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Simulations of Power System Dynamic Phenomena

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***Abstract*--The Power System Simulation package PSS®NETOMAC (Network Torsion Machine Control) offers a wide range of modern methods of analyzing and synthesizing electric power systems. In order to design individual elements of transmission systems or to perform stability calculations on large systems, it is possible to simulate electrical networks in the time domain and also, with the aid of Eigenvalue calculations, to study in frequency domain too. These methods find general application in the design of control systems and in analyzing the behavior of large networks. User support is provided in the form of a graphical interface to facilitate the inputting of the electrical systems and control structures. One uniform database is being used for all calculations regardless of whether steady state, time domain, frequency domain or Eigenvalue and Modal Analysis is being investigated. Standard Windows PCs or Notebooks provide the platform from which PSS®NETOMAC can provide the user with the flexibility, mobility and speed that he needs.**

***Index Terms*--Power System Dynamics, Electromagnetic Transients (EMT), Stability Calculations (RMS), Time Domain, Frequency Domain, Small Signal Stability, Eigenvalue Analysis, Modal Analysis, Graphical Model Builder (GMB), On-the-Loop real time testings**

I. Introduction

It is more than twenty years ago now that mainframe computers first began to be used regularly for the calculation of electromagnetic and electromechanical transients in power networks. From this baseline the early methods have gradually developed into a system of simulation that offers a versatility of application far in advance of every other comparable system in the world [1].

Apart from simulation in the time domain and the latest methods for computing in the frequency domain, the system can also deal very effectively with the optimization of electrical systems and the identification of component parameters. This paper describes the considerable flexibility and adaptability that this program package can offer its users.

In all the program's modes, in addition to a variety of existing elements, it is a simple matter to define any particular model or element, even user-specific ones, which will allow optimum matching to the particular problem under examination. All computing options are based on a uniform database which allows different problems to be analyzed without the need for any additional conversion of data, such as ascertaining system stability in the time domain with subsequent modal analysis in the frequency domain. The bandwidth in which studies of networks can be carried out at present reaches from extremely fast traveling-wave phenomena on overhead power lines to the slow control phenomena of steam turbines (see Fig. 1). A real-time simulation of electromechanical transients of large systems is even possible. The real-time simulation finds use at the interactive testing of real equipment e.g. protection relays [7; 8; 9] or controller equipment by using the test hardware DINEMO-II (Digital Network Model).

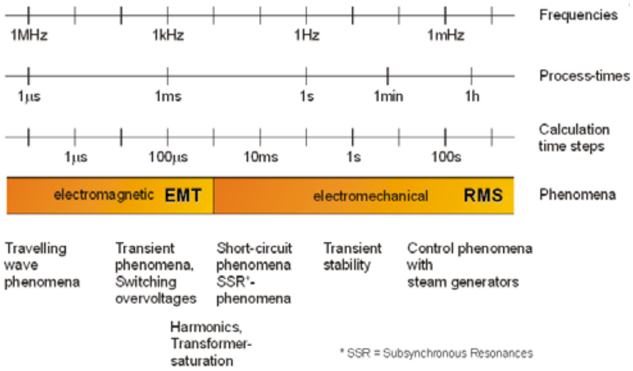

Fig. 1: Bandwidth of Dynamic Simulations

II. Simulation in the Time-Domain

Fig. 2 shows the capabilities of the program package in simulating electrical systems. There are two alternative options in the time domain. The instantaneous value mode (EMT-mode) allows electrical systems to be represented phase-wise.

Symmetrical systems are entered single-phasely and completed to three-phase systems internally. Asymmetrical systems can be accommodated by means of elements in the individual phases. This is also possible for any kind of DC system. Therefore, the instantaneous value mode provides for the total solution of any electromagnetic or electromechanical problem.

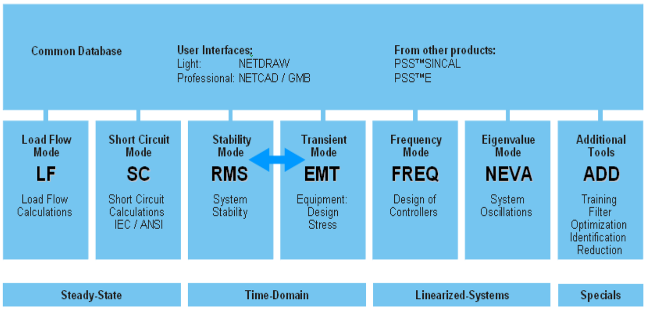

Fig. 2: Possible Ways of Simulation

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Alongside the instantaneous value mode there is the so-called “stability mode” (RMS-mode). Assuming that the admittances have been represented by differential equations in the instantaneous value mode, the stability mode allows the network to be described in single-pole form through complex admittances. This produces a pure fundamental-frequency model of the network to allow electromechanical transient phenomena to be simulated. Similarly in this mode, the generators and other machines can be represented by differential equations of reduced order. Furthermore, it is also possible to employ symmetrical components for the calculations (0-1-2 system), which enables unsymmetrical faults to be calculated in the stability mode too.

The program system solves the differential equations by the difference conductance method. Integration is performed by the trapezoid method in order to assure global numerical stability.

The system matrixes are occupied sparingly, which is taken into account in terms of memory allocation and methods of solution, e.g. for matrix inversion or multiplication (triangular factorization, forward-backward substitution, Diakoptics method).

Points of discontinuity are interpolated by means of the implicit Euler method with a half time step. When there are changes in the system, an extrapolation is made into the past to determine the precise points of zero crossings. In the case of valves, a special examination of the firing pulses is made separately according to time and pulse.

A Instantaneous Value Mode

The instantaneous value mode allows networks, machines and controllers to be modeled by means of differential equations. It can provide a complete solution of all electromechanical and electromagnetic phenomena, including unsymmetrical and non-linear events.

The main field of use is in the design of equipment and apparatus while taking transient phenomena into account. Fig. 3 shows a typical fault situation for a system incorporating a static var compensator (SVC).

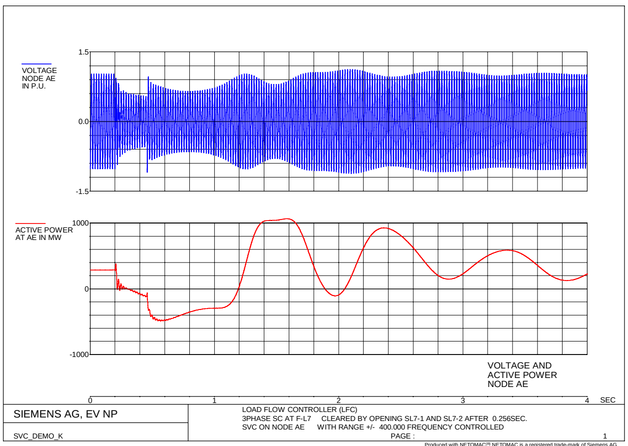

Fig. 3. Simulation Results Instantaneous Value Mode

Exemplary the voltage wave shape is recorded over the variable series compensation so that, for example, the compensator’s surge diverters can be correctly sized. It is also possible to calculate complex electromagnetic events in connection with HVDC and FACTS systems in order, for example, to ascertain intermediate harmonics in HVDC converter systems [2].

B Stability Mode

The stability mode differs from the instantaneous value mode in that it simulates the network with complex impedances instead of as differential equations. Controllers and machines are modeled with differential equations. Machines are used with reduced order in the differential equations (neglecting changes in flow in the d- and q-axes).

In the stability mode the system is viewed as single-pole. Typically, the stability of multi-machine systems is being examined. Fig. 4 shows the same system as in Fig. 3 but this time studied in the stability mode for the same fault situation. It can be seen that there are no DC transients and the electromechanical fundamental-frequency characteristics are retained.

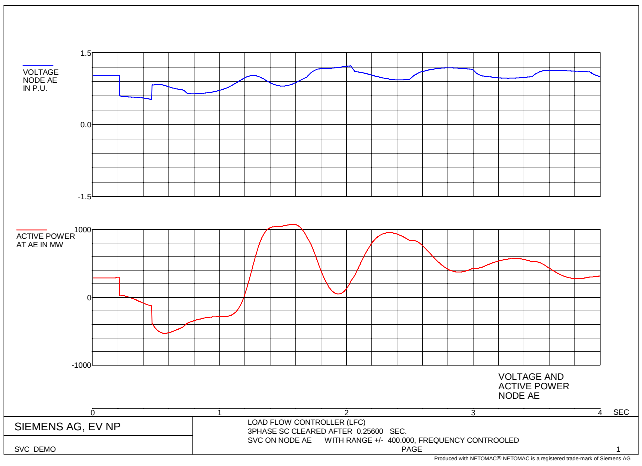

Fig. 4: Simulation Results Stability Mode

So that unsymmetrical faults can be taken into account as well as symmetrical ones, e.g. three-phase faults, universal switching is possible with the aid of symmetrical components (0-1-2 system).

Calculations in the stability mode can also be supplemented by parallel calculations in the instantaneous value mode [3], which makes it possible to take complex short-time events into account when looking at the stability of large systems. One example of this are the commutation processes in HVDC systems which can have an effect on the stability of the entire system, should a malfunction occur.

Thus, the precision of the calculations in the instantaneous value mode for individual parts of the network can be combined with the more extensive network in the stability mode.

In addition to the parallel calculations of the instantaneous value mode and the stability mode it is also possible to employ sequential "swapping" between the two modes so that short-time events that arise during the stability studies can be assessed more accurately.

In the stability mode, HVDC and FACTS systems are connected to the network through variable admittances, variable loads or variable sources (current, voltage, power). So it is possible to simulate the corresponding control systems in detail.

Different kinds of voltage- and frequency-dependent loads and protection systems can be modeled in a similar fashion.

III. Models

During the considerable length of time that the program system has been in use, a large number of models have been created. Some of the most important are listed here. They are either available as macros or can be called up from a library:

- Excitation systems (IEEE specification or user-specific)
- Turbines and turbine governors (IEEE specification or user-specific)
- Power System Stabilizer (PSS)
- HVDC models for the instantaneous value mode and stability mode, including control (Fig. 5)
- Multi-terminal HVDC, including control
- Models for FACTS elements (instantaneous value mode and stability mode for both Thyristor- and GTO-technology)
    - Static compensator
    - Variable series compensation
    - Universal power flow controller
- Models for superconducting energy storage (instantaneous value mode and stability mode)
- Models for circuit-breakers, taking arcing into account
- Load models
- Transformer models
- Generic wind turbine models
- Etc.

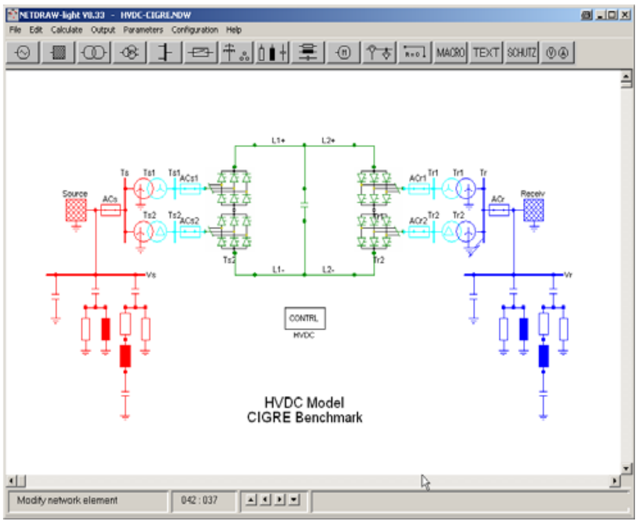

Fig. 5: HVDC Model

A Block-Orientated Simulation Language and Graphical Model Builder (GMB)

The models described in chapter III are build with a so called Block-Oriented Simulation Language (BOSL), the various models and controllers are stored in libraries as macros or graphical symbols so that they can be linked quickly to any required system. Parameters can be assigned individually and changed as necessary; alternatively default values can be used.

For building of these models a Graphical Model Builder (GMB) is used. This Graphical Model Builder uses the powerful Microsoft VISIO interface to create easily dynamic models (Fig. 6). It is a drawing tool that is simple and quick to operate for implementing, editing and documenting of dynamic models.

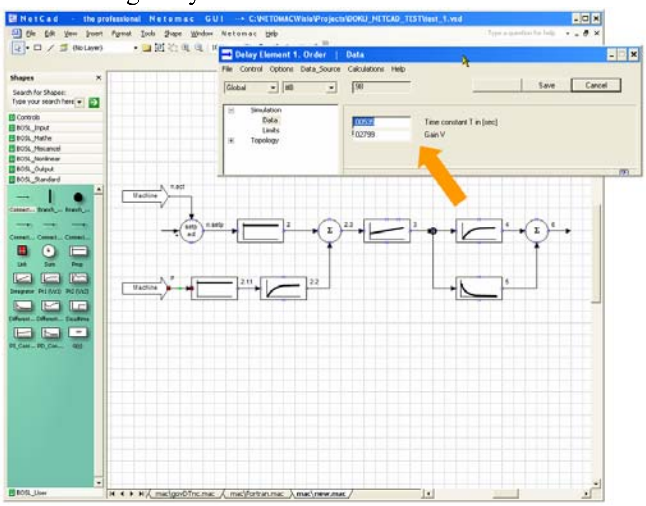

Fig. 6: Graphical Model Builder (GMB)

Besides familiar CAD functions, such as copying, shifting, rotating, zooming, etc., the system has a large symbol library which contains more than 100 different control blocks in the form of symbols. The user establishes system diagrams and the block diagram by graphical connection of library symbols. The data is input via masks that are object-related and have abbreviated aid texts in addition to detailed aid texts. It is also possible to combine groups of linked symbols to form independent new symbols as macro models and to add these to the symbol library or to the user's own library. On the basis of this hierarchical structuring capability ("Subsystems"), the system makes it possible to decide, according to requirements and for the same database, in how complex or simplified a way a system can be illustrated. Individual components can be activated and deactivated and connected to any desired part of the system.

The symbol library "BOSL" (Block-Oriented Simulation Language) contains more than 100 different function blocks. These blocks can be combined to any open or closed-loop control structures or evaluation devices by means of the graphic interface. Besides very simple blocks, such as PID elements, there are also complex "blocks", such as FFT (Fast Fourier transformation). The controllers can be stored as subsystems in a library so as to link them quickly to a system. Parameterizing can be input individually and changed, or the default values can be used. Optionally complex open and closed-loop control and protective functions can be implemented with the block-oriented simulation language. Besides the open and closed-loop control structure, signal processing structures can also be defined by the user (evaluation devices). External, user-defined subroutines can also be coupled (open-loop) and there is an interface to real- time applications (closed-loop). The block-oriented structures can be combined with FORTRAN-like terms, such as mathematical functions, logical terms or instructions, e.g. IF/THEN/ELSE and GOTO/CONTINUE. Input variables are available to the controllers in all sizes. In addition, the variables from other closed and open-loop controllers or the evaluation structures can be used as input variables. All inputs and outputs of blocks can be output.

The user can switch between 2 different block styles: 1. The European DIN symbols (Fig. 6) and 2. the transfer functions. The Graphical Model Builder also offers testing and debugging functionalities like in Matlab/Simulink. A step-function or a sinusoidal signal can be injected at each point of the structure. Also at each point of the structure the block signals can be plotted.

IV. Simulation in the Frequency Domain

The program system incorporates frequency-domain analysis as well as time-domain calculation. For this, beginning from the power flow situation, an automatic linearization of the whole system including network, machines, control systems, machine shafts, etc. is performed around the working point of the system. This gives access to the small-signal behavior of the whole system. Network, machine or control system can be represented as transfer functions (Bode Diagram, Nyquist Diagram) so that ordinary conventional methods can be used for the design of control hardware, for example. Fig. 7 shows a typical example of a calculation in frequency domain.

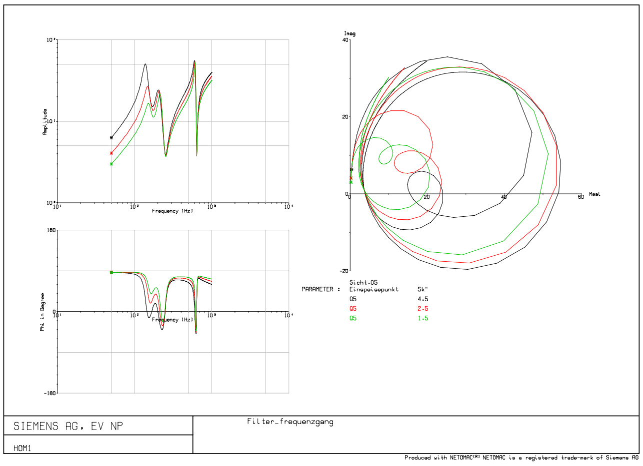

Fig. 7: Simulation Results Frequency Mode

V. Eigenvalue and Modal Analysis

Power systems are steadily growing with ever larger capacity. Formerly separated systems are interconnected to each other. Modern power systems have evolved into systems of very large size, stretching out hundreds and thousands of kilometers. With growing generation capacity, different areas in a power system are added with even larger inertia.

Furthermore the unbundling of generation, transmission and supply is less oriented towards the physical nature of the synchronously interconnected power systems, which span a large area with interaction among the different sub networks and the power plants. However in the new environment with possible higher loading of the transmission system the network operators may be forced to operate the system closer to its stability limits.

As a consequence in large interconnected power systems small signal stability, especially inter-area oscillations, become an increasing importance. Inter-area oscillation is a common problem in large power systems world-wide. Many electric systems world-wide are experiencing increased loading on portions of their transmission systems, which can, and sometimes do, lead to poorly damped, low frequency (0.2-0.8 Hz) inter-area oscillations. This topic is treated intensively for a long time for those power systems, where the extension of the interconnected systems and/or high transmission load led to stability problems.

Inter-area oscillations can severely restrict system operations by requiring the curtailment of electric power transfers as an operational measure. These oscillations can also lead to widespread system disturbances if cascading outages of transmission lines occur due to oscillatory power swings.

The module “NEVA – Eigenvalue- and Modal-Analysis” extends the scope of analysis methods of the electromechanical behavior of electrical power systems (Fig. 8).

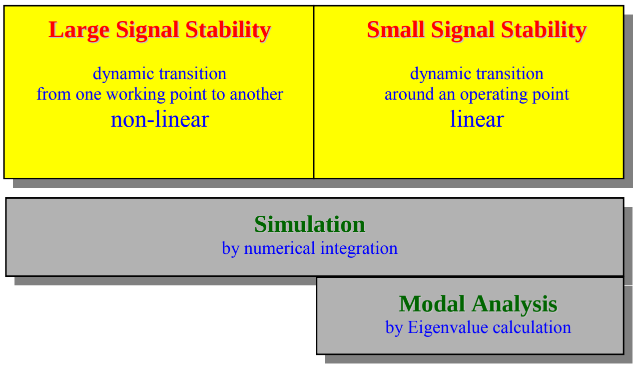

Fig. 8: Analysis of Electromechanical Phenomena

Eigenvalue or Modal analysis describes the small signal behavior of the system, i.e. the behavior linearized around one operating point, and does not take into account the nonlinear behavior of e.g. controllers at large system perturbations. Therefore time domain simulation and modal analysis in the frequency domain complement each other in analyzing power systems.

The **Eigenvalue analysis** investigates the dynamic behavior of a power system under different characteristic frequencies (“modes”). In a power system, it is required that all modes are stable. Moreover, it is desired that all electromechanical oscillations are damped out as quick as possible. For a better understanding the results of an Eigenvalue analysis are given as frequency and relative damping for each oscillatory mode. A damping ratio of 5 % means that in 3 oscillation periods the amplitude is damped to about 32 % of its initial value. The minimum acceptable level of damping is not clearly known. A damping ratio less than 3 % must be accepted with caution. Damping is considered adequate if all electromechanical modes have a predicted damping ratio of at least 5 %. Fig. 9 depicts how the damping of a system can be easily analyzed.

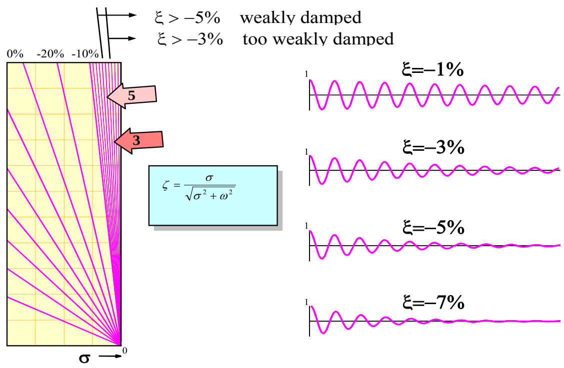

Fig. 9: Criteria of Weak and Well Damped Systems

In addition, system **modal analysis** allows a much deeper view in a system by interpretation not only of the Eigenvalues but by analyzing the eigenvectors of a system which are automatically calculated during the modal analysis:

- The right eigenvector gives information about the observability of oscillation
- The left eigenvector gives information about the controllability
- The combination of right and left eigenvector (residues) indicates the sitting of controllers

Fig. 10 shows the eigenvectors of a 0.3 Hz interarea oscillation.

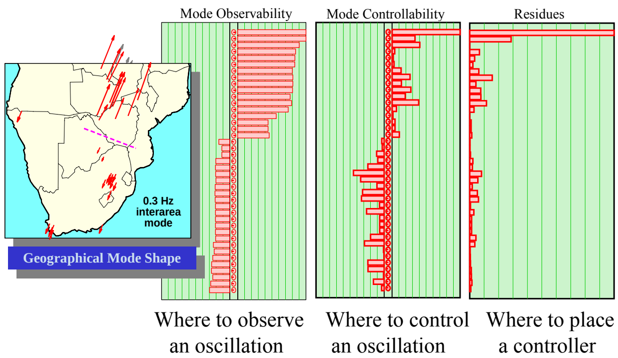

Fig. 10: Eigenvectors of an Interarea Mode

The **damping of interarea oscillations** is very important. The oscillation can be damped when extra energy is injected into the system, which is instantaneously decelerated, and/or when extra energy is consumed in the system, which is instantaneously accelerated.

In real power systems the damping energy is obtained by the modulation of load or generation for a period of time, typically in the range of five to ten seconds. The damping energy must have the correct phase shift relative to the accelerated/decelerated systems. Wrong phase angles can even excite power oscillations. Fig. 11 shows different strategies to damp power oscillations.

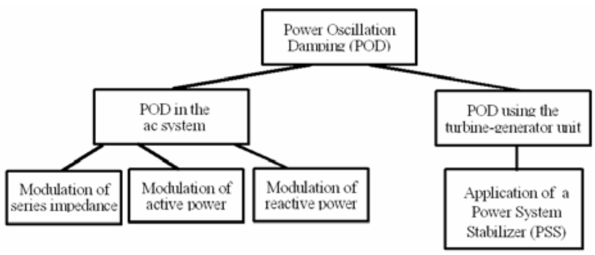

Fig. 11: Strategies to Damp Power Oscillations

Using the system eigenvectors (Fig. 10) the best damping location can be found. Depending on the chosen damping strategy (Fig. 11), the residues chart shows the location(s) for PSS (generator bar chart), for SVC (busbar bar chart), for TCSC (line bar chart), etc.

VI. OUTPUT AND POST-PROCESSING

The outputting of results from the program system is extremely versatile and ranges from a simple display of simulation variables against time to complex evaluations such as the Fourier analysis and stress analysis of machine shafts.

Graphical output can be either on the screen, by printer or plotter or in Metafiles for further processing by word processing or graphics programs. In addition, there is also a facility for producing files of results that can be post-processed with other programs (e.g. COMTRADE viewer). This kind of further processing is sometimes used when the computer simulation is being linked to an external real-time simulator.

There is yet another option for linking the computer simulation to real-time applications in closed-loop mode through the block-orientated simulation language and external devices (DINEMO=DIgital NEtwork MOdel) such as converters and amplifiers [7; 8; 9]. Fig. 12 shows the possibilities of the interactive testing of protection relays.

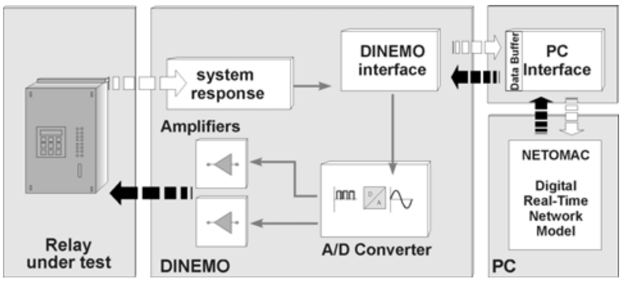

Fig. 12. Interactive Simulation

A Identification and Optimization

The optimization option can be used on all modeling systems in the software package regardless of any specific problems. All the modeling options described earlier are permissible so that linear and non-linear problems can be solved. The user defines the target function with the aid of the graphical interface as an analysis function with any input variables from the network or control system. Supplementary conditions defined by the user can also be taken into account. The parameters to be varied are marked to select them and then given an initial value and an upper or lower limit of variation. Identification and optimization is possible in the frequency domain, time domain, during power flow and for general mathematical tasks defined as block-orientated structures [5].

VII. CONCLUSION

The PSS®NETOMAC program package offers a wide range of options for simulating many different kinds of electromagnetic and electromechanical phenomena in electrical systems.

Analysis in the frequency domain makes an ideal addition to the working modes that are already available. Eigenvalue analysis opens the way to a variety of additional methods, such as the use of reduced dynamic models of networks by lessening of the order. A variety of pre-processing facilities are provided, such as parameter assignment to power lines or motors and the identification of model parameters. User defined optimization procedures allow to improve the overall system behavior. The training mode gives the user educational advantages in complex systems. With the real-time application test of elaborated equipment is easily possible. Thus, the versatility of application offered by the program package is far in excess of any other comparable system of simulation.

[1] B. Kulicke, „NETOMAC Digital Program for Simulating Electromechanical and Electromagnetic Transient Phenomena in AC Systems“, Elektrizitätswirtschaft Heft 1 (1979), S. 18-23

[2] J. Rittiger, B. Kulicke, „Calculation of HVDC converter harmonics in frequency domain with regard to asymmetries and comparison with time domain simulations“, IEEE Winter Meeting, New York 1995

[3] D. Povh, J. Rittiger, B. Kulicke, D. Clodius, „Advanced stability program for the simulation of HVDC in large power systems“, International conference on power system transients, Lisbon Sept. 1995

[4] D. Povh, X. Lei, E. Lerch, B. Kulicke, „Optimization - A New Tool in Simulation Program System“, IEEE Winter-Meeting, Baltimore, Jan. 1996

[5] X. Lei, D. Povh, E. Lerch, „Global Parameter Settings of FACTS-Controllers for Improving Power System Stability“, ICPST, Lisbon, 1995

[6] P Lehn, J. Rittiger, B. Kulicke, „Comparison of the ATP Version of the EMTP and the NETOMAC Program for Simulation of HVDC Systems“, IEEE Winter-Meeting, New York, Feb. 1995

[7] Winter, W.; Kulicke, B.: Automated Closed Loop Testing Of Microprocessor Protective Relays With The Real Time Digital Network Model", ICDS '97, Montreal 1997, Canada

[8] Kulicke, B.; Pannhorst, D.; Winter, W.; Eickmeyer, D.: "Hardware-in-the-loop test using the real time simulator NETOMAC", ICDS '97, Montreal 1997, Canada

[9] De Wilde, V.; Duschl-Graw. G.; Pannhorst, D.; Ruhle, O.: „Sophisticated Real-Time Tests on Protection Relays and Turbine Controllers with DINEMO-II and PSS®NETOMAC“, EUROSIM 2007, Ljubljana 2007, Slovenia