NETOMAC - Calculating, Analyzing and Optimizing the Dynamic of Electrical Systems in Time and Frequency Domain

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Abstract - The simulation system 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 the 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 time domain or frequency domain is being investigated. Workstations, PCs or Notebooks provide the platform from which NETOMAC can provide the user with the flexibility, mobility and speed that he needs.

Keywords: Electromagnetic and electromechanical transients, optimization, identification, eigenvalues, graphical input, network training simulator, real-time simulation.

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 NETOMAC 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 frequency domains in which studies of networks can be carried out with NETOMAC at present reaches from extremely fast traveling-wave phenomena on overhead power lines to the slow control phenomena of steam systems. 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] or control cubicals of FACTS equipment.

II. SIMULATION IN THE TIME DOMAIN

Fig. 1 shows the capabilities possessed by NETOMAC in simulating electrical systems. There are two alternative options in the time domain. The instantaneous value mode allows electrical systems to be represented phase-wise.

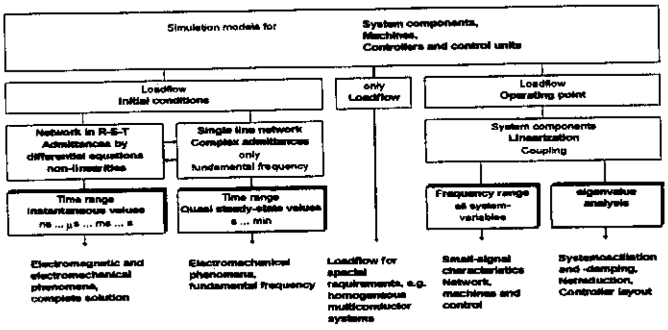

Fig. 1. Possible Ways of Simulation

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.

Alongside the instantaneous value mode there is the so-called "stability 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-mode 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 asymmetrical faults to be calculated in the stability mode too.

NETOMAC also 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.

NETOMAC also provides the facility for calculating eigenvalues so that the oscillatory characteristics of systems can be investigated and details of stability, controllability, observability, damping and oscillation of the state variables of large systems can be ascertained. Taking this as a foundation, 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.

The instantaneous value mode of NETOMAC 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 asymmetrical and non-linear events.

The main field of use is in the design of equipment and apparatus while taking transient phenomena into account. Fig. 2 shows a typical fault situation for a system incorporating a static compensator (SVC).

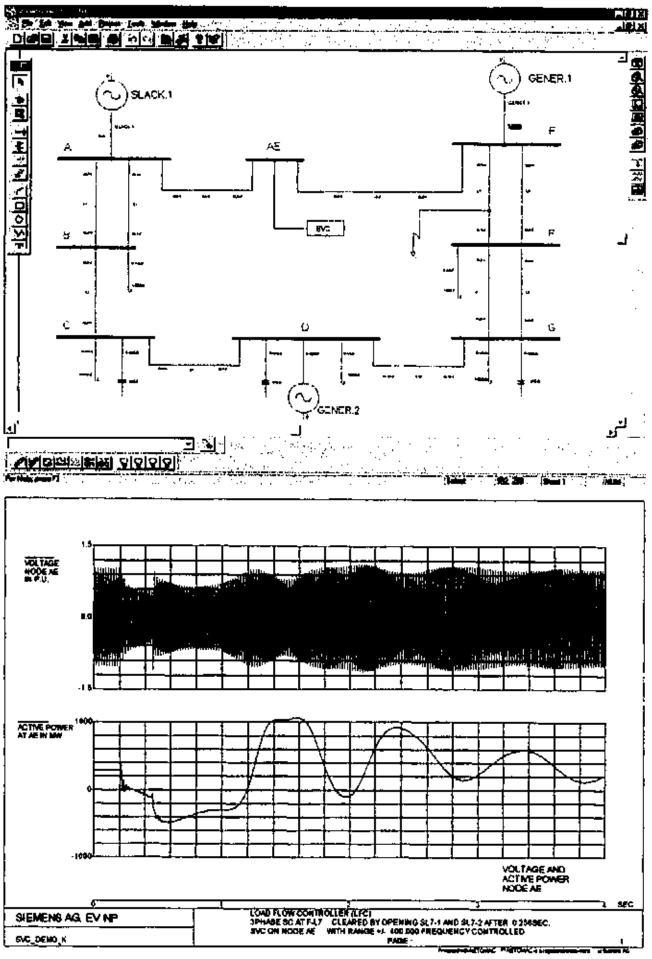

Fig. 2. Results Instantaneous Value Mode

Exemplary the voltage waveshape 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].

Reference [6] reports on a comparison of NETOMAC and EMTP (ATP version) for simulating an HVDC system.

B. Stability Mode

The stability mode in NETOMAC 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 by 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. 3 shows the same system as in Fig. 2 but this time studied in the stability mode for the same fault situation. It can be seen how there are no DC transients and the electromechanical fundamental-wave characteristics are retained.

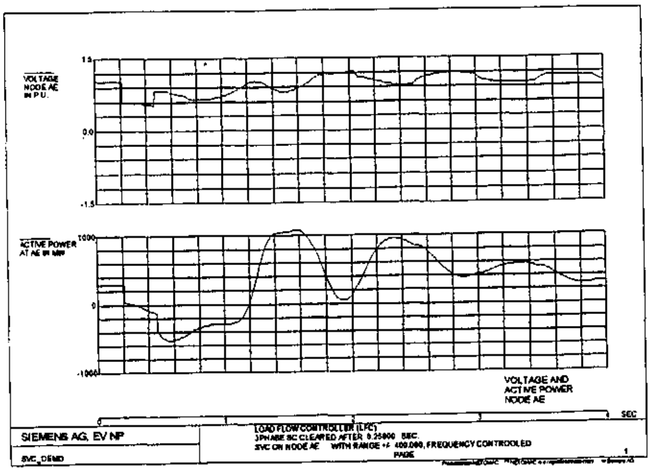

Fig. 3. Results Stability Mode

So that asymmetrical 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 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.

C. Models

During the considerable length of time that NETOMAC 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:

- Voltage regulators (IEEE specification or user-specific)
- Turbines and turbine governors (IEEE or user-specific)
- HVDC models for the instantaneous value mode and stability mode, including control (Fig. 4)
- 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

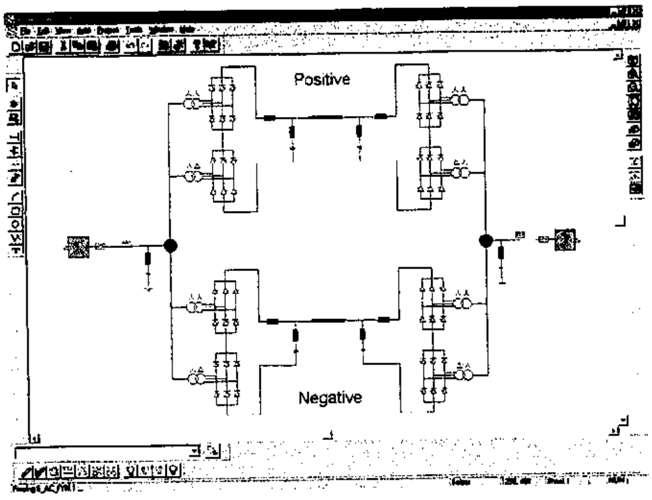

Fig. 4. HVDC Model

D. Block-Orientated Simulation Language

Available from a library are more than 100 different function blocks which, using the graphical interface, can be combined in many different open-loop and closed-loop control structures or analysis systems. As well as very simple blocks, such as PID elements, there are also more complex blocks available too, such as FFTs (Fast Fourier Transformation), for example.

The various controllers can be stored in a library 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.

There are blocks for specific purposes, such as a load-rejection relays for turbines, and others for power electronics purposes, such as firing pulse blocks.

The block-orientated simulation language allows control and protection functions of any complexity to be created for machines and networks.

And, in addition to the open-loop and closed-loop control structures it is also possible for the user to define signal processing structures (for analysis systems).

External, user-defined subroutines can be interfaced into the system too (open system) and there is an interface for closed loop real-time applications.

The block-orientated structures can be combined with FORTRAN-like expressions, such as mathematical functions, logic expressions or instructions such as IF/THEN/ELSE and GOTO/CONTINUE.

All the variables from the networks and from the machines are available to the controllers as inputs. It is also possible to access the variables from other control systems or analysis systems as inputs. All inputs and outputs of blocks can be output if necessary.

III. SIMULATION IN THE FREQUENCY DOMAIN

In addition to the facility for simulation in the time domain, the program also permits the study of networks, machines, shafts and control systems in the frequency domain. As well as allowing the elements of control systems to be analyzed, it also permits the study of networks, protection systems and machines at different frequencies.

A. Eigenvalue analysis

In large-scale electrical systems the relationships between generators, networks and control systems are becoming ever more complex. FACTS elements are used for the fast active control of transmission systems and for filtering purposes in distribution systems.

The analysis of such complex interaction between systems and equipment needs modern methods which are able to describe the behavior of the whole system both simply and clearly.

NETOMAC uses the analysis of system eigenvalues for this purpose. Compared with traditional methods of simulation, this method provides more information about the behavior of the system regarding damping, frequency response, observability, controllability and the effects of system state. Specific areas of application for eigenvalue analysis are inter-system oscillation, voltage stability, modeling of dynamic equivalents, controller design, subsynchronous resonance and harmonics effects.

B. System modeling

A linear model around a working point of the system is created for each component of the system being studied. These linearized models are then linked together to form an expanded model of state and stored sparingly. The expanded model of state combines the equations of system state (differential equations) and algebraic relationships.

C. Eigenvalue solutions

Three methods of providing full and partial solutions for eigenvalues have been implemented in NETOMAC.

All eigenvalue solutions are obtained through the *QR* algorithm. For large systems (more than 1000 state variables) the complete solution of the eigenvalue problem is impracticable, so it is necessary to take recourse to either of two other methods, partial solution through implicit inverse iteration of the state equation or the dominant pole method.

Once the eigenvalues and eigenvectors have been ascertained they can then be analyzed, for which purpose there are different combinations of these eigenvalues and eigenvectors available. From the right-hand eigenvector it is possible to make statements about the observability of system states, and from the left-hand eigenvector statements about controllability.

The participation factor identifies the effects of individual modes on various items of equipment, whereas the transfer function residual identifies the effects of different modes on one item of equipment.

IV. OPTIMIZATION AND IDENTIFICATION

NETOMAC allows electrical systems to be modeled close to reality. These models, in time domain or frequency domain, can be analyzed as well as being subjected to further processing. Fig. 5 shows the application of NETOMAC as a kind of subroutine for automatic parameter studies, for identifying model parameters or for optimization.

Three algorithms, Quasi-Newton, Modified Powell and Least Square, allow the robust identification and optimization of any linear or non-linear problem [4].

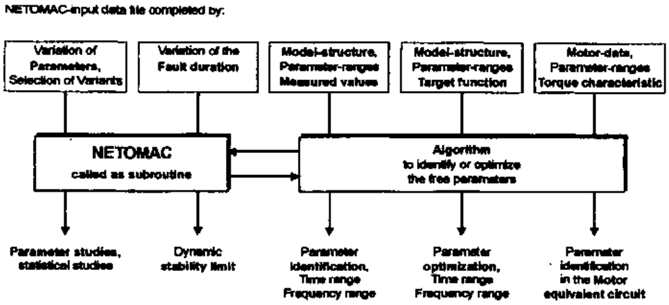

Fig. 5. Use as Subroutine

A. Identification

Identification is possible for any model in the time domain and frequency domain.

The identification part is employed for the following tasks:

- Parameter assignment of asynchronous machines from the torque/speed characteristic, taking saturation into account
- Parameter assignment of synchronous machines
- Calculation of dynamic network equivalents
- Reduction of dynamic loads
- Parameter assignment of control systems
- Parameter assignment of cable and wiring data from the geometry of arrangements (constant and frequency-dependent parameters)

B. Optimization

The optimization option can be used on all NETOMAC modeling systems 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. Optimization is possible in the frequency domain, time domain, during power flow and for general mathematical tasks defined as block-orientated structures [5].

V. GRAPHICAL INPUT

Input to the NETOMAC program is conducted from a graphical interface using the NETCAD® program. NETCAD is a quick, easy-to-use drawing tool for drafting, editing and documenting electrical systems and control structures.

In addition to well-known CAD facilities such as copying, shifting, rotating, zooming, etc., the system also provides a large library of symbols containing all elements of the NETOMAC program in the form of symbols. The user prepares his network diagrams and block diagrams through the graphical connection of library symbols. Fig. 6 shows a network element being selected from the symbol library.

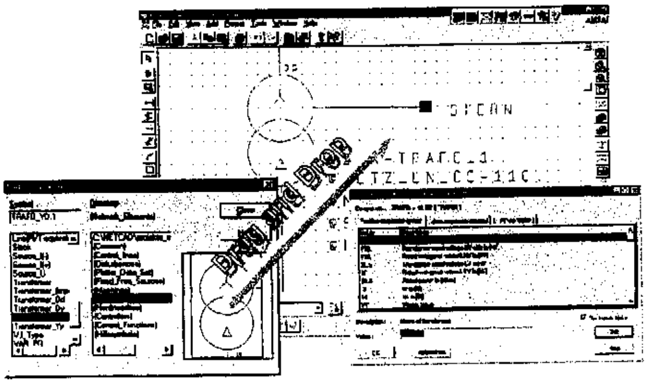

Fig. 6. Graphical Input

Data is entered by means of templates which are object-related and contain detailed help in plain text as well as in abbreviated form. There is also a facility for combining groups of related symbols to produce new, original symbols in the form of macro-models and adding them to the program symbol library or the user's own libraries. It is possible, for example, to combine complex control structures or sub-networks, comprising a large number of different items of equipment, into new symbols. As a result of this hierarchical configurability, depending on the requirements and using the same data, the system allows a choice to be made as to how complexly or how clearly a system should be presented (Fig. 7).

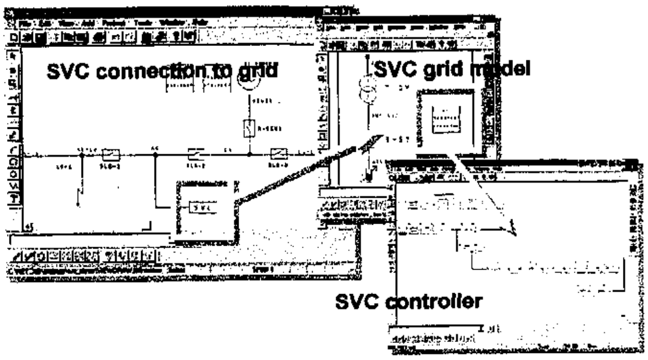

Fig. 7. Hierarchical Structures

Individual components can be activated and deactivated and linked to any point in the system. Thus, it is possible to show and simulate the behavior of different FACTS elements anywhere in the network.

VI. PRE-PROCESSING AND DATA IMPORT

NETOMAC offers many options for pre-processing the actual network calculations through the use of special pre-processing modules, which were dealt with in Section IV.

NETOMAC supports the importing of data from other programs through object-orientated filters, e.g. to the PSS/E stability program. The importing of data in accordance with the "Common Information Model Specification", EPRI 1996, is also supported.

Furthermore a connection and import of data from power system control systems (e.g. SINAUT SPECTRUM) is possible.

A network training simulator is implemented in NETOMAC and finds use in training and education.

VII. OUTPUT AND POST-PROCESSING

The outputting of results from the NETOMAC program 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. This kind of further processing is sometimes used when the computer simulation is being linked to an analog 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]. Fig. 8 shows the possibilities of the interactive testing of protection relays.

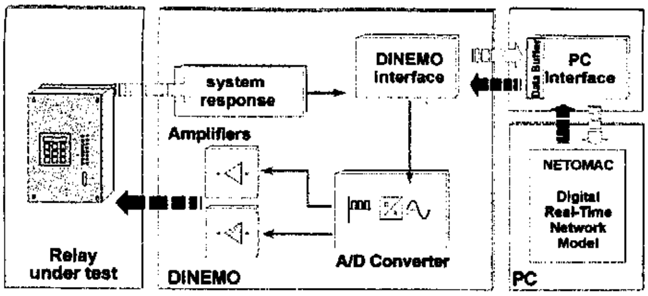

Fig. 8. Interactive Simulation

VIII. CONCLUSION

The NETOMAC program 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 behaviour. 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 NETOMAC is far in excess of any other comparable system of simulation.

IX. REFERENCES

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Bernd Kulicke was born in Wernigerode, Germany, on November 13, 1944. He received the M.S. degree in Electrical Engineering from the Technical University of Berlin and the Doctor degree in Power Engineering from the University of Darmstadt in 1970, on 1975 respectively. From 1970 to 1983 he was with the SIEMENS Company, working in the High Voltage and Power Engineering department. He is responsible for the development of the NETOMAC program and was mainly involved in performing system studies including electromechanical and -magnetical transients and stability problems. In 1984 he was appointed a Professor and Director of the Institute of Electrical Power Engineering at the Technical University of Berlin. Prof. Dr. Ing. B. Kulicke is a member of the IEEE Power Engineering Society.

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Wilhelm R. Winter was born in Germany in 1963. He received the M.S. degree and the Doctor degree in Power Engineering from the Technical University of Berlin in 1995 and 1998 respectively. Since 1995 he is with the Siemens Company. Until 1997 he developed the NETOMAC based Real Time Digital Simulator in cooperation with the Technical University of Berlin. Since 1998 he is working in the Siemens System Planning Department. He is involved in performing system studies including electromechanical and -magnetical transients, stability problems and Eigenvalue Analysis.