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POWER MODULATION OF SIDNEY HVDC SCHEME
PART 2: COMPUTER SIMULATION

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ABSTRACT

The back-to-back Sidney Converter Station (SCS) provides an asynchronous 200 MW tie between the east and west ac power systems of the United States. The addition of the SCS to the network required a Remedial Action Scheme (RAS) integrated in the HVdc control in order to meet ac systems reliability criteria. One of the basic components of the RAS is the frequency dependent power modulation combined with an effective voltage control in the western network. Computer simulations were performed to check design and to provide initial settings for the RAS. As one part of the commissioning of the SCS, field tests of the RAS were conducted. The digital calculations correspond very good to the field test results.

INTRODUCTION

The Sidney Converter Station (SCS) is a 200 MW back-to-back High Voltage Direct Current (HVdc) Station located in Sidney, Nebraska which provides an asynchronous tie between the east and west ac power systems of the United States. Figure 1 is a simplified single line diagram of the SCS. A remedial action scheme (RAS) integrated in the HVdc control was found to be necessary in order to meet Western System Coordinating Council (WSCC) and Mid-continent Area Power Pool (MAPP) reliability criteria. The Western Area Power Administration (Western), owner of the SCS, is a WSCC and MAPP member. Basically stated, the addition of the SCS should not degrade the ac system reliability. Once a conceptual design criteria for the RAS was agreed upon by a joint study group, it reremained for an actual design to be developed and tested. Computer simulation was essential in order to ensure proper design of the RAS.

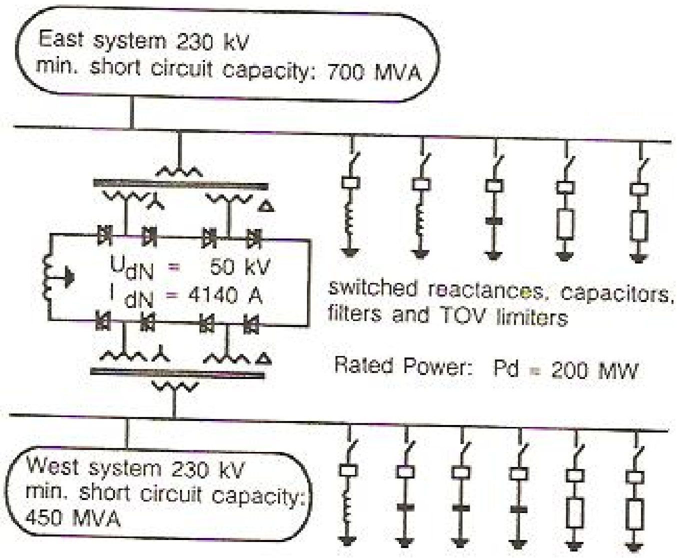

Fig. 1: Sidney Converter Station simplified single line diagram

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PROBLEM DESCRIPTION AND SOLUTION

Powerflow and stability studies in planning stage were run for both the east and west ac system which identified the need for the RAS. These studies used a generic dc model with SCS data. On the east ac system, it was shown that various outage disturbances caused ac system electro-mechanical instability with SCS power transfer west to east and Western Nebraska transfers to the east at a maximum. On the west ac system, two N-1 (prior system intact) outages were found to cause steady state problems. Figure 2 illustrates the ac system configuration in the vicinity of the SCS.

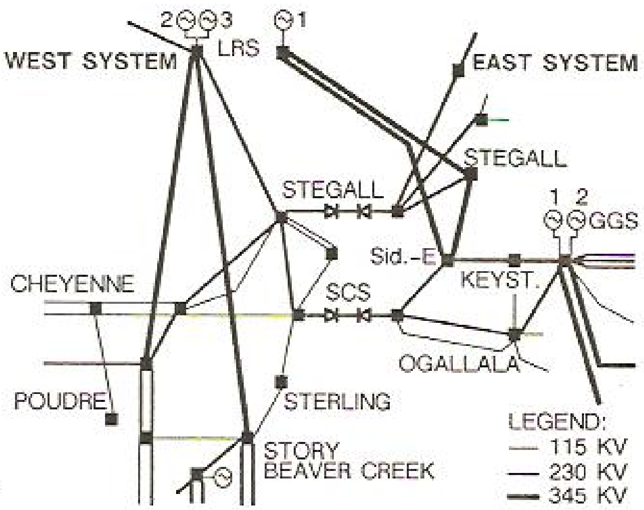

Fig. 2: Sidney Area Transmission

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A Remedial Action Scheme was required which could handle a variety of disturbances on the east ac system as well as the two west system outages. The basic functions of the RAS are:

1. East System disturbances, west to east SCS power transfer only
   a) Frequency dependent power modulation (proportional and bang/bang modes, for stability)
   b) Ramps (for steady state problems and back up modes)

2. West System outages
   a) Ramp down for loss of Laramie River Station (LRS) - Story 345 kV line, SCS transferring power east to west
   b) Ramp down for loss of Sidney - Stegall 230 kV line, SCS transferring power either direction.

Actual design of the RAS began at this point. Studies have been performed on Transient Network Analyser (TNA) |1| and with NETOMAC digital program system |2|. In the TNA study the performance of the complete SCS control (hardware and software) has been demonstrated with a reduced ac power system representation. The digital study, which included an extensive ac power system, was done in order to check the design and to provide initial settings for the RAS parameters such as modulation gain (MW/Hz), ramp rates, and upper and lower power levels for modulation.

Table 1 lists the cases run in the NETOMAC study. Cases A and F are the two worst prior system-intact east system disturbances. Case B was run since it was planned to trip the Sidney - Keystone 345 kV line as a live system test of the installed RAS. The results of the field test and the NETOMAC simulation for this case will be compared in this paper. Cases C, D and E check the west portion of the RAS design.
The reader may wish to refer to the companion paper "Power Modulation of Sidney HVdc Scheme, Part 1: RAS Control Concept, Realization and Field Test" |3| for more detailed background information on the RAS.

THE NETOMAC DIGITAL PROGRAM SYSTEM

The study of transient behaviour and interaction between complex ac networks and HVdc systems requires extensive computer simulations. For this purpose the NETOMAC digital program system is used. The NETOMAC program system has three calculation modes, which are applied depending on the specific task:

- instantaneous values mode
  e.g. used for calculation of fast transient phenomena and HVdc simulation with commutation model for converters,
- rms values mode
  e.g. used for stability studies in ac power systems,
- frequency domain mode
  e.g. used for studying torsional oscillations of turbogenerator shaft systems.

For the representation of network elements various detailed or simplified models are available. These network elements including generators, HVdc stations and control systems can be freely interconnected forming complex networks. For simulation of HVdc systems in

Table 1

Case list summary

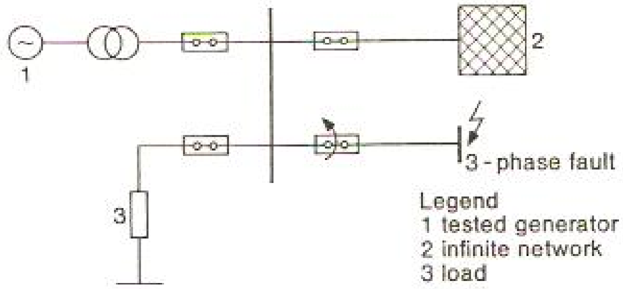
	LINE(S) TO REMOVE	FAULT		MODULATION	RAMPING	SIDNEY POWER TRANSFER	
		TYPE	LOCATION			W == E	E == W
A	Sidney-Keystone, GGS-Keystone 345-kV lines	1phase-ground Stuck Breaker at Keystone	Keystone Open GGS End at 4 Cycles Open Sidney at 12 Cycles	Yes	Yes	Yes	No
B	Sidney-Keystone 345-kV line	None	---	Yes	Yes	Yes	No
C	Sidney-Stegall 230-kV line	None	---	No	Yes	Yes	No
D	Sidney-Stegall 230-kV line	3phase to ground	Sidney 5 Cycle Fault	No	Yes	Yes	Yes
E	LRS-Story 230-kV line	None	---	No	Yes	No	Yes
F	Sidney-Keystone 345-kV line	3phase to ground	Sidney 4 Cycle Fault	Yes	Yes	Yes	Yes

the time domain two different models are available in the NETOMAC program |4|. Using rms value mode the HVdc systems are represented by mathematical equations, which define the relationship between dc-current, dc-voltage, firing angles and the active and reactive power on the ac sides. In the instantaneous value mode the HVdc stations are represented by the commutation model. In both cases control systems for HVdc systems can be modelled by using the block-oriented simulation language of the NETOMAC control module.

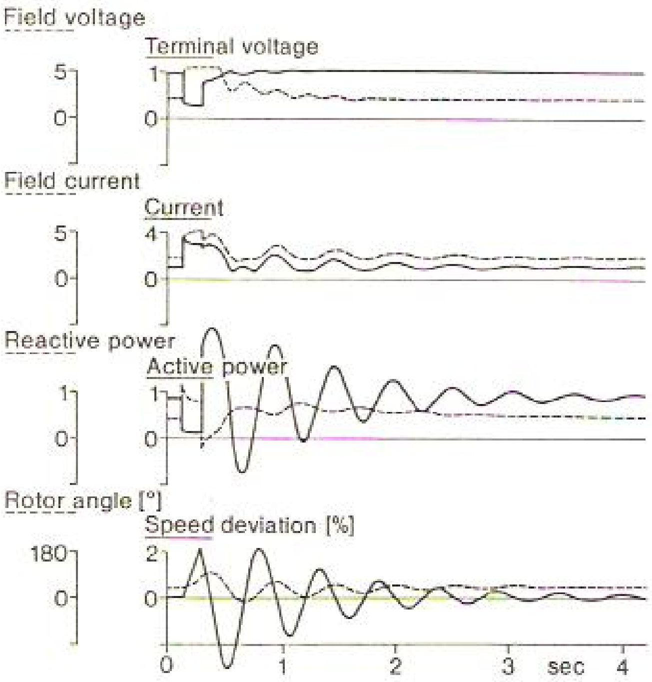
The calculations discussed in this paper with an extensive ac network including SCS and large numbers of generators have been performed in the rms value mode.

SYSTEM MODELLING

The stability study is based on the representation of the east and west ac power systems, SCS with control and the RAS. The modelling of these components will be described in the following.



a) Single line diagram of the test network



b) Results

Fig. 3: Test of the generator excitation control system (type ST3)

Representation of the ac power system

The east and west ac power systems have been reduced to an equivalent network model with 150 busses and 240 branches. The geographical extension covers the states of Wyoming, Colorado, South Dakota and Nebraska. The adjacent systems are represented as equivalent generators which are running with fixed frequency. The east and west ac networks are represented by 345, 230 and 115-kV lines and transformers, 4400 MW east and 9800 MW west side loads distributed over the networks and 26 generators. The generators are simulated according to the two-axes theory including excitation systems, power system stabilizers and speed-governing systems. The models used are based on the IEEE Committee Report |5|. Each generator has been individually tested in order to verify the representation and finally connected to the whole system.

An example of such test is given in figure 3. The generator excitation control system is analysed considering a simplified test network. As shown in figure 3a a single generator is connected to an infinite system and a single load. The 3-phase fault lasting 160 milliseconds initiates oscillations of the generator due to the low voltage at the generator terminals. The excitation voltage is driven to ceiling voltage, leading to an increased excitation current, resulting in a higher synchronizing torque. The excitation system has a positive influence on the transient stability during short circuit conditions and in the subsequent period. The generator oscillations are well damped (figure 3b).

The Stegall Converter Station is simulated in the calculation as feeding unit or load and only the SCS is represented as an asynchronous connection between both ac systems.

HVdc control representation

The open and closed-loop control circuits included in the simulation for the digital study are those necessary to represent the behavior of the real control for steady state operation, power modulation and for the reactions of the control on network faults (three phase, close and remote faults, line switching). A simplified block diagram of the control including RAS is shown in figure 4. This figure shows only those parts, which are activated for one special power direction (west to east).

The normal control mode during steady state operation is the P/V-mode, with which the power transfer and the terminal voltages are kept at their reference values. The voltage control is able to control the sum of the voltage deviations of both ac sides via the firing angle of the inverter. The additional control circuit, which acts in a longer time range and controls both voltage deviations separately via tap changer and switching of reactive elements has not been simulated in the study as these measures are blocked during the RAS action. The power transfer is controlled by the Master Power Control (MPC), which determines the current reference value for the current control circuits. During RAS action an additional signal ΔP^*_{RAS} is added to the power reference value.

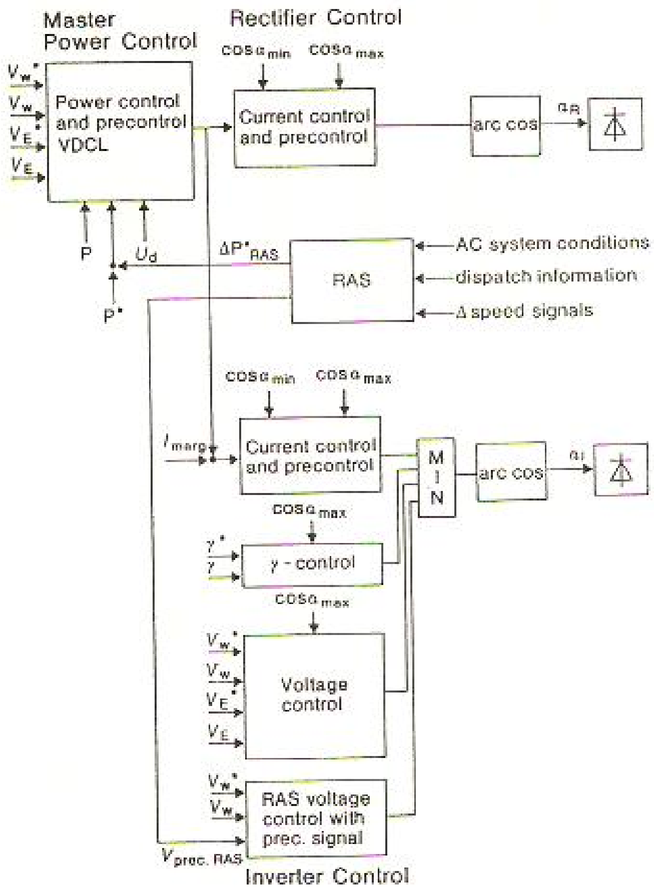


Fig. 4: Principal block diagram of the SCS control including RAS

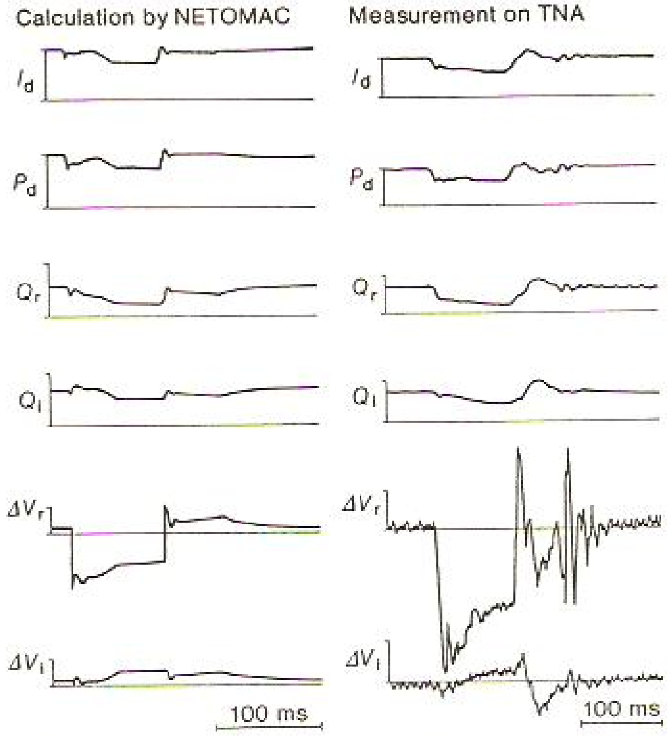


Fig. 5: HVdc simulation compared with measurement on TNA
200 MW power transfer west to east,
3phase remote fault on rectifier side

During normal and RAS operation the rectifier works in current control mode. On the inverter side the voltage control circuit is active, while current- and γ-control circuits are in stand-by. During RAS action, however, the voltage control is done by an additional RAS voltage controller, which has as input the voltage deviation of the west ac network. The reason for this is that the voltage oscillations in the weak western network should be limited. The RAS voltage controller output is added to a signal from RAS, which is dependent on the actual RAS power reference value ΔP^*_{RAS} and on the initial steady state conditions.

In addition the automatic bypass function has been represented in the control scheme in order to simulate the behaviour of SCS during network faults close to the SCS.

The HVdc control, represented for this phase of the study, consists of about 300 control blocks. It has been tested including the reduced network representation as used in TNA for performance of the control hardware. The behaviour of the control during and after network faults on both sides, after line switching and power reference value steps has been checked. A typical example is shown in figure 5, together with the comparison to TNA results for a similar case. Starting from a steady state 200 MW power transfer west to east a 3-phase remote fault has been simulated in the western ac network. It can be seen that the NETOMAC results are in a good agreement with the TNA simulation, the differences, mainly in the voltage reduction during the fault, are due to a different fault location.

Simulation of the RAS

The Remedial Action Scheme is a supplement to the SCS control system and allows power modulation and ramping of the dc tie. The RAS system is activated when the positive speed deviation exceeds an adjusted limit value of the Laramie east generator and/or when the system fault conditions laid down are met (e.g. breaker tripping).

According to the basic design |3| the RAS has been represented in detail using NETOMAC block-oriented simulation language. The simulation of the RAS is performed with about 400 control blocks and mainly comprises the functions given in figure 6. This digital representation with the possibility to record any given internal signal permits the design of the RAS to be analysed and to study the influence of control settings on the modulation.

The performance of the RAS representation has been extensively tested. Figure 7 gives an example of the basic response of the RAS with proportional modulation using following settings:

- initial power 200 MW, west to east SCS transfer
- upper (200 MW) and lower (20 MW) modulation power levels
- modulation gain 600 MW/Hz
- ramp rate 4000 MW/s.

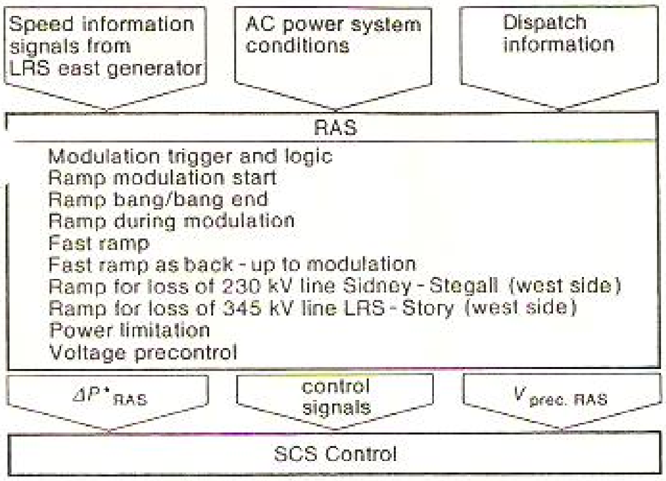


Fig. 6: Remedial Action Scheme main functions

Tripping the 345 kV Sidney-Keystone line (case B, table 1) effects a rotor frequency deviation of the LRS east generator. This speed signal is transmitted approximately 200 km via microwave to the SCS and monitored by the RAS. As soon as the positive speed deviation exceeds a preset threshold the trigger signal for damping measures is set, thereby initiating the fast ramp down of the transfer power to 20 MW. The modulation is then only initiated when the speed deviation signal becomes less then zero, i.e. when the generator rotor angle passes a reversal point. The RAS output ΔP^{*}_{RAS} is added to the initial value of the ransfer power resulting in a power reference value P_{ref}. Modulation is terminated when the speed deviation signal remains within a preset deadband for an adjustable period of time.

STUDY RESULTS

Settings for RAS

The determination of settings for the RAS parameters has been based on following requirements:

Group 1 settings:
To limit the LRS east generator rotor frequency deviation. An optimum damping of generator oscillations is achieved by maximum gain and maximum ramp rates.

Group 2 settings:
To limit the Sidney west 230 kV bus voltage excursions. Minimum voltage deviations are achieved by minimum gain and minimum ramp rates.

Group 3 settings:
To optimise the LRS east generator rotor frequency deviation and Sidney west 230 kV bus voltage excursions.

ccording to the case list given in table 1 an xtensive study with more than 100 NETOMAC calculations has been carried out. Some primary settings are presented in Table 2.

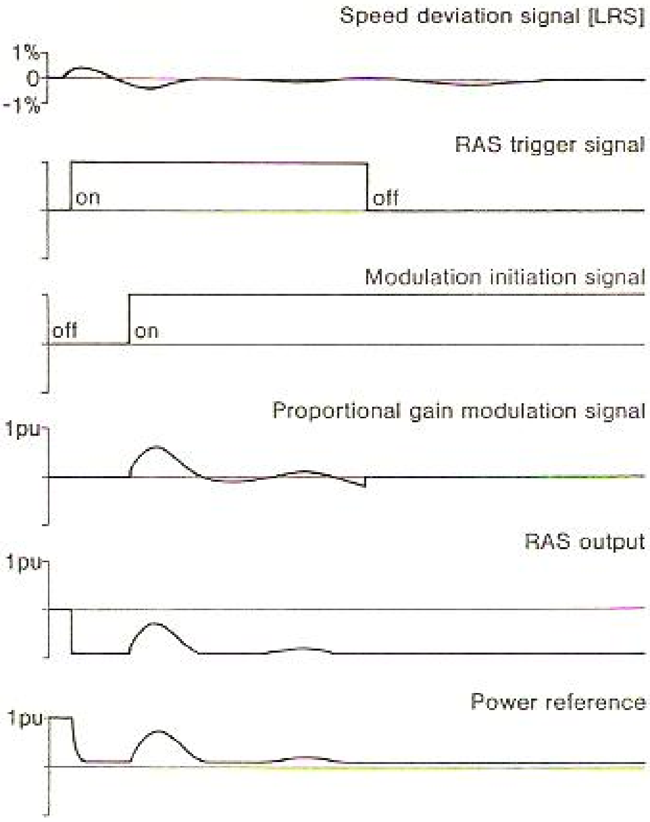


Fig. 7: RAS internal signals
Case B (Table 1) with proportional modulation

Table 2

Primary settings of the RAS

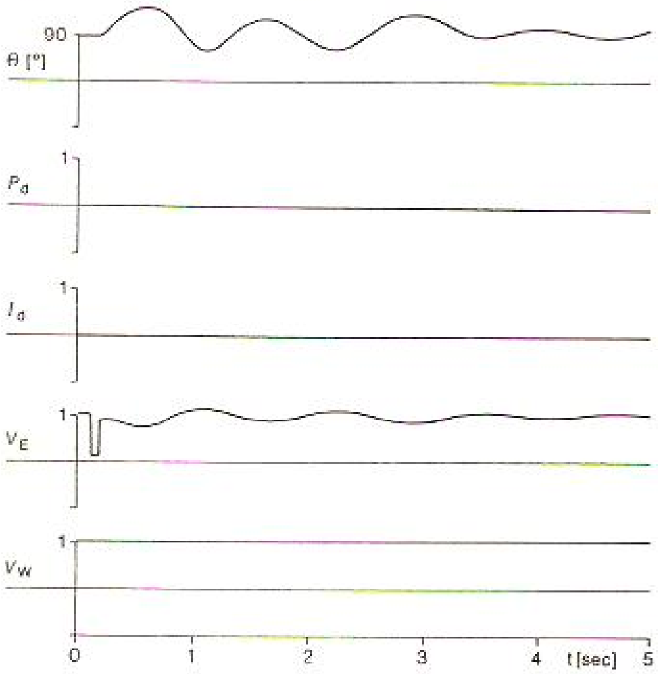
Item	Setting
threshold for initiating the modulation	0.15 Hz
modulation gain with proportional modulation	600 MW/ Hz
modulation depth with bang/bang modulation	100 MW
ramp rates (4000 MW/s for proportional modulation)	
upper and lower power levels for modulation	200 MW to 20 MW
modulation timer for terminating unsuccessful modulation	5 s
deadband of the speed deviation and timer for terminating successful modulation (e.g. 0.075 Hz and 1.5 s for proportional modulation).	

Examples of stability calculations

The effectiveness of the RAS to perform requirements shall be demonstrated for one of the worst east system disturbances, i.e. for a 3-phase fault at Sidney and tripping the 345 kV Sidney - Keystone line after 4 cycles. The case F has been calculated for different operations of the SCS:

(i) east ac power system without SCS,
(ii) SCS running without RAS activated (without power modulation),
(iii) RAS drives the modulation of the SCS.

Figure 8 shows the results of calculations without SCS. As the dc tie is not in operation dc power and dc current are zero and the west ac power system is naturally not influenced by the east side disturbance. The west side ac bus voltage remains constant. The rotor angle of LRS east generator shows large swings, however the east ac system is stable.



θ rotor angle of the LRS east generator
P_d dc power transferred by SCS from west to east (rated power: 200 MW)
I_d dc current (rated current: 4.14 kA)
V_E ac voltage at Sidney east side bus
V_W ac voltage at Sidney west side bus

Fig. 8: 3phase fault in the east ac system and tripping 345 kV Sidney-Keystone line, SCS out of operation

Figure 9 gives the results with a 200 MW west to east power transfer of the SCS. The RAS control is not activated. During the fault the SCS goes into bypass-operation. After fault clearing the SCS tries to recover to normal operation. The power infeed accelerates the LRS east generator and thus the eastern ac system is becoming unstable during the first swing. This confirms the need for the RAS.

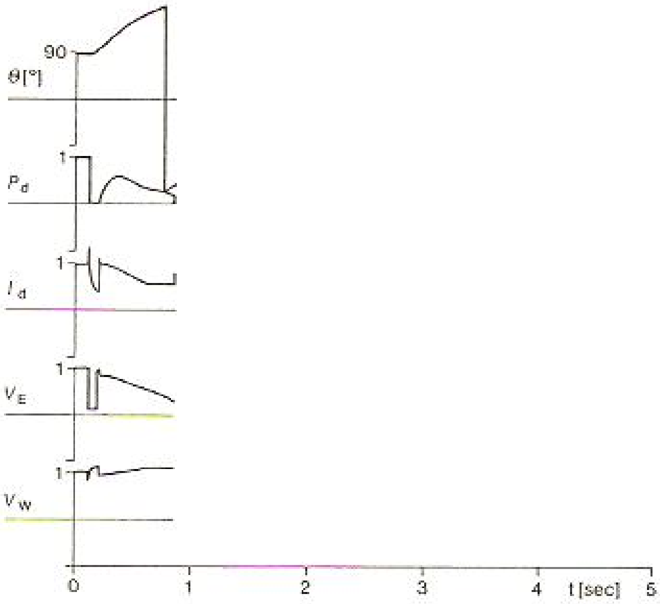


Fig. 9: 3phase fault in the east ac system and tripping 345 kV Sidnex-Keystone line, 200 MW west to east transfer, RAS not activated (Legend see fig. 8)

Figure 10 shows the same case as in figure 9 but with RAS being activated. The operation of SCS at fault initiation and during fault is the same. This leads as in the simulations before to an acceleration of the LRS east generator. RAS reduces the power reference value to 20 MW. After fault clearing the SCS remains on this reduced power level until the rotor

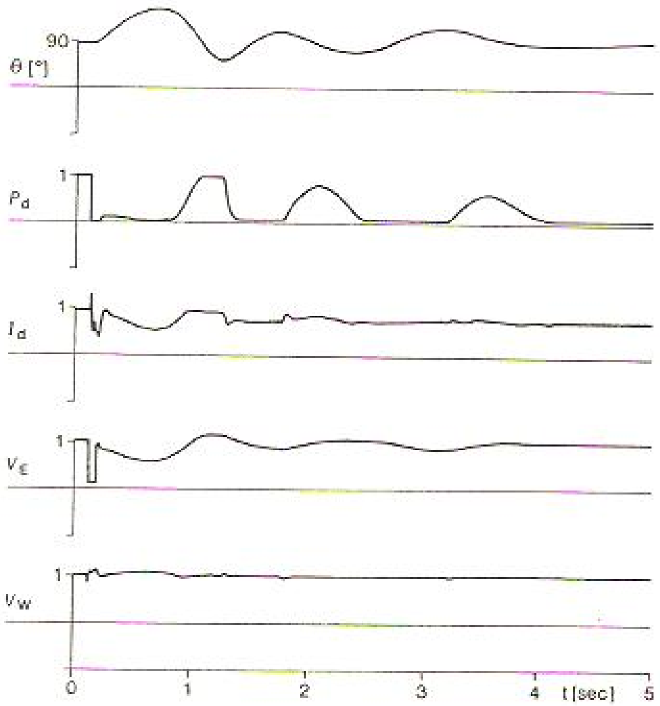


Fig. 10: 3phase fault in the east ac system and tripping 345 kV Sidney-Keystone line, 200 MW west to east transfer, RAS activated (Legend see fig. 8)

swing of the LRS east generator changes direction as can be seen on the oscillogram. Power modulation of the SCS, initiated by the RAS dampens the rotor swings successfully. In addition to the phase position of the modulation signal, the power/time area of the first modulation lift is of major importance for generator power swing damping and is mainly determined by the setting value "modulation gain". The setting parameters must, however, be chosen to ensure that the further modulation blocks have a damping effect and do not cause additional activation. It can be seen from the trace V_w that the ac voltage on the west side is kept well in narrow limits during modulation. The voltage deviations on the east side are larger, but this is understandable as the priority of the voltage control is given to the unfaulty west side and the voltage control on the disturbed east side would oppose to the damping of oscillations.

Comparison of field test and NETOMAC results

As one part of the commissioning of the SCS, actual line trip field tests of the RAS have made. Details of the live testing are presented in |3|. Therefore it was possible to make some verifications of the digital studies using NETOMAC program as a case foreseen for live testing has been calculated before (case B, Table 1).

Figure 11 shows the comparison for the case of tripping the 345 kV Sidney - Keystone line without fault. Due to disconnection of the line the RAS is activated by the speed deviation signal of the LRS east generator resulting in a reduction of the SCS transfer power to 20 MW. Power modulation between 20 and 150 MW dampens the rotor frequency deviation within two swings. The effective voltage control during modulation provides minimal voltage deviation in the western network. On the left side records of the field test and on the right side NETOMAC calculations are plotted. It can be seen that the calculation corresponds very good to the field test.

CONCLUSIONS

Stability studies with extensive ac networks including an HVdc system are only possible using a digital program like NETOMAC. In the paper digital simulation of network elements, their testing and main results of a stability study for SCS are presented. This includes two extensive ac networks with generators, their excitation control and speed-governing system representation, an HVdc with it's standard controls and the additional RAS for modulation and ramping of the power transferred. The representation of the components is confirmed by comparison with TNA results.

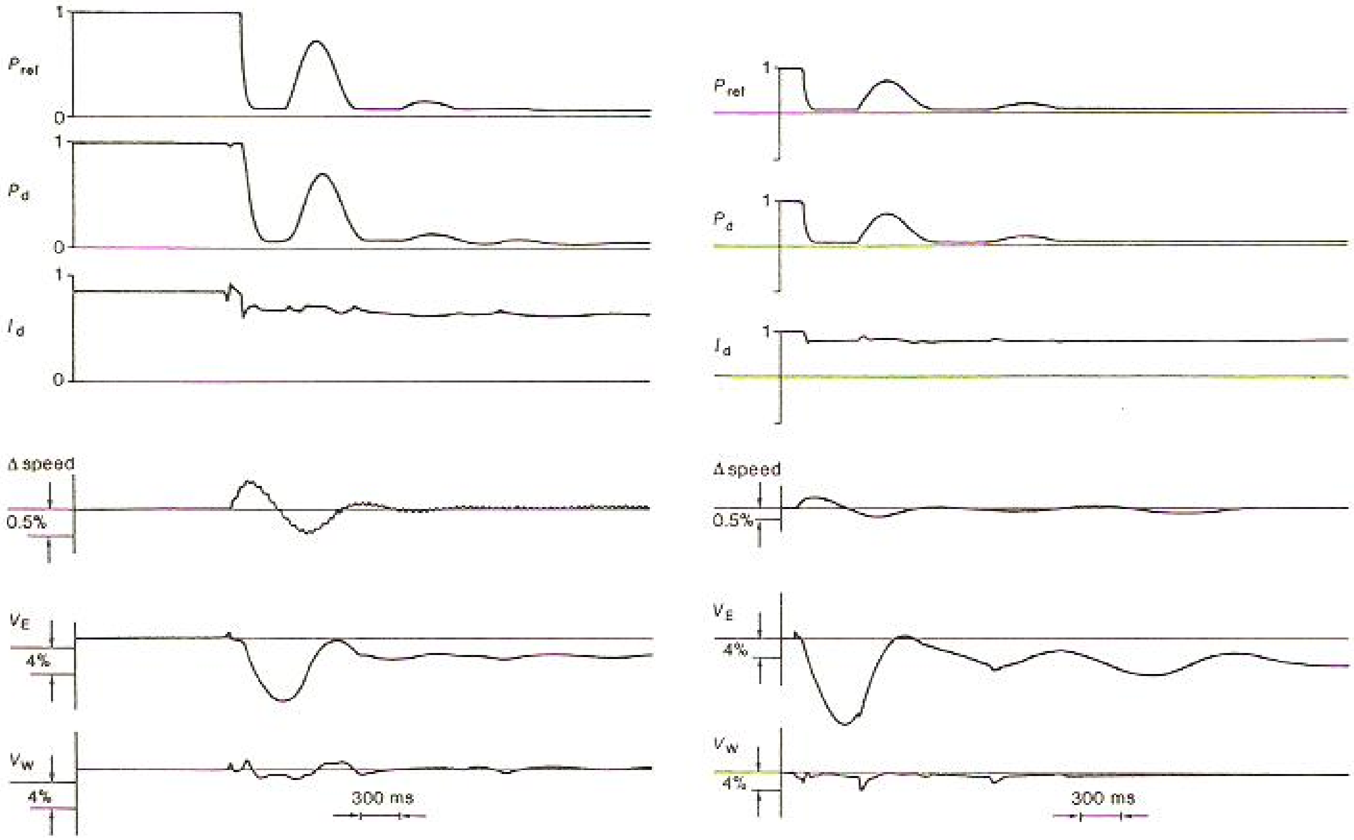


Fig. 11: Comparison between field test (left side) and NETOMAC calculation (right side) tripping 345 kV Sidney - Keystone line, 200 MW west to east transfer (Legend see fig. 7 and 8)

The RAS, which was found to be necessary in order to meet voltage and stability requirements, is presented and it is shown how the optimum parameter settings have been found, with the overall representation of SCS and the ac network representation. Comparison with results of a live field test (line switching) shows good agreement with the results of the digital simulation study. This confirms that the representation is also valid for all the remaining line outage cases of the digital study which were not possible to be tested at site. In these cases it was shown by the simulation that RAS is able to meet the requirements for maintaining area stability and minimizing resultant voltage deviations in the two ac networks.

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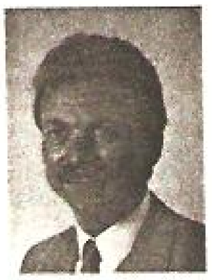
BIOGRAPHIES

Klaus H. Schilling was born in Dortmund/Germany, in 1950. He received the Dipl.-Ing. degree from Technical University Darmstadt in 1976. In the same year he joined the High - Voltage Transmission Engineering - System Planning Department of Siemens AG in Erlangen/Germany. He works on studies for high voltage AC system planning and in the field of transient simulation and substation grounding.



Gerhard Thumm was born in Ludwigsburg/Germany in 1951. He received the Dipl.-Ing. degree from Technical University Stuttgart in 1977. From 1977-78 he was with the Institute for Process Technics and Boiler Technology, and from 1978-82 with the Institute for Electrical Energy Transmission and High Voltage Technics at the Technical University of Stuttgart. In 1982 he joined the High-Voltage Transmission Engineering - System Planning Department of Siemens AG in Erlangen/Germany. He worked in the field of interaction of machines and networks, also including frequency converters and HVDC systems with emphasis to power oscillations, and in the field of static Var systems.

Robert K. Johnson was born in Denver, Colorado, on May 26, 1948. He received the B.S. degree in electrical engineering from the University of Colorado at Boulder in 1971. He joined the United States Bureau of Reclamation (USBR) in 1971 in the Power Operation and Maintainance group. After assignments at the MAPP Coordination Center in Minneapolis, in Minnesota, and at the Billings Office of the USBR, Mr. Johnson returned to Denver in 1978 and moved to the Western Area Power Administration, U.S. Department of Energy.
Mr. Johnson has since been involved in system studies in the Systems Engineering Division. Since 1980, Mr. Johnson's primary responsibilities have been in the area of AC/DC interaction. He has been involved in the feasibility and predesign studies as well as design review analysis for the Miles City and Sidney back-to-back DC stations. Mr. Johnson has coauthored a number of technical papers on the two DC stations. He is a member of the IEEE.

Nicholas S. Klemm was born in Camden, New Jersey, on May 9, 1956. Mr. Klemm received a Bachelor of Science degree in physics from the University of Delaware in 1978. He became an employee of the Western Area Power Administration in 1980, and has been responsible for technical studies and power system protection for the Loveland Area Office, Loveland, Colorado. The Sidney Converter Station became a major project for Mr. Klemm in 1983, beginning with studies aimed at defining a remedial action scheme for the station. Mr. Klemm's main duties included performing initial stability studies to determine the feasibility of remedial action and developing a conceptual remedial action design. He also worked closely with the manufacturer during checkout and testing of the remedial action equipment.

Discussion

R. O. GUNDERSON (Nebraska Public Power District, Columbus, Nebraska): The authors are congratulated on an interesting and timely paper. This paper demonstrates a situation where field tests of a Remedial Action System (RAS) show a good agreement with digital simulations.

When determining a threshold for initiating a RAS, it is not the worst case disturbance that must be considered. Rather the disturbance which is the least severe and requires action by the RAS should determine the threshold for initiating the RAS. This is to insure that the RAS will be initiated for all disturbances requiring corrective action.

The authors state that the disturbances in Table 1 are the most severe conditions requiring remedial action. Would the authors comment on considerations given to less severe disturbances requiring remedial action when determining the threshold for initiating the modulation?

Manuscript received February 23, 1989.

N.S. KLEMM: The authors are grateful to the discussor for the interest shown and for the valuable comments.

Mr. Gunderson is correct in that least severe disturbances should be considered in setting the threshold. This particular application was complicated by the fact that the RAS needed to cover the east AC power system both east and west of the Gerald Gentleman Station (GGS). In particular, the RAS is required to maintain stability of LRS and coordinate with the fast valve/unit tripping scheme at GGS. This created the problem of discriminating between minor faults near the SCS and major faults far east of GGS. It is Western's opinion that the present threshold of 0.15 Hz is the best compromise. There are many conditions that can affect the strength of the power system, such as system configuration and generation units on line. Actual system experience will enable Western to refine the threshold setting to a possibly more optimum value.

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