Advanced Fully Digital TCSC Real-Time Simulation

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Abstract - **TCSC (Thyristor Controlled Series Compensation) are FACTS devices which contribute substantially to improve the dynamic stability of power systems. The series compensation technology uses TCR (Thyristor Controlled Reactor), very similar to the classical shunt compensation by means of an SVC. However, the TCSCs control can only be applied effectively if the TCSC scheme and its rating as well as the control and protection circuits are well matched to the specific network parameters and the specification requirements. Hence, design verification by real-time simulation is imperative to successful TCSC operational performance. In this paper, highlights of the control and protection tests for the hard- and software equipment in the simulator are discussed and results of staged fault tests at site are presented.**

Keywords: Enhanced Fully Digital Real-Time Simulation, TCSC, System Stability, Advanced Control and Protection.

I. INTRODUCTION

Application of series capacitors is a common practice in high voltage power systems with long transmission lines. The tasks are:

- to produce a substantially flat voltage profile at different loads
- improve steady state stability limits by increasing the maximum transmitted power
- act as a reactive power source for the line reactance.

Recent developments in the FACTS-technology permit the use of thyristor controlled series capacitor banks (TCSC) which can improve system performance significantly through:

- inhibition of the subsynchronous resonances
- optimization of load flow
- providing power oscillation damping features.

Series capacitors are installed on isolated platforms per phase. They can be split into switchable segments where each segment forms an independent series capacitor installation, permitting different compensation levels. Each installation is protected by MOVs and/or GAPs, a bypass circuit breaker, a control and a protection system. Control and protection functions plus protective and switching devices are used to protect the series capacitor installation from severe damages due to internal and external faults.

In this paper, the use of a new fully digital RTDS^{TM} ([1], Real Time Digital Simulator) model for the dynamic testing of TCSC control and protection functions is presented. RTDS uses fast DSP (digital signal processors) technology with standard models on TPC (NEC Tandem processor card) in combination with the new 3PC (SHARC 3 processor cards) for advanced modeling requirements like the fully digital TCSC.

This TCSC model has been developed and verified for the Serra da Mesa project in Brazil. It is suitable for combining with physical plant control and protection equipment. In the development of the TCSC model, special attention was given to the specific requirements for testing the latest developments of the series compensation including the hybrid optical current measuring techniques. These measurements are likely to revolutionize the design of the protection schemes for TCSC.

II. POWER SYSTEM AND FACTS SIMULATION REQUIREMENTS

A. *General Requirements for the Power System Simulation*

The combination of intensive computer and advanced real-time simulation is of great benefit for the design verification of FACTS applications. Using computer simulation, the requirements for complex system modeling can easily be accommodated since there are practically no restrictions on the number of elements that can be simulated. As a result of the computer simulation, the type, the basic design and the main control features of the FACTS device, such as power oscillation damping, are defined during the early stage of the project. The next step of the simulation is then to test the physical plant control and protection equipment in a real-time simulator [2].

The use of advanced real-time digital simulators is of great benefit with regard to an enhanced testing of the dynamic system requirements for FACTS devices, such as

- verification of power swing performance with detailed generator models represented by Park equations
- SSTI (subsynchronous torsional interaction) tests with multimass turbine and generator models
- testing of Multi-FACTS in large project applications, e.g. for power system extensions and upgrades.

When using analogue simulators for these tests, certain restrictions always exist which lead to simplified simulation methods. For example, accurate multimass turbine and generator models are practically impossible with analogue replica due to the extremely high quality factor required for the shaft. In this respect, digital simulators possess a clear advantage over the analogue technology [1].

The accuracy and quality requirements for the simulation are defined by the projects specific application objectives. Of main interest for any control and protection equipment is the nominal frequency, which shall be kept within limits given by the real power system. In large interconnected systems, these limits are usually within a band of only few hundred mHz. In weak systems, the fundamental frequency can vary in extreme cases up to +/- 5 Hz, which is a strong challenge for power electronic equipment and its control. With the versatile digital control equipment like SIMADYN D® [3], all power system requirements including frequency variations can easily be matched.

The power system load-flow determines the stability margin, hence this margin is important for studies with power oscillation damping control. The dominant power oscillation frequencies of the system are determined by the

- generator ratings
- the inertia
- parameters of the excitation control.

During the project execution, it is important to mutually compare computer, real-time simulator and site recordings continuously to confirm a good matching of the different types of models in use.

B. Specific Interfacing Requirements for FACTS Testing

Analogue simulators use passive or fast active elements for the converter replica. For the thyristor firing pulse interface connected to the plant control, there usually exists a small, but constant delay between the external firing pulse of the trigger-set and the actual firing of the thyristor, typically 5 to 10 μs. For GTO and IGBT application, this delay can be decreased below 1 μs using FET based models.

Fully digital simulators, even now, have limits for the precision of the firing pulse interface due to the sampling time, which is in fast DSP simulators like RTDS [1] typically at values of 60 to 75 μs for large power system models. This sampling time corresponds to an angle of 1.3 to 1.6 electrical degrees (in a 60 Hz system). In a given simulator set-up, the actual time step is identical for all processors and all racks, based on a centrally synchronized quartz timer. Usually, the firing pulses of an externally connected control are generated with much smaller time steps (less then 5 μs) in a very accurate manner. But, in a standard digital simulator this precision is ignored, because the thyristors can be fired only at the fixed incidents of the given sampling time steps. This leads to a statistical delay of the real thyristor firing, creating a jitter changing from

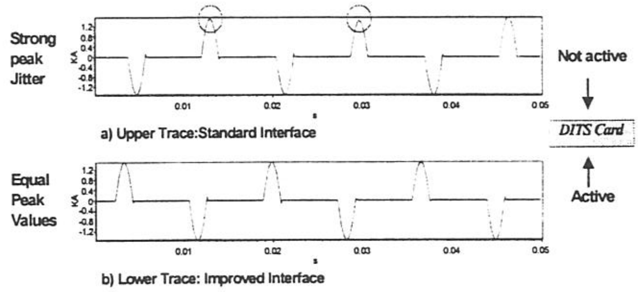


Fig. 1 Benefits of Enhanced Digital Firing Pulse Interfa

period to period - between 0 and 1.6 degrees. The pulse jitter produces considerable differences between the positive and negative TCR peak currents; see the example in the upper TCR current trace of Fig. 1.

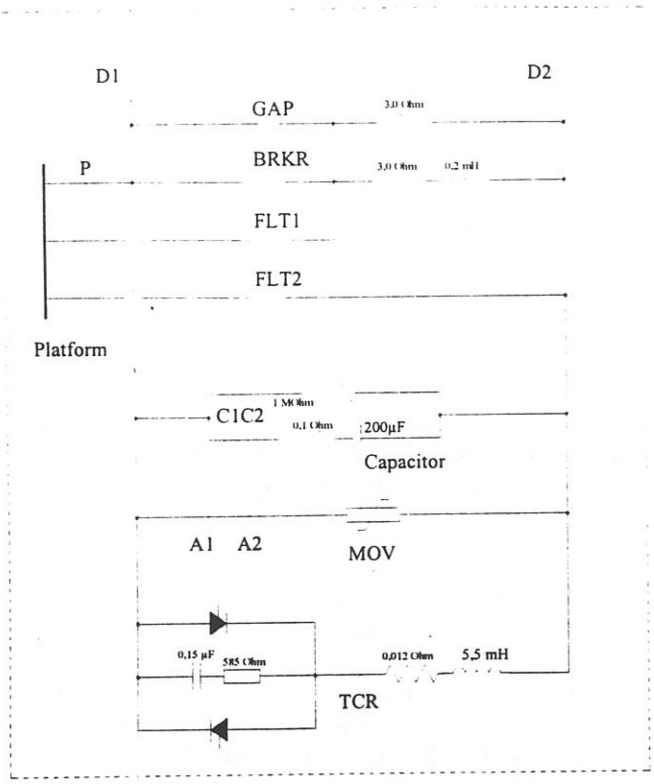
It can be seen, that the TCR jitter is significant, e.g. up to 100 to 200 A, depending upon the selected working point for the firing angle. Such large peak current deviations cannot be accepted for plant control and protection testing. Hence, a new solution for an improved firing pulse interface had to be developed for the RTDS TCSC and SVC models. This development was based on a new type of powerful processor hardware: the SHARC 3PC processor cards and a new type of software called "Network Solution". The software uses a special fast hardware extension, which is called DITS card (Digital Interface Time Stamp). The DITS card registers the exact arrival of the external firing pulse with a precision of 1000 points per sampling, this corresponds to an accuracy of less than 0.1μs for each firing pulse. The time stamp value is then transferred to the TCSC thyristor model and interpolates the numerical solution for the firing instant precisely.

Fig. 1 demonstrates the efficiency of the interpolation with the DITS card: in the lower trace, the jitter is fully eliminated. Additionally, the new Network Solution opens the simulation capabilities of the digital simulator RTDS very widely: It increases for example the number of available switching elements per rack, such as breakers and faults from the former limit of 10 breaker poles to now 56 and the number of nodes is 42 with a maximum of two network solutions running per RTDS rack.

III. DESIGN VERIFICATION OF THE NEW FULLY DIGITAL TCSC MODEL

The TCSC model functions are shown in Fig. 2. Main part is the TCR model with the improved firing pulse interface. The firing pulses can be generated in two ways:

- by means of externally connected plant controls
- internally with the RTDS controls compiler
- internally in case of high thyristor voltage by means of the incorporated Protective Firing (BOD, break-over diode with adjustable level)



The TCR model includes snubber circuits for damping the valve voltage overshoot according to the given basic design values. The quality factor of each model component is freely selectable, which is an important advantage compared to the former analogue TCSC simulator, where

Fig. 2 Fully Digital TCSC Model

the quality factor of the TCR reactor was always limited due to the low operation voltage in the series compensation application. For overvoltage limitation purposes in case of high currents due to line faults, the TCSC capacitor is protected by a MOV arrester. In the simulator, the MOV model parameters are adjustable. MOV supervison by means of energy monitoring is done by the plant protection equipment, which in case of MOV overload fires the triggered spark gap (GAP, see Fig. 2) and closes the bypass breaker (BRKR). FLT1 and FLT2 are used for simulation of fault applications (HV potential versus platform). In this case, the fault current is supervised by means of the current transducer P for protection purposes. With the disconnectors D1 and D2, the platform can be taken out of service via the Open-Loop-Control (OLC).

The RTDS TCSC model was verified at first for the accuracy of the new improved firing pulse interface. This performance improvement has been shown in Fig. 1. For the basic layout of the model, voltage and current waveform measurements in RTDS have been taken for thyristor currents, thyristor voltage and capacitor voltage at different firing angles. The verification has been done by comparison of the measurements with computer

Fig. 2 Fully Digital TCSC Model

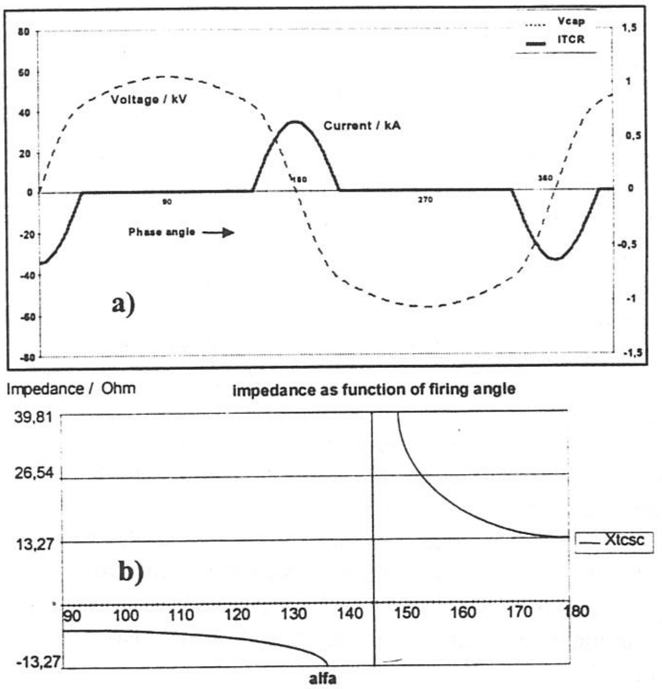


Fig. 3 TCSC Characteristics:
a) Thyristor Current and Capacitor Voltage
b) Variable Impedance

calculations. Examples of these plots are given in Fig. 3 a) - for capacitor voltage versus thyristor current at alpha = 150°. After these basic design verifications at selected operating points, the overall impedance of the TCSC was tested and compared with the design requirements. Fig. 3 b) shows the variable TCSC impedance as a function of the firing angle, measured in RTDS. The plant control uses normally the upper trace of the impedance characteristic in Fig. 3 b), this is the capacitive operating range from 148 to 180°. Additionally, for special control and protection operating conditions, the minimum inductive operating point at alpha = 90° can also be activated.

IV. SELECTION OF THE AC SYSTEM MODEL FOR THE TCSC FACTORY TESTS

The AC system was modeled in two levels of complexity. In the first phase, a simplified set-up with only two line sections, one section compensated with the TCSC and the other uncompensated, plus two 3 phase infeeds was chosen. The short circuit level of both infeeds was selected to 15 GVA; the compensated line was 200 km and the other line was 100 km long. This model was used for protection pre-testing.

For the final factory tests with the integrated closed and open-loop control and protection functions, an extended AC system model has been selected according to Fig. 4. The elements in Fig. 4 were selected using a combination of real system data and equivalent data from computer studies, carried out by Furnas and Siemens. Siemens used both PSS/E™ and NETOMAC® [2] simulations for testing

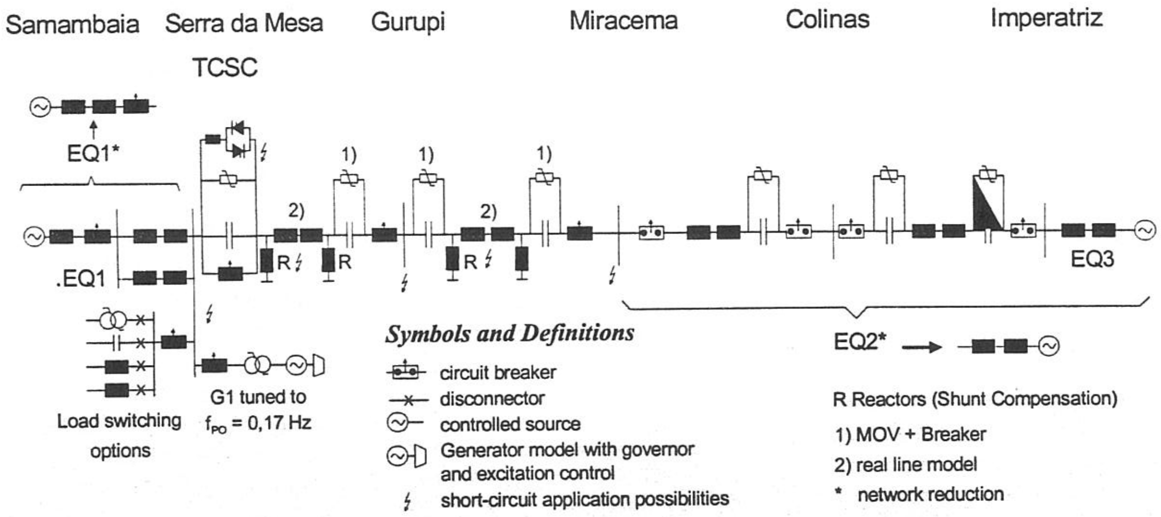


Fig. 4 Power System Model for the TCSC Furnas final Factory Tests with the integrated closed and open-loop Controls and Protection Functions

and verification of specific control and basic design requirements. On that basis, it was possible to limit the set-up Fig. 4 to an economic size of only 2 RTDS racks including 3 SHARC 3PC cards for the new TCSC model and SHARC Network Solution in the southern substation

Serra da Mesa. Additionally, from the complete transmission project with two active TCSCs at oth ends of the AC line (total length over 1000 km), two sections with Fixed Series Compensation were selected as detailed models including series compensation, shunt compensation and breakers for fault application and for simulation of line protection trip. For the rest of the northern scheme including the TCSC at Imperatriz, a simplified power system model (EQ2*) was chosen, see Fig. 4.

The power system model is complemented by two 3 phase source infeeds, which are suitable for modulation functions (in voltage and frequency). Variable loads and a saturable transformer model at Serra da Mesa substation are provided for dynamic load switching events including transformer inrush. For excitation of power oscillations, the Park Generator model G1 has been tuned to swing at the dominant oscillation frequency between 0.17 – 0.2 Hz, given by the computer studies.

V. VERIFICATION OF THE POWER SYSTEM MODEL

One of the main verification criteria for the simulator set-up was the stability performance defined by its dominant power oscillation frequency. Additional criteria were the short-circuit capacities (SCC) at the different substations. Results of the SCC verification by fault current measurement in RTDS and its comparison with the computer simulation in NETOMAC are given in Table 1. An example of the RTDS measurements is shown in Fig. 5. It can be seen from the results in Table 1, that the calculated and the measured values are quite well matching.

(rms)	Serra da Mesa	Gurupi	Miracema
RTDS	8,63 kA	6,78 kA	6,83 kA
NETOMAC	8,46 kA	6,27 kA	6,89 kA

Table 1 – Results of SCC Verification

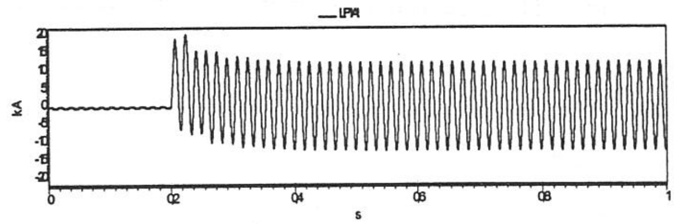


Fig. 5 Example of SCC Measurement (Serra da Mesa Bus)

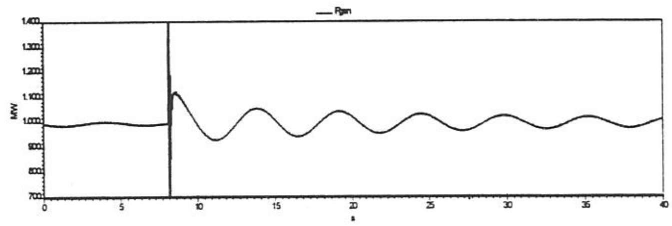


Fig. 6 Measurement of the Power Oscillation Frequency

After tuning the G1 generator model power swing frequency to the predetermined value (see chapt. IV, parameters are the electrical and the mechanical rating in combination with the generator/turbine inertia and the excitation control), the test result of a fault application is documented in Fig. 6. The trace shows an oscillation of the generator power output close to the computer study value of 0,17 Hz.

VI. SIMULATOR FACILITIES AND TEST RESULTS

The set-up of the TCSC Furnas simulator is given in Fig. 7. All cubicles of the Open- (OLC) and Closed-Loop Control (CLC) functions have been connected to the simulator including the new OPTODYN® laser transmission system for signal measuring and monitoring.

The RTDS cubicles with two racks uses a PSCAD™ workstation [1] for programming and running the power system simulation and for transient recording of the main current and voltage signals. Load flow adjustment and its documentation is done by an additional, PC based Steady State Monitoring System with a high resolution digital multimeter. A second, RTDS external Data Acquisition System is connected to the same PC, in order to save input and calculation capacity for the 2 rack RTDS simulator.

Highlights of the transient simulations were the excellent dynamic test results for the plant control and protection equipment. As a unique new test feature, the EMC tests were performed with the control and protection cubicles with the simulation running and with all optical and electrical interfaces active.

After finalizing the OLC, CLC and protection simulator tests, an RTDS based model of the main parts of the Closed-Loop Control has been implemented in the simulator for project follow up and study purposes in the Brazilian Utility FURNAS in the local RTDS simulator in Rio de Janeiro.

Fig. 8 gives an overview of the TCSC closed-loop control. The normal operation of the TCSC will be Impedance Control at the operating point of 16 Ω, in combination with the self-activating Power Oscillation Damping Control (POD). This POD control is the most important feature of the control system and uses the complete capacitive operating range of the TCSC from 13 Ω up to 40 Ω (linear range) and the full inductive operation point at 2.45 Ω (for bang-bang operation). The POD control increases the low inherent damping of the power system which tends to oscillate with a frequency close to 0.17 Hz and it improves the stability of the power transfer, thus increasing the availability of the 500 kV transmission between both Brazilian subsystems.

Additional control functions are implemented to avoid short term and steady state overload conditions of the thyristor valve and the main capacitor. The maximum permissible impedance Z_{MAX} is controlled with respect to the actual valve and line currents. For fast control action, the firing pulses of the thyristors can be blocked temporarily to achieve an instantaneous response. As a supplementary function, Current Control Mode is implemented, which will be used at a future design stage of the power

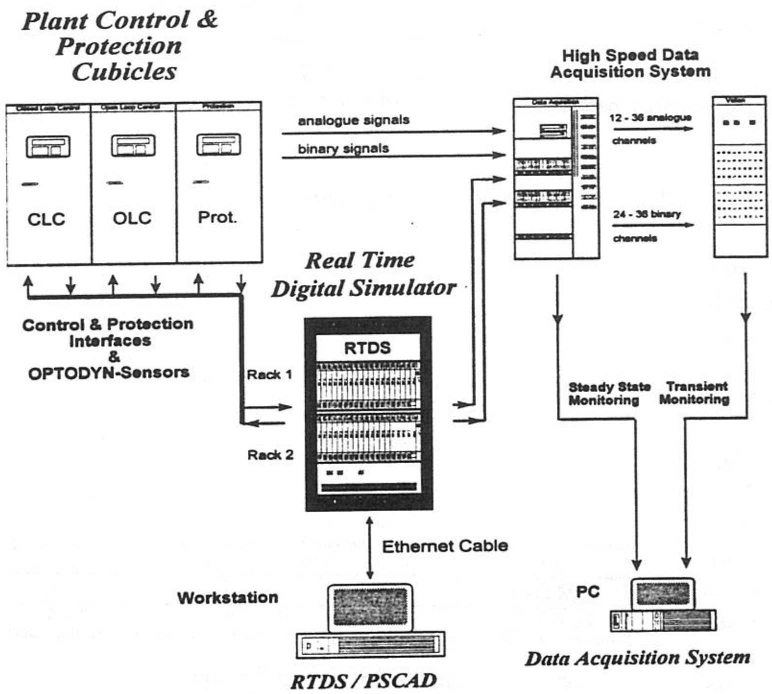


Fig. 7 TCSC Simulator Facilities for Controls and Protection Tests

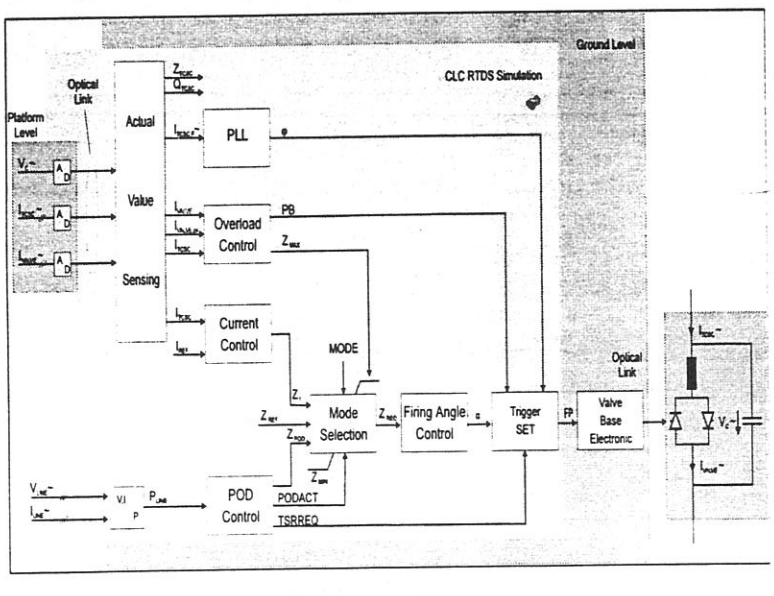


Fig. 8 Blockdiagram of the TCSC Closed-Loop Control

system, when a second parallel transmission line will be available.

For the FURNAS project, the Closed Loop Control (CLC) as well as the Open Loop Control (OLC) and the redundant protection systems are realized with the multiprocessor system SIMADYN D® using sampling rates of typically 0.5 to 1 ms [3]. For digital filters or protection purposes, powerful signal processors with sampling rates of less than 100 μs are used. Highlights of this combined signal and standard processor system are:

1. high configuration flexibility
2. a high degree of reliability and
3. easy control design on the basis of standardized function modules.

For protection and control validation, a large number of tests with various internal and external fault simulations have been carried out. Examples of the faults locations are given in Fig. 4 (external faults) and Fig. 2 (internal faults, FLT1 and FLT2). As an example of the simulator tests, in Fig. 9 the signal recordings for an external fault application is given. The MOV arrester reaches a high energy value of 13 MJ during the fault (100 ms), but the protection remains selective and does not issue any commands or GAP trigger signals, which is correct because the fault is applied on an adjacent line.

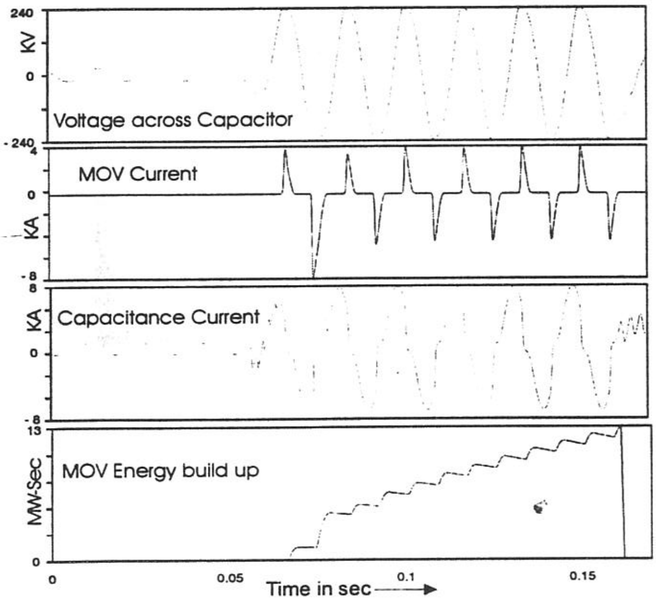


Fig. 9 TCSC Signals in an External Fault Case

VII. POWER SYSTEM STABILITY TESTS

In February 1999 after commissioning, Staged Fault Tests were carried out at the 500 kV system to investigate the operation of the TCSC, especially the verification of the POD control. Several fault scenarios have been applied. The results of one of these on-site tests are recorded in Fig. 10. The initial load flow on the 500 kV transmission line was 450 MW from north to south, when a 300 MW generator was tripped at Tucuruí substation in the northern subsystem. Both TCSCs at Serra da Mesa substation in the south and at Imperatriz in the north were in operation with constant impedance operation mode. The test was repeated several times with the POD controls of both TCSCs in single and in combined operation. All recordings show the active transfer power (P_{LINE}) of the transmission line and the TCSC impedance response (Z_{TCSC}) at Serra da Mesa substation. The plots demonstrate the need and the effectiveness of the POD control, providing more damping to the power system. In Fig. 10 a), without any POD control, the power oscillation increased and finally (not shown in the plots), the transmission system collapsed and was tripped by the line protection after 70 s. In Fig. 10 b), the Serra da Mesa TCSC is active for POD control, the Imperatriz TCSC is in constant impedance mode. This ensures the stability for the power system very clearly. Best damping performance is achieved with the POD functions in both TCSCs active as in Fig. 10 c).

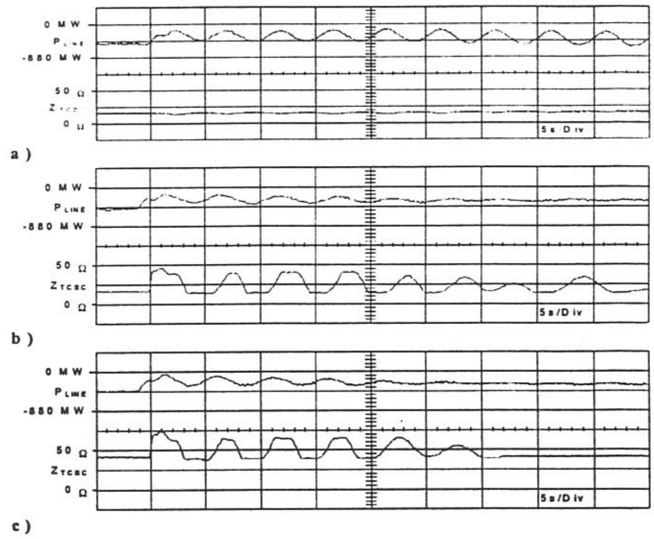


Fig. 10 POD Staged Fault Tests at Site
a) Both POD Controls Off
b) POD Control at Imperatriz Off, at Serra da Mesa On
c) Both POD Controls On

VIII. CONCLUSION

In this fully digital real-time simulation, co-ordinated TCSC control and protection strategies have been investigated with regard to the dynamic system performance. A new hybrid optical sensor based signal measurement system has been integrated in the simulator set-up using a two rack RTDS real-time simulator for the original open- and closed-loop control and protection equipment testing. The new RTDS TCSC model has proven its benefits and capabilities during all phases of the project.

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