INTERCONNECTION OF THE EUROPEAN ENTSO-E-CE SYSTEM WITH THE TURKISH SYSTEM: INVESTIGATION OF THE EXPECTED INTER-AREA-OSCILLATIONS BEHAVIOUR

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Abstract – Due to the enlargement of the European UCTE power system (now ENTSO-E-CE) towards Turkey, which will take place at the end of 2010, the damping behavior of Inter-Area-Oscillations of the extended system is gaining more and more in importance. Previous investigations of the extended UCTE network to Turkey show, that the extended system has a weak damped oscillation with the period $T_P \approx 7s$, therefore the damping behavior of Inter-Area-Oscillations of the extended system using a detailed dynamic model of the Turkish system is investigated. In order to improve the stability of the whole system, the existing damping measures [PSS and AVR] of the power plants in Turkey and also the future [Modified SVC, braking resistor and HVDC connections to the power systems of eastern neighbors of Turkey] are investigated. Because the whole system is extremely nonlinear, the analysis method in state space is not useful; therefore the damping behavior of Inter-Area-Oscillations of the whole system was analyzed in detail using the analysis method of simulations in time domain.

Keywords: Inter-Area-Oscillation, damping measures, UCTE power system, Turkish power system

1 INTRODUCTION

The Union for Co-ordination of Transmission of Electricity (UCTE) is extended already today from Romania to Portugal in East-West direction and from Denmark to Greece in the North-South direction. The North African countries Morocco, Algeria and Tunisia are connected with the European grid by an undersea cable between the countries of Spain and Morocco. Since the beginning of interconnecting national transmission systems in Western Europe in early seventies Inter-Area-Oscillations occur often in the system. In the current outline of the UCTE power system poorly damped oscillation modes exist in East-West and North-South direction [1-2]. These Inter-Area-Oscillations are excited by rapid changes in the power system, e.g. emergency shut-downs of big power plant or switching operations. In times of a deregulated energy market and a possible enlargement of the European power system to Eastern Europe, Middle East and North Africa to the close of the so called "Mediterranean Ring" by the extension of the interconnected system to the countries of Turkey, Syria, Jordan, Egypt and Libya, the damping behavior of these slow Inter-Area-Oscillations is becoming increasingly important. The current step towards closing the "Mediterranean Ring" is the synchronous connection of the Turkish power system [1-2]. Within the framework of this paper, the oscillation behaviour of the UCTE power system including the Turkish power system is analysed to identify the new Inter-Area-Oscillation mode and point out the behaviour of the existing damping measures in the Turkish power system.

2 INTER-AREA-OSCILLATIONS IN THE UCTE POWER SYSTEM

Recordings of a Wide Area Measuring System (WAMS) have shown significant changes of the dynamic system behaviour. The present status of the implementation of WAMS is given in Figure 1. More than fifty devices for recording frequency and power flows at the individual locations are installed in 400 kV and 220 kV order to show all recordings using the same time reference. A lot of recordings of Inter-Area-Oscillations were collected from WAMS, which are mostly excited by power plant outages or failures in the 220 kV or 400 kV voltages level of the transmission grid.

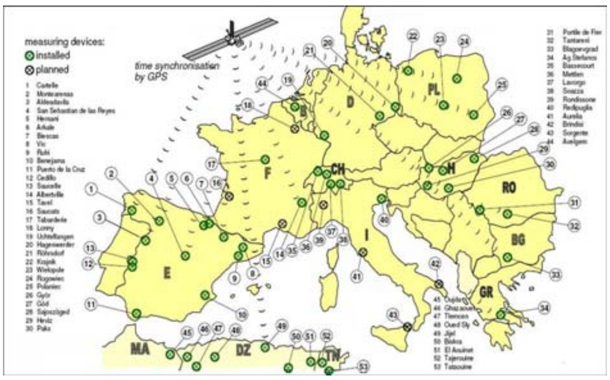

Figure 1: Wide Area Measuring System (WAMS).

Figure 2 shows as example Inter-Area-Oscillation after a power plant outage 1200 MW in Spain. After the power plant outage the frequency decreases immediately in the proximity of the outage (Spain). The decreasing of frequency spreads over the whole system and finally reaches Romania and Bulgaria with a time delay of about 2 s. The frequency of the observed Inter-Area-Oscillation is in the range from 0.22 to 0.26 Hz and in most cases the damping is sufficient. In some cases poor damping was detected.

Figure 3 shows an East-West-Inter-Area-Oscillation caused on 01.05.2005. The damping is very poor in this case, because the amplitude of frequency and power oscillation does not decrease significantly during the first ten oscillation periods.

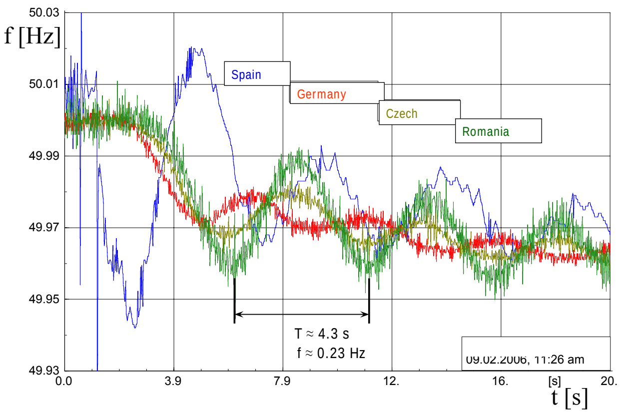

Figure 2: Inter-Area-Oscillation after power plant outage in Spain, 1200 MW.

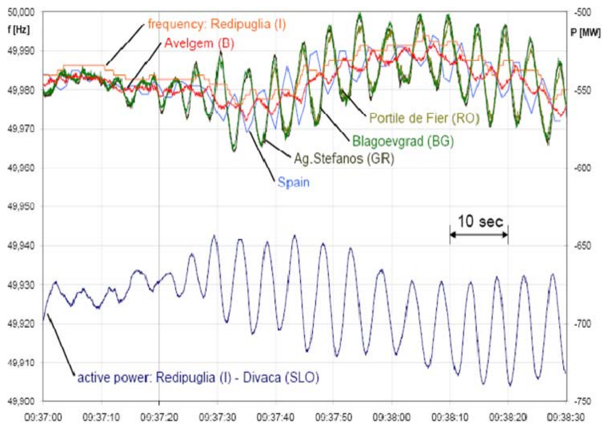

Figure 3: Poor damping East-West-Inter-Area-Oscillation on 01.05.2005.

3 DYNAMIC MODEL OF THE UCTE POWER SYSTEM

To analysis the dynamic behaviour of UCTE power system, enlarged by Turkish power system, a non-linear dynamic model of the current UCTE power system is represented using a specific software package DIgSILENT for power system simulation, see Figure 4. The dynamic model consists of two parts:

1. The Simplified UCTE-network:

This system consists of 65 nodes and is formed as a combination of the grids of member countries (UCTE-system except Balkan system) [3]. Each grid is formed by approximately ten equivalent generators; those have been formed according to coherency principle, which leads to reduce the dimension of the detail model and also the computation time, when a big number of scenarios have to be carried out. The coherent generators are grouped in one node as an equivalent power rating generator. 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 [4-5].

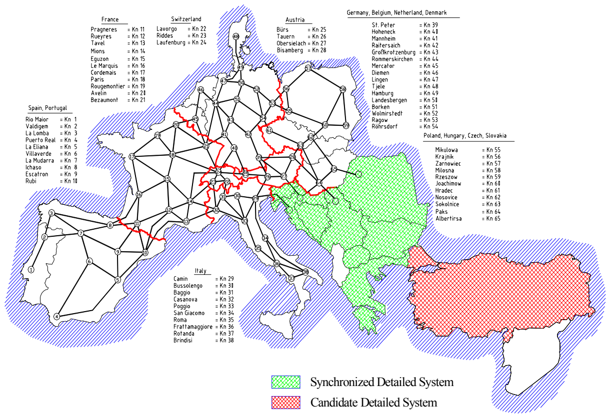

Figure 4: The enlarged UCTE power system covered by the non-linear power system model

2. Detailed Balkan System:

The Balkan system contains the complete transmission system and includes approximately 140 power plant units, 240 dynamic loads, 470 transmission lines and 130 transformers. Each power plant consists of a dynamic model of the power generation unit, depending on its type, a generator, voltage controller and power system stabilizer.

3.1 *Model Validation*

Figure 5 shows the simulation results after power plant outage in Spain, which has to be compared with the recordings in Figure 2. It can be concluded that the described model represents the real system behaviour with sufficient accuracy regarding the analysis of Inter-Area-Oscillations. The dynamic characteristics of frequencies at different locations are in well accordance with the recordings, especially the oscillation frequency, amplitude and damping of the physical quantities. From the time behaviour point of view the dynamic model is a reliable basis for further investigations.

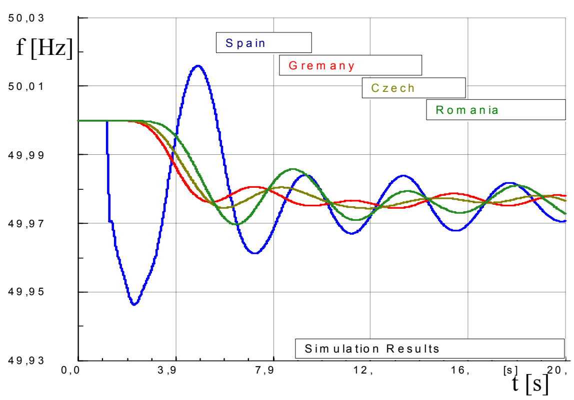

Figure 5: Inter-Area-Oscillation after power plant outage in Spain, 1200 MW.

4 THE TURKISCH POWER SYSTEM

The electric power generation in Turkey is divided into approximately 30% for steam power plants, which are based on the local and imported lignite coal, 30% for hydro power plants, which are located in the East and South-East of the country and 30% for combined cycle power plants based on the imported natural gas, which gains in importance as primary energy resource for power generation [6]. The installed capacity of the Turkish power system is approximately 42 GW in 2008. A typical peak load situation in the Turkish power system (29 GW) takes place in winter, around 6 p.m. on weekdays. The detailed dynamic model of the current Turkish power system includes about 690 generators, 700 static loads, more than 1350 transmission lines and about 810 transformers. Each power plant consists of a dynamic model of the power generation unit, depending on its type, and of a generator, voltage controller [AVR], power system stabilizer [PSS].

4.1 Model Validation

Figure 6 shows the measured and simulated response of the frequency for one node in Western Turkey to an outage of 700 MW of active power (Karakaya hydro power plant, on Friday, 05 March 2010, at 14:29) during a 25 GW high power load situation. The comparison between the measurement and simulation results in Figure 6 shows approximately a good agreement in terms of primary and secondary control behavior like in the real system.

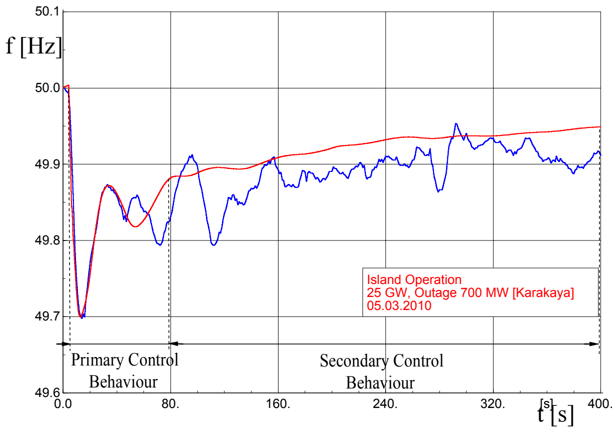

Figure 6: Frequency of the Turkish power system after power plant outage Karakaya, 700 MW.

5 ANALYSIS OF THE DYNAMIC BEHAVIOUR OF THE ENLARED UCTE-SYSTEM EXTENDED BY THE TURKISH POWER SYSTEM

The model of the Turkish power system is connected with the model of UCTE power system by the already exciting two 400 kV transmission lines between Turkey and Bulgaria and a 400-kV transmission line to Greece. Throughout the simulation studies, it has been observed that the most poorly damped operational scenario was the minimum loading of both UCTE and the Turkish power systems. Figure 7 shows a simulated Inter-Area-Oscillation for one node in the Bulgaria-Turkey border triggered by a 1.2 GW outage of power plant in Spain, where the export power from Turkish system to UCTE system is 2500 MW. In this case the load of UCTE and Turkish system are 230 GW and 18 GW respectively. It has to be noted that 2500 MW exceeds the admissible export power. But for demonstrating the relative effects of different damping measures it was important to set up a reference case that is poorly damped.

From Figure 7 the occurring Inter-Area-Oscillation in the low frequency 0.14 Hz has been identified. The identified oscillation period is $T_P = 7$ s and a damping:

$$\omega = \frac{2\pi}{T_P} = \frac{2\pi}{7} \approx 0.9\left[rad/\sec\right] \quad (1)$$

$$\sigma = \frac{1}{T_P}\ln\left(\frac{A_2}{A_1}\right) \approx 0.016\left[1/\sec\right] \quad (2)$$

$$D = \frac{-\sigma}{\sqrt{\sigma^2+\omega^2}} \approx -0.018 = -1.8\% \quad (3)$$

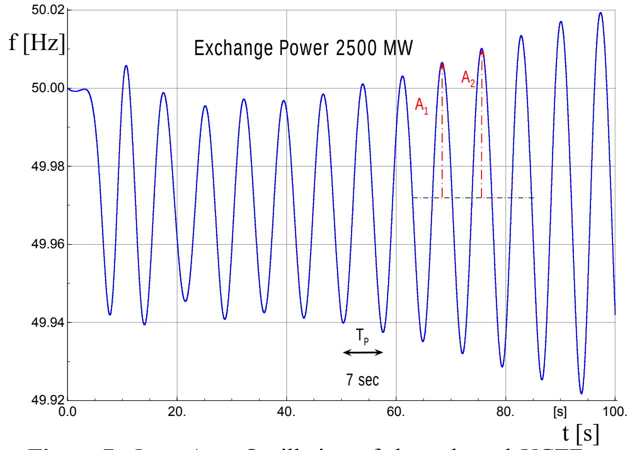

Figure 7: Inter-Area-Oscillation of the enlarged UCTE system after power plant outage in Spain, 1.2 GW.

6 IMPROVEMENT OF THE OSCILLATION DAMPING BEHAVIOUR OF ENLARGED UCTE SYSTEM BY DAMPING MEASURES IN THE TURKISH POWER SYSTEM

6.1 Power System Stabiliser

In the Turkish power system the power system stabiliser devices (PSS) are installed in 21 power plants. These devices are set to be able to damp the local oscillation with a period of T_P = 1s. For the new identified Inter-Area-Oscillation with a period of T_P = 7 s (f_P = 0.14 Hz) the PSS-devices with their parameter settings for local damping are not suitable. Therefore the new settings of PSS-devices in eight power plants in Turkey are implemented to improve the oscillation damping behaviour of the enlarged UCTE-system. The power plants are five large Natural Gas Combined Cycle (NGCC) power plants (Unimar, Aliaga, Adapazari Gebze and Temelli) and three large hydro power plants

(Oymapinar, Karakaya and Atatürk). The power plant locations see Figure 8.

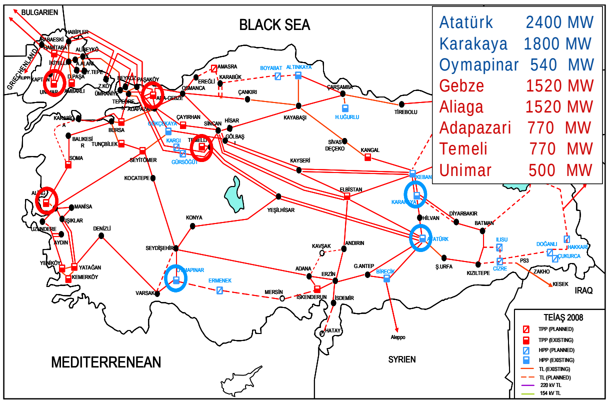

Figure 8: The locations of the retuned power plants.

Figure 9 shows the occurring Inter-Area-Oscillation in the low frequency 0.14 Hz as seen in Figure 7 as reference case and the frequency after the new setting of retuned PSS-devices are applied. As seen from Figure 9 the damping effect is very good, but problem is that it can not be guaranteed that all retuned power plants always are in operation especially hydro power plants. That leads to loss a positive damping source from the system, therefore the Turkish power system has to have another damping measures as backup like SVCs, Braking Resistor or HVDC connections to the power systems of eastern neighbors of Turkey.

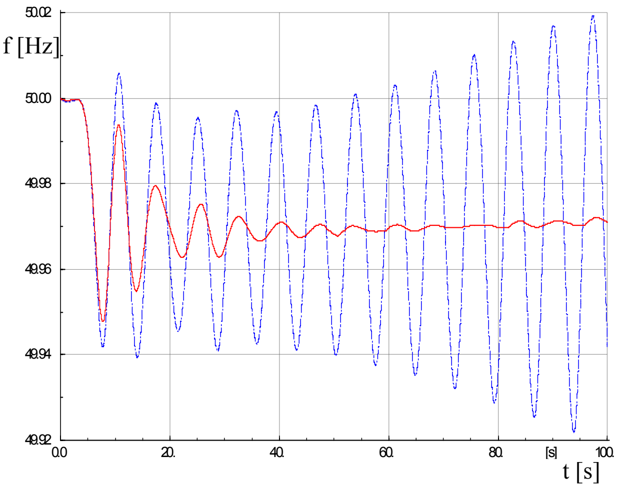

Figure 9: Effect of the retuned PSSs in Turkish power system on the oscillation damping behaviour.

6.2 *Static Var Compensators (SVC)*

In the Turkish power system the Static Var Compensators (SVC) are installed already in 10 zones near of the big steel manufactories (Resistive load). These SVCs in the past were used only to increase the quality of voltage. The existed SVCs today have not only to improve the voltage and the reactive power quality, but also the oscillation damping behaviour of the system using an additional frequency signal in their voltage controller to modulate the voltage of the steel manufactories proportional to the frequency, see Figure 10 .

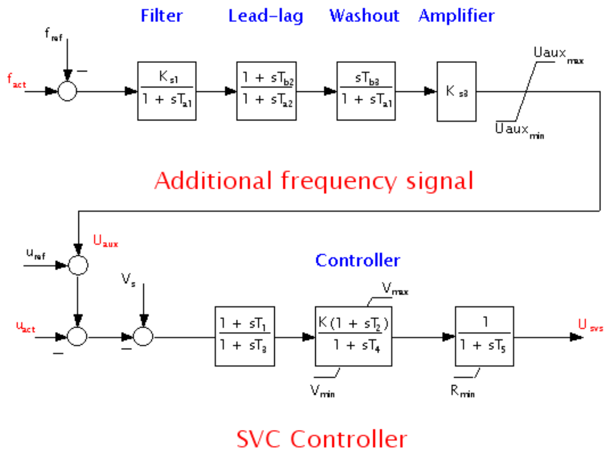

Figure 10: The structure of SVC-controller using an additional frequency signal.

The principle of stabilization with SVCs is shown in Figure 11: An electric generator is connected to an infinite bus and is supplying a resistive load. A SVC is installed near the resistive load to control the voltage, but it can also be used for stability purposes if the voltage is modulated by the frequency. In the following the equations will be given how the SVC has a damping effect.

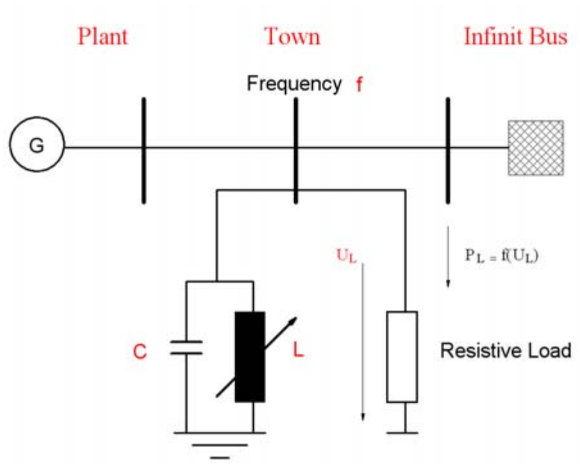

Figure 11: A Generator connected to an infinite bus.

The susceptance B of the SVC can be a function of the frequency f:

$$\Delta B = K_{B,f} \cdot \Delta f \qquad (4)$$

Also the voltage at the load bus is a function of susceptance B:

$$\Delta u_L = K_{u,f} \cdot \Delta B \qquad (5)$$

and therefore:

$$\Delta u_L = K_{u,f} \cdot K_{B,f} \cdot \Delta f \qquad (6)$$

The load P_L at the load bus is a function of the voltage of the load bus:

$$\Delta P_L = K_{P,u} \cdot \Delta u_L \tag{7}$$

and therefore:

$$\Delta P_L = K_{P,u} \cdot K_{u,f} \cdot K_{B,f} \cdot \Delta f \tag{8}$$

or:

$$\Delta P_L = K_{P,f} \cdot \Delta f \tag{9}$$

Equation (9) shows that the active power of the load can be modulated in phase to the frequency using the SVC to contribute to the damping of the system.

In this study, three of the existing static VAR compensators have been selected to use 20% of the applied reactive power by means of the additional frequency signal in the voltage controller with a total of ± 165 MVAR. Figure 12 shows the occurring Inter-Area-Oscillation in the low frequency 0.14 Hz as seen in Figure 7 as reference case and the frequency after the additional frequency signal in the SVC voltage controller are applied. As seen from Figure 12 the damping effect is very good.

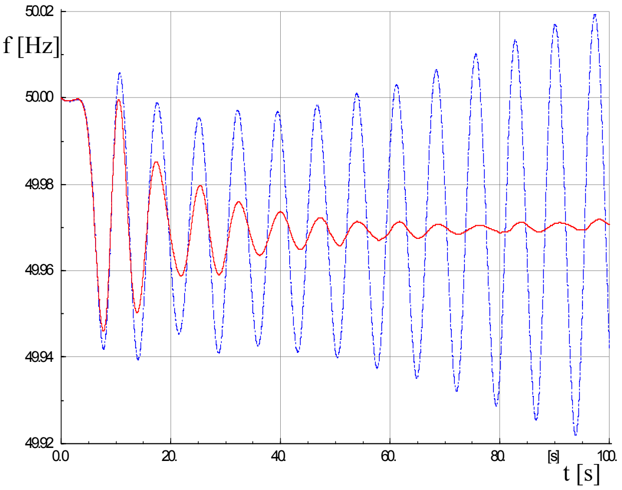

Figure 12: Effect of the modified SVCs in Turkish power system on the oscillation damping behaviour.

6.3 Braking Resistor

The retuned PSS and SVCs with the additional frequency signal have very good effect in improvement of the oscillation damping behaviour, but they have the disadvantage that the damping is lost, if power plants for the retuned PSSs and the steel manufactories for modified SVCs are not in operation. Therefore the installation of braking resistor is the next back up solution.

Figure 13 shows the effect of the braking resistor (as assumption the braking resistor is installed near of Ankara with rated value 25 MW) as the only damping measure in the Turkish power system. The results show that the braking resistor is able to guarantee the stability of the system. The braking resistor are switched on in the positive half cycle and off in the negative half cycle.

6.4 HVDC-Connection to Persian Power System

HVDC-connection to eastern neighbors of Turkey like Persian power system is investigated in this chapter as additional back up solution, see Figure 14. The Persian system is represented as a generator supplying one load which is adopted in this case to 25 GW. The generator is controlled by standard controllers. The rectifier controller is adjusted to work as a constant exchange power by controlling the firing angle of the Thyristor Bridge to keep the exchange power in the reference value. An additional frequency signal is added to the rectifier controller, where in the opposite side the firing angle of the Inverter stayed constant.

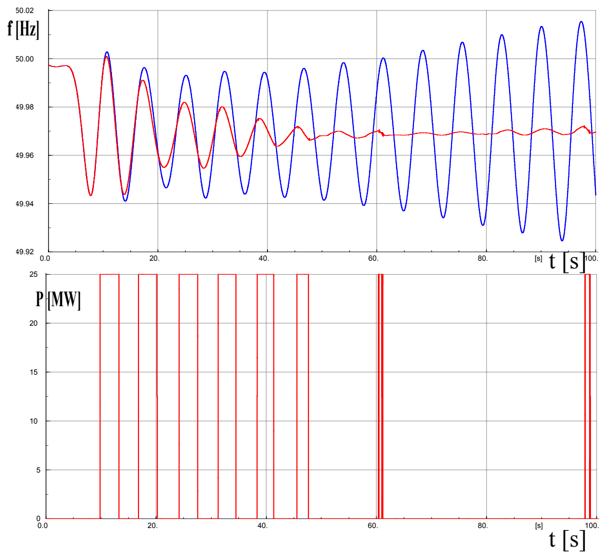

Figure 13: Effect of the Braking resistor in Turkish power system on the oscillation damping behaviour.

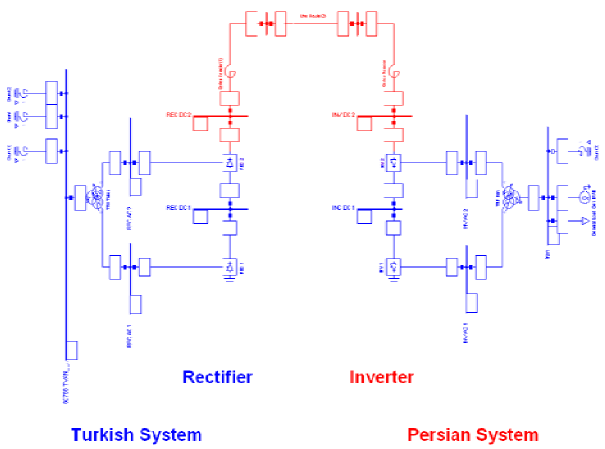

Figure 14: HVDC-connection between Turkish and Persian systems.

Figure 15 shows the effect of the HVDC-Connection between the Turkish and Persian power systems on the oscillation damping behaviour as the only damping measure in the Turkish power system. The results show that the HVDC-Connection helps the enlarged UCTE power system to become stable and improve the oscillation damping behaviour of the whole the system.

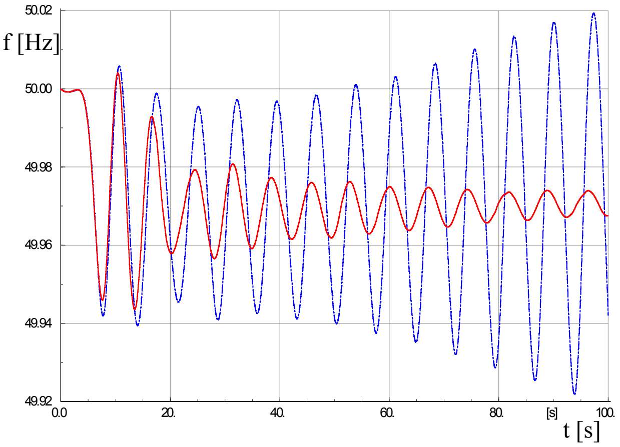

Figure 15: Effect of the HVDC-Connection between the Turkish and Persian power systems on the oscillation damping behaviour.

7 SYNCHRONISATION OF UCTE AND TURKISH POWER SYSTEMS

On 18.09.2010 at 9:25 (CET) the first line between Turkey and Bulgaria was closed, consequently at that time the Turkish power system was synchronised with the UCTE power system. Stable operation of both systems takes place. However, the new already by model calculations predicted inter-area mode with a time period of 0.15 Hz and 7 seconds respectively becomes clearly visible, see Figure 16. After that the second line between Turkey and Bulgaria as well as the line between Turkey and Greece were closed successfully.

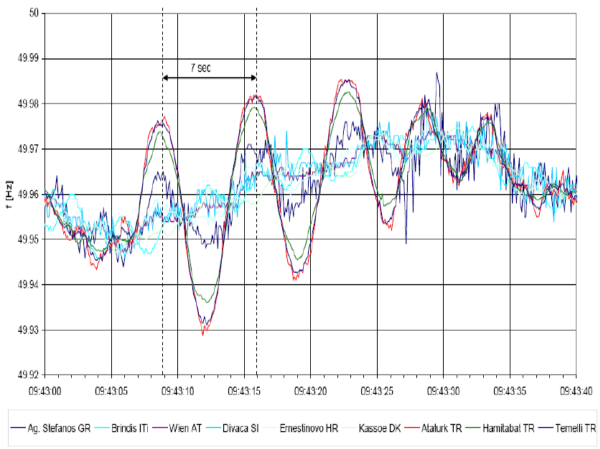

Figure 16: New Inter-Area-Oscillations 0.15 Hz (Turkey against UCTE) after the first line between Turkey and Bulgaria was closed.

8 CONCLUSIONS

The aim of this work was to study the stability of European Power System (UCTE) enlarged by the Turkish Power System. The calculations of this study were based on a non-linear simulation model which is represented using a specific software package DIgSILENT for power system simulation.

The UCTE dynamic model could be validated by the measurement collected from the recording of WAMS. The model represented the real behaviour and it is therefore a reliable basis for further investigations.

The Turkish Power system is modeled with its complete transmission system and could be validated by the measurement collected from the recording of WAMS in the Turkish power system. The model represented also approximately the real behaviour.

A new critical Inter-Area-Oscillation mode in the enlarged UCTE power system has been identified in the frequency range of 0.15 Hz (T_P = 7s) accompanied by insufficient damping.

The retuned oscillation damping devices (PSS) of the power plants in Turkey improve the oscillation damping behavior of the whole system, but it has to be noted that hydro power plants are used in the middle and peak load, that means during the out of service time of these power plants the system losses a positive damping source coming from the retuned PSS-devices.

For the safety of the stability of the whole system, the Turkish system needs at least to ± 165 MVAR- SVC using the additional frequency signal in the voltage regulator as additional damping measure.

As an additional measure, a braking resistor is recommended to 20 MW.

HVDC-connection to the power systems of the eastern Turkish neighbors like Persian power system will help to improve the oscillation damping behavior of the enlarged UCTE power system.

On 18.09.2010 at 9:25 (CET) the Turkish power system was synchronised with the UCTE power system. The already performed extensive model calculation results were proved by the first measurement analysis of the enlarged system.

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