COMPUTER AND REAL-TIME SIMULATION OF LARGE POWER SYSTEMS

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ABSTRACT

Successful operation of a power system depends largely on the engineer's ability to provide safe, reliable and economic service to the customer. Advanced simulation technologies provide useful means to the engineer for the design and analysis of the power system, and assisting them in making reasonable decisions. Due to powerful software and advanced real-time simulators, it became possible to simulate the dynamic behavior of very large power systems including HVDC and FACTS, and to verify the performance of these complex systems with the original control and protection equipment in a fast and accurate manner. The simulation covers all stages of development and operation of a power system, such as planning, design, test and also during operation. In this paper advanced software and real-time power system simulation technologies are presented. With practical examples benefits of the simulation for large power systems are demonstrated.

1.0 INTRODUCTION

Deregulation and privatization in the power market are significantly changing relations between power generation, transmission and distribution. Utilities are faced to be oriented in the direction of overall cost reduction, high reliability and quality of power supply. In this new environment the simulation of power systems plays a more and more important role.

The simulation was further developed during the last few years. Due to powerful computers and new software as well as advanced real-time simulators, it became possible to simulate the dynamic behavior of very large power systems as well as to verify the performance of the original control and protection equipment fast and accurately. Today the simulation covers all stages in the development of a power system, such as during planning stage, for the design and the implementation of new equipment and complex subsystems like HVDC and FACTS.

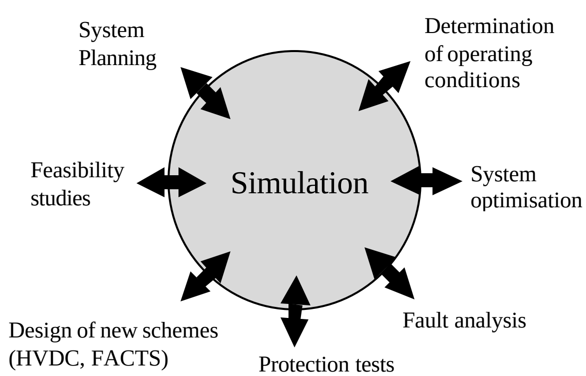


Fig. 1 Simulation for Power Systems

Figure 1 shows the fields in which the simulation is used. During system planning the future performance of the system and possible technical bottlenecks can be analyzed. This is the basis for feasibility studies of future transmission projects. Especially for the complex technology of HVDC and FACTS, simulation can also help to test the protection behavior, to analyze faults and to suggest possible improvements. In addition, system operation can be optimized in order to provide highly economic and reliable operation.

The simulation of power systems in steady state condition is primarily used in the planning phase or in control centers to optimize the steady state system operation. However, investigations on system behavior under dynamic and transient conditions are required for complex systems where the performance is determined by the power plant control and the control of power electronic equipment. In the paper, both advanced methods computer study by the powerful program NETOMAC® and real-time simulation facilities are introduced. Applications of these facilities for the simulation and verification of large power systems including HVDC and FACTS equipment are presented. The benefits and the fields of application of both solutions to simulate the power system are demonstrated.

2.0 COMPUTER STUDIES

2.1 ADVANTAGES OF A UNIVERSAL PC TOOL

For dynamic network studies powerful PC tools such as NETOMAC, PSS/E or EMTDC are used. Especially, the program NETOMAC provides a tremendous variety of simulation options for HVDC and FACTS feasibility studies [1]: there is practically no limitation to the number of generators, lines, nodes, HVDC links and FACTS devices that can be simulated either in stability mode or commutation mode or in combination of both of them.

NETOMAC (Network Torsion Machine Control) is a simulation program system used widely for the simulation of electromechanical and electromagnetic transient phenomena as well as for the steady-state behavior of a power system.

As shown in figure 2, NETOMAC provides in the time domain an instantaneous value mode similar to the EMTDC program and a full stability mode like the PSS/E and BPA program under the same surface.

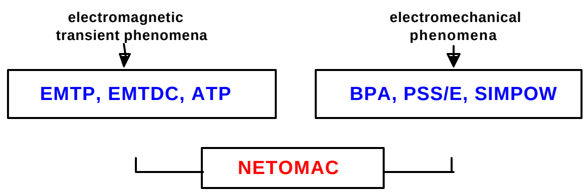


Fig. 2 Multiple Use - A Significant Feature of the Program NETOMAC

Using block-oriented simulation language, all elements of the power systems including linear or nonlinear passive elements, fixed-frequency voltage source, synchronous and asynchronous machines with torsion shaft vibration systems can be described. FACTS and HVDC links as well as control systems etc. can also be easily modeled and calculated for different purposes. Figure 3 shows the capabilities of the NETOMAC program in simulating different phenomena.

The instantaneous value mode allows electrical systems to be represented phase-wise. Symmetrical systems are entered in single-phase form and are completed to three-phase systems internally. Asymmetrical systems can be accommodated by means of elements in the individual phases. In this mode, the admittances are represented by differential equations, so that each element in a complex system including FACTS devices and HVDC systems can be exactly modeled. Therefore, the instantaneous value mode is used for the total solution of any electromagnetic or electromechanical problem.

In the so-called "stability mode", the network is described in single-phase form by complex admittances. This produces a fundamental-frequency model of the network in order to simulate electromechanical transient phenomena. In stability mode, the generators and other machines are represented by differential equations of full or reduced order. Furthermore, it is possible to use symmetrical components (positive, negative and zero sequence system) for the calculations, so asymmetrical faults can also be calculated in the stability mode.

NETOMAC provides also frequency-domain analysis. From the load flow, a linearization of the full system including network, machines, control systems, etc. is performed around the steady state operating point. With the FFT (Fast Fourier Transformation) technique, the system frequency behaviors, including subsynchronous resonances and the system harmonics can be analyzed. The linearization of the system gives also an access to the "small-signal oscillation behavior" of the full system.

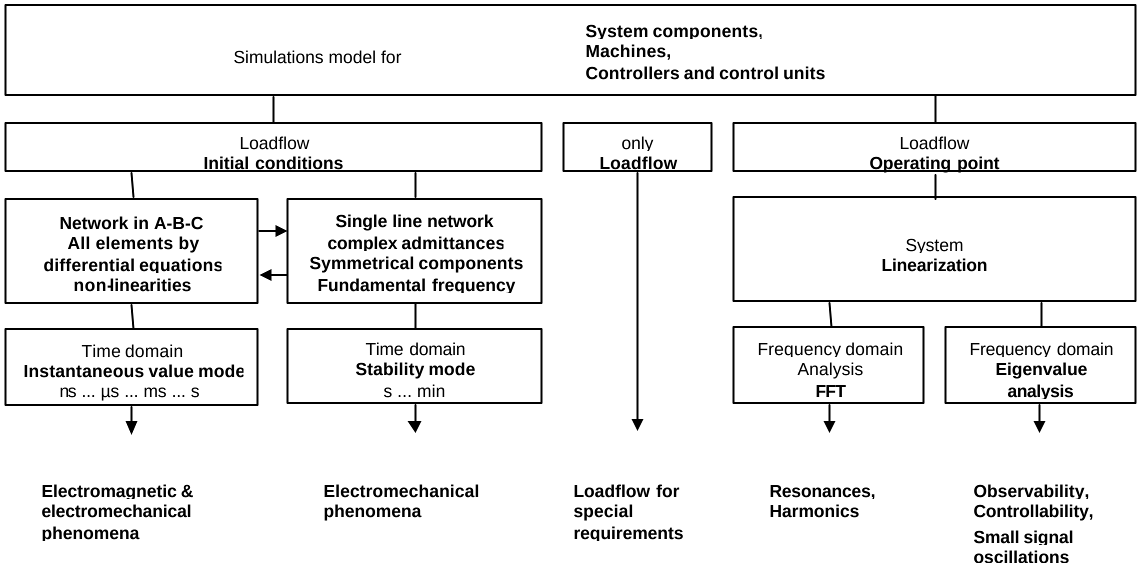


Fig. 3 Overview of the NETOMAC Simulation Program

Using NETOMAC "Eigenvalue analysis", the oscillatory characteristics of systems can be investigated. Stability, observability, controllability and the damping of oscillations in large power systems can be investigated systematically. It is possible to design control equipment, such as power system stabilizers, and to draft smaller dynamic models in which only the dominant state variables are taken into account.

Additionally a couple of useful features support the user to achieve high efficiency:

?? Graphical interface for data input and result output
?? Dynamic network reduction
?? Identification of unknown quantities
?? Optimization of parameters
?? Interactive simulation for training purposes
?? Automation of variant investigations
?? Filters and converters for the data exchange with other programs.

The main benefit of such a wide field of applications is the ability to use one surface and one database for the whole range of complex transient and dynamic investigations in large power systems.

2.2 MULTIPLE USE OF A UNIVERSAL PC TOOL FOR A CONCRETE FEASIBILITY STUDY

Future energy exchange between Norway (NORDEL) and continental Europe (UCTE) will have economic and environmental benefits for both parties. As a consequence, a feasibility study for new 500 kV HVDC links with a transmission capacity up to 4 x 800 MW in addition to the existing 3 HVDC links (see figure 4) was carried out [2].

The characteristics of the Norwegian power system indicate that the power exchange shall primarily be based on pump storage agreements. For the study it was assumed that all converters in Norway work during power import situations as inverters and during power export situations as rectifiers.

For the studies the relevant parts of the UCTE system in Denmark, the Netherlands and in Germany, the NORDEL system in South Norway and up to 7 converter stations including the converter controls were modeled. As the main focus is on the dynamic behavior of the Norwegian power grid, the AC system in South Norway and the main connections to the Swedish power grid were modeled in details. The simulation model of the NORDEL grid according to figure 5 comprises approximately 120 generators (including their turbine and voltage controllers), the 420/300 kV system and parts of the 130 kV transmission system. Included are FACTS like series compensation devices and several Static Var Compensators (SVC).

The main attention was paid to the import situation because of the interactions between AC and DC and the interactions between the converter stations that are working now in inverter mode in the Norwegian system. The difficulties are a result of the following conditions:

?? A weak AC system (due to low generation) compared to the HVDC power transmission capability especially after line outages that may weaken the AC system considerably
?? Interactions between multiple converters working in inverter mode

?? Close distances between the converter stations

?? Long cables of the new HVDC links (550 km).

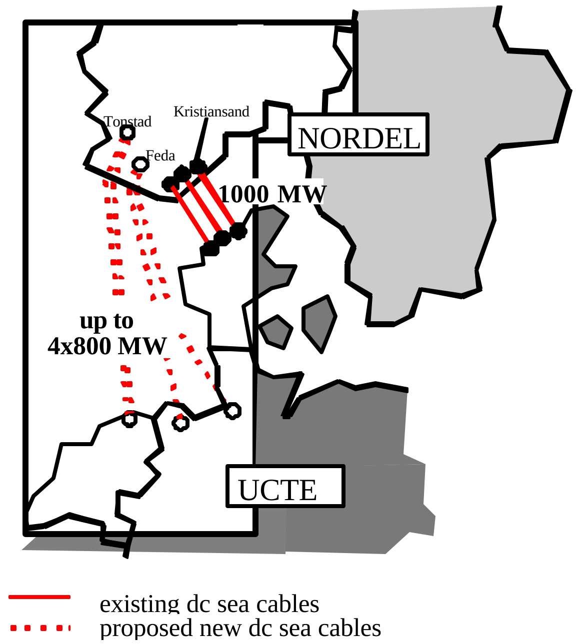


Fig. 4 Proposed Interconnection of the NORDEL and the UCTE System using HVDC Sea Cable

In the first phase the investigations were carried out in the stability mode of NETOMAC.

Common commutation failures of the converter stations for power import in Norway were observed for nearly all considered contingencies in the Norwegian system.

Even for remote and single-phase faults common commutation failures could not be avoided. However, the system showed satisfactory behavior for all fault cases considered, when such repetitive commutation failures which severely disturb the system, could be avoided by preventive measures. The most critical faults are outages of highly loaded ac lines in the converter area, for example the outage of the Holen-Kristiansand line because it considerably weakens the AC system.

Figure 6 shows as an example the outage of the heavily loaded line Holen-Kristiansand for the power import situation in Norway. The frequency and the system voltage which is supported by the SVCs in Tonstad and in Kristiansand show good behavior. The high overcurrents of the new HVDC converters are a result of the relatively large amount of energy stored in the long DC cables. For the cases where two or three new converter stations were used, repetitive commutation failures were observed subsequent to 3 phase AC line faults as a result of the transient voltage drop at the HVDC busbars and the converter interaction. These critical cases were investigated in details by use of the instantaneous value mode of NETOMAC. The features of NETOMAC allow the switchover between the different modes in an easy way.

A just simple tuning of control parameters without further countermeasures could not guarantee safe operation for all fault scenarios. The system behavior was very sensitive to control parameter variations. Repetitive commutation failures could be avoided and satisfactory system behavior could be achieved by temporary power reduction of the converters in Feda and Tonstad.

Figure 7 monitors the valve voltage and the firing angle before, during and after the fault. During the fault recovery the firing angle of the inverter is close to the commutation limit, but with the described measures the system remains stable.

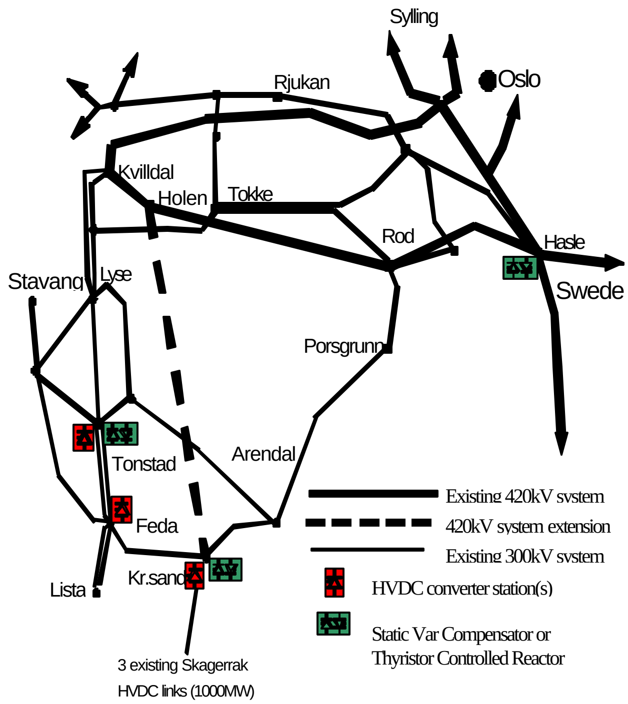


Fig. 5 The High Voltage Power Grid in Southern Norway relevant for Studies

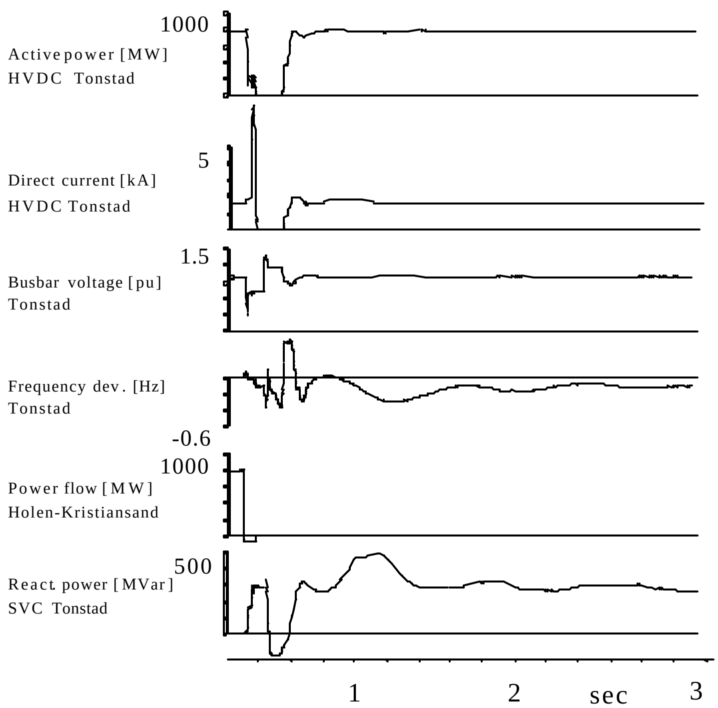


Fig. 6 Influence of the HVDC Transmission in Tonstad during the Outage of the Line Holen-Kristiansand

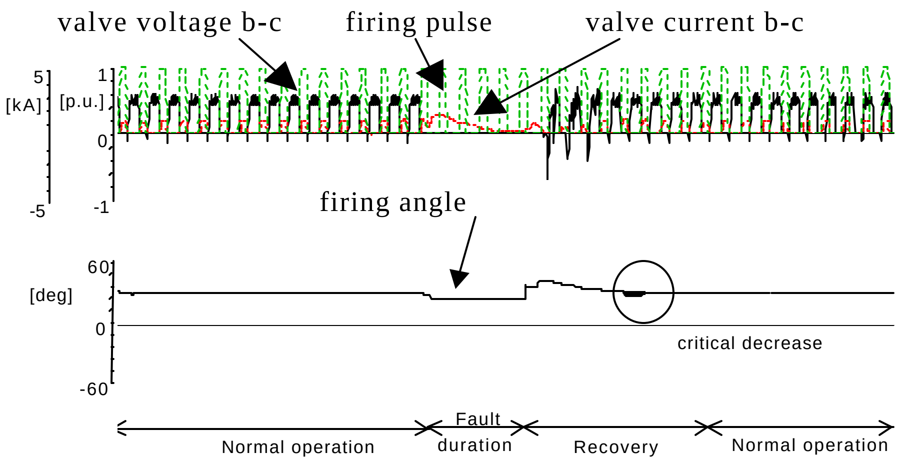


Fig. 7 Simulation in the Instantaneous Value Mode

The export situation was found to cause no problems for two, three or four new converter stations, because the converters are working as (uncritical) rectifiers in Norway on one side and on the other side the strength of the UCTE system and the sufficient electrical decoupling of the inverter stations helps to avoid commutation problems.

However, for the export case power oscillations between Norway and Sweden were observed. A detailed investigation was carried out with the NETOMAC "Eigenvalue analysis" (figure 8) using the same database as in the previous studies. These oscillations can effectively be damped by the TCR located in Hasle (ref. to figure 5). The eigenvalue moves in the uncritical direction.

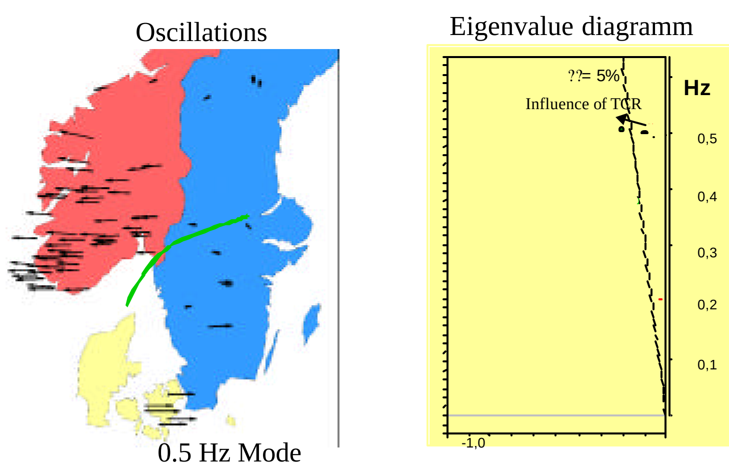


Fig. 8 Results of "Eigenvalue analysis" in the NORDEL system

These examples demonstrate clearly that the computer study allows a wide range of complex investigations and supports the evaluation of measures to increase the system stability. These investigations for the HVDC links between the power systems NORDEL and UCTE are typically for links between a strong and a weaker power system. The experience is valid for similar projects too, e.g. for an HVDC link between Australia and Tasmania.

3.0 REAL-TIME SIMULATION

For development and acceptance tests of FACTS and HVDC in large power systems an advanced AC/DC Simulator based on RTDS™ (Real Time Digital Simulator) is used to verify the performance and functionality of the real control and protection equipment [5]. During this performance verification, the following important features of the different models should be considered [3]:

?? The transformer model needs a high quality saturation replica (including vector group and on-load tap changer)
?? Accurate modeling of the thyristor, IGBT and GTO controllers is essential for high performance transient testing of FACTS and HVDC. In specific cases, the analogue valve models offers transient benefits over the fully digital simulator
?? Generator and turbine modeling requires the use of Park equations, a high quality multi-mass model for the shaft with regard to proper SSR (subsynchronous resonance) testing. Speed and excitation control is a must for correct load-flow settings
?? Variation of fault conditions by means of high precision sequence controllers gives the essential flexibility for application of repetitive events. This is useful to define the worst-case test condition (e.g. maximum transformer inrush leads to the utmost harmonic content in the fault recovery condition)
?? Controlled electronic sources are of great benefit for equipment pre-testing under defined resonance conditions, e.g. with a specified 2nd or 3rd harmonic content in the bus voltage of the specimen under test

A summary of the simulation models and the requirements is given in figure 9.

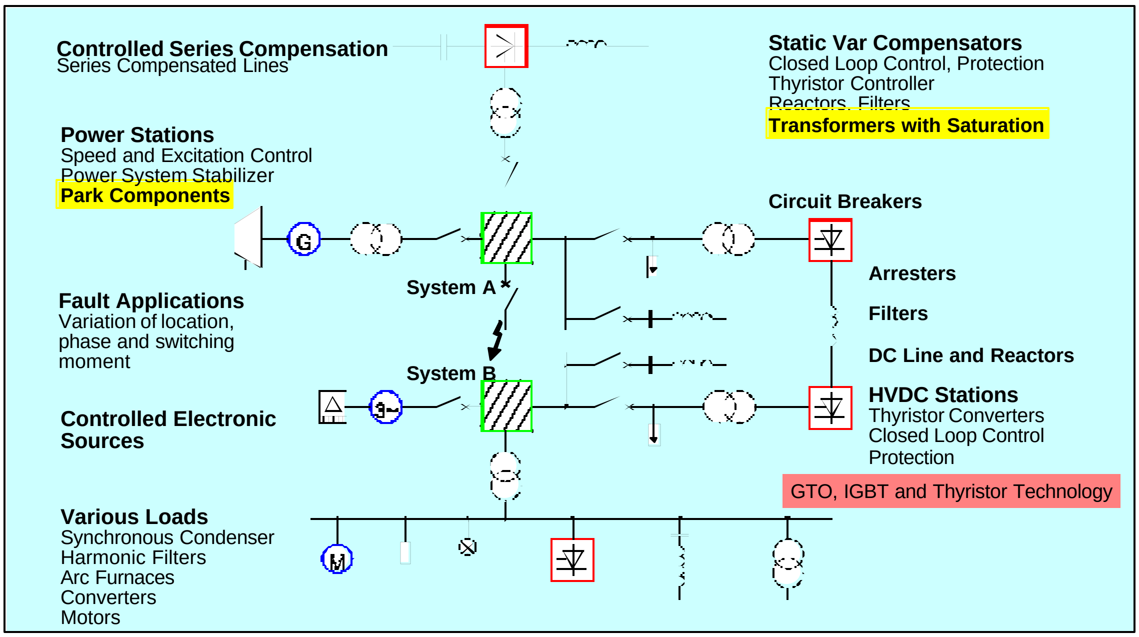


Fig. 9 Overview of Power System Models for Real-Time Simulation

For each project, a specific simulator set-up in either fully digital or hybrid version needs to be chosen. Both technical and economical aspects must be regarded. Best choice is the use of a combined computer and real-time simulation, as described in the previous sections. In this case, the size of the AC system in the real-time simulator can be minimized by a computer based network reduction, ref. to a companion paper [7].

3.1 STRUCTURE AND TASKS OF ADVANCED AC/DC REAL TIME DIGITAL SIMULATORS

The structure and the facilities of the AC/DC Simulator are shown in figure 10. Eight test stations can operate coordinated for large power system simulations or independent for parallel work on different projects. Six of these test stations are specially designed for FACTS and HVDC investigations. One station covers the specific requirements for protection testing and a special test station is used for Custom Power applications.

The analogue converter models are still in use for dedicated applications with regard to the high frequency (over 10 kHz) requirements. The power system models are completed by new digital models in a close cooperation with the worldwide largest supplier of digital simulators (RTDS Technologies Inc., Canada).

The advanced hybrid and fully digital simulator matches all transient requirements for converter testing perfectly. In a companion paper [6], a new fully digital FACTS simulator for controls and protection testing is described in more details. In addition to the hybrid and fully digital real time closed loop simulation the method of digital data injection (playback of NETOMAC runs) can be applied at each test station.

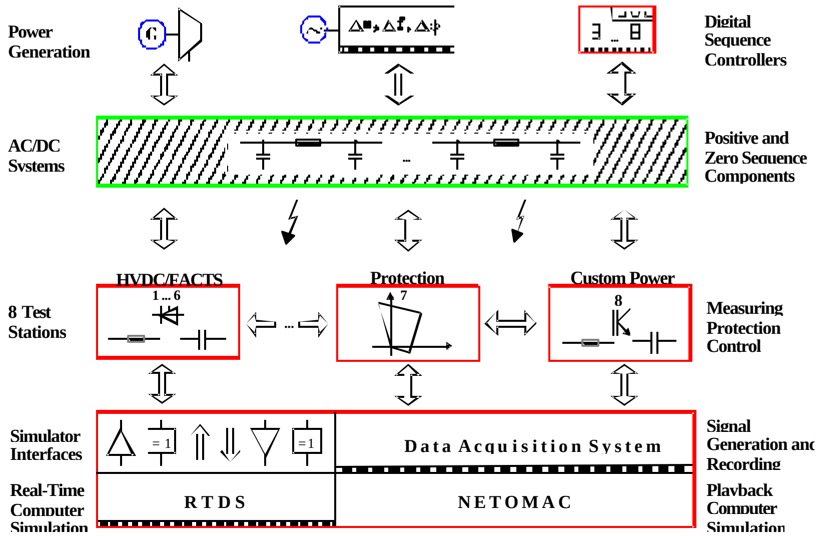


Fig. 10 Advanced AC/ DC Real Time Simulator Facilities

The AC/DC Simulator has been used for the design verification and acceptance tests of all major HVDC projects from Siemens, also for the Chinese TIAN-GUANG HVDC long distance transmission [4]. In Fig. 11, the set-up for the hybrid HVDC simulator model is given. Unique feature of this set-up is the use of a digital DC line model in combination with an advanced analogue converter model for detailed valve fault applications with regard to extensive DC line protection testing [5].

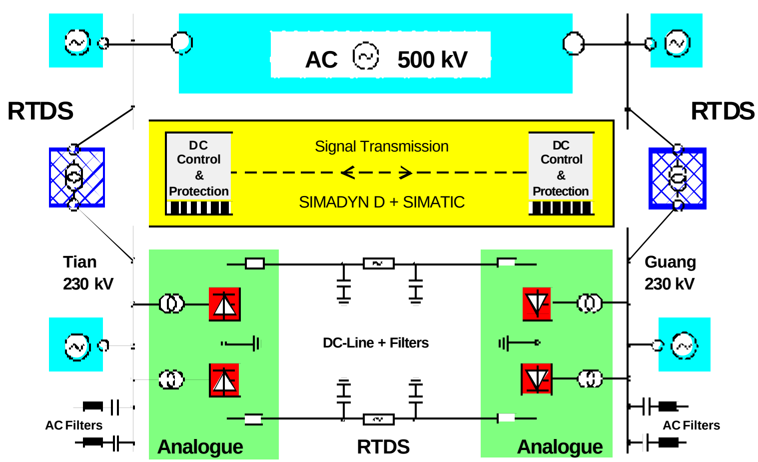
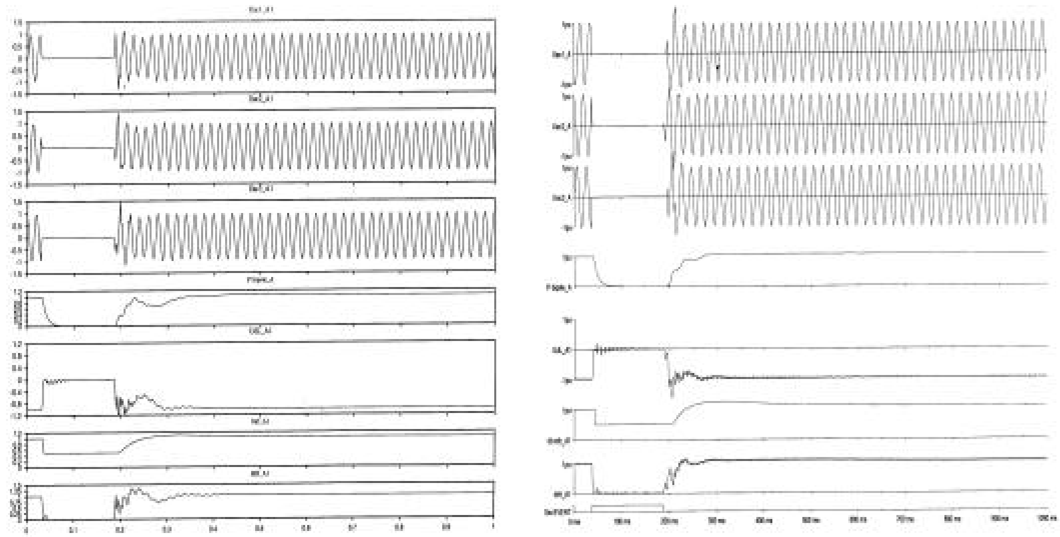


Fig. 11 Hybrid HVDC Simulator Set-up for the Investigation of Parallel AC/DC Operation

The long distance HVDC transmission includes two terminal stations, each configured as a bipolar 12 pulse HVDC system with a total rated power of 1800 MW. The DC lines have a length of 960 km and are rated for a DC voltage of +/- 500 kV.

The recordings in figure 12 show a test case with a three-phase fault at the HVDC rectifier bus. In the test the AC system operates at a maximum short circuit level with full bipolar HVDC load transfer. After 150 ms AC fault clearance time the HVDC performs fast restarting.

In the first step the HVDC link was investigated for network planning and design by computer studies. For the verification and during the acceptance test phase the advanced real time simulation was used. The recordings of both methods show a very similar result. This fact underlines the high accuracy, efficiency and reliability of both approaches.



A - Computer Study **B - Advanced Real-Time Simulation**

Fig. 12 Comparison of the results of Computer Study and Real-Time Simulation

4.0 CONCLUSION

The simulation of large power systems comprises two basic approaches – computer study and real-time simulation. The computer study is an important task for the detailed and complete system representation in order to investigate the performance of existing systems and the feasibility of their intended, future extensions. It is used in the planning stage, for the design of innovative equipment, to analyze disturbances and to develop mitigation strategies for operational problems and their optimization. Additionally, the real-time simulation is needed for the on-line verification tests and the disturbance analysis of the original protection and control equipment under realistic and customer specific conditions.

The combination of both approaches supports an optimized project development, a short and efficient commissioning and a safe operation. Future upgrades can be handled easily and economically.

The prerequisite for these benefits are advanced tools like the program system NETOMAC and skilled engineers with experiences on studies which have been verified by the comparison between simulations and field tests. The application of RTDS opens the simulation facilities for the testing of physical control and protection equipment in a very effective way. Many tests that have been up to now very difficult or even impossible to be applied in real-time are now relatively simple to be carried out by using this advanced simulation technology.

5.0 REFERENCES

[1] X. Lei, E. Lerch, D. Povh, O. Ruhle, "*A large integrated power system software package NETOMAC*," POWERCON´98, International Conference on Power System Technology, Beijing, China, 1998

[2] J. Rittiger, R. Witzmann, T.H. Carsen, "*Feasibility study for increased power exchange between Norway and continental Europe by new HVDC links*", 11 CEPSI Conference, Kuala Lumpur, Malaysia, Oct. 1996

[3] D. Jakominich, R. Krebs, D. Retzmann, A. Kumar, "Real-Time Digital Power System Simulator - Design Considerations and Relay Performance Evaluation", in Conference Proceedings of ICDS´95, College Station, Texas, USA, April 1995, and at ICDS selected for IEEE PES Summer Meeting 96 SM 411-9-PWRD

[4] M. Claus, H. Messner, D. Retzmann, G. Wild, H. Li, Y. Han, Z. Wang, "*Verification of HVDC Controller Using an Advanced Hybrid Real Time Digital Simulator*," POWERCON´98 (session paper), International Conference on Power System Technology, Beijing, China, Aug. 1998

[5] M. Claus, H. Pfister, D. Retzmann, M. Schmidt, G. Wild, P. Forsyth, T. Maguire, "*Simulation of Extended Power Systems in Real-Time – Experiences and Results*," 12 CEPSI Conference, Pattaya, Thailand, Nov. 1998

[6] D. Retzmann, M. Claus, G. Kuhn, A. Kumar, X. Lei, I. Baran, P. Forsyth, T. Maguire, "*Advanced Fully Digital TCSC Real-Time Simulation*," CEPSI 2000 Conference, Manila, Philippines, Oct. 2000

[7] X. Lei, B. Buchholz, E. Lerch, A. Menze, D. Retzmann, O. Ruhle, "*Reducing the Order of Large Power Systems on Static and Dynamic Conditions*," CEPSI 2000 Conference, Manila, Philippines, Oct. 2000