ADVANCED FULLY DIGITAL TCSC REAL-TIME SIMULATION

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ABSTRACT

TCSC (Thyristor Controlled Series Compensation) are FACTS devices which contribute substantially to the improvement of 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 TCSC´s 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, the use of a new fully digital RTDS™ (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 modelling 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 revolutionise the design of the protection schemes for TCSC. Highlights of the control and protection tests for the scheme hard - and software equipment in the simulator are presented and compared with site-recordings.

1.0 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
?? improved 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.

2.0 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 modelling can easily be accommodated since there are practically no restrictions on the number of elements that can be simulated. As a result of such 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 [2-5].

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 [4, 6] 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, 4].

The accuracy and quality requirements for the simulation are defined by the project 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? [4], 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 ?s. For GTO application, this delay can be decreased below 1 ?s using a FET based GTO model.

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 ?s 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 synchronised quartz timer. Usually, the firing pulses of an externally connected control are generated with much smaller time steps (less then 5 ?s) in a very accurate manner. But, in a standard digital simulator this precision is not possible, 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 period to period - between 0 and 1.6 degrees. The pulse jitter produces considerable differences between the positive and negative TCR peak current values; see the example in the upper TCR current trace of Fig. 1.

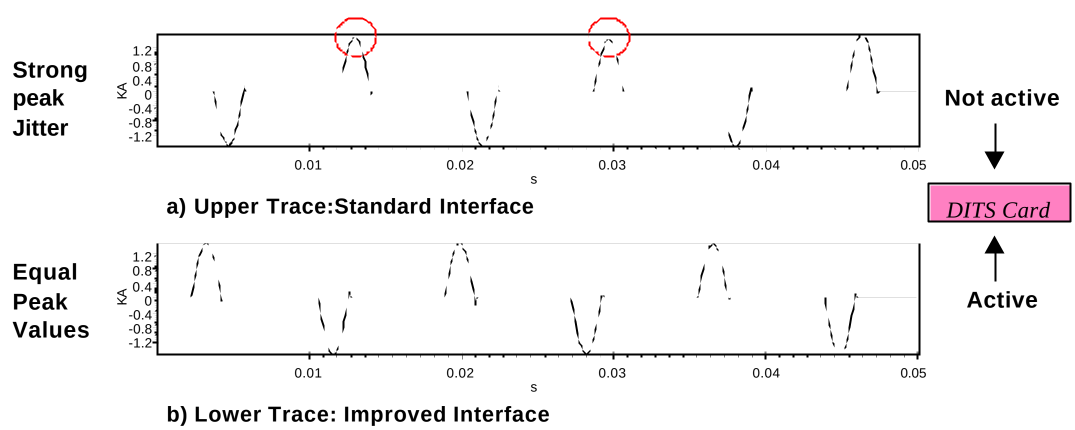


Fig. 1 TCR Currents with Digital Firing Pulse Interface

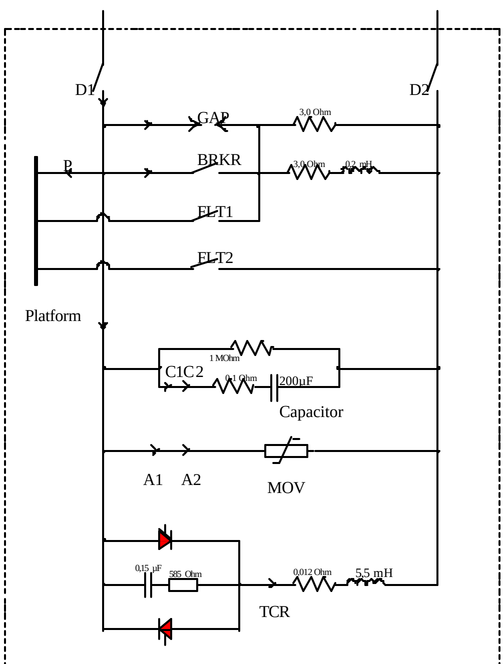
It can be seen, that the TCR jitter varies between 30 A to 100 A from the ideal value, depending upon the selected working point for the firing angle. Such large peak current deviations cannot be accepted for plant control and protection testing. Hence, a new solution for an improved firing pulse interface 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 0,1?s 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.

3.0 DESIGN VERIFICATION OF THE 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)



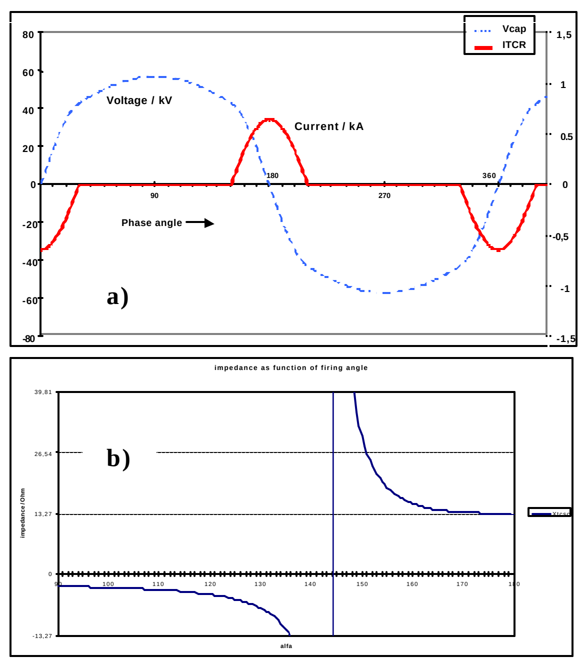


Fig. 2 Fully Digital TCSC Model

Fig. 3 TCSC Characteristics:
a): Thyristor Current and Capacitor Voltage (? = 150⁰)
b): Lower part: Variable Impedance

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 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 calculations. Examples of these plots are given in Fig. 3 a) - for capacitor voltage versus thyristor current at alpha = 150^0. 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, this is the capacitive operating range from 148 to 180^0. Additionally, for special control and protection operating conditions, the minimum inductive operating point at alpha = 90^0 can also be activated.

3.1 SELECTION OF THE AC SYSTEM MODEL FOR THE TCSC FACTORY TESTS

The AC system was modelled in two phases. In the first phase, a simplified set-up as shown in Fig.4 was chosen. The short circuit level of both the sources are 15 GVA; the compensated line is 200 km and the other line is 100 km long.

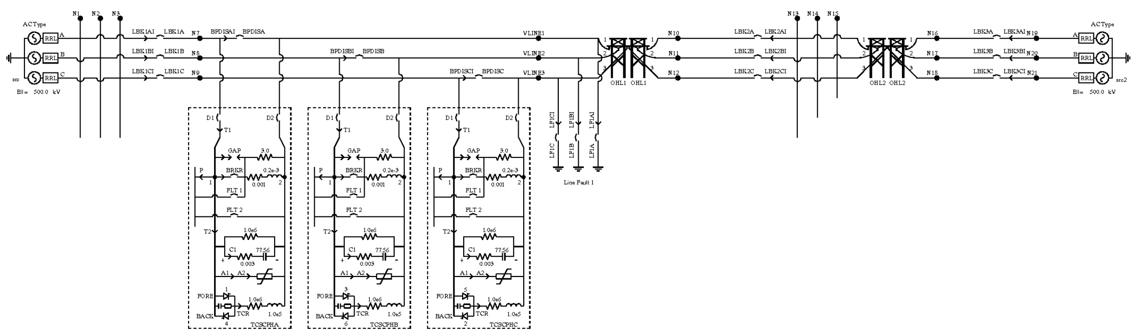


Fig. 4 Simplified AC System Set-up for the initial Protection Tests

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. 5. The elements in Fig. 5 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© [2-4] simulations for testing and verification of specific control and basic design requirements. On that basis, it was possible to limit the set-up Fig. 5 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 both ends of the AC line (total length over 1000 km), two sections with Fixed Series Compensation were selected as detailed models including series compensation (FSC1-3), shunt compensation, 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.

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 rush. 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. Source EQ3 was helpful for flexible adjustment of the pre-fault loadflow conditions.

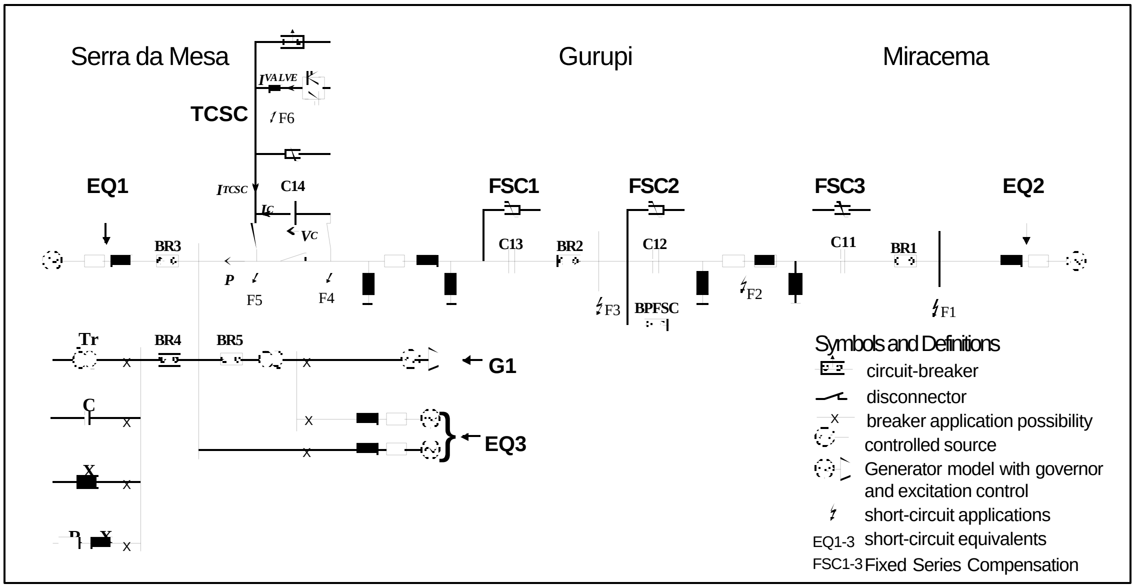


Fig. 5 Power System Model for TCSC Furnas Contr ols Testing

3.2 OVERVIEW OF THE TCSC CONTROL AND PROTECTION SCHEME

The general architecture of the series capacitor control and protection scheme is shown in Fig. 6. Optical measuring signals from the platform are processed by the bank protection unit SIMPROT 98. Depending upon the type of fault, four reactions are possible (ref. to Fig. 2):

?? Bypass command to the breaker followed by reinsertion
?? Trigger signal to the gap
?? Permanent lock out of the bypass breaker
?? Line trip due to bypass breaker fail

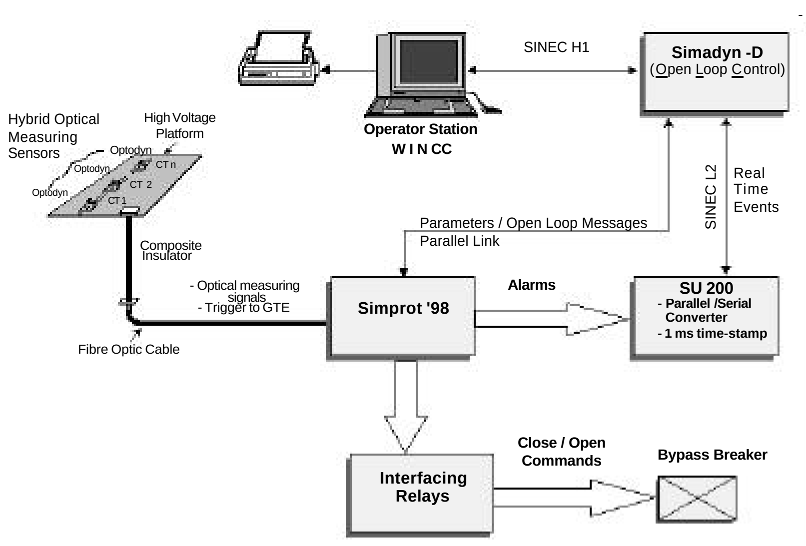


Fig. 6 General Architecture of the Series Capacitor Control an Protection Scheme

Besides these commands, the protection unit also provides alarm outputs for real time event recording and sends messages to the WINCC (Windows Control Centre) based HMI (Human Machine Interface), for logging purposes. An open loop control interacts with the substation switchgear to open and close disconnectors, earthing switches and bypass breaker with interlocking facilities. Protection settings are done via WINCC.

Signal transmission for controls and protection measurements as well as for valve control signals from ground to platform level and vice versa is achieved by fibre optical links. For measurement purposes at 500 kV platform level, the OPTODYN? system is used, which allows a potential-free sensing, fast sampling and transmission of the digitised signals to the DSPs located at the control and protection systems at ground level. The power supply for the associated electronic equipment as well as the data exchange is handled by laser transmission technology. Fig. 7 gives an overview of the advanced current measurement sensors and Fig. 8 shows the typical arrangement of the sensors on the platform.

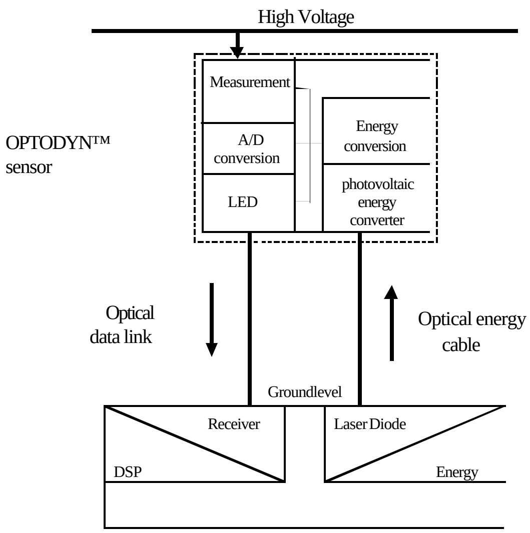


Fig. 7 Typical Arrangement of the OPTODYN-sensors on a platform

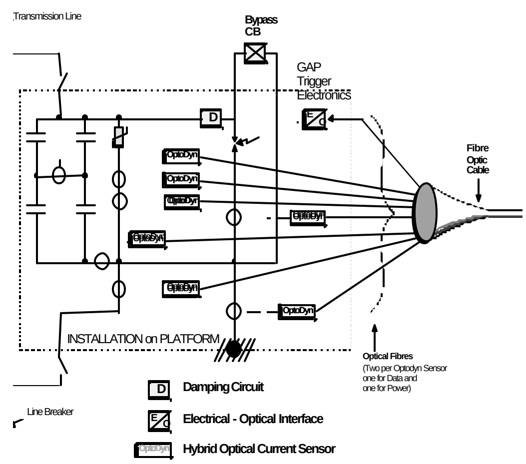


Fig. 8 Blockdiagramm of the TCSC Closed-Loop Control

3.3 SIMULATOR FACILITIES AND TEST RESULTS

The set-up of the TCSC Furnas simulator is given in Fig. 9. 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 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. Some of the test results are explained in the next section.

After finalising 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. 10 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 ?, 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 ? up to 40 ? (linear range) and the full inductive operation point at 2.45 ? (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. The POD function increases the stability of the power transfer, thus improving 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 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 system, when a second parallel transmission line will be available.

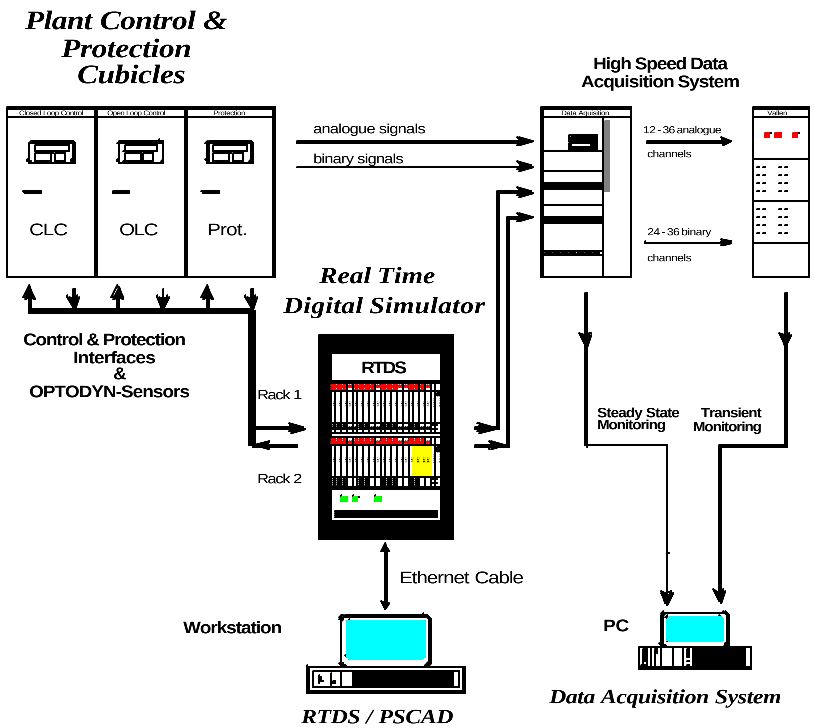


Fig. 9 TCSC Simulator Facilities for Controls and Protection Tests

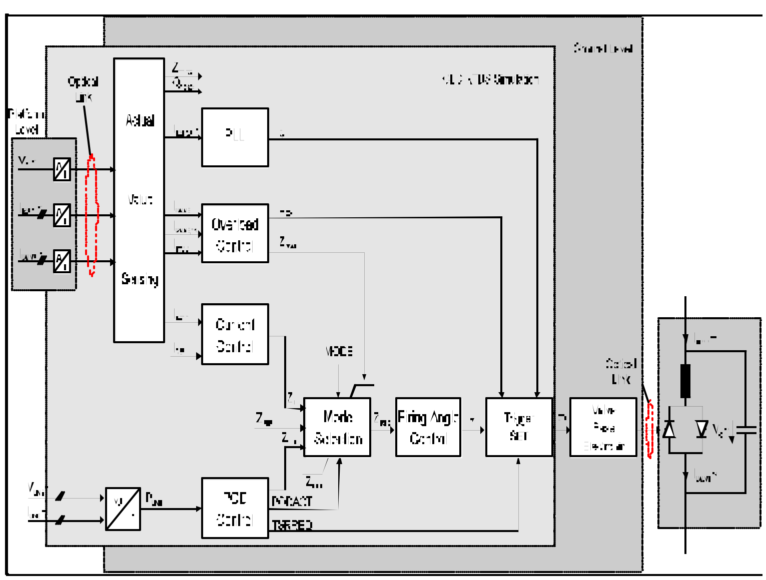


Fig. 10 Blockdiagramm of the TCSC Closed-Loop Control

For the FURNAS project, the Closed Loop Control (CLC) as well as the Open Loop Control (OLC) and the redundant protection systems are realised with SIMADYN D. SIMADYN D? is a multiprocessor system with sampling rates of typically 0,5 to 1 ms. For special tasks, such as digital filters, protection purposes or trigger set functions, 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. the high degree of reliability and
3. easy control design on the basis of standardised function modules.

In the RTDS Controls model, the RTDS Controls Compiler library is used in a special manner in order to achieve the real sampling times of main control functions independent from the RTDS simulation time steps. The RTDS time steps (in this simulation 75 ?s) are regarded as continuous, quasi analogue system, and the control functions are operating with larger time steps, here 520 ?s. This is very close to the real controls sampling frequency of 1920 Hz (32 samplings per period of the 60 Hz power system frequency). An example of such a control model function (digital filter) is given in Fig. 11. In part a), the mathematically calculated frequency transfer characteristic is shown for magnitude and phase, and in Fig. 11 b), the verification of the model function with its 60 Hz bandpass and 2nd and 3rd harmonic notch characteristic is documented. The upper trace of Fig. 11 b) shows the filter output signal, when the filter input is fed by the lower traces frequency sweep signal with constant magnitude. Using FFT (Fast-Fourier Trans-formation) for the filter output signal, the same transfer characteristic as shown in Fig. 11 a) is achieved.

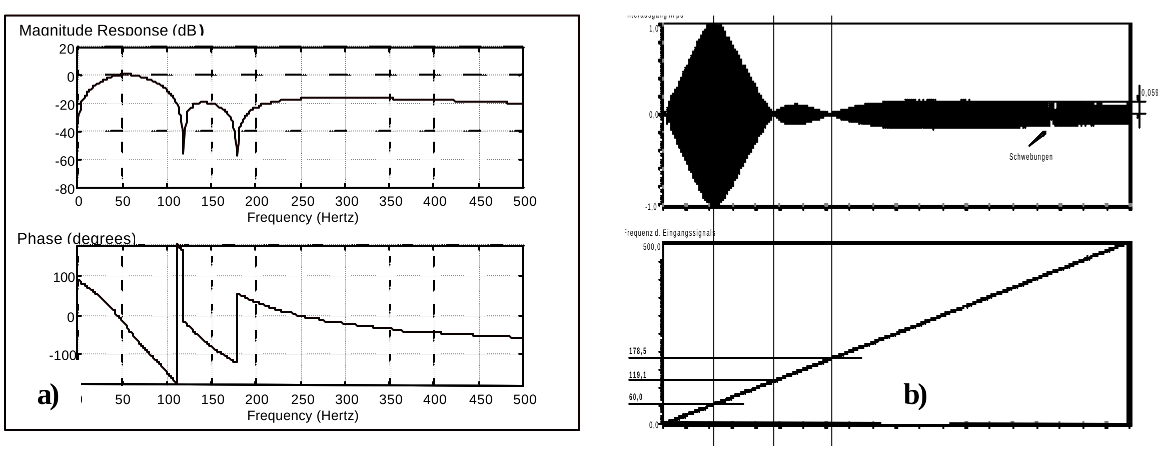


Fig. 11 Example of CLC Model in RTDS: Digital AC Filter

a): Magnitude and Phase response **b): Verification by Frequency Sweep**

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. 5 (external faults) and Fig. 2 (internal faults, FLT1 and FLT2). As an example for the signal monitoring, Table 1 shows the protection test recordings being in use:

Analogue output signals	Digital input signals	Digital output signals
Line current	Gap triggering signals	Bypass breaker status
Gap current	Signals for bypass breaker closing	
Platform current	Signals for bypass breaker opening	
Capacitor and capacitor unbalance current	Signals for line breaker opening (*)	
Arrester current of low and high ratio CT	Signals for line breaker closing (*)	

Table 1 Example of Data Recordings: RTDS analogue and digital signals for Protection Testing
all signals single-phase except (*)

In Fig. 12 and 13, signal recordings for external and internal fault applications are given. In the recordings of Fig. 12, 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. In the next case in Fig. 13, the fault is applied internally on the platform. The MOV energy reaches a value of 13 MJ within a time < 20 ms, due to high fault current. The gap trigger signal and a bypass breaker close command are issued as soon as the MOV-current exceeds the set value. A reinsertion command is issued by the series capacitor protection system after a set delay of 0.5 sec. The bank gets reinserted, since the line fault gets successfully cleared. The oscillatory nature of the capacitance voltage and current is due to its discharge into the gap through the damping circuit.

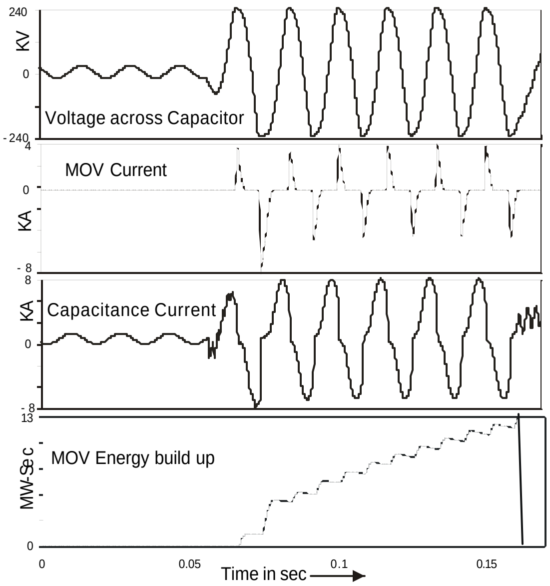


Fig. 12 TCSC Signals in an External Fault Case

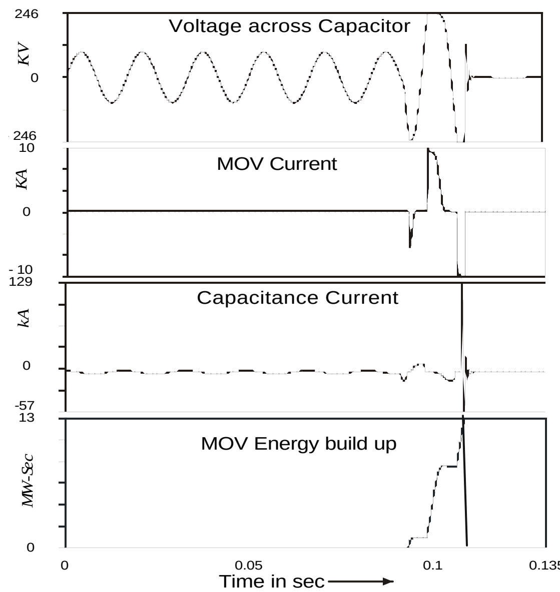


Fig. 13 TCSC Signals at an Internal Fault case

4.0 POWER SYSTEM STABILITY TESTS

A. POD Simulator Tests

The POD control was also implemented in the RTDS control model and then tested for a large number of various fault cases and system conditions and verified against the plant control simulator tests.

Fig. 14 shows the result of a test case for the POD control in the real control with SIMADYN D at an initial load flow of 500 MW from north to south followed by a system fault and load shedding of 400 MW at Serra da Mesa substation. The recordings in Fig. 14 a) shows a weakly damped oscillation on the 500 kV line power flow with the POD control blocked. In Fig. 14 b), the POD function is active and achieves fast stabilisation of the power swings.

B. Staged-Fault Site Tests for POD

In February 1999, 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. 14. 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 Truce 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. 14 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. 14 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. 14 c).

The comparison of simulator and staged fault site test results shows the stability improvement capabilities of the POD control under both reduced system and full system test conditions. This confirms the quality of the control development and its testing.

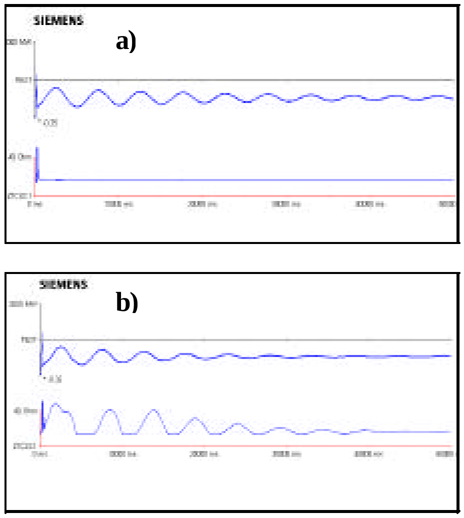


Fig. 14 POD Tests in the Simulator
a) POD Control Off
b) POD Control On

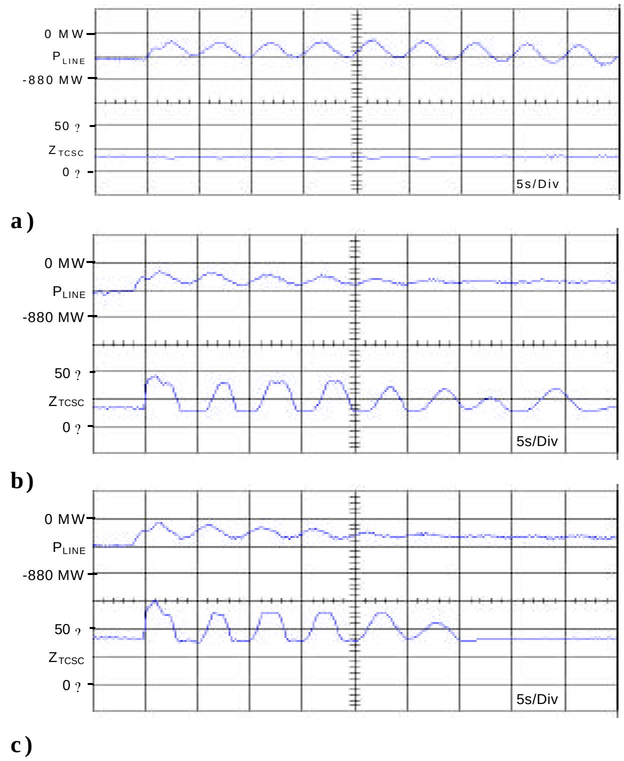


Fig. 15 POD Staged Fault Tests at Site
a) Both POD Controls Off
b) POD Control at Imperatriz Off, at Serra da Mesa On
c) Both POD Controls On

5.0 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.

A detailed TCSC control model has been implemented for further study applications independent from the availability of physical control equipment. Its performance was verified with simulator test results of the plant control equipment. The advanced fully digital Real-Time Simulator project tests and the staged fault site tests confirmed – under different test conditions - the TCSC stability improvement features to the power system very clearly.

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