Some Generalizations of an Analysis of 2016-2017 Blackouts in the Unified Energy System of Russia

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***Abstract* — The paper presents a brief description of the sequence of events and processes observed during three cascading blackouts that occurred in 2016 - 2017 in the Unified Energy System (UES) of Russia. The key factors that contributed to their occurrence, development, and interruption were determined. The objectives of research on the development of measures to reduce the risk of such system-wide accidents are formulated.**

***Index Terms* — analysis, blackouts, generalizations, recommendations, UES of Russia.**

I. Introduction

During the years 2016–2017, the UES of Russia went through several major system-wide blackouts with complicated development of emergency processes and massive grave consequences for consumers. The most typical of them in terms of the uniqueness of the cascading development processes, and the consequences for consumers are the blackouts in the Interconnected Power System (IPS) of the Urals on August 22, 2016 (which extended to the entire UES of Russia), in the IPS of Siberia on June 27, 2017, and in the IPS of the East on August 1, 2017 [1–4, a.o.].

Each of the mentioned blackouts, as well as several others, were analyzed in detail by the corresponding Commission of Rostechnadzor (Federal Environmental, Industrial, and Nuclear Supervision Service of Russia). This analysis underlay the conclusions of the Commission about the causes of the blackouts, the inadequate operation of individual components and subsystems, and fostered the recommendations for the measures to prevent such emergencies and their undesirable development. Apart from the official conclusions of the Commission, for each such a serious system-wide accident with consequences for many consumers, there are usually other materials that reveal the specific features of the events and processes of the accident development. This additional information often helps to understand the analyzed system blackout in more detail.

It is worth noting that the ongoing major system-wide cascading accidents are subject to mandatory thorough analysis in all countries, without exception. The findings of such an analysis reveal the general mechanisms of the development of such accidents and the recovery of electric power systems (EPSs) after them. This analysis also facilitates the formulation of generalized recommendations to prevent severe system blackouts, counteract their development, and restore the systems. Examples of such generalizations can be found in [5–12], and in some other publications. Each cascading blackout is unique in terms of a combination of its causes, events, and processes of development. However, individual states and events can manifest themselves in several system-wide blackouts. Such frequently recurring states and events require priority attention and analysis of their causes, and the development of measures to prevent them in the future.

This paper aims to summarize the previously performed analysis of specific system blackouts in the UES of Russia with the view to identifying common factors in their occurrence and development, and, based on this analysis, drawing general conclusions and recommendations to eliminate the impact of these factors.

II. A brief characteristic of cascading system blackouts

A. Blackout in the UES of Russia on August 22, 2016 [1, 2]

The diagram of the electrical networks of the accident area indicating the cutsets of the emergency separation of the UES of Russia is shown in Fig. 1. Fig. 2 indicates the results of monitoring the electrical frequency in the eastern Fig. 2. Results of frequency monitoring in the eastern part

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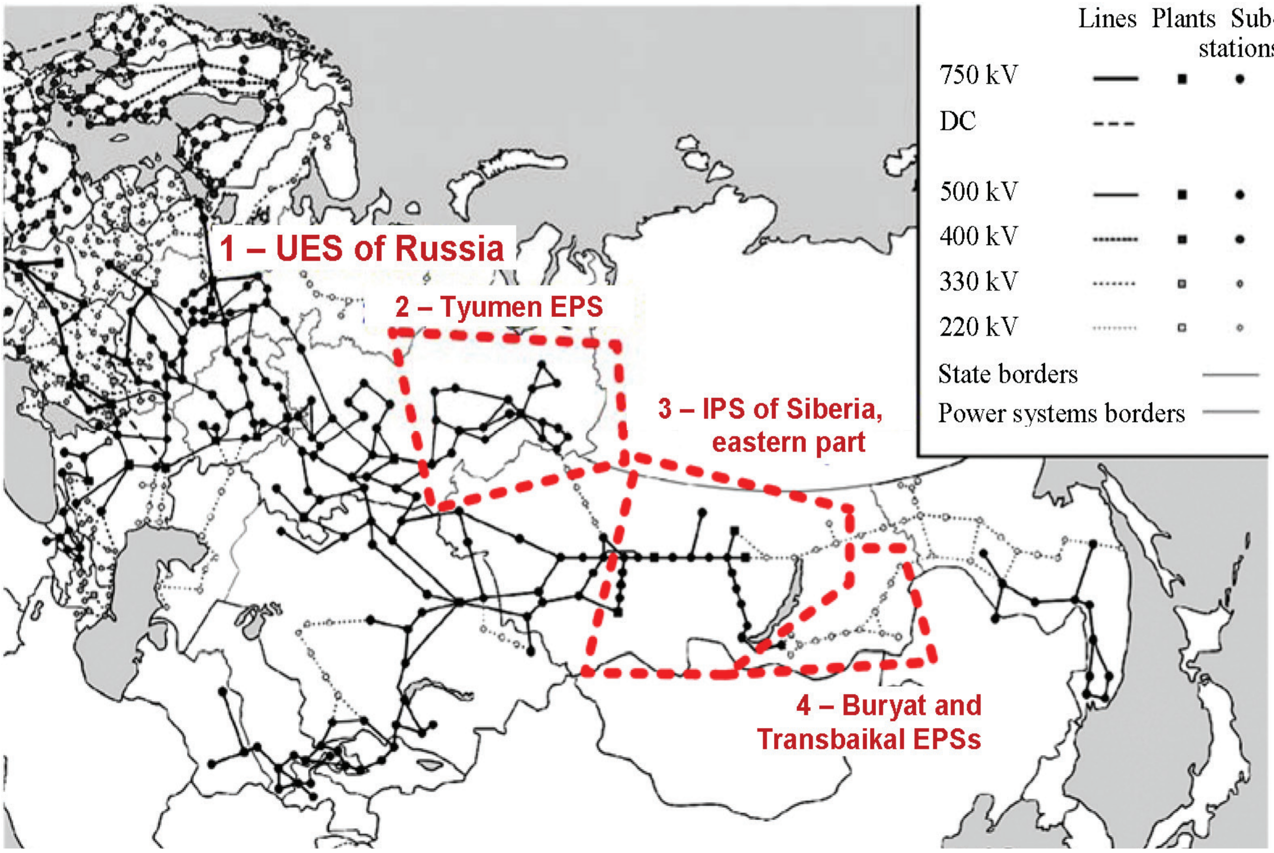

Fig. 1. A scheme of Russia's UES division into four asynchronously operating parts during the blackout on 08.22.2016.

of the IPS of Siberia during the blackout on August 22, 2016 (measurement in Irkutsk, frequency [Hz] vs time [s]):

(a) within 50 minutes after the blackout started;
(b) in the initial stage of the blackout;
(c) a sharp rise in frequency due to separation of the eastern part of the IPS of Siberia from the UES of Russia.

Part of the IPS of Siberia. The sequence of the main events and processes during the blackout was as follows:

- The primary cause of the blackout was a short circuit at the outdoor switchgear of the Reftinskaya TPP (thermal power plant) due to the condenser destruction and oil ignition;
- Short-circuit was eliminated by distant redundant protection (due to failures of main and backup protection) with disconnection of outgoing 500 kV overhead lines (OHL). The failed protections include electromechanical protective relays;
- The protection of long-range redundancy 500/220 kV autotransformer (AT) failed;
- The generators of Reftinskaya TPP with a total capacity of 2.3 GW were tripped by process protections due to a prolonged voltage slump during the long short-circuit;
- The out-of-step conditions occurred due to a long time of short-circuit elimination and disconnection of 500 kV overhead lines outgoing from the Reftinskaya TPP by out-of-step protection, which resulted in islanded operation of the Tyumen power system with surplus power of 1.4 GW;
- The frequency in the UES of Russia decreased to 49.742 Hz;
- There were weakly damped slowly decaying synchronous oscillations of generators in the UES of Russia;
- Active power flows increased above the permissible ones in some of the controlled cutsets of the IPS of Siberia due to the uneven loading of power plants because of their unsatisfactory participation in frequency control during the oscillations. Steady-state stability was lost, the out-of-step conditions occurred, the out-of-step protection tripped transit 500 kV overhead lines, and the eastern part of the IPS of Siberia was disconnected for islanded operation with surplus power of 2.1 GW;
- A long transient process in the eastern part of the IPS of Siberia with damped oscillations of the rotors of generators and subsequent overload and stability loss in the cutset of Irkutsk - Buryatia, caused the separation of the Buryat and Transbaikal power systems for islanded operation with a power shortage;
- To restore power balance, in surplus subsystems, the power plant units were unloaded, in deficient ones - the automatic frequency load shedding was involved.

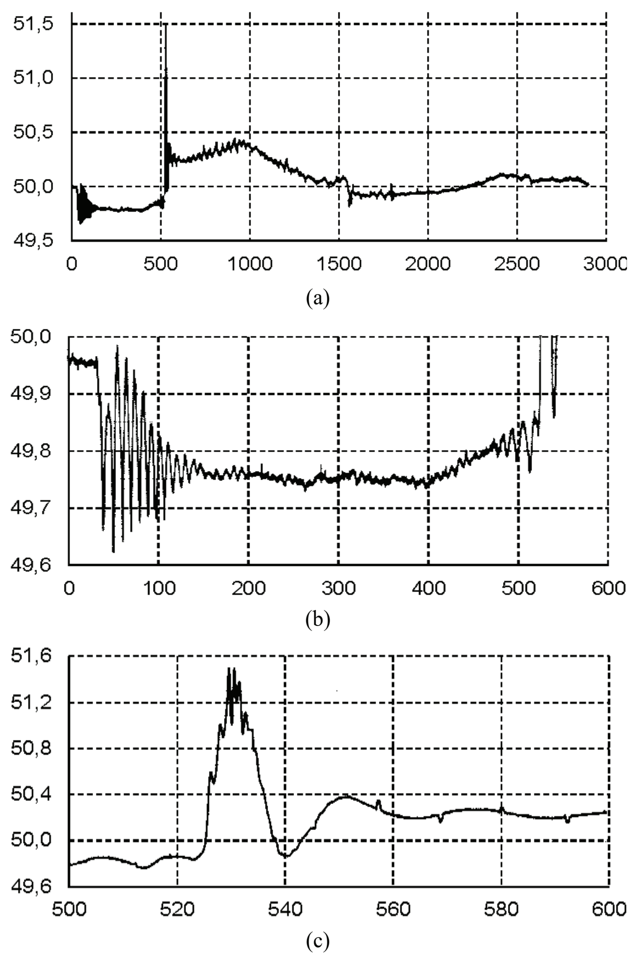

Fig. 2. Results of frequency monitoring in the eastern part of the IPS of Siberia during the blackout on August 22, 2016 (measurement in Irkutsk, frequency [Hz] vs time [s]):
(a) within 50 minutes after the blackout started;
(b) in the initial stage of the blackout;
(c) a sharp rise in frequency due to separation of the eastern part of the IPS of Siberia from the UES of Russia.

B. Blackout in the IPS of Siberia on June 27, 2017 [3]

The diagram of the electrical networks in the blackout area and the results of monitoring the electrical frequency in the eastern part of the IPS of Siberia are shown in Figs. 3 and 4. This blackout is characterized by the following time sequence of events and processes:

- Emergency control devices at the Bratsk hydropower plant (HPP) falsely generated and implemented control actions to disconnect the load of 825 MW, including 750 MW at the Irkutsk aluminum plant;
- The emergency control devices at the 500 kV Ozyornaya substation (SS) malfunctioned and disconnected the load at the Bratsk aluminum plant of about 650 MW;
- Due to the overload of several 500 kV backbone electrical network components, a multi-frequency out-of-step conditions occurred among four parts of the UES of Russia: the European part, including the IPS of the Urals; the western part of the IPS of Siberia; the eastern part of the IPS of Siberia; and unit 2 of Beryozovskaya TPP;
- The out-of-step protection tripped seven 500 kV overhead lines, which separated the eastern part of the IPS of Siberia (part of the Krasnoyarsk power system, and Irkutsk, Buryat and Transbaikal power systems) for islanded operation with surplus power and a short-term increase in frequency to 52.6 Hz;
- The operation of the over-frequency protection relay and the relays of power units at the Ust-Ilimsk HPP, Bratsk HPP, and Nazarovskaya TPP decreased the total load by 3.28 GW;
- At the same time, the overload protection relays at the Boguchany HPP tripped seven hydroelectric units operating at an increased frequency, which caused a decline in power output from 2 GW to 0 GW;
- Due to false operation of protection relays, Krasnoyarskaya TPP-2, Ust-Ilimsk HPP, and Bratsk HPP were additionally unloaded by about 0.8 GW;
- As a consequence, the frequency in the separated part of the IPS of Siberia went down to 47.7 Hz; the action of the frequency load shedding disconnected a total of 3.4 GW of load at the Irkutsk, Bratsk and Krasnoyarsk aluminum plants to restore power balance in the post-emergency conditions.

C. Blackout in the IPS of the East, August 1, 2017 [4]

The scheme of electrical networks of the blackout area and the results of monitoring the electrical frequency in the western part of the IPS of the East are shown in Figs. 5 and 6. The sequence of events and processes during the blackout was as follows:

- During the repair of the electrical network, a single-phase short circuit occurred on the 220 kV overhead line Khabarovskaya SS – Volochaevka traction SS, which caused disconnection of the line, and partitioning of the IPS;
- In the separated deficient eastern part of the IPS of the East, automatic load shedding and the actions of personnel established balanced post-emergency conditions;
- In the western part of the IPS, there were slow frequency oscillations with a period of 2 s, and a range of oscillations from 53 to 47 Hz;
- As a result, the group active power controller at the Zeya HPP was deactivated, and over-frequency protection relay tripped one unit at the Zeya HPP, two units at the Bureya HPP, and one unit at the Neryungrinskaya TPP;
- The arisen active power shortage and frequency decrease triggered the automatic load shedding and disconnection of 500 kV Amurskaya SS - Heihe (China) overhead line;
- Due to a voltage rise to 560 kV in the area of the Bureya HPP, the 500 kV overhead lines of the Bureya HPP - Amurskaya SS and Bureya HPPs – Khabarovskaya No.1 SS were disconnected by the automatic

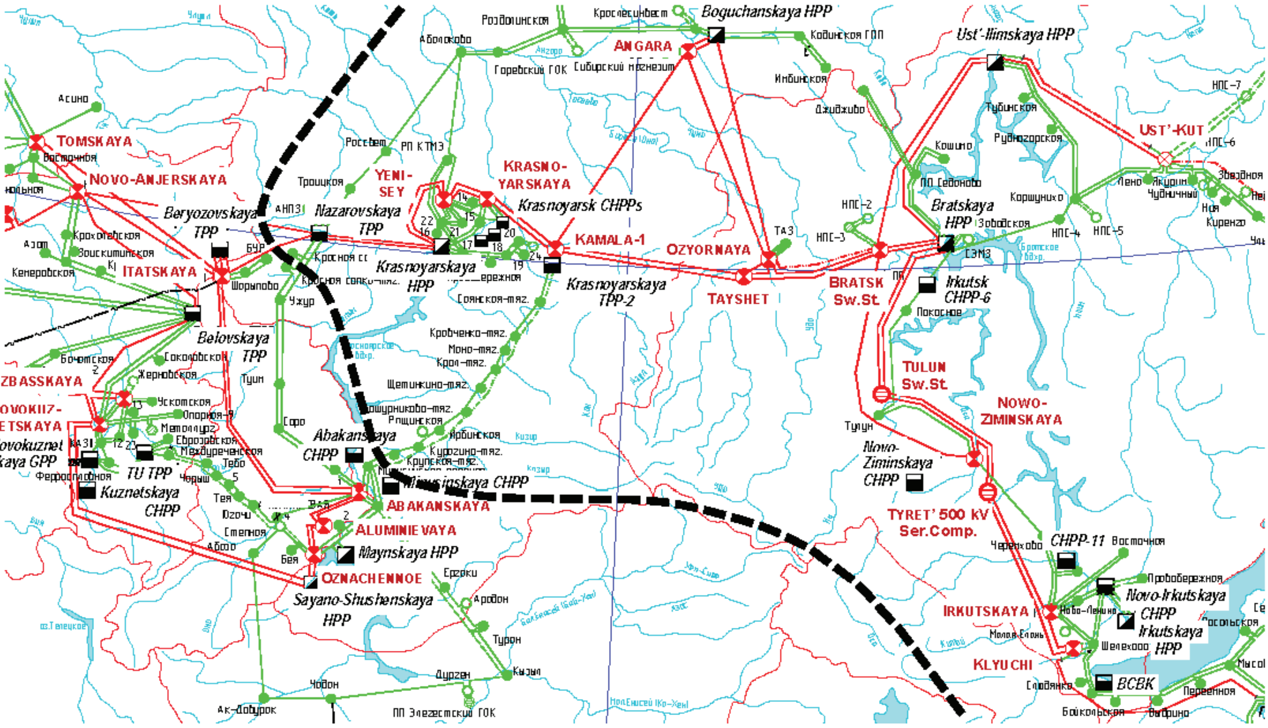

Fig. 3. The main electrical networks in the area of blackout in the IPS of Siberia on June 27, 2017. The bold dotted line denotes the cutset of separation of the eastern part of the IPS of Siberia for islanded operation.

overvoltage limiter; and overspeed protection tripped one more hydroelectric unit of the Bureya HPP;

- As a result of an increased active power shortage in the western subsystem of the IPS, the frequency decreased to 46 Hz, and an avalanche-like development of the emergency process occurred with a massive shutdown of power plants and consumers;
- This cascading development of the blackout led to the isolation of the Blagoveshchensk load center with a single source (the Blagoveshchensk CHP) for islanded operation.
- The subsequent unfolding of the emergency caused power shedding of this plant to zero with the auxiliary power loss and complete de-energization of consumers in the Blagoveshchensk load center.

III. Analysis of key factors of the occurrence and development of the considered blackouts

The analysis of the above sequence of events and processes that occurred during the analyzed blackouts allows us to identify the following key factors that determined the specific features of the cascading development of these blackouts:

a) Failures, false operation, actions of relay protection and emergency control devices, which are inadequate to the current state of the system (for example false triggering of emergency control at the Bratsk HPP at the beginning of the accident on June 27, 2017, in the IPS of Siberia; failure of the main and backup protections during liquidation of short circuit at Reftinskaya TPP during the accident in the UES of Russia on August 22, 2016). It is worth noting that the failed relay protection and emergency control equipment have different element bases: at Reftinskaya TPP, it is electromechanical, while at Bratsk HPP, it is microprocessor-based. Therefore, the causes of failures are different;

b) Correct operation of emergency control devices, adequate to the current (but off-design) EPS topology and conditions, which aggravates the emergency (for example disconnection of the hydroelectric units at the Boguchany HPP by overload protection when frequency increased during the blackout in the IPS of Siberia on June 27, 2017; tripping of the units at the Zeya HPP, Bureya HPP, and Neryungrinskaya TPP by over-frequency protection during low-frequency steady-state synchronous oscillations in the western part of the IPS of the East during the blackout on August 1, 2017);

c) Correct operation of emergency control devices, contributing to counteraction and termination of a blackout and its development (operation of some emergency control devices in the later stages of the blackout development, out-of-step protection and automatic load shedding in almost all cases of the blackouts at issue);

d) Continuous or weakly damped synchronous oscillations of power plant generators in EPS (for example low-frequency sustained synchronous oscillations of generators at power plants in the western part of the IPS of the East during the blackout on August 1, 2017; weakly damped oscillations in the separated eastern part of the IPS of Siberia during the accident on August 22, 2016).

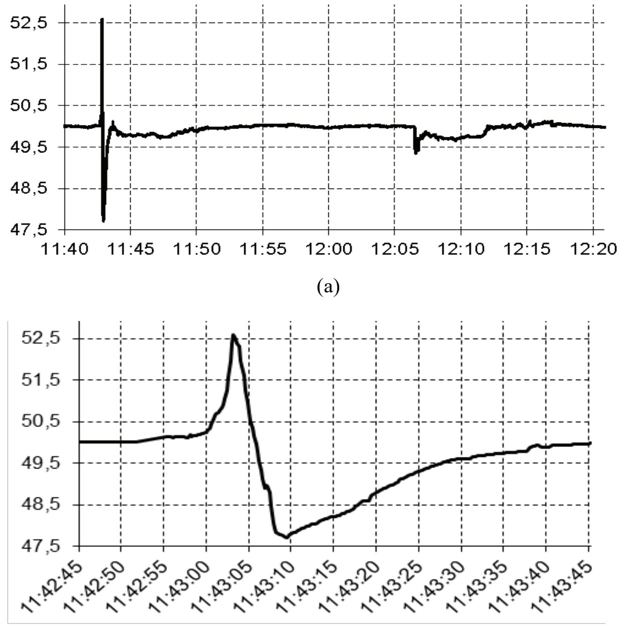

Fig. 4. Results of frequency monitoring in the eastern part of the IPS of Siberia during the blackout on June 27, 2017 (measurement in Irkutsk, frequency [Hz] vs Moscow time [hh:mm:ss]): (a) from the beginning to the end of the blackout, (b) in the initial stage of the blackout.

A detailed analysis of factor A) should focus particular attention on the unique case of a cascading failure of the main and backup protections during the elimination of a short circuit at the Reftinskaya TPP during the blackout on August 22, 2016, which requires in-depth scrutiny.

According to the findings of the analysis of several recent system-wide blackouts, the Ministry of Energy of the Russian Federation have stated that the electric power systems have a wide variety of microprocessor-based devices for relay protection and emergency control made by different manufacturers. In many of them, the measuring elements have an unacceptable level of error in the measurements of frequency when it deviates from the nominal one, which leads to failures in operation or false operation of the devices [13]. An important reason for the malfunctioning of microprocessor-based devices of relay protection and emergency control is the imperfection of the algorithms embedded in them [14]. Other factors are discussed in [8, 14, 15, a.o.]. In general, this problem requires thorough research, including the investigation of the statistics of failures of microprocessor-based devices.

As can be seen from the analysis of the system-wide accidents at issue, the failures and false operation of relay protection and emergency control devices are the root causes of such accidents, along with two others. These

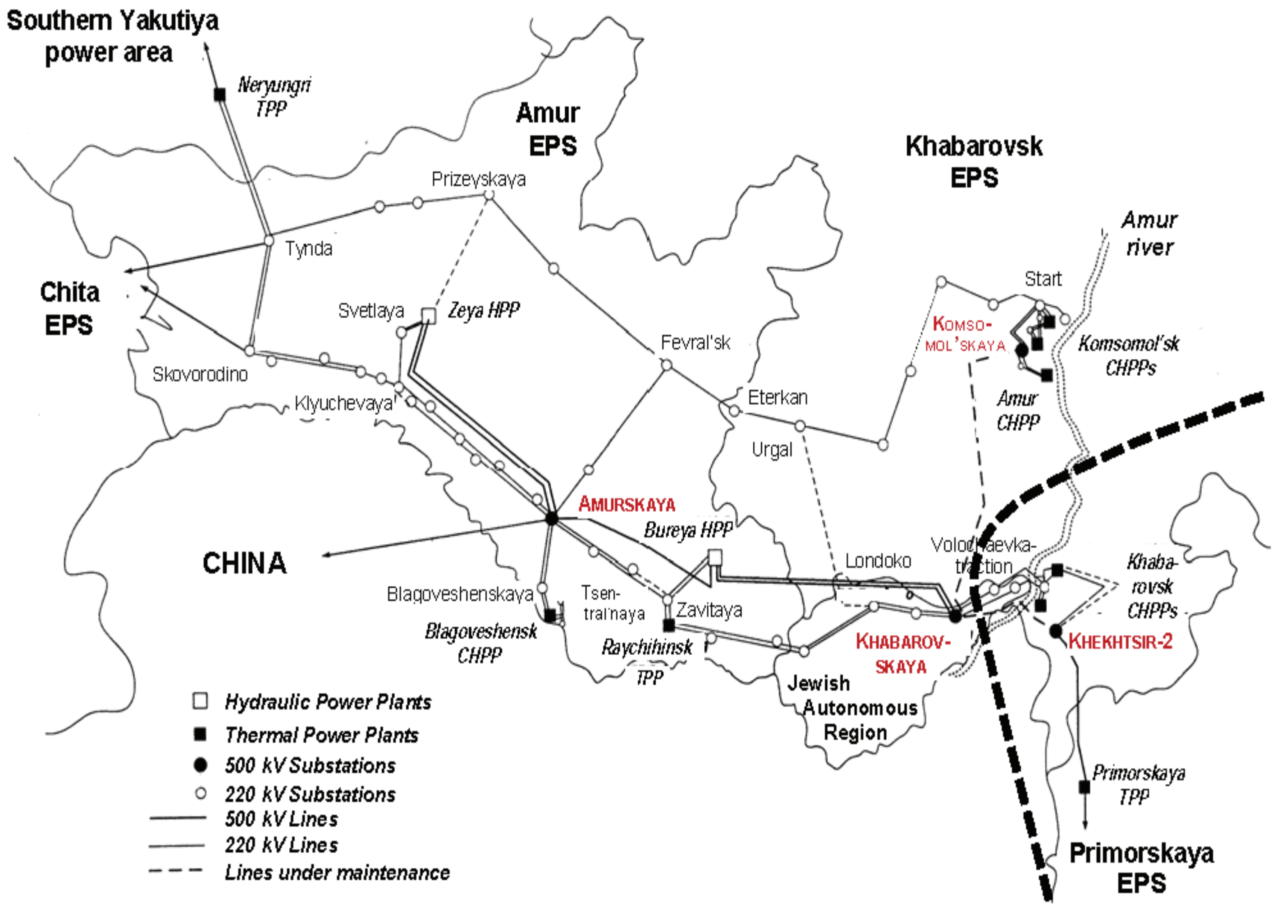

Fig. 5. A scheme of the main network of the IPS of the East as of 08.01.2017. The bold dotted line denotes the cutset "Crossing through the Amur river" along which the eastern part of the IPS of the East was separated for islanded operation.

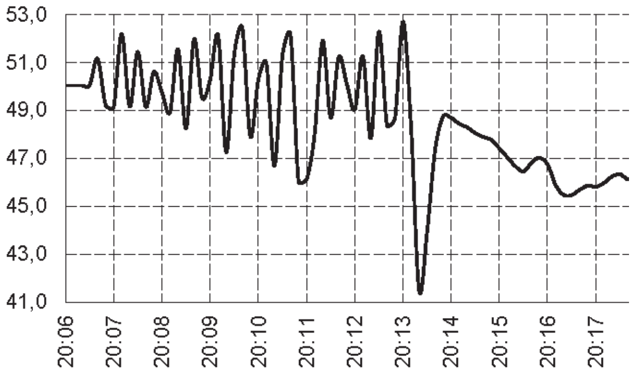

Fig. 6. Results of frequency monitoring in the western part of the IPS of the East during the blackout on 01.08.2017 (measurement on 220 kV buses of the Blagoveshchenskaya substation, frequency [Hz] vs Khabarovsk time [hh:mm]).

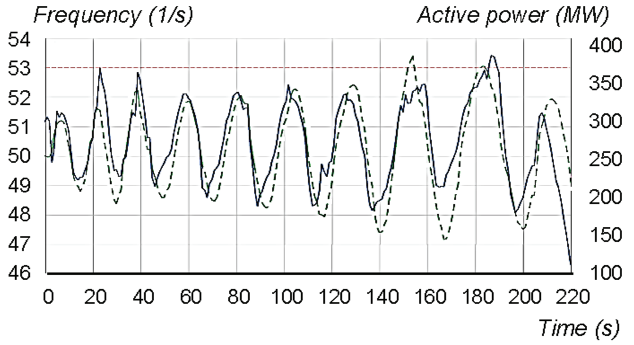

Fig. 7. Full-scale oscillograms of the rotor speed (dashed line) and active power (solid line) of the hydro-generator of the Bureya HPP during the accident on 08.01.2017.

are the human factor (erroneous actions of personnel, errors in the design and settings of the relay protection and emergency control, and others), and the off-design extreme external impacts. This fact is confirmed by the statistics of the 1960s - 1980s [8, a.o.].

It is also important to note that the proper (failure-free) operation of relay protection and emergency control devices according to the EPS current topology and operating parameters, which can be off-design (factor B - see above), exacerbates the emergency. A typical example in this regard is the operation of over-frequency protection relay to disconnect the units of the Zeya HPP, Bureya HPP, and the Neryungrinskaya TPP during frequency fluctuations in the separated western part of the IPS of the East during the blackout on August 1, 2017 [4]. The long period of oscillations (2 s), with their large amplitude, created favorable conditions for the operation of over-frequency protection relay, since the frequency at the upper part of the oscillation amplitude appeared to exceed the frequency control settings for a longer time than the automatic response delay required to prevent the relay operation in the case of short-term frequency variations above the trip setting. The avoidance of such conditions is a nontrivial task and requires in-depth research. One of the solutions for the cases like the blackout in the IPS of the East can be measures to eliminate the causes of low-frequency synchronous oscillations of generator rotors in the EPS (Fig. 7).

The positive effect of emergency control devices in the later stages of the blackout, out-of-step protection, and automatic load shedding in all cases (factor C) of interrupting the cascading development of the emergency process does not require comments. This fact once again confirms the well-established opinion of specialists that the out-of-step protection and load shedding are the last frontiers in counteracting the development of cascading emergencies and preventing the complete shutdown of EPS. Meanwhile, in extremely challenging situations, these automatic schemes do not help either, which is demonstrated by the catastrophic uncontrollable development of a system-wide emergency in the IPS of the East on August 1, 2017, with a complete blackout of the town of Blagoveshchensk and the auxiliary power loss at the Blagoveshchenskaya CHP [4].

Of interest is the cause of factor D, which to a greater extent manifested itself in the form of low-frequency sustained synchronous oscillations of generators in the western part of the IPS of the East during the accident on August 1, 2017 [4], and, to a lesser extent, in the separated part of the power system of Eastern Siberia in the accident in the IPS of Siberia on June 27, 2017. [3]. Presumably, such a cause could be the discrepancy between the settings of power system stabilizers of HPP units with respect to the derivatives of operating parameters, the existing topology, and the conditions of the electrical network of the corresponding part of the EPS. Moreover, the relative weakness of the electrical network plays a significant negative role. Similar situations were studied in [16]. As a result, instead of damping the oscillations, the PSSs of HPP and TPP units amplified the system oscillations.

The reliability of the given explanation of the cause of continuous synchronous oscillations of power plant generators under the conditions prevailing in the islanded EPS is also indirectly confirmed by the fact that the current industry standard [17] reflects the requirements for tuning power system stabilizers in a rather fragmentary manner. In particular, this standard suggests voluntary certification of tuning of the power system stabilizers. However, it does not propose a procedure for tuning their coefficients with respect to the derivatives of the power system operating parameters to changing topology and operation conditions. The development of this procedure requires special studies using, for example, frequency methods of stability analysis or modal analysis of EPS [18, 19, a.o.], or other possible approaches. Thus, the industry standard requires adjustment [17].

The elimination of the possibility of weakly damped low-frequency oscillations by using the procedure for adapting the tuning of power system stabilizer will eliminate the non-standard operation of the emergency control devices in the off-design conditions similar to those that developed during the system-wide accident in the IPS of the East.

IV. Conclusion

The analysis of large-scale system-wide cascading blackouts in the UES of Russia in 2016 - 2017 revealed several factors that determine the occurrence and development of these unique accidents with severe consequences for the system and consumers. The examination of these factors makes it possible to formulate recommendations by area of research with the view to developing the necessary methods and procedures for improving relay protection and emergency control systems (especially those based on microprocessor) and increasing their reliability. Based on this analysis, it is also possible to design the procedures for providing adaptable tuning of regulation coefficients of power system stabilizers by the derivatives of operating parameters and modernize the standards determining the conditions for normal operation and prevention of severe cascading blackouts in the electric power systems.

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