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Oscillation Behaviour of the Enlarged UCTE Power System Including the Turkish Power System

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Abstract: Due to deregulated energy market conditions and the planned extension of the UCTE power system towards Eastern Europe, as well as towards the Middle East and North Africa to close the so called "Mediterranean Ring", the oscillation damping behaviour of the UCTE power system is gaining more and more in importance. Within the present paper, the oscillation damping behaviour of the enlarged UCTE power system after the synchronous connection with the Turkish power system is analysed, using time and frequency domain methods. Firstly the Turkish power system is analysed as a separate network in isolated operation as the case still is today. Subsequently the enlarged UCTE-system, including the Turkish power system is analysed. Differences in the oscillation behaviours are shown, precarious system constellations are identified and measures to solve occurring problems are given and discussed.

1. INTRODUCTION

Inter-Area-Oscillations occur since the beginning of interconnecting national transmission systems in Western Europe in the early seventies. In the current outline of the UCTE power system poorly damped oscillation modes exist in East-West and North-South direction (Dudzik *et. al*, 1998; Grebe, 2000; Kurth, 2005; Spanner *et. al*, 1998). These Inter-Area-Oscillations are excited by rapid changes in the power system, e.g. switching operations or emergency shut-downs of big power plant units. The damping behaviour of these slow Inter-Area-Oscillations is gaining more and more in importance, not least due to deregulated energy market conditions and the extension of the UCTE power system towards Eastern Europe, as well as towards Middle East and North Africa to close the so called "Mediterranean Ring" (Grebe, 2000; Kurth *et. al*, 2005). One possible next step towards closing the "Mediterranean Ring" is the synchronous connection of the Turkish power system, which is also one of the two main topics currently investigated by the UCTE Working Group "System Development". Within the framework of this paper, the oscillation behaviour of the UCTE power system including the Turkish power system is analysed to identify expectable problems and point out indications for necessary measures.

2. DYNAMIC MODEL OF THE UCTE POWER SYSTEM

The analysis of the dynamic behaviour of the enlarged UCTE-system is based on a detailed non-linear dynamic model (Kurth *et. al*, 2005; Spanner *et. al*, 1998) of the current UCTE power system, enlarged by the Turkish power system, including approximately 630 power plant units, 3000 dynamic loads, 6500 transmission lines and 900 transformers, see Fig. 1. Transmission lines and transformer stations, connecting the transmission systems on different voltage levels with coupling transformers are included in the model. Each power plant consists of a dynamic model of the power generation unit, depending on its type, and of a generator, voltage controller, frequency controller, power system stabilizer and non-linear filters.

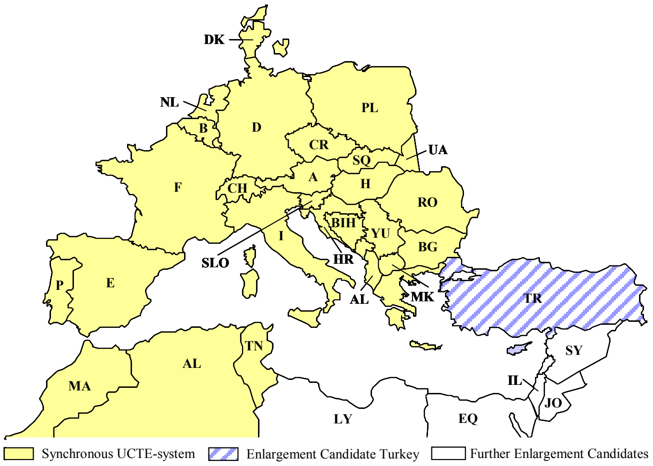

Fig. 1. Map of the enlarged UCTE power system covered by the non-linear power system model

3. THE TURKISH POWER SYSTEM

Today's electric power generation in Turkey is mainly based on the local resource lignite, as well as on hydro power (Agoris, 2006). Furthermore, the import of natural gas also gains in importance as primary energy resource for power generation. The demand of electric energy can be divided into households and industry, approximately one half each. A typical peak load situation in the Turkish power system takes place in winter, around 6 p.m. on weekdays. The main load centres within the Turkish power system are located in the west and north-west of the country. However, due to the big

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hydro power potential, considerable electric power generation capacities are situated in the eastern and south-eastern part of Turkey. The electric power transmission is therefore mainly designed for transits over long distances. High load flows from south-east to north-west, involving high transmission losses, are typical for the Turkish transmission system (Tor *et. al*, 2005).

3.1 *Validation of the Dynamic Model with Measurements*

The analysis of the dynamic behaviour of the Turkish power system is based on the model of the current Turkish transmission system on extra-high voltage level (380-kV) (TEIAS, 2005; Gubernali, 2003), shown in Fig. 2.

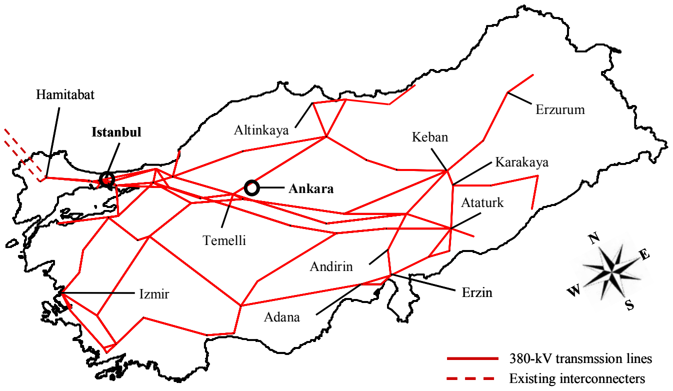

Fig. 2. Model of the Turkish extra-high voltage transmission system

Fig. 3 shows the measured and the simulated response of the frequency for one node in southern Turkey to a drop-out of 650 MW of active power during a 22 GW peak load situation. In 2004 the absolute peak load in the Turkish power system complied with 23 GW (TEIAS, 2005). Therefore the distribution of generation is parameterised according to a typical peak load situation. The comparison between measurement and simulation in Fig. 3 shows a good compliance.

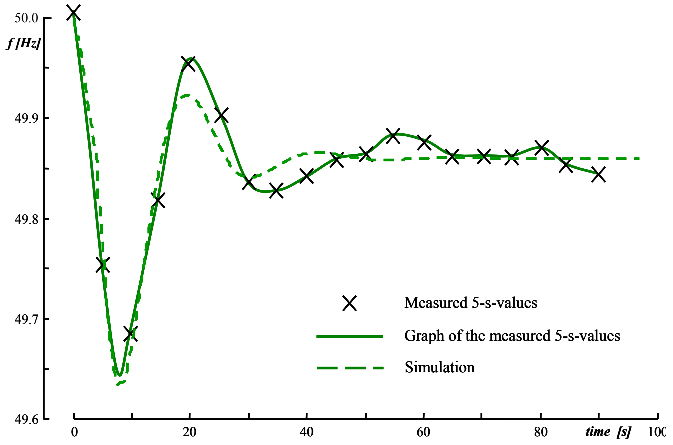

Fig. 3. Comparison of simulation and measurement of the frequency for a drop-out of 650 MW of active power in the Turkish power system

3.2 *Analysis of the Dynamic Behaviour of the Turkish Power System in Isolated Operation*

By analysing the dynamic behaviour of the Turkish power system in isolated operation, the dominant oscillations and therefore the dominant eigenvalues $s_P = \sigma_P \pm j\,\omega_P$ can be identified, based on the load scenario defined in Chapter 3.1.

Via modal analysis (Wang, 1997) the most poorly damped and therefore dominant eigenvalues are determined.

Knowing the eigenvalues, the oscillation period

$$T_P = 2\pi / \omega_P \tag{1}$$

and the damping

$$D_P = |\sigma_P| / \omega_P \tag{2}$$

can be calculated.

With the related left and right eigenvectors, the mode-shapes and participation factors concerning the angular velocity ω_G of each particular generator can also be derived. On this basis the phasor diagrams of the oscillating generators can be drawn. The direction is given by the mode-shapes and the magnitude is given by the participation factors. Regions of coherent oscillating generators are separated from each other by so called “node-lines”.

Eigenvalue Analysis:

The very highly damped oscillation visible in Fig. 3 in the time domain complies with the Primary-Control-Oscillation. The eigenvalue $s_P = -0.11 \pm j\,0.34$, calculated via modal analysis and shown in Table 1 can be assigned to the Primary-Control-Oscillation, because the participations of the generators are not directed against each other.

Table 1. Dominant oscillations in the Turkish power system in isolated operation

Oscillation:	Eigenvalue s_P:	Oscillation Period T_P:	Damping D:
East-West	-0.22 ± j 4.28	1.46 s	5.1 %
North-South	-0.60 ± j 5.51	1.14 s	10.9 %
Primary-Control	-0.11 ± j 0.34	18.7 s	32.1 %

The oscillation periods of the two other oscillations considered in Table 1 are both in the range of one second. Therein the North-South-Oscillation shows a good damping of $D = 10.9\%$ and also the East-West-Oscillation with $D = 5.1\%$. With a damping $D \geq 3\%$ these oscillations are sufficiently damped (Spanner *et. al*, 1998).

In Fig. 4 the participation with respect to the angular velocity ω_G of the generators for the North-South-Oscillation and for the East-West-Oscillation are shown for the regarded 22 GW load situation. Both, the East-West- and the North-South-Oscillation possess one node line.

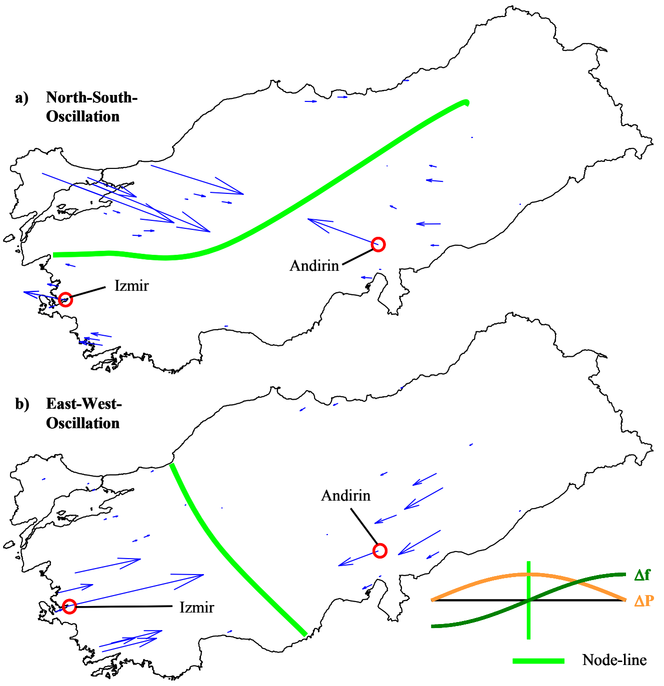

Fig. 4. Mode-shapes and participation factors concerning the generators' angular velocity ω_G shown as phasor-diagram

Analysis in the time domain:
Due to the fact that the identified dominant Inter-Area-Oscillations have very small amplitudes in comparison to the Primary-Control-Oscillation, they are not directly visible in the range of the frequency illustrated in Fig. 3.

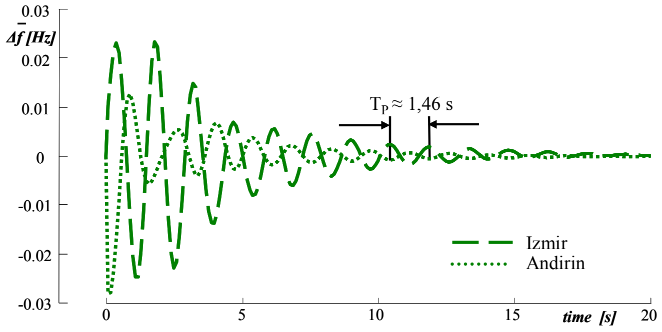

Fig. 5. Deviation between the frequency in the node "Izmir" in western Turkey and the frequency on the node-line and the deviation between the frequency in the node "Andirin" in southern Turkey and the frequency on the node-line

To make these oscillations visible, Fig. 5 shows the deviation between the frequency in the node "Izmir" in western Turkey and the frequency on the node-line and the deviation between the frequency in the node "Andirin" in southern Turkey and the frequency on the node-line. Both generators, the one in "Izmir" and the one in "Andirin", participate strongly in both considered oscillations. In case of the North-South-Oscillation they participate in the same direction, because they are located on the same side of the node-line. In case of the East-West-Oscillation in opposite direction, because they are located on opposite sides of the node-line, see Fig. 4.

During the first periods, a superposition of several oscillations occurs, see Fig. 5. After the decay of the stronger damped oscillations, the dominant East-West-Oscillation with an oscillation period of $T_P = 1.46$ s can be identified in the nodes "Izmir" and "Andirin", which are located in the two regions oscillating against each other.

4. THE ENLARGED UCTE POWER SYSTEM

The effects of the Turkish power system on the oscillation damping behaviour of the enlarged UCTE-system are analysed in this chapter. Therefore the model of the current UCTE-system is connected with the Turkish part model. As basis for the simulations a poorly damped Inter-Area-Oscillation, occurred within the UCTE-system, triggered by a 1.4 GW outage of Block 2 Civeaux in France is used (Kurth *et. al*, 2005). With a dominant eigenvalue $s_P = -0.013 \pm j1.42$ which corresponds to an oscillation period $T_P = 4.42$ s and a damping $D \approx 1\%$, this Inter-Area-Oscillation is poorly damped.

4.1 Analysis of the dynamic behaviour of the enlarged UCTE-system extended by the Turkish power system

Based on the detailed model of the current synchronous UCTE-system, see Fig. 1, and extended by the Turkish part model, the dynamic behaviour of the enlarged UCTE-system is analysed in this chapter. It is assumed, that the connection between the Turkish power system and the UCTE-system is realised by the already existing two extra-high voltage transmission lines on 380 kV level between Turkey and Bulgaria. These two existing but currently still not coupled transmission lines connect the nodes "Babaeski" and "Hamitabat" in Turkey with the node "Maritsa" in Bulgaria (UCTE, 2005). The resulting enlarged UCTE-system has a large extent in east-west direction, even more than the Base Condition, especially due to the weak connection between Turkey and Bulgaria.

In scenario I no active power exchange between Turkey and Bulgaria takes place. In scenario II an active power import to Turkey and in scenario III an active power export from Turkey of 500 MW is analysed. In scenario IV, the additional impact of an exchange between Spain and France on the oscillation damping behaviour is considered.

Scenario I: no active power exchange between Turkey and Bulgaria. As expected the dominant eigenvalues change for the enlarged UCTE-system in comparison to the UCTE-system in its current extend. Via modal analysis, now two new dominant eigenvalues can be identified: A poorly damped East-West-3-Oscillation (EW-3) with three node lines and an oscillation period of $T_P = 3.7$ s and a damping of $D = 3.6$ %, and another poorly damped but slower East-West-1-Oscillation (EW-1) with an oscillation period $T_P = 6.3$ s and a damping of $D = 2.8$ %, see Table 2.

The East-West-2-Oscillation (EW-2) corresponds with an oscillation period of $T_P = 4.8$ s to the dominant oscillation in the UCTE-system in its current extend, but now with two node-lines. However, this oscillation is sufficiently damped, with a damping of $D = 7.7\ \%$.

Table 2. Dominant Inter-Area-Oscillations in the enlarged UCTE-system: scenario I (no import/export to/from Turkey)

Oscillation:	Eigenvalue $\boldsymbol{s_P}$:	Oscillation Period $\boldsymbol{T_P}$:	Damping $\boldsymbol{D}$:
EW-1	-0.03 ± j 0.99	6.3 s	**2.8** %
EW-2	-0.10 ± j 1.31	4.8 s	7.7 %
EW-3	-0.06 ± j 1.70	3.7 s	3.6 %

In Fig. 6 and Fig. 7 the mode-shapes and the participation factors concerning the angular velocity ω_G of the generators are shown in a phasor-diagram for the two poorly damped oscillations EW-1 and EW-3. In case of the poorly damped EW-3 oscillation, three node-lines emerge, one between Spain and Morocco, one following the western border of Germany and one between Bulgaria and Turkey, see Fig. 6. The generators in Morocco, Algeria and Tunisia participate stronger in this oscillation than other parts of the system. Showing the poorly damping behaviour, with only one node-line along the east border of Germany, the EW-1 oscillation is the one of highest interest, see Fig. 7. The generators of Greece, Bulgaria and especially Turkey participate very strongly in this Inter-Area-Oscillation.

Scenario II: Active power import to Turkey. Table 3 shows that for a 500 MW-import to Turkey the two faster oscillations EW-2 and EW-3 are barely affected and the EW-1 oscillation is even better damped.

Scenario III: Active power export from Turkey. If Turkey exports 500 MW of active power, this also does barely affect the two faster oscillations EW-2 and EW-3, see Table 4. However, the export does strongly decrease the damping of the slower EW-1 oscillation. A further increase of the active power export compromises the dynamic stability of the enlarged UCTE-system. Due to the fact that the Turkish and the Bulgarian power systems are weakly connected over few transmission lines, a bottleneck analogous to the one between France and Spain exists, shown by (Kurth *et. al*, 2001).

Table 3. Dominant Inter-Area-Oscillations for scenario II: 500 MW **IMPORT** to Turkey

Oscillation:	Eigenvalue $\boldsymbol{s_P}$:	Oscillation Period $\boldsymbol{T_P}$:	Damping $\boldsymbol{D}$:
EW-1	-0.05 ± j 0.99	6.4 s	**4.6** %
EW-2	-0.10 ± j 1.31	4.8 s	7.9 %
EW-3	-0.06 ± j 1.70	3.7 s	3.7 %

Table 4. Dominant Inter-Area-Oscillations for scenario III: 500 MW **EXPORT** from Turkey

Oscillation:	Eigenvalue $\boldsymbol{s_P}$:	Oscillation Period $\boldsymbol{T_P}$:	Damping $\boldsymbol{D}$:
EW-1	-0.01 ± j 0.99	6.3 s	**1.3** %
EW-2	-0.10 ± j 1.31	4.8 s	7.9 %
EW-3	-0.06 ± j 1.70	3.7 s	3.6 %

Scenario IV: Changing active power flows between Spain and France. Based on simulation scenario III, the active power exchange between Spain and France is now varied based on 160 MW power export of Spain. If no active power flow between Spain and France takes place, this results in a slight increase in damping of the EW-1 oscillation, with a damping $D = 1.4\%$. In contrast, if Spain imports active power from France, this results in a further increase in damping of the EW-1 oscillation.

However, due to the fact that in case of the EW-1 oscillation the participation of the Turkish generators is the strongest, the load flow between the Turkish and the Bulgarian power system have a stronger effect on the damping behaviour of this oscillation, see Fig. 7.

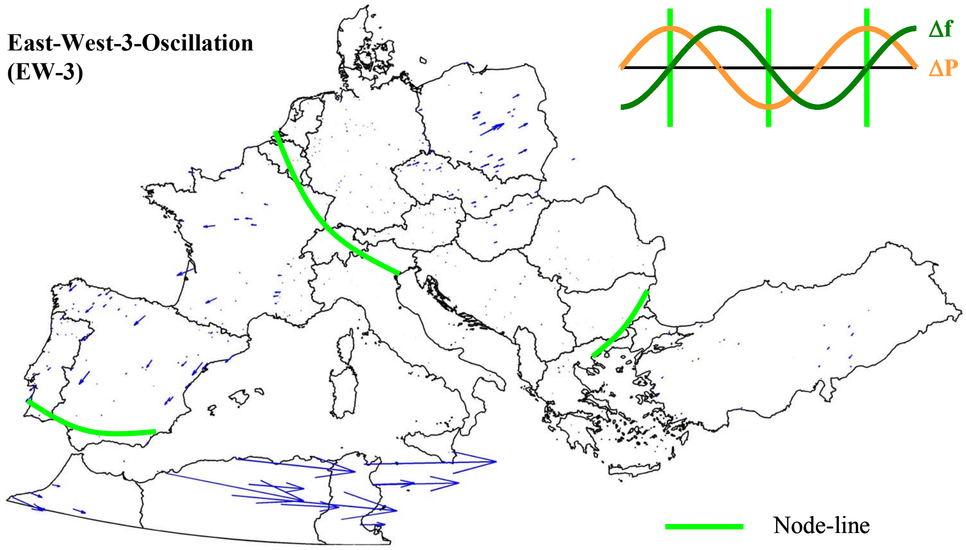

Fig. 6. Mode-shapes and participation factors concerning ω_G, shown as phasor-diagram for the EW-3 oscillation, scenario I

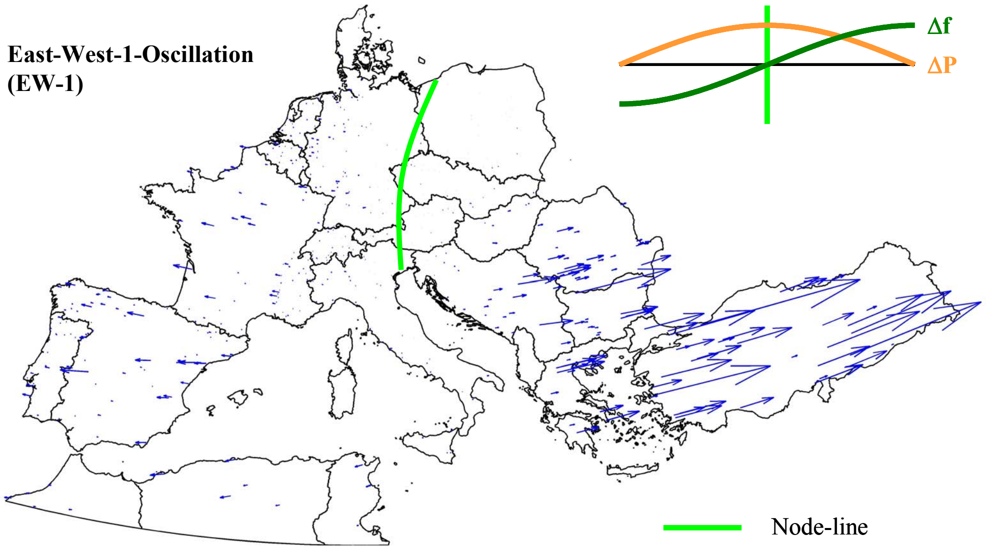

Fig. 7. Mode-shapes and participation factors concerning ω_G shown as phasor-diagram for the EW-1 oscillation, scenario I

4.2 Dynamic behaviour of the Turkish power system as part of the enlarged UCTE-system

A deeper insight into the participation of the single components of one individual power plant or group of power plants on the considered dominant eigenvalues, can be shown with so called "momentum diagrams". Each partial momentum shows the component's influence on the considered eigenvalue and is determined via modal analysis and converted into two corresponding parts (Kurth *et. al*, 2005): a damping momentum

$$m_{\mathrm{D}} = -\frac{2T_{\mathrm{A}}\sigma_{\mathrm{P}}}{\Omega_{\mathrm{N}}}\omega_{\mathrm{P}} \tag{3}$$

and a synchronizing momentum

$$m_{\mathrm{S}} = \frac{T_{\mathrm{A}}}{\Omega_{\mathrm{N}}}\left(\omega_{\mathrm{P}}^2 - \sigma_{\mathrm{P}}^2\right) \tag{4}$$

with T_{A} being the average acceleration time constant and Ω_{N} the rotation rate of network.

In Fig. 8 the influence of the voltage controllers (VC) and speed controllers (SC) within the Turkish power system on the damping behaviour of the dominant EW-1 with $T_{\mathrm{P}} = 6.3\,\mathrm{s}$ is shown. The y-axis shows the damping momentum m_{D}, given by (3) and the x-axis shows the synchronizing momentum m_{S}, given by (4). The vector $\mathrm{m}_{(\mathrm{UCTE+T})}$ in Fig. 8 represents the momentum of the enlarged UCTE-system, including the Turkish power system. All dynamic components, the dynamic loads, voltage controllers, speed controllers and power system stabilizers are included. The vectors $\mathrm{m}_{(\mathrm{UCTE+T})}$ - $(\Delta\mathrm{m}_{(\mathrm{VC,UCTE})} + \Delta\mathrm{m}_{(\mathrm{VC,T})})$ and $\mathrm{m}_{(\mathrm{UCTE+T})}$ - $(\Delta\mathrm{m}_{(\mathrm{SC,UCTE})} + \Delta\mathrm{m}_{(\mathrm{SC,T})})$ also represent the momentums of the enlarged UCTE-system, but without voltage controllers and speed controllers, respectively.

Fig. 8 reveals, that the voltage controllers of the power plant units within the Turkish power system do have a very strong negative damping momentum $\Delta\mathrm{m}_{\mathrm{D}(\mathrm{VC,T})}$, almost as big as the negative damping momentum $\Delta\mathrm{m}_{\mathrm{D}(\mathrm{VC,UCTE})}$ of the voltage controllers within the remaining UCTE-system. Hence, the voltage controllers within the Turkish power system have a strong contribution to the poorly damped EW-1 oscillation. The negative damping momentum $\Delta\mathrm{m}_{\mathrm{D}(\mathrm{SC,T})}$ of the speed controllers within the Turkish power system is typical for a high share in speed controlled hydro power plants. In contrast the speed controllers within the remaining UCTE-system have a stronger, positive momentum $\Delta\mathrm{m}_{\mathrm{D}(\mathrm{SC,UCTE})}$, which is typical for a higher share in speed controlled fossil fired plants. However the negative contribution of the speed controllers within the Turkish power system to the poorly damped EW-1 oscillation is relatively low.

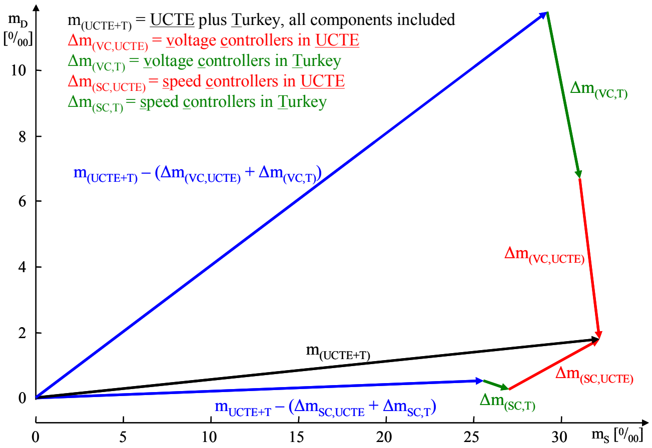

Fig. 8. Momentum diagram for the voltage controllers (VC) and speed controllers (SC) for the EW-1 oscillation

5. IMPROVEMENT MEASURES

Obviously the analysed enlarged UCTE-system, including the Turkish power system, shows a modified oscillation damping behaviour. Not least due to the bottleneck between Turkey and Bulgaria the enlarged UCTE-system has a large extent. The resulting EW-1 oscillation with $T_{\mathrm{P}} = 6.3\,\mathrm{s}$ is poorly damped. Furthermore an import of active power to Turkey strengthens, an export weakens the damping of this oscillation. The bottleneck between Spain and France does influence this oscillation accordingly. Due to the fact that the generators of the eastern hemisphere participate stronger in the EW-1 oscillation than the generators of the western hemisphere, the changing load flow between Turkey and Bulgaria has a stronger influence. Therefore, before connecting the Turkish power system to the UCTE-system in the current state, the damping of the occurring dominant 6.3 s-Oscillation (EW-1) has to be ensured, also for different load flow situations to retain a stable system operation. As shown in Fig. 8 both, the voltage and speed controllers within the Turkish power system contribute to this oscillation.

Due to the fact that the damping effect of power system stabilizer decreases with higher oscillation periods, caused by the limitation of the generator excitation, new concepts have to be investigated and applied. One possibility to influence the effect on these slow oscillations is the adjustment of the transient initial gain of the voltage controllers, see Fig. 9 (Kurth *et. al*, 2001). The same applies for speed/primary controllers of hydro power plants. The transient speed controller gain $K_{\mathrm{n,tr}}$, see Fig. 9, has to be parameterised in such a way, that not only the pressure oscillations within the plant are sufficiently damped, but also the slow inter-area-oscillation will be excited as little as possible. Hence, existing transient gains have to be checked and their parameterisation reflected taking into account the new dominant 6.3 s-Oscillation. Both measures promise to improve the damping behaviour. However, the possible effects seem to be limited, see Fig. 8.

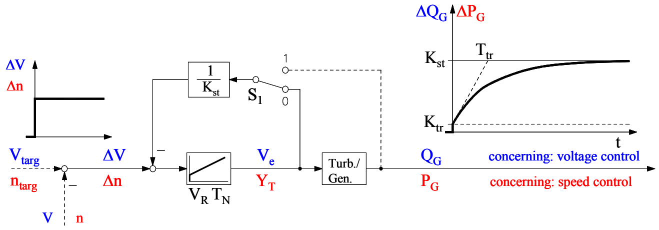

Fig. 9. Block diagram and step response behaviour of the transient gain of voltage/speed controllers

Investigations of novel concepts aim to damp slow oscillations directly on the turbine side. Advanced control measures based e.g. on flatness-based feed-forward control of pumped storage plants are very promising and currently investigated by (Treuer *et. al*, 2007). Due to the high penetration of hydro power plants in South-east Turkey, these advanced control concepts have the potential to be both very effective and relatively simple to damp these slow inter-area-oscillations in the enlarged UCTE power system and hence ensure a secure system operation. Furthermore, the potential of flexible AC-transmission systems (FACTS) to damp this oscillation has to be analysed (Buchholz *et. al*, 2005).

6. CONCLUSIONS

The connection between UCTE and Turkey will not be securely possible under stability considerations, since a satisfactory damping of the resulting 6.3 s-Oscillation is not assured for all considered system configurations. Hence, damping measures have to be applied.

Furthermore a stronger connection of the Turkish power system by further transmission lines has to be considered, due to the fact that a stronger intermeshed network increases in damping. However, a strong connection is limited, because of the geographic bottleneck between the European and Asian continent. An annual increase of electric power consumption within the Turkish power system by 8 %, as well as additional large-scale hydro power plants in the eastern part of Turkey is expected (Agoris, 2006). Therefore scenarios with higher load in the Turkish power system have to be considered, as well as higher active power exchanges between Turkey and the remaining UCTE-system.

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