corresponding integrator. This gives rise to an RC circuit transient. EMTP blocks PI abruptly.

Figure 5 shows some selected variables of the SVC control, 230kV busbar voltages and TCR current for a single-phase short-circuit, as obtained from EMTP and TNA simulations. The fault clearing is obtained by removing one of the Fortaleza-Banabuiu transmission line. Figure 6 shows the result of a phase A - phase B short-circuit.

The results of many simulations have proved the SVC model developed for EMTP reliable enough to use in detailed studies, as SVC parameter tuning, overvoltage investigation etc.

5 - CONCLUSIONS

At the *expansion planning* stage, a general model of SVCs may be adequate for long-term studies. Short-term studies, however, demand detailed modeling of SVCs. This is particularly so where the SVCs have a preponderant influence on system transient behaviour. In such cases, the control, synchronising and firing systems must be modeled in detail adequate to reproduce their transient behaviour under real system conditions.

6 - REFERENCES

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3 - A. J. P. Ramos and H. Tyll, "Dynamic Performance of a Radial Weak Power System with Multiple Static VAR Compensators", IEEE Trans on Power System vol. 4, pp. 1316-1325, November 1989.

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7 - APPENDIX - System Data

. Transmission Lines - per circuit, 230kV
..r1 = 0.09 ohm/km, x1 = 0.5 ohm/km,
..y1 = 3.2E-6 S/km (positive sequence).
..r0 = 0.5 ohm/km, x0 = 1.5 ohm/km,
..y0 = 2.0E-6 S/km. (zero sequence)
. Transformers
.. Fortaleza: 100MVA, 230/69kV, X = 14% tap = 0.95 (four equal units)
.. Russas: 16,67MVA, 230/69kV, X=38%, tap=0.95
.. Mossoró: 39MVA, 230/69kV, X = 38%, tap=0.88
. Loads (constant impedance type)
Bom Nome 230kV: 22.6MW, -2.9Mvar; Milagres 230kV: 61.7MW, 42.3Mvar; Banabuiu 230kV: 5.6MW, 2.8Mvar; Fortaleza 69kV: 190MW, 46.5Mvar; Russas 69kV: 11.7MW, 0.4Mvar; Mossoró 69kV: 21.7MW, 7.4Mvar.
. SVC data
.. Transformer: 200MVA, 230/26/2kV, (H-L1-L1) XH = 1.6%, XL1 = XL2 = 26%
.. Fixed capacitors: 373 microFarad per phase,
.. Surge capacitor: 0.1 microFarad, per phase,
.. TCR: 2x11.4 mH per phase branch, Q = 247.
.. Snubber circuits: 864 ohm, 0.25 microFarad.
. SVC Control system (see block diagram Fig.2)
.. K (regulating droop) = 0.0
.. PI regulator (BCL): Kp = 0.32V/V; Tn = 11ms; LSPI = 2.82V; LIPI = -2.77V.
.. PD regulator (FCL): KD = 0.74V/V; TD = 19ms; LSCR = 0.50V; LICR = -0.90V; LSBM = 3.0V; LIBM = -3.0V; Working Point, WP = 0.0V
.. Current Limiter (CL); IREF1 = 2.20pu; IREF2 = 1.50pu; IREF3 = 1.00pu.
.. Undervoltage Blocking Scheme (UBS)
REF230FF = 70%; REF230FT = 50%; REF 69FT = 50%

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Discussion

J. Schwartzenberg and **R. Fischl,** (Drexel University, Philadelphia, PA): We wish to congratulate the authors for a very interesting paper on SVC modeling and would appreciate their response to the following comments and questions:

1. Have the authors encountered any problems with numerical stability of their EMTP model, when performing transient studies, arising from errors in the prediction of the instant when the thyristor is turned off as discussed in References [1] and [2]?
2. Have the authors obtained any field data to verify the accuracy of their EMTP or TNA SVC models?
3. It would have been useful if the authors plotted the errors between the EMTP and TNA SVC models. Of particular interest are the values of the maximum absolute errors and at what points in time they occur. Specifically, if the largest errors occur during turn-on or turn-off periods, then one can evaluate the accuracy of the EMTP's prediction of the SVC response.
4. When examining the responses of the TNA and EMTP models in Figures 5a & 5b, it seems that the PD regulator input signals are opposite in polarity.

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A. N. Vasconcelos, A. J. P. Ramos, J. S. Monteiro, M. V. B. C. Lima, H. D. Silva and L. R. Lins (CHESF, Recife, Brazil): The authors thank the discussers for their interest on the paper. We address the questions in the same order, as follows:

1 - We didn´t encounter any numerical oscillation when the existing snubber circuits are modeled. In our case, there are power system transients with overvoltages sufficient high to operate the thyristor protective firing (BOD - Breakover Diode). Since the BOD operates based on thyristor valve instantaneous voltages, the thyristor recovery voltage following a turn-off must be properly reproduced for correct operation of the BOD. Thus, our problem is not to eliminate numerical oscillation but to reproduce adequately the turn-off transients. The method used by NETOMAC [2] to avoid numerical oscillation is a convenient way to reduce computer costs when the thyristor recovery voltage is not of interest.

We intend to develop an improved thyristor valve model so that the thyristor recovery voltage, as registered in field, be reproduced adequately, as shown in Figure 1. This model must consider the thyristor dynamic characteristics (recovery charge Qrr) [1]. It requires a time step much smaller than that required to simulate system transients. In this case the approach proposed by Gole [1] will be very advantageous. Unfortunately it is not an available facility of the EMTP. The use of time step smaller than 20 microseconds suppresses or attenuates excessively the voltage peak so that we never obtain the voltage transient as verified in field (overshoot aproximately 20%). Time steps between 20 and 30 microseconds give rise to recovery voltage transients with overshoot in the range of 0 to 20%, depending on how close time increment is with respect to the point of current zero crossing. Figure 2 shows the thyristor recovery voltage obtained with the EMTP model.

2 - We have field data obtained from a single-phase short circuit applied at the end of a 230kV transmission line circuit. This field test showed a significant influence of the dynamic characteristic of the load. The active and reactive load don´t restore immediately after fault removal, but slowly according to its dynamic characteristic. As the TNA and EMTP simulation make use of impedance type load, the agreement between simulation and field test with regard to regulator performance was poor for such large disturbance.

3 - The simulation carried out in the TNA intended to verify SVC control system performance and parameter tunning. The several variables concerned with power system and SVC control system were registered with conventional paper oscillographs. No care was taken to obtain precise data to compare with results from the EMTP model, that was developed some years later.

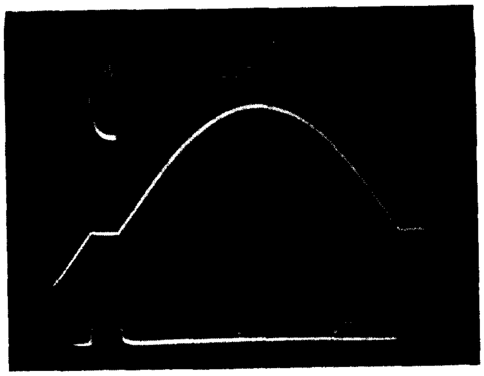

Figure 1 - Field Test - Thyristor valve voltage and current for firing angle 100°.

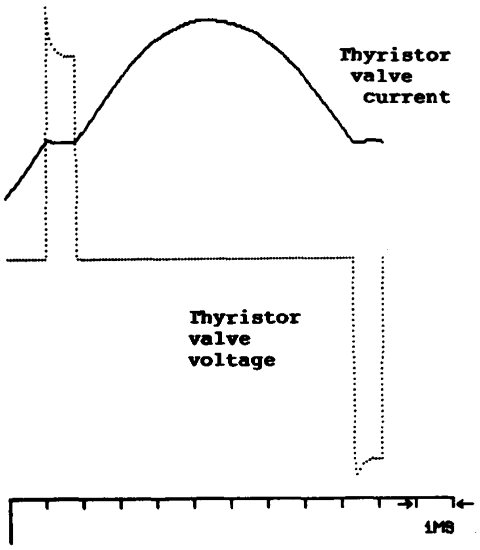

Figure 2 - EMTP Model - Thyristor valve voltage and current for firing angle 100°. Time step 30 microsecond.

4 - The PD input signal in Figure 5a, 5b and 6a, 6b are, in fact, with opposite polarity. The oscillograph channels for such signals were connected with opposite polarity for more convenient use of available space an the oscillograph paper.

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