Damping of Interarea Oscillations in Large Interconnected Power Systems

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Abstract - **Power systems are steadily growing and formerly separated systems are interconnected with each other. With increased generation capacity, different areas in power systems are added with inertia, making system prone to interarea oscillations. The deregulation in the electrical power system market on the other hand leads to higher loading of the transmission network resulting on an operation closer to the stability limits. As a consequence the improvement of small signal stability, especially the damping of interarea oscillation becomes an increasing importance. Damping can be improved by accordingly modulating either the generation or the load in the power system. Examples for interarea oscillations and possibilities to increase system damping are described for interconnected power systems in Europe, South America and Africa.**

Keywords: Interarea oscillations, small signal stability, eigenvalue analysis, PSS, FACTS, HVDC.

I. INTRODUCTION

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 ever 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 [1], [2].

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, like during the black out in western North America on August 10, 1996, [3].

II. METHODS OF ANALYSIS OF INTERAREA OSCILLATIONS

Inter-area oscillations can be investigated by simulation method in the time domain. In addition to that, a more powerful approach in the frequency domain is available to enable systematic analysis of the small signal stability problem. The latter approach is known as Eigenvalue analysis or modal analysis [1], [4]. Eigenvalue analysis investigates the dynamic behavior of a power system under different characteristic frequencies (i.e. modes). Inherent patterns behind complicated phenomena of system dynamics are indicated. Different modes, which are mixed with each other in curves of time domain simulation, are identified separately. It is indicated, which generator coherent groups swing against each other and which generators play a significant role and which not [5]. Furthermore information can be derived regarding the most effective sites of controllers, retuning existing ones or installing additional ones, taking into account the observability and the controllability.

In a power system, it is required that all modes, i.e. eigenvalues, are stable. Moreover, it is desired that all electromechanical oscillations are damped out as quickly as possible. For a better understanding the results of an Eigenvalue analysis are given as frequency and relative damping for each oscillatory mode. Given an oscillatory mode: $s = s + jw$ (1/second), the damping ratio (or relative damping) is defined by $z = -s/\sqrt{s^2 + w^2}$. 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 %

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.

III. DAMPING OF INTERAREA OSCILLATIONS

For many power systems the reduction to a system with two subsystems with equivalent inertias and an equivalent coupling impedance is possible when a particular inter-area power oscillation is studied. Nearly any contingency in one of the two subsystems excites power oscillations, which means that the equivalent inertia of the one system is temporarily accelerated while the equivalent inertia of the other system is temporarily decelerated and vice versa.

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. 1 shows different possibilities to damp power oscillations.

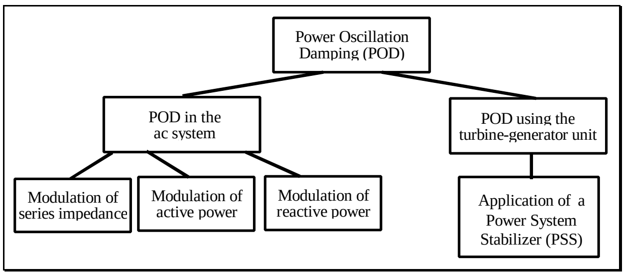

Fig. 1 : Strategies to damp power oscillations

In the following chapter examples of power oscillation damping in large interconnected systems are demonstrated. The studies have been performed using the NETOMAC® program [6], [7], which combines time domain and frequency domain analysis under one common database.

IV. APPLICATION EXAMPLES

A. UCTE/CENTREL System

After expansion of the UCTE system by CENTREL (Poland, the Czech Republic, Slovakia and Hungary) power system stability has an increasing importance also in the Transeuropean Synchronously Interconnected System (TESIS). Recordings of a Wide Area Measuring System (WAMS) have shown significant changes of the dynamic system behaviour, which in principle were predicted by the simulation studies carried out before [8] - sometimes poorly damped low frequency power swings were indicated.

A model dedicated to the analysis of steady state and dynamic behavior of the interconnected system has been set up. Almost the complete 220/400-kV transmission grid of UCTE/CENTREL is represented. The dynamic model contains

2300 transmission lines
820 transformers 400kV/220 kV
380 generators

Typical load-flow situations obtained from real-time operation were considered. In order to limit the model size, all the units of one generation site are aggregated in one machine, which is valid as far as small-signal stability studies are concerned. The dynamic data, that is the generator characteristics, the excitation controllers, the power system stabilisers, the turbine characteristics and the governors, are mostly described by detailed models in accordance with the IEEE standard.

The model could be validated by the recordings collected from WAMS. As an example Fig. 3 shows the simulation results after power plant outage in Spain, which have to be compared with the recordings in Fig. 2. It can be concluded that the model represents the real system

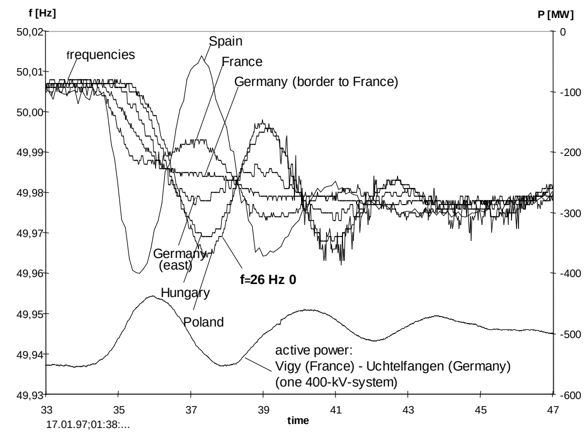

Fig. 2: Interarea oscillation after power plant outage (900 MW) in Spain, WAMS recording

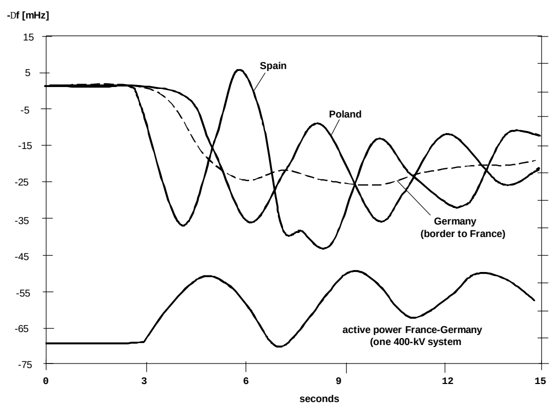

Fig. 3: Interarea oscillation after power plant outage (900 MW) in Spain, simulation

behavior with sufficient accuracy. The dynamic characteristics of power flows and frequencies at different locations are in well accordance with the recordings, especially the oscillation frequency, amplitude and damping of the physical quantities.

In the interconnected UCTE/CENTREL system two dominant east-west inter-area swing modes in the low frequency range between 0.2 and 0.5 Hz have been identified. The geographical mode shape of these modes is given in Fig. 4 and 5.

For global mode 1, which is the mode with the lowest system frequency of approx. 0.2 Hz, the western part of the system formed by the generators in Spain and Portugal swings against the eastern part mainly formed by the CENTREL machines (Fig. 4). Along a line from Belgium, the western border of Germany, Swiss and Italy the oscillation cannot be observed, at this border of the oscillation the frequency deviation is minimum. The damping of the global mode 1 is relatively weak (3.7%) for the given load flow scenario.

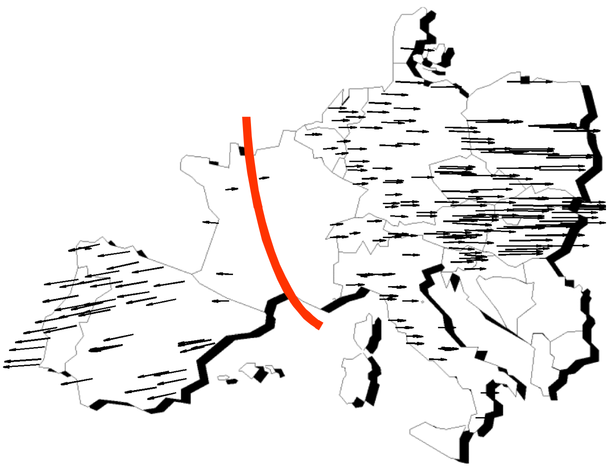

Fig. 4: Geographical mode shape Global Mode 1

Three coherent groups participate in the second inter-area mode (global mode 2) with a frequency of about 0.3 Hz (Fig. 5): Spain and Portugal, forming the first group, are almost in phase with the group of CENTREL and eastern parts of Germany and Austria. The centre of Europe (France, Italy, Switzerland and the western parts of Germany and Austria) forming the third group is in phase opposition to these two coherent structures. The maximum rotor speed deviation is given for some polish generators. The damping of global mode 2 (8.9%) is much better than for mode 1.

The global load flow in the system influences the damping of the interarea modes. It can be shown by simulation and measurement that the load flow from the border of the system to the center decreases the damping especially of Global Mode 1 [9]. Damping ratios down to values below 2% may occur for a power flow from Spain to France of 800 MW which can lead to restrictions in the power exchange between France and Spain. Table 1 shows the impact of variation of the load flow between Spain and France on the damping of the global interarea modes.

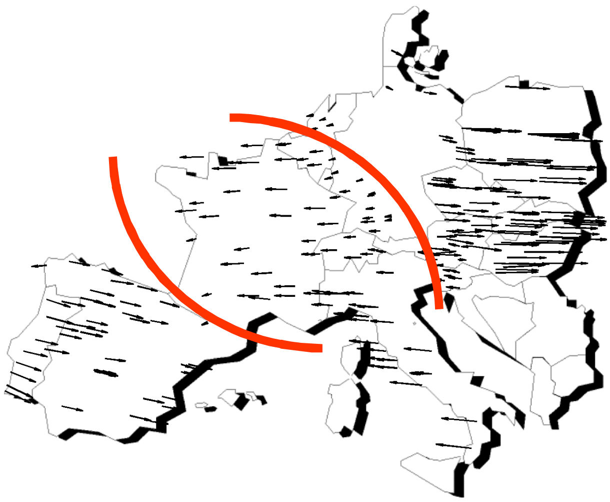

Fig. 5: Geographical mode shape Global Mode 2

Table 1: System damping depending on load flow between Spain and France

Frequency	Global Mode 1 0.21 Hz	Global Mode 2 0.31 Hz
Scenario	ζ [%]	ζ [%]
400 MW France → Spain	5.9	9.3
150 MW Spain → France	4.2	9.0
800 MW Spain → France	1.8	8.1

The system response subsequent to a load outage of 500 MW in Spain is given in Fig. 6A, resulting in a power flow of approx. 800 MW from Spain to France. Frequency deviation in Spain, Germany and Poland shows the weakly damped interarea oscillation of approx. 0.2 Hz (mainly Global Mode 1) which corresponds to the a.m. damping ratio below 2 %. Furthermore the phase shift of approx. 180° is clearly visible between the frequency in Spain (West) and Poland (East).

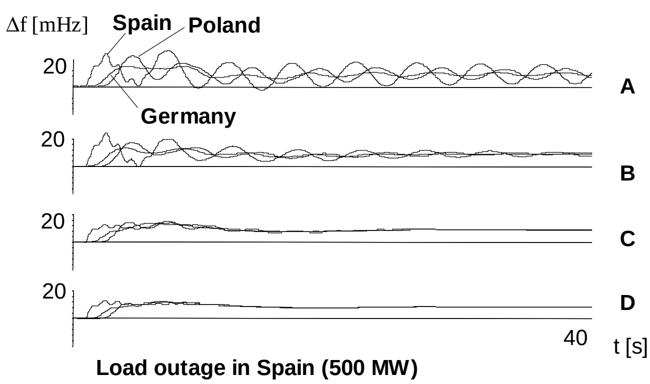

Fig. 6: System response for different stages of PSS optimisation

In order to investigate the possible improvement of system damping PSSs have been added or existing ones optimized in the simulation model. The locations for the improvement of controllers have been identified by evaluation of the residues of the transfer function $\Delta\omega/\Delta V_{exitation}$ taking into account the observability and controllability of the oscillation mode as well as the dynamic properties of the excitation systems through which the PSS operate. Based on this information in a theoretical approach 8 controllers at big generators in CENTREL and Spain have been replaced by controllers with an additionally frequency input which proved to be very effective for damping of interarea oscillations in multi-machine systems. Fig. 6B shows that system damping can be slightly improved by optimisation of PSS in CENTREL. A much better effect can be achieved by optimising or introducing PSS in Spain (Fig. 6C). Best results can be achieved by combination of both (Fig. 6D). Frequency domain analysis indicates that the damping of both global modes improve significantly to values above 15 % [9].

B. Brazilian System

The two main electric power systems in Brazil - the South system and the North system – have been interconnected in 1999 in order explore hydrologic diversity between the systems, achieving major energy benefits.

Two transmission alternatives were considered and analysed to establish the 1020 km North-South interconnection:

- DC bipole with +/- 400 kV
- Single AC compact transmission line

In both cases this interconnection should link the 500 kV substation of Imperatriz (North system) to the Serra da Mesa power plant (South system) - see Fig. 7 - and should transmit up to 1300 MW in both directions.

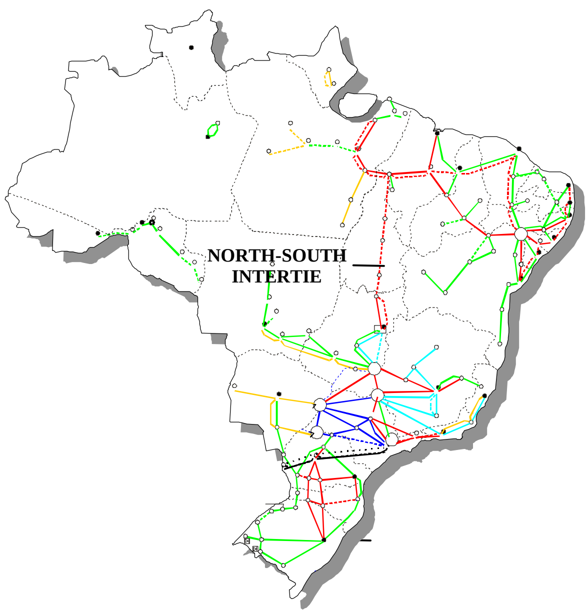

Fig. 7: The Brazilian power system

When comparing the technical behavior of both alternatives it was verified that the AC solution presented a low frequency (0.18 Hz), poorly damped interarea oscillation mode. This oscillation of wide amplitude (+/- 300 MW) represented a serious technical restriction. On the other hand the AC alternative presented significant advantage in terms of cost and strategic and political benefits, as six hydroelectric plants are expected to be built along this route in the next two decades and other 500 kV AC transmission links are planned for making cheap energy available to a rapidly growing new Federal State.

The decision was made in favor of the AC transmission alternative. The interarea oscillation problems have been solved by a series compensation scheme that combines FACTS controllers (Thyristor Controlled Series Capacitors, TCSC) with conventional equipment (Fixed Series Capacitors, FSC). The line is provided with 54 % of fixed series compensation split into six banks and two TCSC banks each providing 6 % of series compensation in steady state conditions (see Fig. 8).

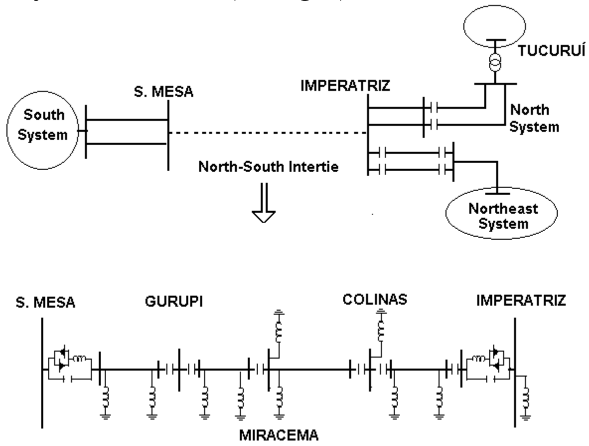

Fig. 8: One line diagram of the line

The task of the TCSC is purely damping out the interarea oscillation between the two systems. The damping effect can be achieved by appropriately modulating the transmitted power to control the generator torques. A POD (Power Oscillation Damping) structure has been developed by computer simulation and verified by real time simulation [10]. The on site system performance testing showed that the TCSCs were very effective in damping the low frequency interarea oscillations. Fig. 9 shows the line power (site measurement) subsequent to a trip of 300 MW in Tucurui (North system) with the PODs enabled and disabled demonstrating the necessity of this FACTS application for a stable system operation.

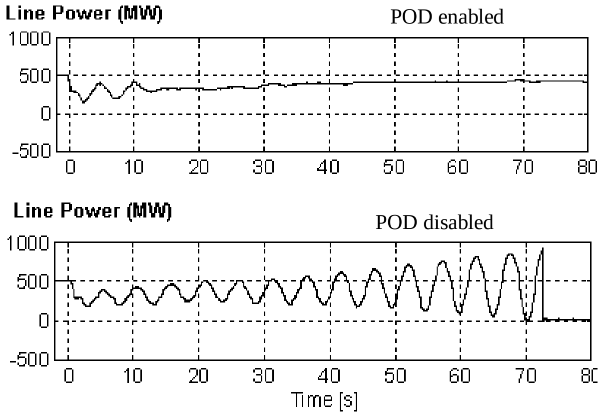

Fig. 9: System stabilization by controlled series compensation

The system interconnection has been in reliable operation since March 1999 with the TCSCs providing adequate damping for all scenarios, even for those with low power transfer (below 200 MW).

Similar damping effects can be achieved by shunt modulation (Static Var Compensator, SVC) affecting the system voltage and thus the generator torque [11].

C. Southern African Power Pool (SAPP)

SAPP is a multinational interconnected power system including Republic of South Africa, Zimbabwe, Mozambique, Republic of Congo, Namibia, Zambia and Botswana. A simplified geographic diagram of the system is shown in Fig. 10. The SAPP system covers a huge geographic area roughly 3000 kilometers long and 3000 kilometers wide. The simulation model comprises about 160 generators and 800 buses.

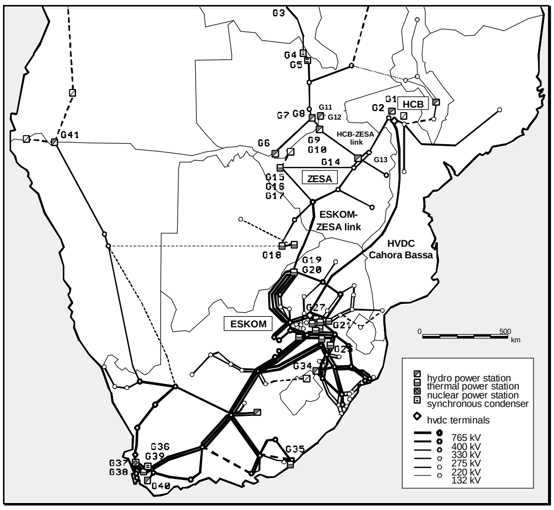

Fig. 10: The high voltage grid of Southern Africa (SAPP)

The SAPP system was formerly separated into two large ac systems connected by a 1400 kilometer long HVDC line. Lately, the two systems were synchronized by a 300 kilometer ac line to enable flexible power exchange and increase the frequency robustness in the northern subsystem.

However, the interconnection gives rise to weakly damped oscillations in the frequency range of 0.3 to 0.4 hertz. Persistent power oscillations can cause line tripping and generators can become unstable. This inter-area mode is excited easily by nearly any faults in the system and has already led to line tripping between Zimbabwe and Republic of South Africa. Fig. 11 shows the undamped power oscillation on the ESKOM-ZESA line subsequent to a generation outage in the ESKOM system which led to the instability of the link and to system separation. Modal analysis demonstrates that there is an undamped 0.3 Hz interarea mode (-0.4%) where the generators of the HCB/ZESA system swing against the ESKOM machines. Fig. 12 shows the geographical mode shape of the 0.3 Hz mode.

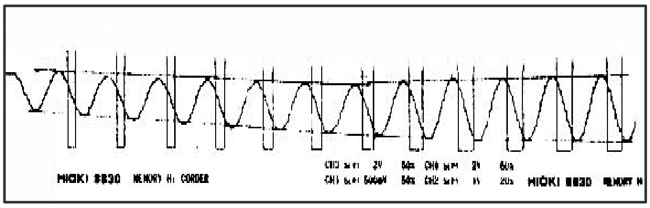

Fig. 11: Power oscillation between ESKOM and ZESA leading to system separation

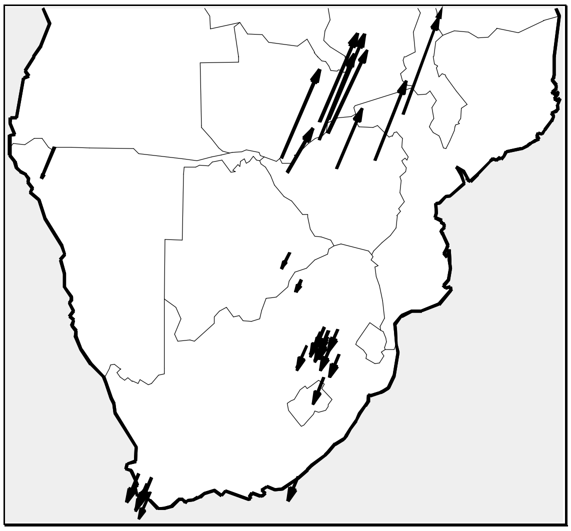

Fig. 12: Geographical mode shape of the 0.3 Hz mode (ζ -0.4 %)

Modal analysis shows that the HVDC Cahora Bassa can be used to damp the power oscillations on the ESKOM-ZESA interconnection and to improve system stability. For this reason the so called GMPC (Grid Master Power Controller) [12] was designed in order to meet the following requirements :

- Frequency control in the power system of Mozambique when the hydro power plant at Cahora Bassa is not connected to the power system of Zimbabwe (ZESA-HCB link open).
- Improvement of transient stability of the HCB-ZESA-ESKOM interconnection if the ZESA–HCB line and the ZESA-ESKOM line are closed.

- Damping of power oscillations between ESKOM and ZESA and ZESA and HCB if the ZESA–HCB line and the ZESA-ESKOM line are closed.

Fig. 13 shows how the power oscillations on the ESKOM – ZESA link can be damped if the HVDC Cahora Bassa is used for active power modulation. In both cases a 100 ms three phase fault at the inverter station of the HVDC near Johannesburg in South Africa occurred. If no POD of the HVDC is applied dangerous power oscillations between ESKOM and ZESA can be observed which can lead to the tripping of the ESKOM-ZESA line.

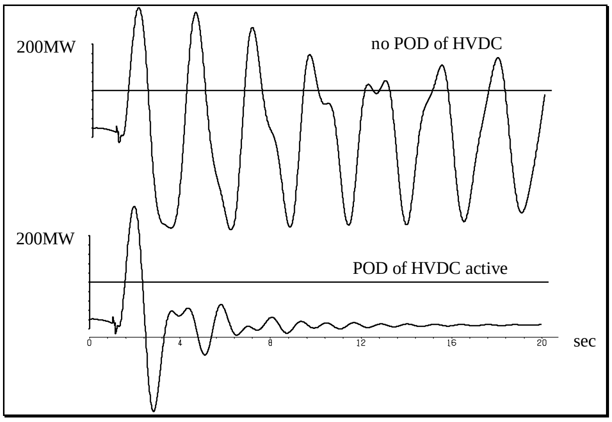

Fig. 13: Damping of power oscillations between ESKOM and ZESA using the HVDC

If the fast power modulation including the overload capability of the HVDC is used the transient stability margin of the interconnected system can be improved and the power oscillations can be damped out quickly.

The input signal for the power modulation of the HVDC is the angle difference of the voltage vectors at the rectifier station of the HVDC at Songo substation (Mozambique) and at the inverter station of the HVDC at Apollo substation (South Africa). This input signal ensures optimum damping of the power oscillations, however, fast telecommunications and a global positioning system (GPS) are required to ensure a common time base for the derivation of the angle difference from the measured voltage angles.

V. CONCLUSIONS

Interarea oscillation is a typical phenomenon in large power systems. As systems are getting larger either by growing or by interconnecting weakly damped interarea oscillations may emerge. System damping can be improved by modulation of power thus injecting or consuming extra energy in the system in an appropriate phase. The examples given here show that this can be done by modulating power at the source – the power plant – by means of PSS or by affecting the power flow in the system. HVDC and FACTS with their ability to change the power flow directly or indirectly within ms offer the possibility to improve the system dynamic and stability and thus to make better use of the installed capacity. Detailed analysis and planning of existing and new systems allow for stable and reliable operation which is the essential basis for a unrestricted trading in open energy markets.

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