Characteristic numbers of primary control in the UCPTE power system and future requirements

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1 Summary

In relation with investigations in the UCPTE[1] and Unipede[2] as well as with local measurements the steady state behaviour of primary control of the UCPTE/CENTREL[3] power system is described. In this context the development of characteristic numbers of the power system since 1976 is of main interest. Future requirements are deduced from its historical development, the operating experience and dynamic simulations studies. Potential savings of costs are shown without worth mentioning affecting security and reliability of the power system.

2 Primary and secondary control in the UCPTE interconnected network

Within the UCPTE - which was founded in 1951 - the operating management of the interconnected network is accomplished in a decentralized manner by the interconnection partners. In a co-ordinated collaboration the economic use of the operational devices for generation and transmission is obtained and a high standard of supply quality is reached. Thereby the independence of the companies was maintained and reciprocal competition was increased successfully.
Only interconnection allows all companies to operate economically profitable large generating units, for only within interconnection is it possible to control their spontaneous fault caused by a disturbance technically. All interconnection partners take part in this [1] whereby the reserve power - which is kept for that goal - is activated by primary control. To a certain extent the frequency-dependent decrease of consumer load in the whole interconnected system helps also.
The deviations from normal operation point due to the effect of primary control in the interconnected system are compensated by the proportional integral secondary control :

- the balance between generation and consumption in the failure-stricken area is brought back and the agreed exchange powers are restored
- the frequency is brought back to its reference value.

The use of the network characteristic lines procedure enables both goals to be achieved whereby only the secondary control of the failure-stricken area is solicited. According to the UCPTE recommendations [2] the time for the re-establishment of the normal state should not exceed 15 min. At the latest after that time the primary control power activated previously is removed.

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[1] UCPTE: Union for the Coordination of Production and Transmission of Electricity
[2] Unipede: International Union of the Producers and Distributors of Electricity
[3] CENTREL: Networks of the countries Poland, Czech and Slovak Republik and Hungary

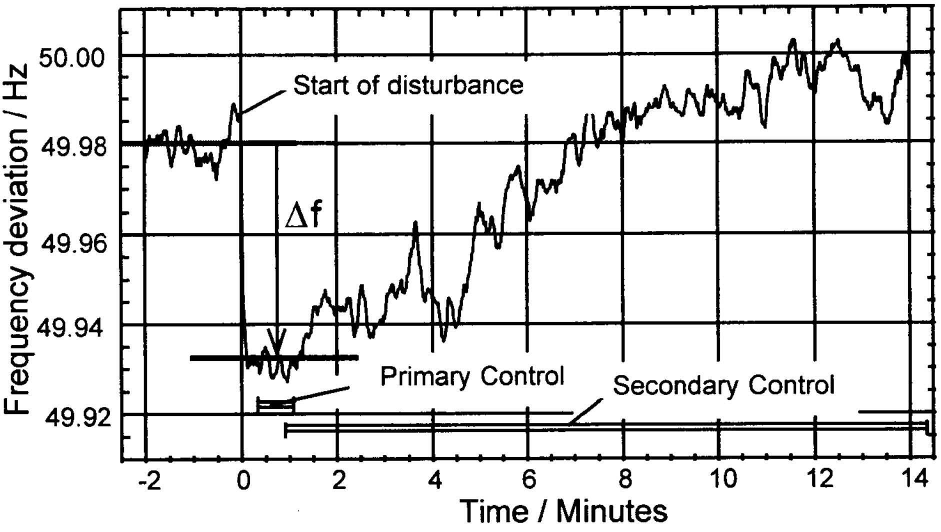

Fig. 1 Typical frequency curve caused by a 1300 MW disturbance in the UCPTE Network

Figure 1 shows as an example a frequency curve measured in the UCPTE network after a 1300 MW disturbance (power plant fault) that illustrates the influence zones of primary and secondary control.

3 Characteristic numbers relevant to primary control in the UCPTE network

3.1 Development of the characteristic number from 1976 till today

In this paragraph the quasistationary state brought back by primary control after activating the primary control reserve after a disturbance is highlighted. Thereby the ratio between lost power ΔP and the appearing quasistationary frequency deviation Δf determines the network characteristic number (power number)

$$\lambda = \Delta P / \Delta f . \qquad (1)$$

The network characteristic number of individual network areas is calculated by submitting the analyzed network to isolated operation and by switching off a chosen power plant [3,4]. A switch-off of rather small power plants suffices for this causes a frequency deviation big enough for the determination of the network characteristic number in isolated networks.

On the contrary in a large interconnected system the determination of the network characteristic number with individual events is not possible because only small system changes occur which are not situated high enough above the stochastic fluctuations. In order to eliminate the influence of the latter on the result statistical evaluations are necessary. The last such evaluation of the network characteristic number was performed by the UCPTE in 1981 [5], whereby the basic data was provided by Elektrizitäts-Gesellschaft Laufenburg, Laufenburg/Switzerland, (from now on EGL).

These investigations were carried on again by EGL for the period between January 1988 and the end of 1995 for every power plant or consumer failure that occurred where $|\Delta P| \geq 600$ MW. During the period of investigation 1316 accountable disturbances appeared whereby the network frequency was recorded with a special computer system [6].

In Figure 2 the occurred permanent frequency deviations are presented in function

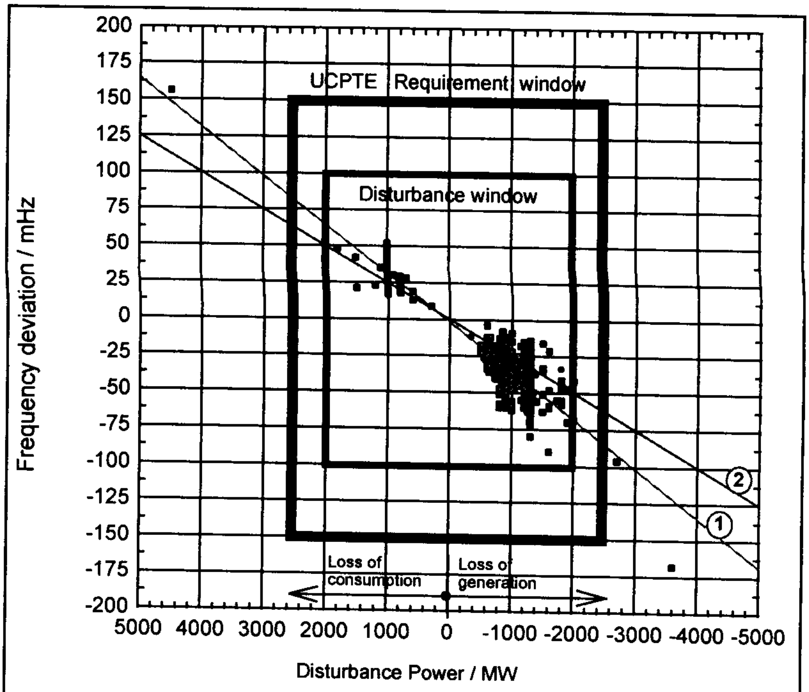

Fig. 2 Frequency deviation caused by disturbances

■ UCPTE-Network without CENTREL: 1285 disturbances

①—— Regression for the period: 1.1.1988 - 17.10.1995,
λ_{UCPTE} = 30 000 MW/Hz

● UCPTE-Network including CENTREL: 31 disturbances

②—— Regression for the period: 19.10.1995 - 10.2.1996,
λ_{UCPTE} = 40 000 MW/Hz

of their disturbance powers. The squared marks indicate 1285 disturbances occurred before the connection of the CENTREL network on 18th October 1995, the 31 circles mark cases happened afterwards.

Among the power plant failures the disturbance powers -900, -1000, -1200 MW clearly appear in an aggregated fashion; this is due to the great number of these current block sizes in the UCPTE network. In the investigation period of eight years only two cases with disturbance powers $|\Delta P| > 2000$ MW appeared (25th January 1990: ΔP = -3600 MW, 30th May 1991: ΔP = -2700 MW).

These failures were not caused by the switch-offs of individual generating blocks because of internal block faults but were produced by network failures with line openings. Thus several power plants were simultaneously struck by the disturbance and this led to a higher disturbance power.

Among the consumer switch-offs a clearly visible concentration appears near + 1000 MW which is due to the failure of one of the two 1000 MW HDVC links between France and Great Britain that usually exports power towards Great Britain. During the examination period only one disturbance with $|\Delta P| > 2000$ MW occurred on the 20th May 1993 with ΔP = 4500 MW. This disturbance was also caused by network failures with line switchings which occasioned rather large consumer load network areas to be isolated.

The frequency deviations for which $|\Delta P| \leq 2000$ MW are usually included in the domain $|\Delta f| \leq 100$ mHz. This fact is illustrated by the "disturbance window" in Figure 2. The "requirement window" which is also drawn marks the current minimal UCPTE requirement for primary control [2,7] according to which the stationary frequency deviation for disturbances where $|\Delta P| \leq 2500$ MW should be limited to $|\Delta f| \leq 150$ mHz. This minimal requirement was always fulfilled during the investigation period. The demand stipulating that the dynamically appearing frequency minimum for aforementioned disturbances should not lead to $f = 49$ Hz and hence that no load switch-off should be triggered was also fulfilled.

If regression lines are drawn through the aggregation of squares and circles their

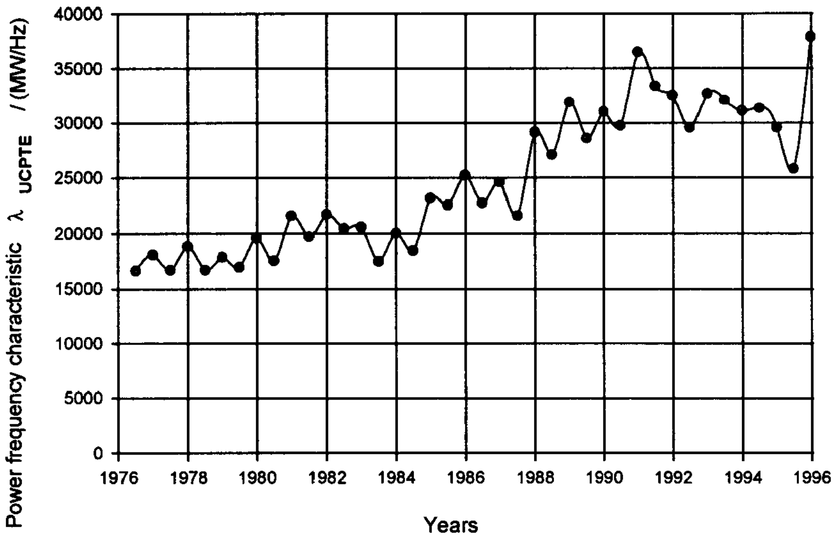

Fig. 3 Half year average values of the power frequency characteristic from 1976 to1996

slopes indicate the mean network characteristic numbers. For the UCPTE network it amounted to about 30000 MW/Hz before the CENTREL extension. After connection of the CENTREL networks the network characteristic number increased to 40000 MW/Hz because the CENTREL power plants also contribute to primary control.

It is noticeable that the regression lines run nearly exactly through point zero. One can deduce from this behaviour that the power plant primary control devices control in a linear manner during generation or consumption losses and that if the available control reserve is used it is only very seldom completely used.

The results of these investigations and of other already performed ones are summarized in Figure 3. The period between 1976 and 1981 is based on 1250 disturbances from the previous investigations [5]. The values between 1982 and 1987 stem from 406 disturbances chosen and analyzed as an example by EGL. The values since 1988 were found out from the same data as in Figure 2. The following facts appear :

- In 1976 the network characteristic number amounted to about 17000 MW/Hz, e.g. failure of power plant Oberzier on 9th April 1975:
$\Delta P = 2500$ MW,
$\Delta f = 150$ mHz,
$\lambda = 17'000$ MW / Hz
- Between 1976 and 1991 a continuous increase was to be observed e.g. disturbance in the Rhone valley on 17th February 1985:
$\Delta P = 4200$ MW,
$\Delta f = 200$ mHz,
$\lambda = 21'000$ MW / Hz
- In 1988 the mean network characteristic number equalled 30000 MW/Hz
- Until 1991 the mean network characteristic number increased continuously up to 30000 MW/Hz
- After 1991 the mean network characteristic number went back to the value of 1988
- In the winter half-year 1995/96 a sudden increase to 40000 MW/Hz took place (CENTREL connection October 1995)
- The summer/winter fluctuations amounted to between 2000 and 3000 MW/Hz approximately during the whole period

3.2. Relative network characteristic number and droop

The network characteristic number depends on the size of the network and therefore on the consumer power as well as on the number of primary controlled power plants included in the network. A few significant relations can only be found with characteristic values independent of the size of the network, which one obtains by normalizing by the nominal power P_N at the time of disturbance (sum of the powers of all power plants present in the network) and by the nominal frequency $f_N = 50$ Hz. Thus one obtains the relative network characteristic power.

$$\lambda^* = \lambda\ f_N / P_N \qquad (2)$$

The primary control power activated in the power plants is expressed with the relative power plant-sided power number λ^*_{KW} by

$$\Delta P_{Pr} / P_N = \lambda^*_{KW} \Delta f / f_N \qquad (3)$$

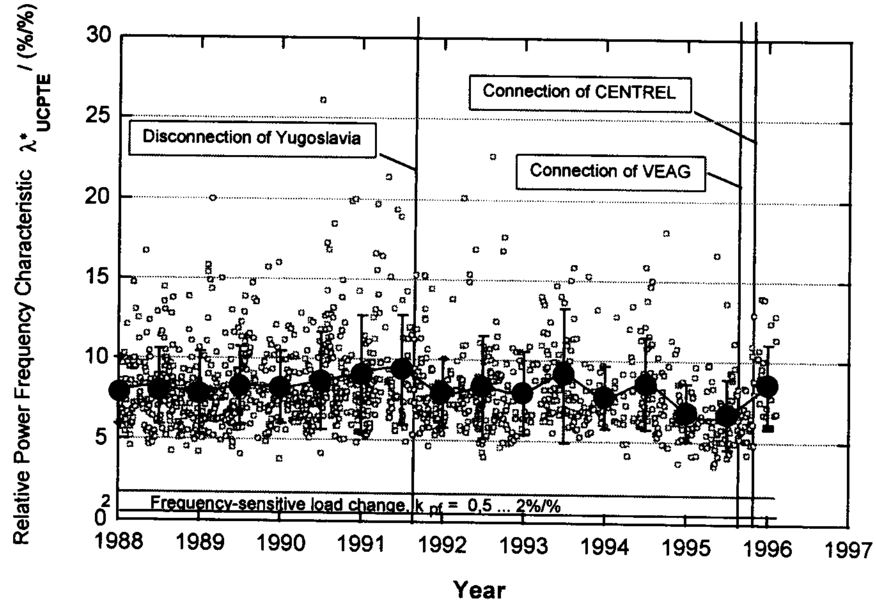

Fig. 4 Observed Relative Power Frequency Characteristic UCPTE/CENTREL half-yearly values and standard deviation

By analogy the change of the consumer active power may be given using the consumer droop:

$$\Delta P_V / P_N = k_{pf} \Delta f / f_N \qquad (4)$$

In order to eliminate a disturbance power both contributions from eq. (3) and (4) are used :

$$\Delta P_P / P_N = (\Delta P_{Pr} + \Delta P_V) / P_N \qquad (5)$$

From this we can immediately see that the power plant-sided power number λ^*_{KW} and the consumer droop k_{pf} contribute additively to the relative network characteristic number

$$\lambda^* = k_{pf} + \lambda^*_{KW} \qquad (6)$$

By inverting the relative network characteristic number, one obtains the resulting network droop:

$$\sigma = 1 / \lambda^* \qquad (7)$$

which shall from here on be used as a further examination value for network control.

The nominal network power at the time of disturbance P_N - which is necessary for the calculation of the relative characteristic number - was determined approximately using the yearly values of generation and the daily values of consumption found in UCPTE yearly and quarterly reports [9, 10].

In figure 4 the thus calculated network characteristic numbers of the period 1988 to 1996 are presented. Until 1991, the relative network characteristic numbers λ^* increased uninterruptedly, which is due to the then constant increase of the relative primary control power normalized by the UCPTE network load activated during disturbances. Afterwards λ^* tended to decline but increased again after the connection of the CENTREL network. The summer/winter fluctuations are, as expected, almost eliminated thanks to the normalization until 1991. The summer/winter fluctuations which occurred after 1991 indicate

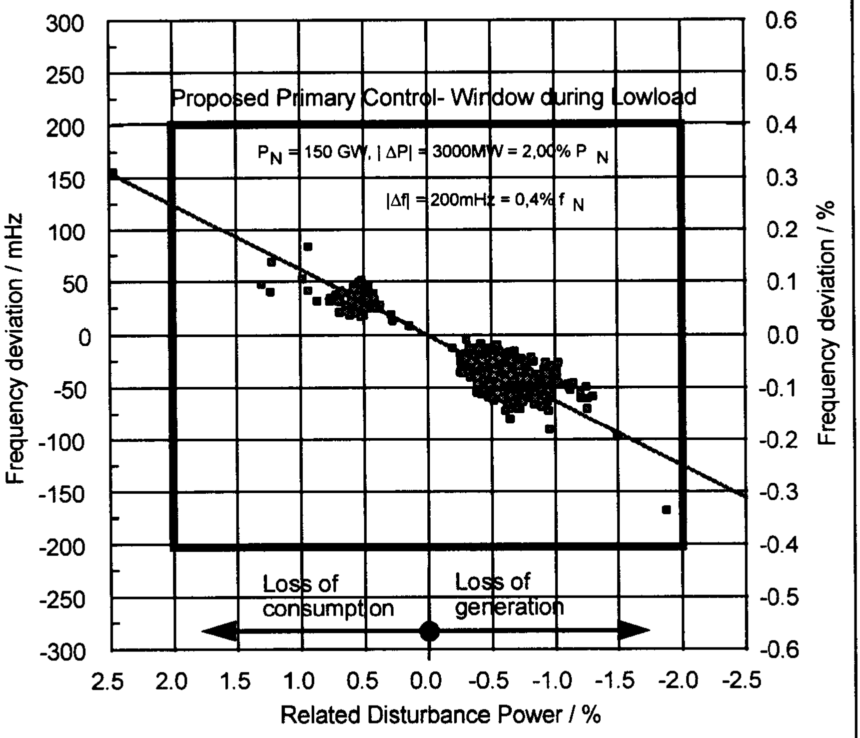

Fig. 5 Measured Frequency Deviation versus Related Disturbance Power

■ UCPTE/CENTREL : 1316 Disturbances

—— Regression for the period: 1.1.1988 - 10.2.1996

Droop s ≈ 13 %

that the maintained power control was not adapted proportionally to the load and to the power plant generation in opposition to the former UCPTE recommendations.

The range of values of the consumer droop k_{pf} in the UCPTE network calculated with measurements [11] is presented in figure 4 from 0.5 to 2 %/%. Therefore with $\lambda^* = 8\%/\%$ consumers frequently take part for up to a quarter in primary control.

In figure 5 the percentual frequency deviations are shown in function of the percentual disturbance powers for each disturbance. In this normalized representation the mean resulting network droop is immediately derived from the regression lines crossing the aggregation of dots. The thus calculated and statistically verified value of the resulting network droop of the UCPTE and UCPTE/ CENTREL interconnection equals $\sigma_{\text{Network}} = 13\%$. It is guaranteed with this network droop that a disturbance power of 2.5 % will not lead to a steady state frequency deviation greater than 150 mHz. Hence the disturbing power - which may thus be eliminated - ranges between 4750 MW during workdays low load (190 GW) and 7500 MW during high load (300 GW).

The former UCPTE recommendations [2,12] contain the more severe requirement that during a frequency deviation of 150 mHz the primary control to be maintained on the power plant side equalling 2.5 % should be activated. If one considers the frequency-dependent load decrease

$$\Delta P_V = k_{pf} \Delta f / f_N P_N =$$

$$2\%/\% \cdot 3\% \cdot 300\,\mathrm{GW} = 1800\,\mathrm{MW}, \quad (8)$$

a power plant failure of over 9000 MW can be controlled during high load maintaining $\Delta f = -150\,\mathrm{mHz}$. However, the mastering of such a disturbance is likely to bump on technical limits other than the reserve maintenance. The dimensioning of the reserve power should therefore be adapted to the present conditions especially after the connection of the CENTREL network.

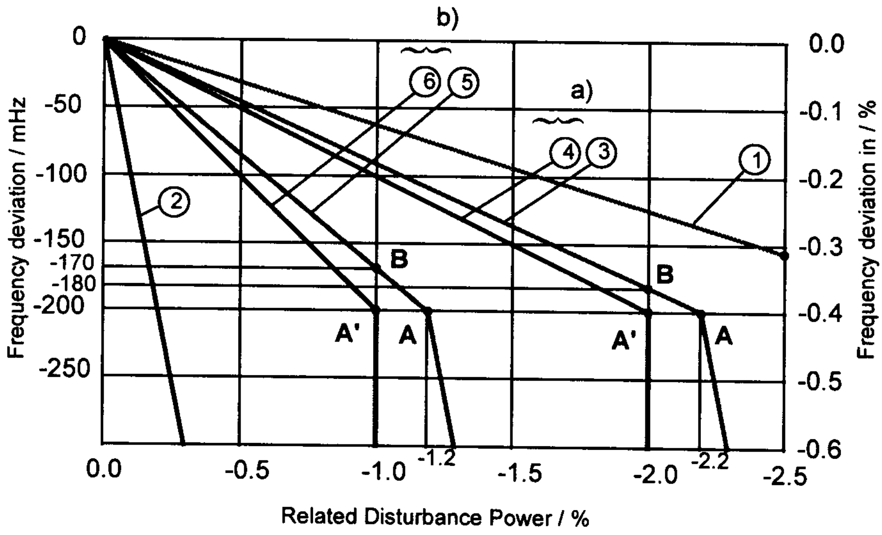

Fig. 6 Quasistationary Primary Control behavior at Low- (150 GW) and Highload (300 GW)

1 Today's control strategy, $\sigma = 13\ \%$

2 Consumer droop characteristic, $\sigma = 200\ \%$, $k_{pf} = 0{,}5\ \%/\%$

a) Primary Control behaviour at Lowload, $P_N = 150$ GW, $\Delta P = 3000$ MW $= 2\ \%\ P_N$

3 Future Control strategy, system droop, $\sigma = 18\ \%$

4 Speed governor droop, $\sigma = 20\ \%$

b) Primary Control behaviour at Highload, $P_N = 300$ GW, $\Delta P = 3000$ MW $= 1\ \%\ P_N$

5 Future control strategy, system droop, $\sigma = 33\ \%$

6 Speed governor droop, $\sigma = 40\ \%$

4. Possibilities for a reduced requirement for primary control in the UCPTE network in future.

4.1 Dimensioning of the control power

It is assumed for the greatest expected disturbance that a double block failure should be mastered without any network or customer nuisance. The increased block sizes require a reserve power increased to 3000 MW compared with the previous UCPTE requirement of figure 2. Nevertheless, because of its range equalling today to $2.5\,\%\,P_N$, the real value maintained today in the UCPTE network is often definitely higher, which makes us suggest a departure from this percentual measurement of $2.5\,\%\,P_N$ performed up to now. The control power to be maintained equalling 3000 MW should be activated with $\Delta f = -200\,\text{mHz}$, which is in accordance with the recommended measures for the first step (49,8 Hz) of the 5 step-plan of DVG [8]. The results of paragraph 4.2 show that this requirement suffices also from a dynamic aspect.

As one can see from figure 2 the likelihood of even greater failure powers in the UCPTE network is very small. From 1988 to 1996 only two of the illustrated disturbances with $|\Delta P| \geq 600$ MW had greater disturbance powers. Furthermore, usually not more than 3000 MW generating power is injected on a single busbar and hence the previous disposition is also justified from this point of view. Therefore a risk of stability would exist in the UCPTE network if during a disturbance more than 3000 MW had to be transported in the failure-stricken region.

This additional load flow may provoke either overloads and subsequent load switch-offs and even the appearance of isolated networks or inadmissible network oscillations, which endanger operation.

In the critical low load case (summer, feast day) with 150 GW the quasistationary behaviour presented in Figure 6 with the new requirements occurs:

- The primary control reserve of 3000 MW to be maintained in the power plants is used up with a frequency deviation of $\Delta f = -200\,\mathrm{mHz}$. This leads to the power plant characteristic line with a droop equalling $\sigma = 20\,\%$, line 4.
- The consumer characteristic line $\sigma = 200\,\%$ changes the power plant characteristic line to the network characteristic line with $\sigma = 18\,\%$, line 3. (With $k_{pf} = 0.5\,\%/\%$, the consumer droop was based upon the minimal value calculated from measurements [11].)
- Hence a failure power of 3000 MW only leads to a resulting frequency deviation of $\Delta f = -180\,\mathrm{mHz}$, point B, line 3.

Therefore, the current network characteristic number of 40'000 MW/Hz diminishes by more than half back to a load similar to that between 1976 and about 1985, which according to the operation experiences of those days does not have any disadvantages. The network characteristic number is mainly determined by the power plant-sided power number of 3000 MW/200 mHz = 15'000 MW/Hz. The influence of the consumer droop comes addititively, the contribution of which is worth at least 1500 MW/Hz depending on the network load and the consumer characteristic and often equals 4000 MW/Hz approximately. Therefore, the resulting network characteristic number expected practically chiefly equals more than 16'500 MW/Hz and may amount to 19'000 MW/Hz, which would also fulfil the current requirements.

4.2 Dynamic requirements for primary control

The following analyses of the primary control behaviour and the thereof derived proposals for future requirements in the UCPTE/CENTREL interconnection only concern the quasistationary system behaviour. As a complement simulation studies of the dynamic behaviour were performed in order to also adapt the dynamic requirements to the new facts and possibly to show new potentials of saving costs.

Figure 7 shows a result of these investigations [13] for the critical case of a 3000 MW power plant switch-off during low load (150 GW). Thereupon the linear activation of the primary control power within 30 seconds suffices in order for the higher power change speed required until then within the 5 first seconds to disappear [2].

These reduced dynamic requirements for primary control may also be fulfilled by modern processes maintaining active power reserve like de-activation of preheaters in steam power plants [14] and hence the efficiency-diminishing valve-throttling in the thermal process may be reduced a great deal.

The maximal dynamic frequency deviation equals $\Delta f = -180\,\mathrm{mHz}$ so there is a sufficient safety margin up to the triggering threshold of the frequency-dependent load switch-off.

As a complement the current UCPTE/CENTREL high load case of 300 GW is shown. The maximal frequency deviation equalling about 400 mHz is clearly smaller than in the low load case.

The physical explanation for this result is the increase of the accumulated kinetic energy - proportional to the interconnection size - of all rotor masses rotating synchronously with the network frequency and of

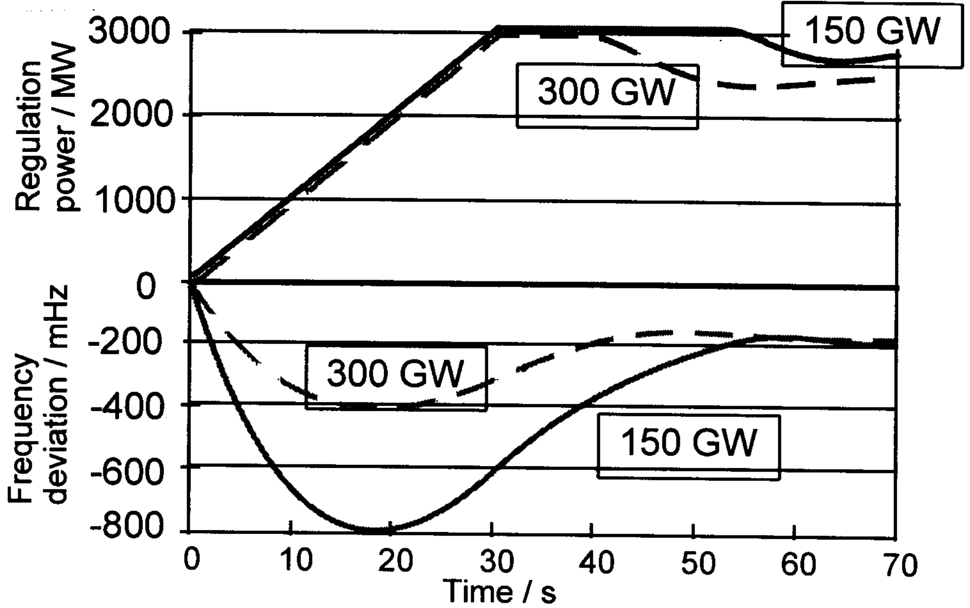

Fig. 7 Dynamic Primary Control behavior at Low- (150 GW) and Highload (300 GW)

the frequency-dependent load decrease in the whole interconnected system. Both help the limitation of the dynamic frequency fall to > 49 Hz thanks to primary control.

The working points appearing after termination of the control procedure correspond to those in figure 6 (point B) e.g. the frequency deviation equals 180 mHz during low load and 170 mHz during high load.

The control reserve still available in the power plants is then needed in order for a sufficient control lever that maintains a stable working point still to be available.

In order to establish the concepts for the individual turbine control devices one must consider that a consumer switch-off or a power overload appearing suddenly because of a network separation must be mastered technically in an isolated network by regulation [15].

5. Saving potentials

The new requirements lead to savings of the reserve to be maintained. The following indications are rough estimations and should solely elucidate the possible dimension of savings.

Investment costs as well as operation costs of the maintenance of the primary control reserve depend on its maintenance technique and of the costs structure of the power plant park in every company. The highest costs usually appear in the usual technique of valve-throttling of thermal power plants. In that case one must consider the additional consumption of fuel (0.5% for a reserve maintenance of $5\% \cdot P_N$) and the costs of generation displacement [14,16]. The latter may be particularly high if the control reserve is maintained in cheap base load power plants. An estimation revealed that in that case a decrease in control reserve equalling e.g. 100 MW may yield a operation costs saving of about 10 mio DM per annum.

Beside the suggested decrease in primary control reserve in the UCPTE/CENTREL interconnected network further savings may be reached for the control power still to be maintained thanks to the use of alternative and/or of modern techniques and of new control strategies :

- de-activation of preheaters in steam power plants
- load switch-off of large thermal consumers, e.g. district heating switch-offs
- load switch-off of large electrical consumers, e.g. aluminium foundries
- load switch-off of the pumped storage stations during pumping operation
- controllable pumping turbines

The aforementioned measures cannot replace power plant-sided controlled maintained fast reserve completely but can only be used in a complementary fashion and must be harmonized according to their influence on the system.

6. Outlook

In our days of increasing competition, deregulation and restructuring of electric economy the evaluation of network services and therefore primary and secondary control will play an important part, and this particularly because of their reckoning separated from that of energy costs and transit fees.
The use of modern and efficient control strategies will lead to considerable potential savings of investment and of operation costs.

7. Bibliography

[1] Wirkleistungs-Regelung im UCPTE-Netz
UCPTE-Jahresbericht 1990

[2] Empfehlung zur primären und sekundären Frequenz- und Wirkleistungsregelung in der UCPTE
Juni 1995

[3] Luder, H. u.a.: Bericht über Abschalt- und Regeluntersuchungen der Schweiz im westeuropäischen Verbundnetz
Bulletin ASE 55, 1964

[4] Tillmann, H.-B. u.a.: Regelverhalten des Veag-Netzes, experimentell ermittelt im Rahmen der osteuropäischen Zwischensystem-Erprobung
Elektrizitätswirtschaft Jg. 94 (1995), Heft 3

[5] Regelverhalten des UCPTE-Netzes
UCPTE-Jahresbericht 1981/82

[6] Asal, H.: Frequenzverhalten und Stabilität im westeuropäischen Verbundnetz
Elektrizitätsverwertung Heft Juli 1982

[7] Empfehlung für Massnahmen zur Frequenzhaltung und gegen Grossstörungen
UCPTE-Jahresbericht 1982-1983

[8] Deutsche Verbundgesellschaft: Massnahmen für die Versorgung im Störungsfall
Heidelberg, Juni 1980

[9] UCPTE-Jahresbericht 1994

[10] UCPTE-Halbjahresbericht, 1. Halbjahr 1994

[11] Welfonder, E.: Netztechnische Anforderungen an die Primär- und Sekundärregelung
VDI-Berichte Nr. 1245, 1996

[12] UCPTE: Empfehlung zur Frequenz im Verbundbetrieb der UCPTE
Oktober 1996

[13] Anforderungen an die Primärregelung im UCPTE-Verbundbetrieb
Deutsche Verbundgesellschaft, Heidelberg, 12.´96

[14] Hühne, W. u. L. Vogelbacher: Regelverhalten von Dampfkraftwerken bei der De-Aktivierung der Niederdruck-Vorwärmer zur Bereitstellung der Wirkleistungssekundenreserve
VDI-Berichte Nr. 1245, 1996

[15] Grebe, E.: Anforderungen an Turbinen-Regelkonzepte im Hinblick auf Verbund- und Inselbetrieb.
VDI-Berichte Nr. 801, 1990

[16] Näser, W. und E. Grebe: Kosten von Regelmassnahmen im Netzbetrieb VDI-Berichte Nr. 1245, 1996

Heutige Anforderungen an die Primärregelung im UCPTE-Netz basierend auf statistischen Störungsauswertungen und dynamischen Simulationen

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Kurzfassung

Das Verhalten der Primärregelung des westeuropäischen UCPTE-Netzes während der letzten 20 Jahre wird durch Messungen und statistische Störungsauswertungen anhand der Netzkennzahl beschrieben. Nach der Zuschaltung der CENTREL zum UCPTE-Netz erhöhte sich diese Netzkennzahl erheblich, was auf eine weiter verbesserte Primärregelung schließen lässt. Diese Beobachtungen sowie dynamische Netzberechnungen lassen den Schluß zu, dass sowohl die Höhe der vorgehaltenen Primärregelreserve als auch deren Einsatzgeschwindigkeit bei der heutigen Netzgröße reduziert werden könnte, was erhebliche Einsparpotentiale freisetzen würde. Dabei ist aufgrund dieser erhöhten Netzgröße mit keiner Verschlechterung der Versorgungqualität und -sicherheit zu rechnen.