IFAC / CIGRE Symposium on
Control of Power Systems and Power Plants
August 18 - 21, 1997
Beijing, China

NEW FREQUENCY AND POWER OSCILLATIONS IN THE ENLARGED WESTEUROPEAN INTERCONNECTED NETWORK REASONS AND COUNTER MEASURES

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Abstract: After the interconnection of the networks of Poland, the Czech and Slovak Republic and Hungary (CENTREL-System) to the UCPTE-System of West-Europe in Oct. 1995 low damped or even undamped frequency and power oscillations were observed. This oscillations occur up to now if more than ca. 1000 MW active power is exported from the east part to the west part of the system or vice versa. In this paper in principle the relations and chains of causality which can lead to such low damped and dangerous oscillations not only in the UCPTE System are shown.

Keywords: Westeuropean UCPTE System, New low damped Oscillations, Reasons and Counter Measures

1. INTRODUCTION

After the connection of the CENTREL system and the separation of the Yugoslav network, the Westeuropean UCPTE network has taken a more longitudinal East-West basis structure, see figure 1. Therefore the appearance of the slowest oscillation mode of the system has to be expected also in this East-West direction where the Spanish generator rotors oscillate in phase opposition to the CENTREL generator rotors after a system fault e.g. a plant tripping. The greatest load flow in the network will thereby always appear on the so-called „Line of constant frequency" whenever the angles of the generator rotors have reached their greatest amplitude (or the rotor speed equals zero exactly). In general this oscillations are mainly influenced or even destabilised by the voltage controllers of the generators.

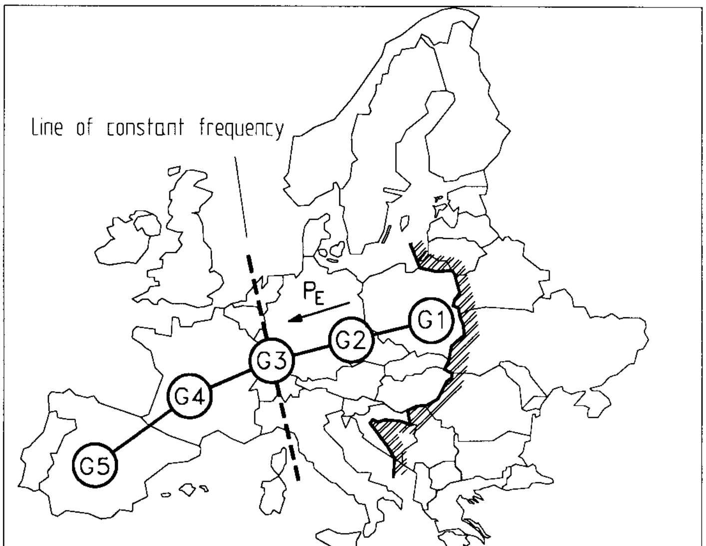

Fig. 1 Overview about the UCPTE-System of today and a longitudinal five-generator-model describing the occured frequency and power oscillations

2. EQUIVALENT OSCILLATION MODEL

This slowest and least damped mode of oscillation of the network can therefore be modelled in first approximation by a simple equivalent consisting of five synchronous machines and four line elements, as shown in figure 1. Using that equivalent we may first present the fundamental relations about the appearance of frequency and power oscillations. However the results obtained enjoy general validity. Beside the aforementioned slowest basis mode further modes are conceivable in the network:

- For example generator 1 (CENTREL) could oscillate in phase with generator 5 (Spain) against generator 3 (Germany); generators 2 and 4 would thereby remain idle and would constitute two other „lines of constant frequency".
- The oscillation of the northern generator rotors against the Italian ones would also be conceivable as a mode, however with a shorter period and better damping.

In figure 2, as an example of the today low damped or even nearly undamped East-West basis mode, the measured frequency oscillation of a few eastern countries which appeared after a plant tripping in Spain and a tie line flow between Germany and France are shown. Among the frequency oscillation the slowest East-West basis mode of the network with period T_p=3.68 s can clearly be identified; the line of constant frequency runs along the Franco-German border and the further the generator rotors are from this line the more they oscillate. The tie line power flow reaches its extreme values exactly when the frequencies (or the rotor speeds) are crossing zero and hence exactly when the rotor angles reach their maximum amplitude.

3. CAUSES OF THE APPEARANCE OF LOW DAMPED OR EVEN UNDAMPED OSCILLATIONS

If frequency and power oscillations proceed in an low damped or even undamped manner, one or several network elements (mainly control devices) are necessary for providing the system more oscillation energy than the natural damping devices (e.g. generator damper windings) can absorb from the network. These control devices are usually the generator voltage regulators.
In figure 3, this relation is shown by an electric equivalent system where a generator supplies a infinite bus through a line; figure 3b indicates the equivalent circuit. This equivalent system could represent one side of the network up to the line of constant frequency for example in the case of the slow East-West basis mode of the UCPTE network, and that line itself may be modelled by the infinite bus. In figure 3a, the generator rotor is shown at working point 1 with the rotor angle φ_P relatively

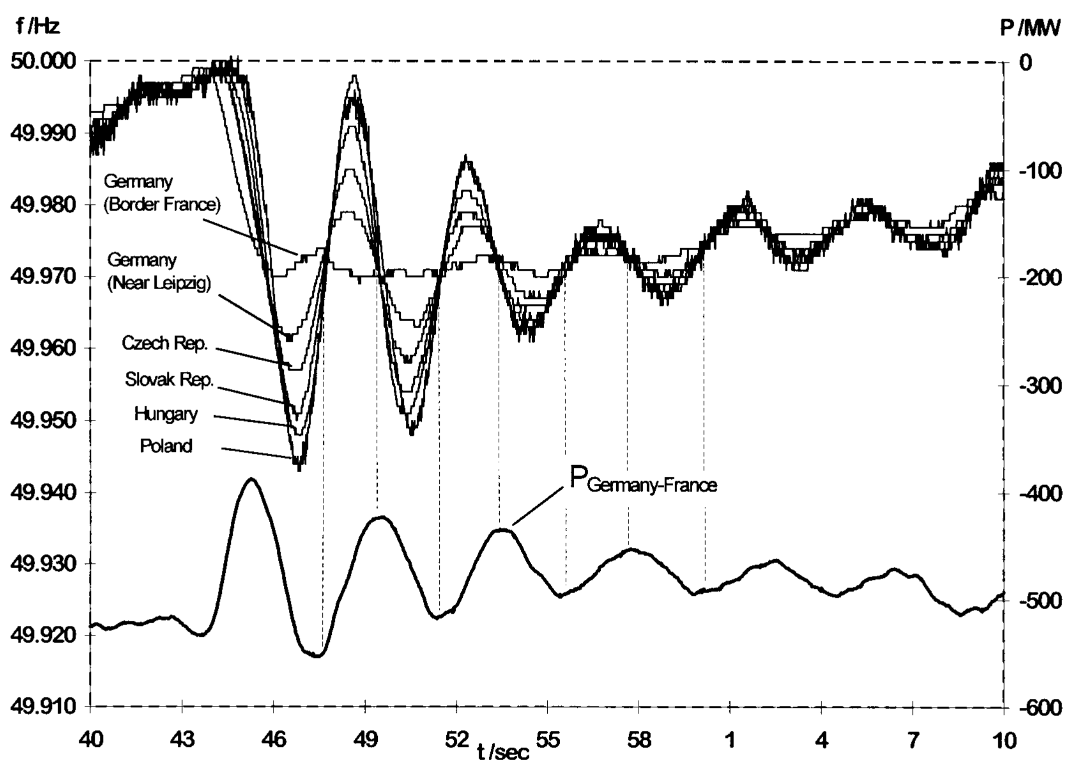

Fig. 2: Frequency and Power oscillations after power plant disconnection in Spain

to the voltage of the external network. The generator voltage u_G is defined by the transient electro motoric force (emf) u_P' and the voltage of the infinite bus u_K through the voltage divider of the reactances x_d' and x_L. The transient emf u_P' is in effect during the time period of the oscillations, while it is directly linked to the exciter winding and the latter is on the other hand almost constant during the oscillations. Only by introducing a voltage regulator this transient emf may be influenced notably during the oscillations.

If the rotor reaches its maximum amplitude after an fault and oscillates for example from point 1 to point 2, the generator voltage is diminished by the x_d'-x_L-voltage divider and inversely. Hence the generator voltage oscillates in phase opposition to the rotor angle of the generator rotor. These facts are also shown in figure 3c where the braking and accelerating surfaces of the oscillation without voltage control (case a) resulting of the $p_G'(\varphi_P)-$ characteristic are shown additionally. The $p_G'(\varphi_P)-$ characteristic amounts to in the absence of consumers :

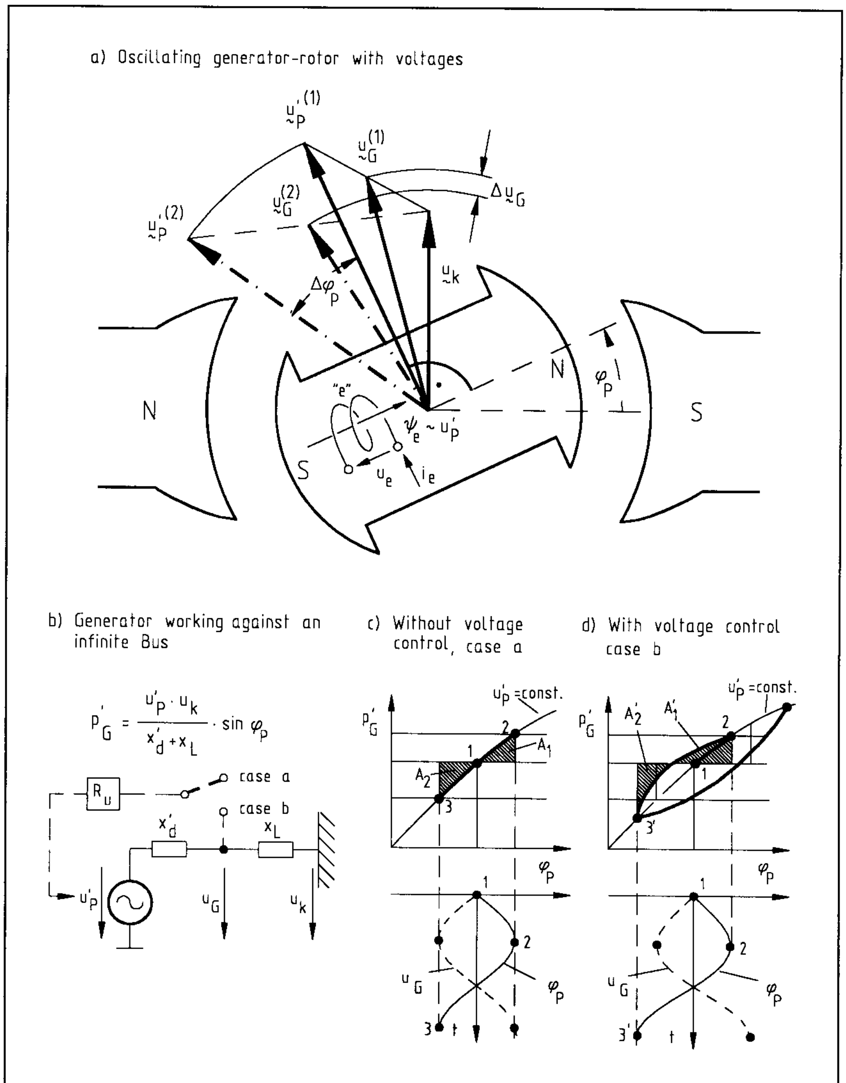

Fig. 3: Rotor oscillations caused by voltage controllers

$$p_G' = \frac{u_P' \cdot u_k}{x_d' + x_L} \cdot \sin\varphi_P \,. \qquad (1)$$

The influence of the damper windings is neglected for the sake of simplicity, hence an undamped oscillation is represented in figure 3c. If the voltage control is in operation (case b), the relations as presented in figure 3d follow:

1. The rotor oscillates - after an excitation - e.g. from working point 1 to working point 2
2. As the rotor angle φ_P increases the generator voltage u_G decreases
3. The voltage control increases the transient emf u_P' in order to control u_G via the voltage divider x_d'-x_L
4. Therefore the $p_G'(\varphi_P)-$ characteristic rises according to equation (1) and the rotor moves above the former $p_G'(\varphi_P)-$ characteristic (u_P' = constant) to new working point 3'.
5. Due to the rising of the $p_G'(\varphi_P)-$ characteristic, the accelerating surface A_1' becomes $A_1'>A_1$ hence the braking surface $A_2'>A_2$.
6. Therefore the working point 3' lies below the working point 3; the rotor is unstable.

4. INFLUENCE OF POWER TRANSIT ON THE NETWORK STABILITY

For modelling the influence of power transit on the network stability, in the model shown in figure 3b the generator power is increased in order for the rotor working point to move from 40° to 60°. On the basis of this power increase the u_P'-u_G-diagrams are reckoned and shown for both extreme cases:

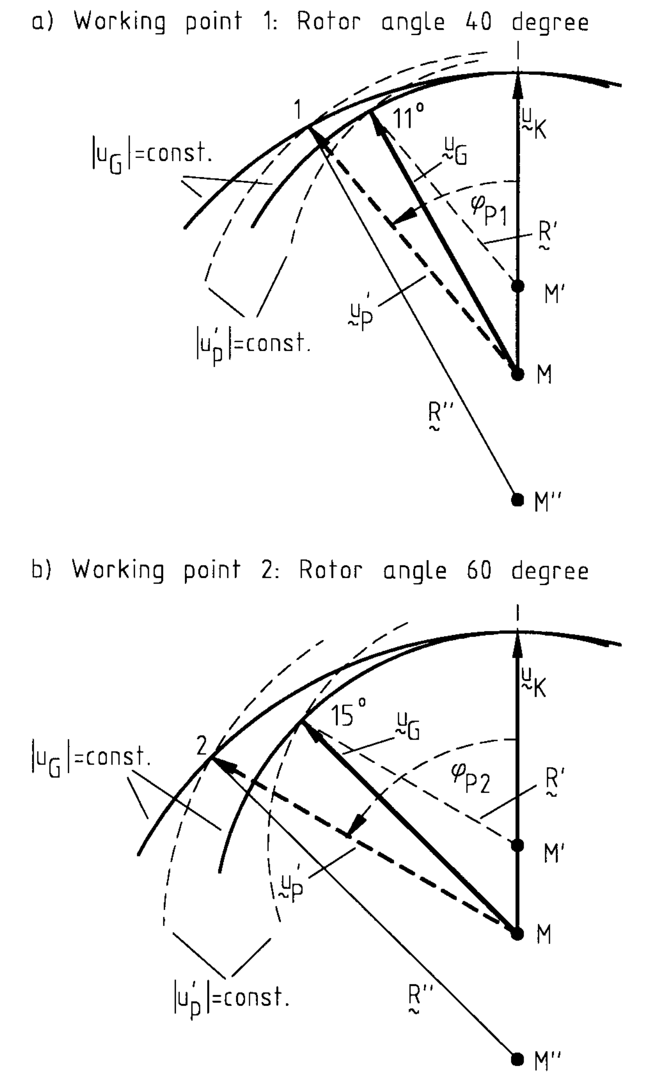

Fig. 4: Influence of the increase of the exchange power to the generator voltage

a) u_G =const (quasi stationary behaviour)

b) u_P' =const (oscillatory behaviour)

According to figure 3b, the vectors u_P' and u_G equal:

$$\underset{\sim P}{u}' = (1 + \frac{x_d'}{x_L}) \cdot \underset{\sim G}{u} - \frac{x_d'}{x_L} \cdot \underset{\sim k}{u} \qquad (2a)$$

$$\underset{\sim P}{u}' = \alpha \cdot \underset{\sim G}{u} - \frac{x_d'}{x_L} \cdot \underset{\sim k}{u} \qquad (2b)$$

$$\underset{\sim P}{u}' = R'' + M'' \quad . \qquad (2c)$$

If we rewrite the equation in function of u_G, we find:

$$\underset{\sim G}{u} = \frac{\underset{\sim P}{u}'}{\alpha} + \frac{\frac{x_d'}{x_L}}{\alpha} \cdot \underset{\sim k}{u} \qquad (3a)$$

$$\underset{\sim G}{u} = R' + M' \quad . \qquad (3b)$$

Equation (2) describes the evolution of the transient emf u_P' around the centre M'' with the radius R'' due to the change of the angle of the generator voltage u_G with a constant amplitude (quasi stationary behaviour). Equation (3) describes the evolution of the generator voltage u_G around the centre M' with a radius R' due to the change of the angle of the transient emf u_P' with a constant amplitude (oscillatory behaviour).

In figure 4a these two equations are shown for working point φ_P =40°. The angle between the trajectories of the vector u_G for the quasi stationary case and the oscillatory case amounts to 11°. Thus with this angle the amplitude of the generator voltage u_G will diverge from its stationary value and will therefore induce the voltage controller to control this voltage.

In figure 4b this behaviour is presented for working point φ_P =60° (increased load flow). In this case this change angle has increased to 15°; thus the voltage controller will be induced to a larger control operation at the same oscillation and will therefore destabilise in this case the system more.

5. IDENTIFYING THE MOST DESTABILISING VOLTAGE CONTROLLER

In the equivalent from figure 1 five generators form a chain where the load flows from East to West. If one excites the generators with torque impulses in such a way that only the slowest East-West basis mode appears, the rotor angle deviations and the voltage curves presented in figure 5 result:

Generators 1 and 2 oscillate in phase opposition to generators 4 and 5; the middle generator 3 stays nearly undisturbed.
This behaviour corresponds exactly to the first basis oscillation of the Westeuropean UCPTE network.
If one considers the voltage evolutions illustrated in figure 5b, one observes that these voltage evolutions all oscillate in phase together and furthermore in phase with generators 4 and 5, but in phase opposition to generators 1 and 2. Besides, the voltage of generator 3 shows the greatest amplitude whereas the voltages of generators 1 and 5 show the smallest one. This effect occurs because the load flow oscillation on the lines linking East to West increases with every other oscillating generator up to the line of constant frequency and hence the oscillating voltage deviations of the generators increase also because of the voltage losses caused by the load flow and the line impedances.
On the west of the line of constant frequency the load flow and therefore the voltage deviations diminish again with every further generator, and thus the voltage oscillation profile appears according to figure 5b.
In figure 3 it was shown that the voltage control has a strong destabilising effect when the rotor angle φ_P and the generator voltage u_G are in phase opposition; otherwise it must act in a stabilising manner.
In figure 6 the rotor speeds are illustrated after a torque impulse for the cases:

- w: no voltage control in the system
- 1...5: only one voltage controller at the generator 1...5 respectively.

As we can see from figure 6, the voltage control of generator 2 really destabilises the most while the voltage control of machines 4 and 5 act in the most stabilising manner.
If we apply this to the real UCPTE network we may say - based upon figure 2 - that during a strong East-West load flow the voltage control devices of the machines in the Czech Republic and in Slovakia destabilise the system the most whereas France's voltage control devices act in a stabilising way. The line of constant frequency will then appear near the France-German border, with respect to the slow basis mode.

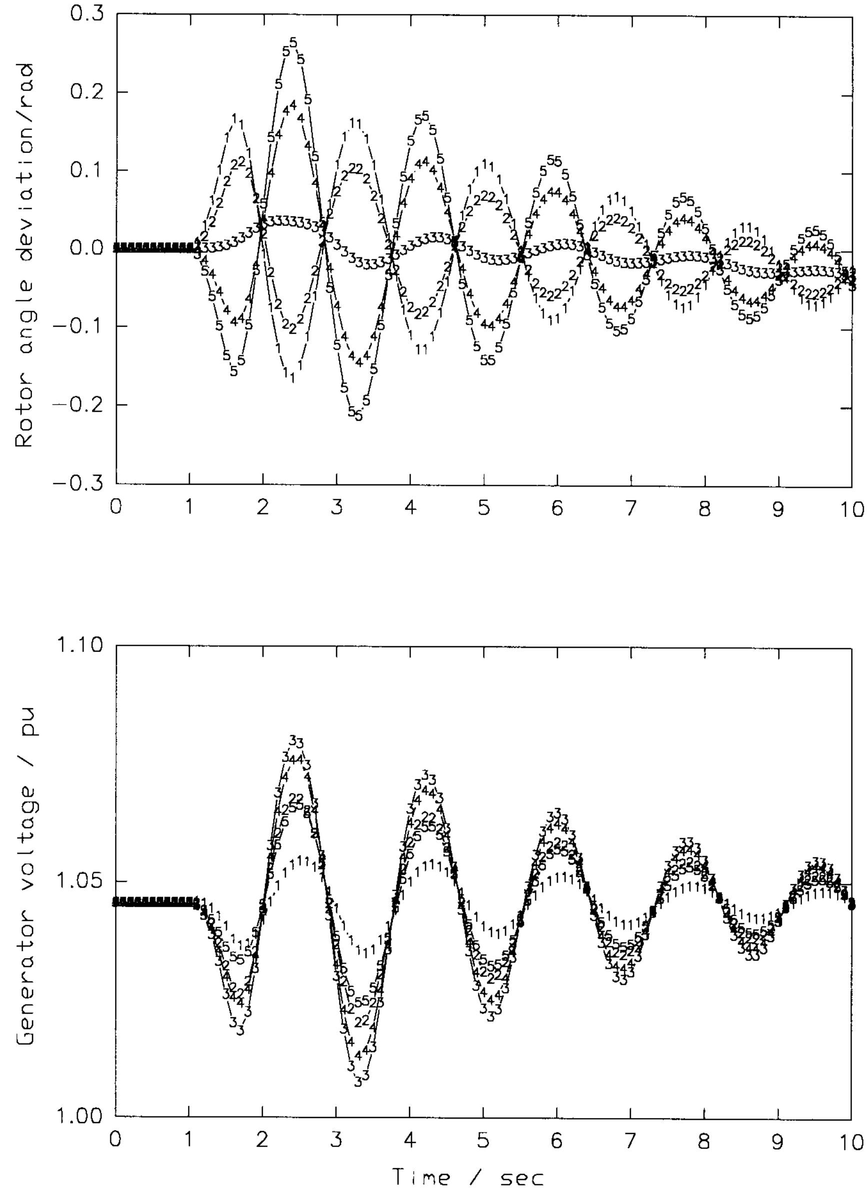

Fig. 5: Rotor angles and generator voltages of the five-machine-model after a torque impuls

6. COUNTERMEASURES

With this results the best counter measures against the frequency and power oscillations are on the one hand the reduction of the gain of the voltage controllers in the area of generator 2 and on the other

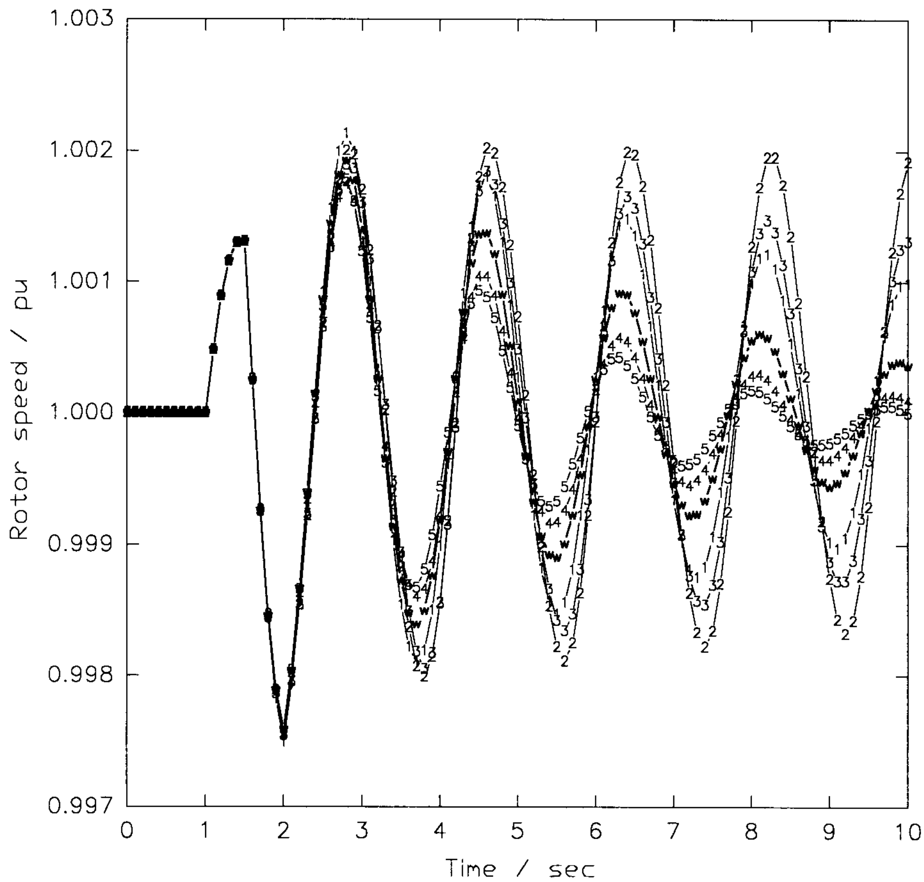

Fig. 6: Rotor speed of the five-generator-model after a torque impuls
"w": without voltage controller
"1...5": controller in gen. 1...5 respectively

hand the installation of power system stabilisers (PSS) in the areas of generators 1 and 5, because in this areas the greatest deviations of rotor speed (or frequency) occur.
But also the installation of FACTS at the border of Germany - France seems to be useful, because in this area the greatest oscillation of load flow can be expected. These FACTS should modulate the load flow in such a manner, that the natural damping of the influenced generators increase.
Today this different countermeasures are under study and the PSS-solution is preferred up to now. But also the FACTS-solution is still under discussion.
So for the load dispatchers in the involved dispatching centres only the observation and reduction of the load flow from East to West is up to now the only way to guarantee the stability of the system.

7. CONCLUSION

In the UCPTE-system after the interconnection with the CENTREL-system frequency and power oscillations occur if the East-West-load-flow or West-East-load-flow is greater than 1000 MW. The basic reasons and relations of this oscillations can be explained very clearly with a simple five-machine-model. The voltage controller can be clearly identified as the most destabilising element in the system. Counter measures could are reduction of the gains of the voltage controllers in special areas of the network depending on the main load flow direction (area #2 and/or area #4) or installation of appropriate PSS in the distant areas of the network where the maximum of rotor speed amplitude has to be expected (area #1 and area #5). Also FACTS-solution should be further on under consideration