Advanced Stability Program for the Simulation of HVDC in large power systems

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Abstract – **This paper shows the performance of the NETOMAC program system for the simulation of HVDC on the example of a complex multiterminal system. The program's features are briefly summarized. An improvement of the existing program is discussed that makes it possible to study complex HVDC system configurations in large power systems effectively and economically. As an example the interconnection of the ac grids in eastern and western Europe by a multiterminal HVDC link is studied. In order to prove the feasibility of the multiterminal link, a new calculation model for stability studies was used. Some results are compared to calculations using a detailed commutation model in order to prove the accuracy of the new solution technique.**

Keywords: digital simulation, NETOMAC, advanced stability model, multiterminal HVDC

I. THE NETOMAC SIMULATION PROGRAM

A. Description of the existing program system

The NETOMAC program system [1] is a simulation tool for calculation of any electromechanical and electromagnetic transients. It comprises frequencies of 10^{-8} to 10^{+4} Hz so that the whole range for transients in electrical networks can be studied. That means that with the same program system the influence of lightnings as well as the control dynamics of steam turbines can be studied. The program is in use since two decades and has been developed continuously. Figure 1 summarizes the program's features.

The program can roughly be divided up in two parts. These are the "transient part" where all components are modelled with their differential equations and the "stability part" where the ac network is described by complex admittances. The generators and control functions are, however, also in the stability part described by their differential equations. A special advantage of the stability part is that also unsymmetrical ac faults can be considered. For stability calculations, the time step is in the range of 10–200ms, depending on the machine model for short term or long term dynamics respectively. For instantaneous value calculations a time step of less than 1ms must be used. A sequential switching over between the two program parts is possible during simulation.

The NETOMAC program includes, besides the full performance of the EMTP program and the stability calculation part, also additional features like e.g. parameter identification, optimization routines and the possibility of frequency domain simulation. An advantage of the pro-

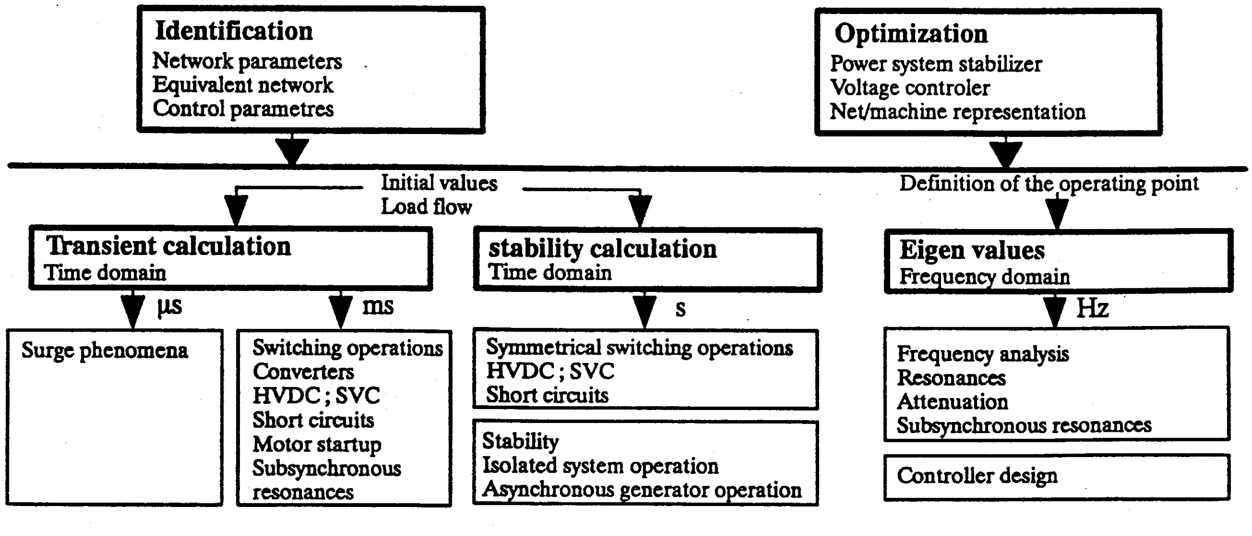


Figure 1 : **The features of the NETOMAC program**

gram is the interpolation of switching instant to prevent numerical problems occurring due to discontinuous current flow. This makes it possible to use a relatively large time step of 100μs for converter applications.

When developing the program system, a major demand was flexibility for user's convenience. This aim was achieved by a Block Oriented Simulation Language (BOSL). The user can refer to a library where all relevant basic elements for the modelling of control structures can be used and interconnected freely according to the user's requirements. Complex mathematical and logical expressions can easily be realized by using FORTRAN syntax like IF/THEN/ELSE/ENDIF structures. It is further possible to use external FORTRAN subroutines as BOSL functions.

Both systems – ac network and BOSL – can be interconnected. This means that all network and generator quantities like voltage, current, frequency etc. can be used as input values for control structures. The BOSL output values can be used to influence network elements :

- excitation of generators
- mechanical torque of turbines
- voltage and current sources
- active and reactive power of loads
- firing pulses for converter applications
- tap changer of transformers
- nonlinear RLC–network elements

Furthermore, interrupt criteria for the simulation can be defined and random controlled statistical studies can be performed.

For "instantaneous value calculations", each passive network element is mathematically described by a first order differential equation that is solved by numerical integration using the trapezoidal rule. This solution technique is the same as that used by the EMTP program. The solution technique also includes all relevant nonlinear elements like diodes, thyristors, GTO's, surge arresters etc. and frequency dependent transmission lines and cables.

Synchronous as well as asynchronous machines are described by the complete, nonlinear Park's equations. It is possible to take into account torsional oscillations of the generator shaft as well as saturation effects. Moreover, the user can define the machine's rotor circuit in d/q–axes freely according to his special requirements.

B. Improvements made to the simulation program

The described NETOMAC program system was improved in such a way that it became possible to perform instantaneous and stability calculations not only sequential but also in parallel. The ac network can be divided up in different, independent network partitions. This means that in the admittance matrix no coupling between the different partitions exists.

The different network partitions are coupled using the BOSL module. Any value like voltage, current etc. of a partition can be taken as an input value for the BOSL module, where it can be modified and subsequently be applied as an input value for any other partition in order to control, for example, voltage and current sources or variable loads there. When using the BOSL module as an interconnection between the different network partitions, the user has complete control over the coupling quantities, which improves the program's flexibility.

The integration time step of the different partitions can be chosen freely by the user and in general does not have to be equal. This is necessary to fulfil continuity conditions when switching nonlinear elements in order to avoid numerical noise. Switching operations can be performed in all partitions at any instant.

With this improvement, it is possible for the user to model complex HVDC system easily. The dc circuit is modelled in one partition and the differential equations are solved (see figure 2). It should be mentioned that line modelling with frequency dependent line parameters is possible, using the Marti Model for transmission lines .

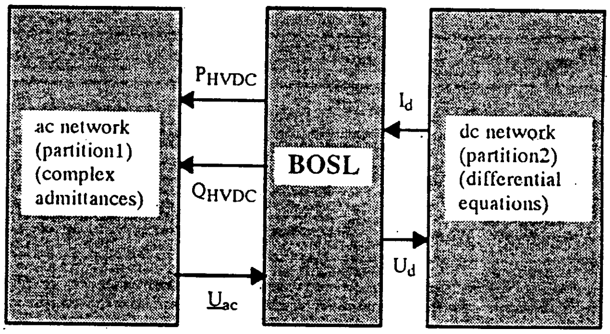


Fig. 2 : Coupling of two partitions using the BOSL module

The ac networks are modelled in another partition. In order to save calculation time, the ac networks are modelled with complex admittances for stability calculations. The generators and control functions are, however, described by their differential equations. The interconnection between the ac networks and the dc circuit is achieved by the BOSL module. The quasi–stationary equations for direct voltage, active and reactive power of the converters and the complete converter control circuit are modelled there.

One advantage of this new solution technique is that the dc circuit need not be modelled by control structures, like in other stability programs, in order to accurately take into account the dc transients during contingencies. Another advantage is that any switching operation including contingencies can easily be carried out in the ac and in the dc circuit.

In order to save calculation time, the dc circuit is calculated with a time step of e.g. 1ms, whereas, the ac system can be calculated with a time step of 10–20ms except during contingencies. For the fault period, the time step of the partition with the ac network is changed also to 1ms. After fault clearance, the time step is switched back to 10–20ms in order to study for example power oscillation damping using the HVDC.

Therefore, the above described NETOMAC improvements create a powerful tool for studying the dynamic behavior of large interconnected ac and dc systems. It should, however, be mentioned that with the ASM it is not possible to study harmonic phenomena because only the fundamental frequency equations of the converter are used. Also faults in the valve bridges cannot be calculated because the thyristors are not modelled in the ASM. To study these effects a NETOMAC commutation model with a detailed representation of the valve bridges and the trigger set is required.

The above described model was used for the feasibility study of a interconnection of the power grids in Eastern and Western Europe using a multiterminal HVDC interconnection. This application is discussed in the following in order to demonstrate the performance of the ASM. In the meantime further studies like e.g. the feasibility of the interconnection of the South Norwegian power grid and the UCPTE system using six HVDC sea cable links were carried out. For this application especially the interaction between the converters in the South Norwegian ac system was of interest because the six converter stations are in close electrical proximity.

II. HIGH POWER LINK BETWEEN EASTERN AND WESTERN EUROPE

In November 1992, a letter of intent concerning the preparation of a feasibility study on a East–West High Power Transmission System was signed by the power system companies from Russia, Belarus, Poland and Germany.Concerning the creation of a general European energy market which was started by signing the Energy Charter in December 1991, the above mentioned partners intend to estimate possibilities for the integration of their networks by realization of an interconnection with high power capacity enabling the following objectives:

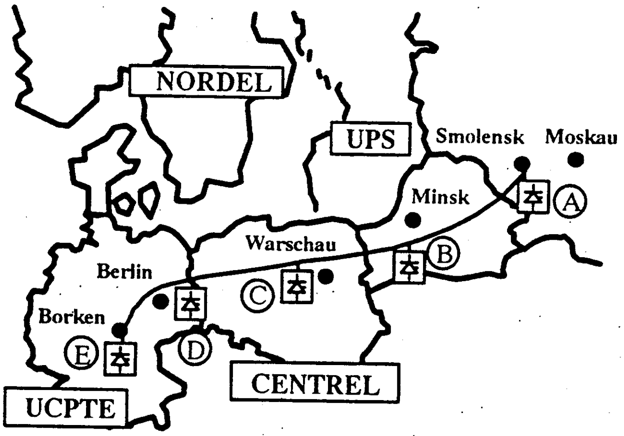
- transmission of large amount of energy
- optimization of energy production in the power stations of the partners
- mutual exchange of power plant reserves

Three basic configurations have been considered and investigated in the study:

1) high power dc–line and 5 converter stations
2) high power 750 kV ac–line, substations and 2 HVDC back–to–back stations
3) using existing ac–lines and a HVDC back–to–back station between Poland and Belarus.

Synchronous operation of the UCPTE– and the UPS–system is presently not possible because of different frequency regulation processes. The most economic configuration seems to be a dc–link with a max. transmission capacity of 4000 MW in the ultimate layout consisting of two +/– 500 kV bipolar systems.

The transmission route of the High Power Link and possible substations can be seen in figure 3 . The commissioning of the High Power Link in the final layout is planned after the year 2000. At that time, the networks of CENTREL (Poland, Czech Republic, Slovak Republic and Hungary) will be integrated into the UCPTE–system. Regarding the High Power Link, the border between the UCPTE– and UPS–system has been assumed for the investigations to be between Poland and Belarus.



HVDC : Length : 1800 km
Capacity : max. 4 GW
Voltage : +/– 500 kV

Fig. 3 : The configuration of the multiterminal system

III. THE MULTITERMINAL HVDC SYSTEM

The multiterminal system consists of five bipolar converter stations which are connected by two parallel dc overhead lines per dc pole. The rated power per pole is 2000 MW with a direct voltage level of 500 kV and a direct current of 4000 Amps.

The idea was that for a fault on one of the two dc lines the faulty line should be disconnected by dc breakers and the second line should take over the full direct current until fault clearance in order to reduce the disturbance on the connected ac systems. For this reason, an accurate model of the dc circuit including the line breakers was required. In conventional stability programs, this is not possible because in this case the transient behavior of the dc quantities is normally modelled as a simple transfer function, which is not very convenient for usage, especially when the dc circuit is complex and when dc faults must be studied.

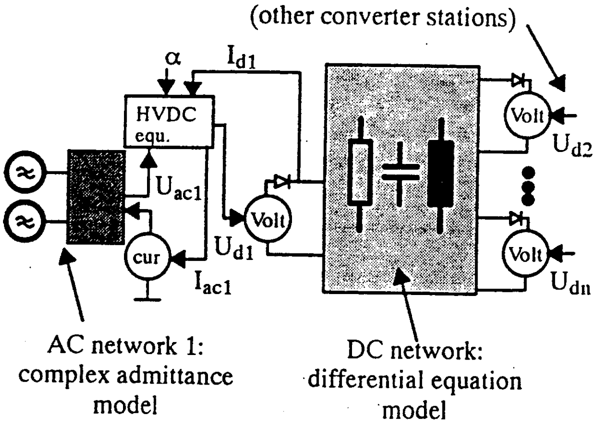


Fig. 4 : **The NETOMAC Advanced Stability Model Solution Technique**

The converter model [2] is shown in figure 4 . The model describes the converter characteristics using quasi steady state HVDC equations. The thyristor valve bridges are not modelled. This means that a commutation model with a detailed representation of the valve bridges has to be used when e.g. faults in the valve bridges must be studied. An additional logic ensures the accuracy of the simulation results during fault transients so that the results become comparable to commutation model calculations, where the thyristor bridges including the trigger set are modelled in detail. For the dc side, the direct voltage is calculated and supplied to the dc network model using voltage sources. The active and reactive power demands of the converters are calculated and fed into the connected ac systems so that the interaction between the ac and the dc system is represented properly.

The control functions of the multiterminal system contain all capabilities that are the current state of the art [3],[4]. The implementation of some improvements ensures that even at transient conditions communication between the stations is not required The control consists of a supervising master controller and the control circuits of the converter stations. The main task of the master controller is the steady state setting of power and current orders in the whole system. In the case of a terminal outage, the system keeps stable operation even if there is a temporary loss of telecommunication between the master controller and the converter stations. It should be noticed that all control functions are represented in detail and no simplifications were made.

The converter station A, which is working as a rectifier station, is used as the voltage setting terminal (VST). At the inverter stations current control is used in steady state operation. It is possible to use an inverter as the voltage setting terminal if this should be required to improve system performance.

IV. INVESTIGATION OF THE MULTITERMINAL SYSTEM

In order to prove the technical feasibility of the multiterminal transmission system detailed studies were carried out. Three examples cases are presented in the following.

Figure 5 shows the direct voltage at the voltage setting terminal and the converter station's direct currents of the positive pole. The plots show the system's reaction to a ground fault in one line system of the positive dc pole. Approximately 100ms after fault occurrence the faulty line

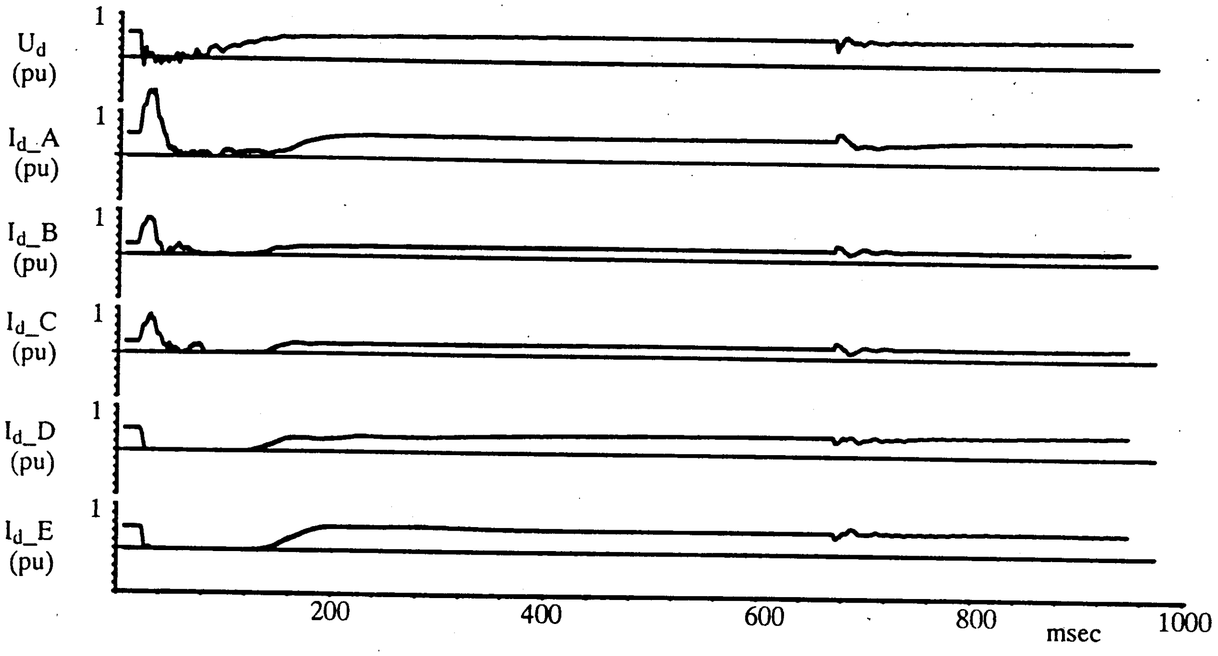


Fig. 5 : **Direct voltage of VST and direct currents of the converter stations for a fault in the dc circuit**

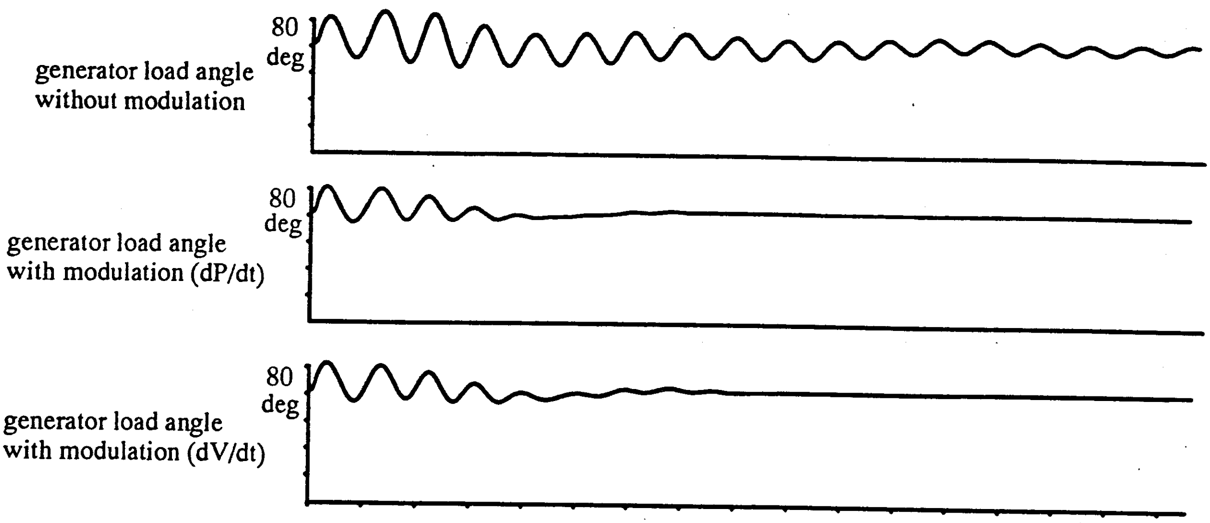


Fig. 6 : Damping of power oscillations by power modulation of the multiterminal HVDC system

section is tripped by the dc breakers. For approximately 550ms only the second line system of the positive pole is available for energy transmission in this line section. Then, 500 ms after fault clearance the line is switched in again at 650ms, as indicated by the short transient.

The second example is shown in figure 6 . The power oscillations of one, particularly large, generator resulting from a 3 phase fault in the UCPTE network was investigated. It was attempted to damp these oscillations by modulation of the DC power order in station E. The plots show the generator load angle for three studied cases. The first track gives the load angle oscillation for constant DC power without modulation. The second track shows the response when the DC power is modulated, based on a signal derived from the derivative of the power of the machine in question (dP/dt). In the last case the modulation signal is derived from the rate of change of the converter E busbar voltage. Although the system response here is not quite as good as in the previous case, it has the advantage that the modulation signal is locally available and therefore not dependant on the operation of telecommunications equipment. In both cases with modulation the generator oscillations were rapidly damped out, while the unmodulated system oscillated for about 40 seconds.

The reaction of the multiterminal system to the outage of terminal A is shown in figure 7 . According to the control characteristic , converter station E now determines the system's voltage level, which decreases as a result of the energy outage of the rectifier terminal A. It can, however, be seen that the whole system keeps stable, having defined operating points for the other converter stations. This makes it possible for the master controller to calculate the new loadflow conditions or to determine other countermeasures, without taking the whole system out of operation.

Except the above described example cases a number of ac faults in the UCPTE system and in the UPS were studied.

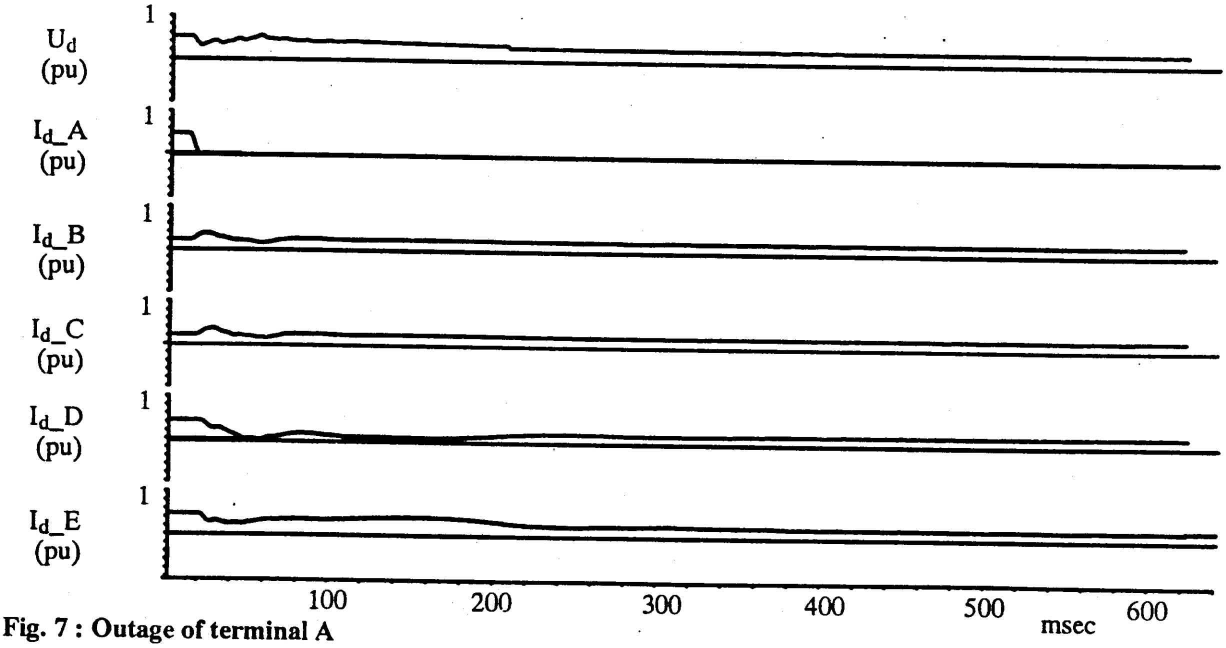


Fig. 7 : Outage of terminal A

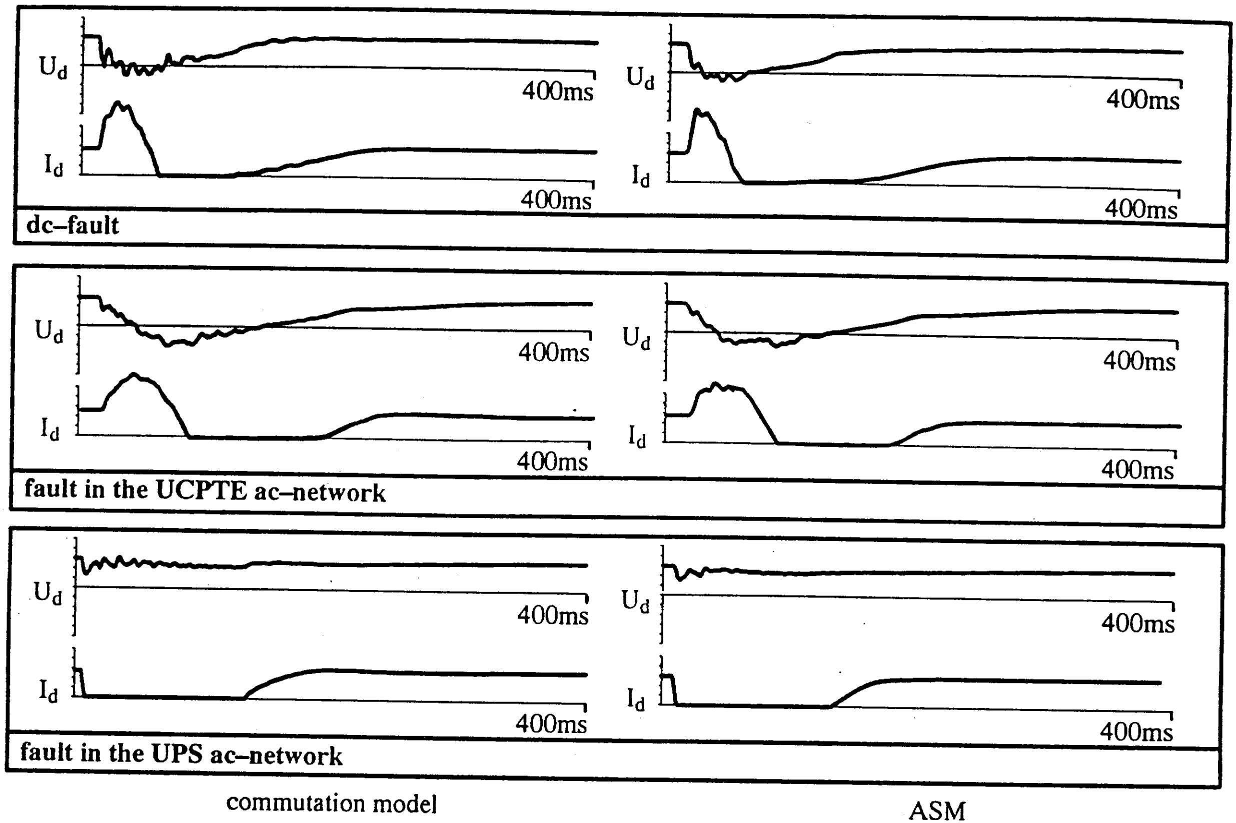


Fig. 8 : Comparison between the ASM and a commutation model

V. COMPARISON OF SIMULATION RESULTS

In order to prove the accuracy of the ASM, comparison studies using a detailed commutation model were carried out. Figure 8 shows the direct current and the direct voltage of converter station A for three different fault scenarios. It can be seen, that good agreement between the two models – also for the transients during the fault – is obtained. It should be mentioned here that all other quantities show similar good agreement. The great advantage of the ASM is the reduced calculation time which is required for time saving, economical stability studies of large power systems. Compared to the commutation model, the calculation time of the ASM was about 20 times shorter, because time steps of 1ms and 10–20ms respectively can be used instead of a maximum possible time step of 100μs for the commutation model. For the multiterminal study a relatively small ac system was used. It should be noted that the time factor improves rapidly when the size of the connected ac systems increases. E.g. for the above mentioned HVDC system study of the Norwegian ac system a time saving factor of more than 100 was observed compared to a commutation model. For this study besides the six HVDC interconnections the ac system in southern Norway and the relevant parts of the UCPTE system with thousands of network branches and hundreds of generators were modelled in detail.

VI. CONCLUSION

The performance and an important improvement of the NETOMAC program were discussed. This improvement makes it possible to perform transient and stability calculations in parallel. It was shown that this program extension can be used for fast and economic studies of very large ac power grids including complex HVDC converter configurations. As an example some study results of a proposed multiterminal HVDC interconnection between Eastern and Western Europe were presented A comparison of the ASM with a detailed commutation model of the whole system showed good agreement so that the ASM can be used e.g. for system stability studies and optimization of the control functions. The great advantage of the ASM is the reduced calculation time in comparison to a commutation model (up to 100 times depending on the seize of the ac networks).

VII. REFERENCES

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