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Dynamic properties of bulk power interconnections

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The paper describes changes in dynamic properties of the present-day bulk electric power systems (EPS) in the course of their development, on the basis of operating experience and numerous studies. The character, reasons and consequences of these changes are analysed. The dynamic properties of EPS are becoming worse leading to a decrease in the reliability of consumer supply. Consideration is given to the emergency control measures that reduce the negative consequences for consumers in such systems.

Keywords: bulk systems, system dynamics, emergency control

I. Introduction

By about the mid-1970s the experience of operation and design studies of present-day complex electric power systems (EPS) led experts to conclude that, in the course of system development, besides the known advantages of EPS interconnection for parallel operation, qualitatively new negative features of EPS operation were displayed. They are: the appearance of numerous objects on the expanding territory that are interconnected and interdependent through technology, operating conditions and control; the growing mutual impact of operating conditions on individual system parts; possible cascading of disturbances occurring in individual areas of the system over large territories; complication in the character of transients during disturbances; an increasing danger of a large system emergency of a cascading character; the appearance of phenomena such as 'frequency waves', subsynchronous electro-mechanical resonance, etc.[1–3].

A major reason for these peculiarities of emergency conditions of the modern EPSs is the change in their dynamic properties, which imply properties that determine the character of system behaviour in emergency conditions. The main factor causing the worsening of dynamic properties of EPSs in the course of their development is found to be the complicated structure of the main grids in the system, heavier conditions, deterioration of the dynamic characteristics of the equipment and the complication of the structure and functions of means of control[4].

These factors and regularities lead to the aggravation of unfavourable consequences for consumers as a result of emergencies. So, it is necessary to pay a great deal of attention to the comparatively new problem of the EPS survivability as its ability to withstand disturbances, preventing their cascading with size, and interruption in consumer supplies[5] as well as developing approaches to addressing survivability requirements in controlling the EPS development and operation[2,6]. (In the literature the term 'survivability' is not used. However, the term security is used in a sufficiently close sense.)

II. Character of transients in EPS during emergencies

One of the main reasons for cascading of system emergencies is the EPS stability loss with the appearance of asynchronous running and subsequent system splitting[2,3]. The experience of the EPS operation and the studies of long-term schemes for developing the unified electric power system (UEPS) of the former USSR[2,4,6–8] show that the occurrence and delay of asynchronous conditions in the interconnection with the complex scheme can result in the development of emergencies with the appearance of three or more different frequencies of oscillations. The resynchronization conditions here become more complicated due to the mutual impact of the individual EPSs parts.

The complexity of the studied interconnection is illustrated in Figure 1. It presents a calculated scheme in a simplified form in a single-circuit representation. The scheme covers a territory of 3000 km from north to south (in the western part) and about 8000 km from west to east over eight time zones, including the republics of the former USSR, the borders of which are shown in the figure.

The total installed capacity of the power plants in the

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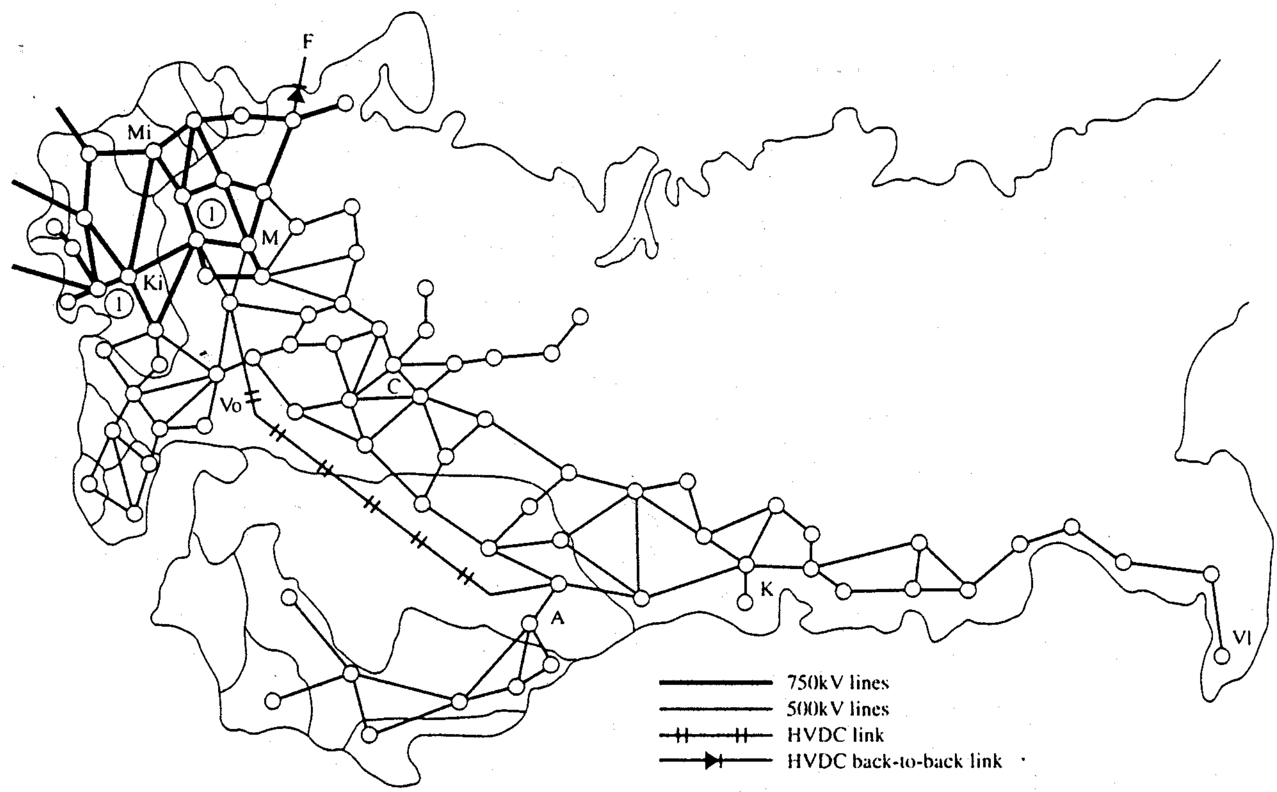

Figure 1. Base scheme of UEPS of the former USSR: M—Moscow; Vo—Volgograd (Povolzhie); C—Chelyabinsk (Ural); K—Krasnoyarsk (East Siberia); Vl—Vladivostok (Far East); Ki—Kiev (Ukraine); Mi—Minsk (Byelorussia); A—Alma-Ata (Kazakhstan); F—Finland.

considered scheme amounts to 570 GW, of which 30% is nuclear power plants (in the European part), 20% is hydro-power plants (basically in Siberia and on the Volga river), and the remaining part refers to thermal power plants.

Increase in complexity and length of interconnections leads to the fact that some of the properties of EPSs that are only slightly significant in small systems are substantially displayed in large interconnections, determining to a great extent the character of transients in the course of disturbances. For example, the maximum deviations of frequency in transients due to power imbalance have the highest value and occur earlier in the vicinity of the disturbance ('frequency wave') and decrease with distance from it. This phenomenon was first confirmed and analysed in 1979 in the full-scale system tests of parallel operation of the interconnection of Siberia and UEPS[3]. The similar property of decrease in influence of the disturbance with the distance from it is typical of the response of generators to any disturbances (for example, short circuit or line disconnection) in the short-term[9]. The latter is illustrated by the transient in the UEPS scheme, as in Figure 1, at emergency disconnection of a 750 kV line (1–1) in the western part of the interconnection (Figure 2).

The indicated property of the bulk EPS substantially influences the choice and adjustment of control means, including emergency control systems. For example, in an emergency imbalance of power due to a more intensive reaction of units in the specific areas of EPS, a part of the control actions of emergency control devices (ECD) will be neutralized and an increase in control actions may be required.

At the same time, in spite of the availability of an ability of disturbance impact decrease for the bulk interconnections, the violations of the EPS operation become sufficiently frequent in the areas that are fairly remote from the disturbance location. For example, in the studies for EPS of UCPTE the unexpected shutdown of the 1300 MW power plant in Germany led to strong swings of the generators in the distant regions of the interconnection (Spain, Yugoslavia)[10]. Transfer capability of the AC tie-line between UCPTE and NORDEL is studied in Reference 11 for the conditions of transient stability at generation disconnection in both interconnections, at

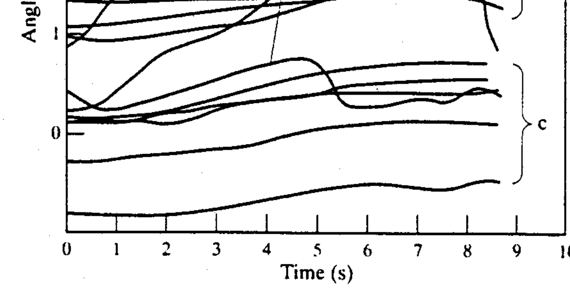

Figure 2. Motion of the UEPS generators at emergency disconnection of the 750 kV transmission line in the western part of the system: (a) near the emergency disturbance; (b) in the eastern part of UEPS; (c) in the middle part of UEPS.

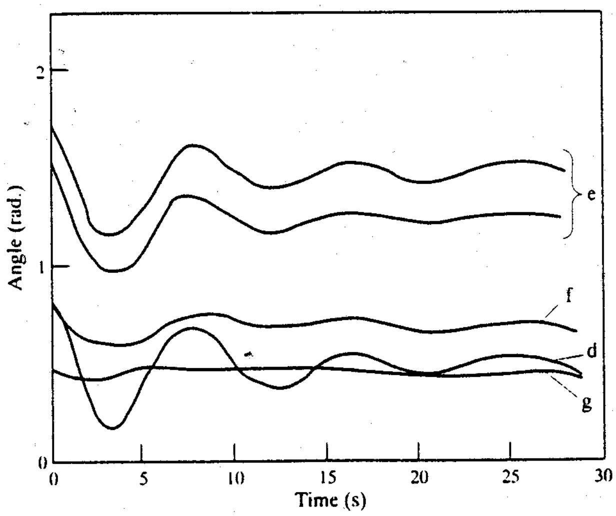

Figure 3. Motion of the UEPS generators at power shedding (1000 MW) in the western part of the system: (d) in the east of Siberia; (e) in the centre of Siberia; (f) in the Urals; (g) in the west of Ukraine.

short circuit near the studied area and at disconnection of the HVDC back-to-back link Finland–Russia. The last disturbance that is considerably remote from the studied network section typically is the most dangerous and results in stability loss of the tie-line UCPTE-NORDEL if special measures are not used (static VAR compensators in heavily loaded zones of NORDEL). Similar results are obtained in studying UEPS[3,7,9].

The low-frequency weakly damped oscillations that appear in a different way as a subsynchronous resonance are observed in many similar cases. In particular, in Reference 10, the multi-frequency transient with periods of oscillations of 5 s (basic frequency), 2.5 s and 1.3 s were observed at disconnection of a 380 kV transmission line between France and Spain. Similar results were obtained for a series of the UEPS schemes in Reference 8. The curves of change in power angle of the UEPS generators at power shedding by 1000 + j500 MVA in Western Ukraine are shown in Figure 3. As is seen from Figure 3, the emergency disturbance influences the whole UEPS and the response to disturbance is found to be even stronger in the regions remote from it than in the neighbourhood of the disturbance. The low frequency oscillations were also observed in other interconnections[12].

The considered phenomena were studied in detail by the modal analysis methods[8,13]. It was revealed that the predominating modal components on low frequencies are shown in all parts of the interconnection, i.e. oscillations at these frequencies will embrace the whole interconnection at any disturbances that renders the UEPS stability problem highly complex.

The zone of disturbance response in the bulk EPS is determined by the strength of connections between individual system areas. This is illustrated by the results of studies presented in Table 1 on four variants of the UEPS schemes for the future. These variants differ in allocation of power plants depending on the construction and number of transmission lines needed. Variant 1 is formed on the principle of self-balance of the individual regions of UEPS, therefore, the construction of large transmission lines is not required. The self-balance principle envisages an approximate equality of generation and load in the regions, which are interconnected EPSs of Russia (Centre, North Caucasus, Ural, Siberia, Far East), North-West of Russia jointly with the Baltic states and Byelorussia, Ukraine, Republics of Caucasus, Kazakhstan and Republics of Central Asia. Variants 2–4 are characterized by different levels of increased development of generation in Siberia and transmission of electric energy to the European regions of UEPS.

In the studies performed it was planned to reinforce the electric network by a 1150 kV AC transmission line and a + 750 kV HVDC multiterminal transmission line to transmit power from Siberia (area of Krasnoyarsk) to 2 GW in variant 2, to 8 GW in variant 3, and to 20 GW in variant 4.

In Table 1 all indices were averaged for one disturbance. The emergency disconnections of transmission lines were considered as disturbances. The zone of disturbance response was estimated by the number of generators on which power imbalance at the moment of disturbance exceeded 2% of their operating capacity. The severity the consequences of disturbance was determined as a possible value of capacity of disconnected consumers at stability loss. The results of studies show

Table 1. Indexes of severity of disturbances in different variants of the UEPS development scheme

Variants	Characteristics of variants	Indices: Disturbance response of zone	Severity consequences (P, GW)	Number of subsystems at stability loss
1	Absence of 1150 kV and HVDC links	18	1.67	2
2	A circuit of 1150 kV transmission line without HVDC links	22	3.4	2
3	A circuit of 1150 kV line and HVDC link Ekibastuz-Tambov (750 kV)	23	4.15	2
4	Two (four in some sections) circuits of 1150 kV transmission line without HVDC links	27	15.65	3–4

that variant 4 has the worst stability indices. This is the largest zone of disturbance response, the average severity of an emergency considerably exceeds the similar index for other variants of UEPS. The number of possible stability losses in variant 4 is also significantly higher than for other variants and the character of the transients is substantially more complex. Thus, for variants 1–3 at stability loss of a system (not local) character, two groups of generators with the boundary of division in the same cutset in the Povolzhie region, that is a bottleneck, are always singled out. In variant 4, as a rule, three and in some cases four groups of generators are formed. In this case the division boundaries between the subsystems formed can change with the disturbance location, this considerably complicates the emergency control.

The studies showed that the traditional emergency control devices—shutdown of generation and load—are sufficiently efficient for the UEPS stability in variants 1–3. The forcing capability of HVDC links is efficiently used in variant 3. At some disturbances it is difficult to provide the UEPS stability with the aid of only traditional emergency control devices in variant 4.

Thus, reinforcement of transmission lines in the bulk EPSs complicates their transients at disturbances. This fact and the response of almost the whole system to a disturbance are illustrated by Figure 4. This figure represents the transient character at a disturbance in the western part of the interconnection for one of the 'limiting' variants of the UEPS development[9]. In this variant, consideration was given to the creation of three power centres (two at the north of the European part of the country in the area of Arkhangelsk and to the east of it, and one in East Siberia in the area of Krasnoyarsk) with the capacity of 20 MW each, with transmission of electric energy by many 1150 kV AC transmission lines.

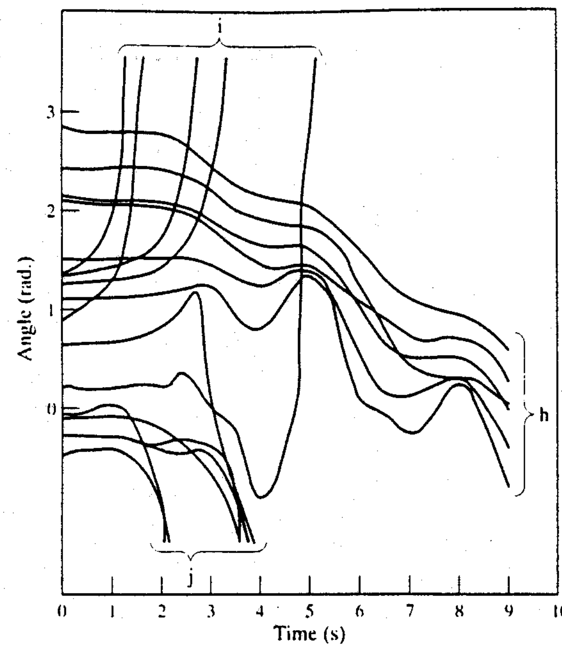

Figure 4. Motion of generators in the 'limiting' variant of the UEPS development with emergency tripping of the 750 kV transmission line in the western part of the system: (h) in Siberia; (i) in the north-western part of UEPS; (j) in the south-western part of UEPS.

III. Emergency control

To improve the stability and survivability of the bulk EPSs, special requirements are needed for the emergency control. The reasons for the development of many system emergencies are insufficient equipment of EPSs with the necessary emergency control devices, incorrect adjustment, insufficient adaptivity, and lack of coordination and inefficiency of operation of current emergency control devices[2,6]. The problem of developing new principles and methods of emergency control becomes real. Different new methods for improving controllability of the system in emergency conditions and the emergency control system as a whole are considered now as efficient measures for the improvement of stability and survivability of the bulk EPSs[2,3,7–10]. Particular attention is given here to automatic devices for preventing instability as its consequences due to the increased numbers of interconnections, the concentration of electricity production and consumption in the nodes that are not balanced with respect to power and load, and the installation of extended transmission lines with high transfer capability become more serious[14]. This is confirmed by the results of studies presented above.

For example, formation of the back-bone network of interconnections using the HVAC transmission lines that have large charging capacity necessitates the installation of large VAR compensators both for generation and for absorption. The studies have shown that for efficient control of the operation of transmission lines in the system these compensators must be controlled for 1150 kV transmission lines. Simultaneously, the controlled VAR compensators can provide a significant effect from the standpoint of the EPS stability increase and substantial improvement of their dynamic properties. This is shown by the calculated results for different variants of UEPS development[7–9]. In particular for variant 4 of the UEPS development the controlled VAR compensators allowed a substantial effect in stability improvement to be achieved. Moreover, only disconnection of reactors on 1150 kV transmission lines results in the qualitative improvement of dynamic properties of this variant. In practice, it can be achieved fairly simply with controlled reactors in which the conditional disconnection is provided by the control system.

Great possibilities for improving controllability of the main grid of EPSs and correspondingly their stability and survivability can be provided by the HVDC links. Efficiency of their use for improving dynamic properties of EPSs are confirmed by many studies[7–9]. This effect is determined by the forcing capability of HVDC links, high speed and good damping features of their control systems. In particular, for the considered 'limiting' variant of UEPS development, the use of HVDC multi-terminal transmission lines instead of AC transmission lines to transmit power from the power centres allows a qualitative improvement of dynamic properties of the system, achieving the UEPS response to disturbances that is analogous to Figure 2.

At the same time, the problems can arise in EPS stability and survivability at faults on the HVDC links themselves with large power flows, mutual coordination of numerous regulators (including thyristor converters) in the complex closed multi-loop circuits, selective commutation of DC network elements, and torsional oscillations of turbogenerator shafts[8]. These problems necessitate special studies and substantiation of methods and measures for their removal.

To decrease the consequences for consumers, load shedding with the aid of emergency control devices must be short term. The studies have shown that the load reconnection improves the transient, if it is performed with regard to the parameters of generator motion. Based on it, the role of superconducting inductive energy storage systems for improving stability by short-term generation of active power (instead of short-term load shedding) is obvious. Besides, these systems have good damping properties provided by the control system. At the same time, introduction of these storage systems into the EPS scheme can lead to torsional oscillations of turbogenerator shafts that are analogous to the use of HVDC links in EPS that necessitate special studies.

The studies have shown that, at the EPS stability loss, possible power shortage can be decreased by preventive system division by a selected cutset with a minimum power flow that does not necessarily coincide with that of the cutset with stability loss. For example, for the described variant 3, i.e. development of UEPS in one of the cases of stability loss, the preventive division decreases power shortage from 3.38 GW to 1.8 GW and the transient process quality is also improved. The preventive division can be carried out in practice by emergency disconnection of the given line.

IV. Conclusions

Analysis of reasons for displaying the enumerated phenomena in the bulk EPSs can lead to the following conclusions. A limited disturbance impact zone is typical of EPSs which have an inhomogeneous (anisotropic) network structure at comparatively weak connections between the system areas. A display of the reaction to a disturbance in the remote regions in indicative of the inhomogeneity (anisotropy) of the structure of the main EPS grid and the appearance of bottlenecks in it. A certain unfavourable combination of EPS parameters may be the reason for the appearance of weakly damped low-frequency oscillations having a system character. The bottlenecks in EPS can be avoided due to their strengthening by means of additional tie-lines creating. At the same time reinforcement of the EPS transmission lines, by itself, results in an extension of the disturbance impact zone, a complication of the character of the processes at the disturbances and emergency control of EPS.

The solution of the problems of improving stability and survivability of the present-day and future interconnections requires large-scale studies in order to consider the dynamic properties of EPS to reveal their peculiarities for determining the requirements for the emergency and other control systems. Studies are also needed to select an efficient system of devices that operate in series that does not allow the stability loss, localize and limit the emergency process development and provide the elimination of emergency conditions. The complexity and laboriousness of such studies substantially increase with the system development due to the increase in scheme dimensions, the necessity of studying a broader scope of factors which determine the character of transients, and the necessity of considering the longer transients. Such studies require the corresponding development of methodical approaches, mathematical models and methods for EPS stability and survivability analysis.

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