Analysis of Mechanisms of Blackout Development in Electric Power Systems

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***Abstract*—The objective trends in the development of electric power systems make its control increasingly more difficult. To avoid the cascading development of emergencies and decrease the risk of blackouts the methodological, technical and software developments are necessary. The paper presents a formalized technology for the analysis of developing emergency processes of a cascade character in electric power systems. The approach is based on classification of events and states in the system that are caused by these processes and determination of interrelations between them. The technology is illustrated on the example of analysis of system blackout in Moscow electric power system in 1948.**

***Index Terms*—blackout, cascade system emergency, electric power system, emergency control, mechanisms of development.**

I. Introduction

Bulk electric power systems (EPS) experience tens of thousands of disturbances yearly. Most of the disturbances are eliminated by relay protection and emergency control devices and normally are practically unnoticeable to consumers. Failures of these devices, personnel errors and some other accidental factors may result in a cascading development of the emergency that is localized and eliminated by emergency control system of a higher level. Here the emergency control action disconnects EPS elements, splits EPS into isolated subsystems and disconnects secondary consumers. These events do not lead to severe consequences for the system and consumers, and usually EPS is restored quite fast. However, the insufficient efficiency and reliability of emergency control as well as other related reasons lead to unique severe blackouts, often with catastrophic consequences for EPS and consumers.

Development of system emergencies in EPS has been systematically analyzed since the beginning of the 1960s. Gradually the events and states that occurred in the course of a cascading development of emergencies were classified, and schemes of occurrence and development of cascading emergencies were formed [1]-[4], etc. In the 1970-1980s a systematic work was performed to analyze system blackouts in the Unified Energy System of the USSR [2], [5], etc. Similar analysis was carried out in other countries as well, and for some particularly large emergencies the processes of their development were modeled [6], [7], etc. Principal progress in understanding the mechanisms of development of cascading system emergencies was made after introduction of the notions “marginal state” and “triggering event”. The latter “triggers” an irreversible development of emergency situation [1], [3]. In fact triggering event takes place near the marginal state of the EPS.

Based on the previous studies the paper presents a formalized technique for analysis of cascading emergency processes in the bulk EPS. The technique is based on the classification of EPS states and events that stimulate transition from one state to another. The suggested technique is used to describe the December 1948 Moscow blackout.

II. Basic Statements

A lot of events occur during EPS operation. The events differ by their origin and their qualitative and quantitative characteristics. The common way of retrospective analysis of emergency contingencies in EPS is to detach from the entire set of events the certain time sequence (“chain”) of events which had an impact on the development of emergency contingency.

The suggested approach (see [8], [9], and [10] for more details) is based on the following:

1) Qualitative classification of the events:

a) A-events – accidental events, including:

- *Disturbances* – first of all short circuits in transmission lines, and moreover lines breaks, unplanned switching of EPS components and load/generation on/off. Disturbances change the EPS state in an accidental way.
- *Wrong Actions*, i.e. false operation of relay protection or automatic control devices or erroneous

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switching performed by personnel. Wrong Actions worsen the EPS state.

– *Failures*, i.e. relay protection or emergency control device fails or misses the necessary personnel actions for the proper change in the EPS state. Failures prevent the EPS state changes addressed by *P-event* (see below) or other *A-events*.

b) N-events – natural (regular) events, i.e. actions of the laws of nature in EPS, which manifest themselves as a natural response of EPS to the aggregate of all previous events. *N-events* can result in both deterioration and improvement in the EPS state, and also an imperceptible (negligible) change in the state.

c) P-events – purposeful events (control actions), i.e. correct and successful control actions for planned changing the EPS state or as a response to *A-events* and *N-events*. *P-events* improve the EPS state. They are performed by relay protection, emergency control devices and personnel by switching certain generating, loading and transmitting EPS components.

2) *Three gradations of changes in the EPS state* in terms of reliability of its further operation (i.e. in terms of the risk of blackout):

a) Negative change (i.e. deterioration) in the state, which implies a decrease in the transfer capability margins in the main network and generating capacity reserves;

b) Positive change (i.e. improvement) in the state, which implies an increase in the above characteristics;

c) Imperceptible change as an insignificant (negligible) change in the above characteristics.

The generalizations of above discussion are the following:

- While *A-events* and *P-events* impact on the concrete components of EPS, the *N-events* are responses of the entire EPS to those impacts.
- *A-events* and *P-events* always lead to *N-events* which in their turn are a direct cause of EPS state change. Therefore, the system effect of any event directly results from *N-event*.
- Probability and system effect of event are the values depending on the previous events, first of all on those *N-events*, which worsen the EPS state. In more detail, these events raise:
  1) the probability of *A-events* occurrence (for example, the probability of short circuit in an overloaded transmission line is much higher than in a normally loaded or underloaded line).
  2) the negative system effect of *A-events* (for example, accidental redistribution of power flows in "heavy" operating conditions result in a larger overloading of the transmission lines than similar redistribution in "easier" conditions).
- The most dangerous (potentially the most worsening the EPS state and, hence, the risk of blackout) case is a combination of *A-events* and those *N-events* which worsen the EPS state. It is this combination that can lead to the formation of a cause-effect cycle is possible which (if considered in time scale) is a process of cascading deterioration in the EPS state, i.e. cascading development of emergency situation.
- Appearance of such a dangerous cycle means that the sequence of events at some instant of operation has brought the EPS into some marginal state, in which the next event becomes *triggering*, i.e. starting an uncontrollable cascading process of further events (first of all, tripping the EPS components) with disastrous consequences (system blackout). Triggering event separates a period where multiple "undirected" factors (finally contributing but not directly connected to a blackout) are accumulated, from the "blackout-directed" sequence of events with clear cause-effect relationships between the subsequent phases.

Based on the above definitions, we can split all the events taking place in EPS into three groups (*A-*, *N-*, and *P-events*), and establish cause-effect relationships between the events. Using such a qualitative classification of events we can represent and analyse a scenario of any emergency situation in EPS [8], [11].

III. The Moscow Electric Power System in 1948 December 18

Let us consider the blackout that have occurred in USSR, Moscow EPS in 1948, December 18 [12], including its starting, development and consequences. The one-line diagram of Moscow EPS is presented in Fig.1.

The Moscow EPS operated as a part of interconnected power system "Centre" which included also Gorky, Ivanovo and Yaroslavl EPSs, and energy pool "Upper Volga" (three EPSs with a total capacity comparable with one third of the Moscow EPS). Due to low transmission capability of 110 kV intersystem ties (not more than several tens MW) the mutual emergency assistance of the EPSs could not be significant.

At the end of 1948 the generation capacity of Moscow EPS was around 1750 MW (including the power plants of industry), and peak load was around 1500 MW. Available capacity of Moscow EPS in 18th December at 9:00 a.m. (morning peak) was around 1660 MW.

In the morning of December 18 a burst of powdery ground peat was happened in Shaturskaya thermal power plant. The burst caused ignition of peat storage bins and fire of fuel supply facilities. During the two hours the plant had to reduce power from 180 to 10 MW. In a day only the output was restored up to 100 MW, and in two days – up to 160 (and later – to 180) MW. Therefore in December 18 the Moscow EPS operated without any active power reserve. Nevertheless it managed to provide the load-peak (1465 MW at 18:00) without restriction of consumers supply.

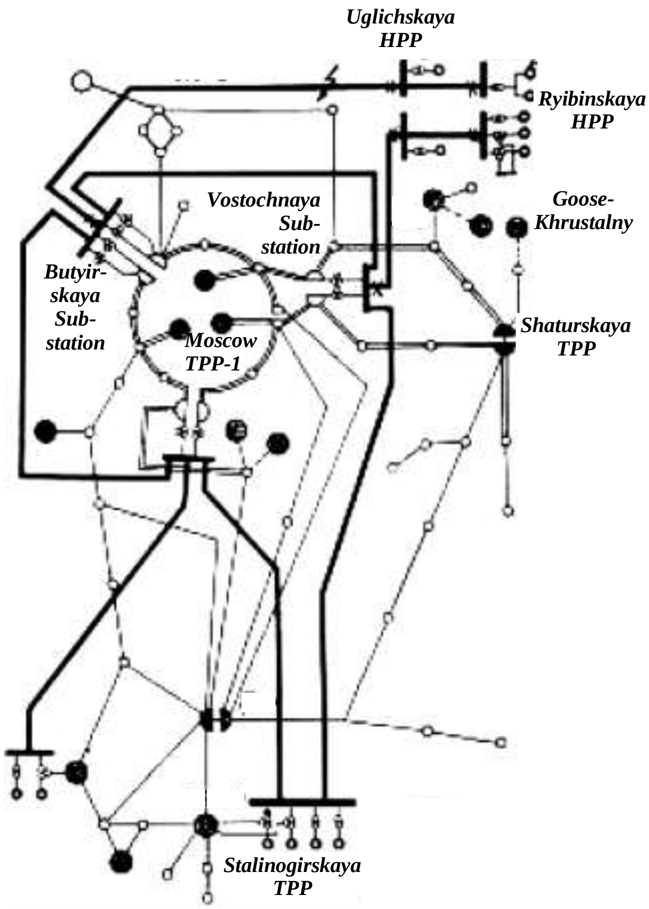

Figure 1. 220-110 kV electric network of Moscow EPS in 1948, Dec 18, 8:10 p.m.: TPP – thermal power plant, HPP – hydropower plant; ▬ 220 kV, ── 110 kV.

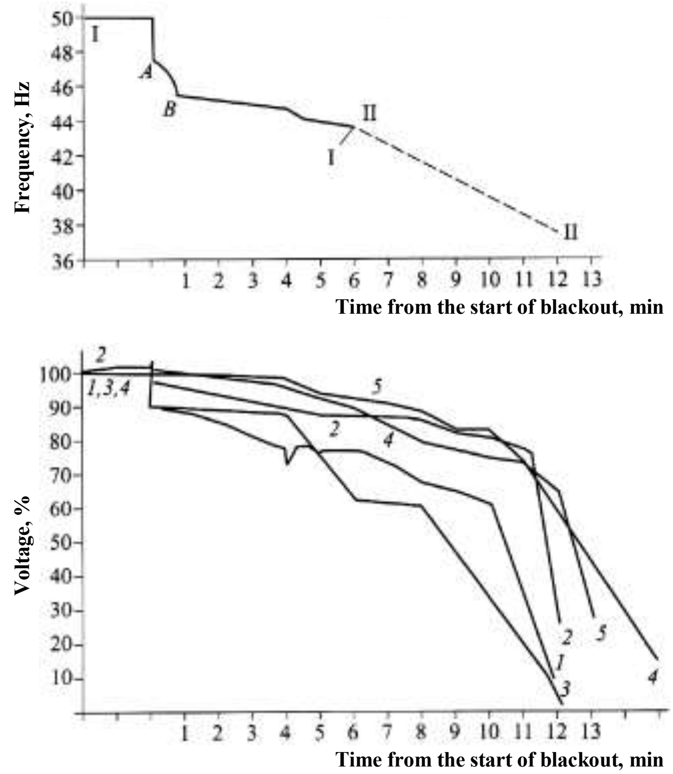

Figure 2. Frequency of Moscow EPS and voltages in nodes of the system during the blackout:

Frequency:	*Voltage:*
I-I – data from recorder of frequency meter;	1 – at 6 kV buses of Central substation;
II-II – is restored from records of turbines rotation speed in log books of some CCPPs.	2, 5 – at 110 kV buses in the two TPPs;
	3 – at 30 kV buses in one of the nodal substations;
	4 – at 6 kV buses in one of CCPPs.

IV. Blackout Development and Analysis

Let us describe start and development of the blackout in terms of qualitative classification of events (see Section II).

Among accidental events the significant for blackout start events were following:

- Absence in the EPS of the reserve of generation;
- A wire break of 220 kV line followed by a single-side short circuit;
- Misoperation of relay protection (wrongful delay of opening the line).

The set of these accidental events led to the sequence of interdepended *N-* and *P-events*, which in turn provoked frequency and voltages collapses in the EPS (Fig.2).

The proposed qualitative classifications of events into three groups allows us to represent the time-consequence (scenario) of this emergency situation as shown in Fig.3. Such a representation makes it easy to track the blackout development. Generally it looks in that way:

- Due to a short circuit and a delay of its clearing the opening the unaffected line was performed earlier that opening the affected line. This way the Moscow EPS lost of 300 MW from Volga HPPs. The only remaining 110 kV tie with Upper Volga EPSs was disconnected by system separation (islanding) automation.
- The raised lack of active power caused frequency decrease. All available for automatic load shedding load (around 7% of total load of the EPS) was shed by that automation. Meanwhile the frequency continued to decrease.
- Due to further frequency decrease the performance of auxiliaries' mechanisms of TPPs in Moscow EPS was also decreased. Naturally, the output was decreased and the generators became overloaded with a current.
- The dispatcher commands to disconnection of appr. 130 MW of load were given and performed too late to restore the power balance in EPS.
- Total system blackout occurred in 15 min after the start of the process. The power supply of only a small amount of loads was saved (about 6% of the system load including the power plants auxiliaries), which were islanded together with separated generators of TPPs.

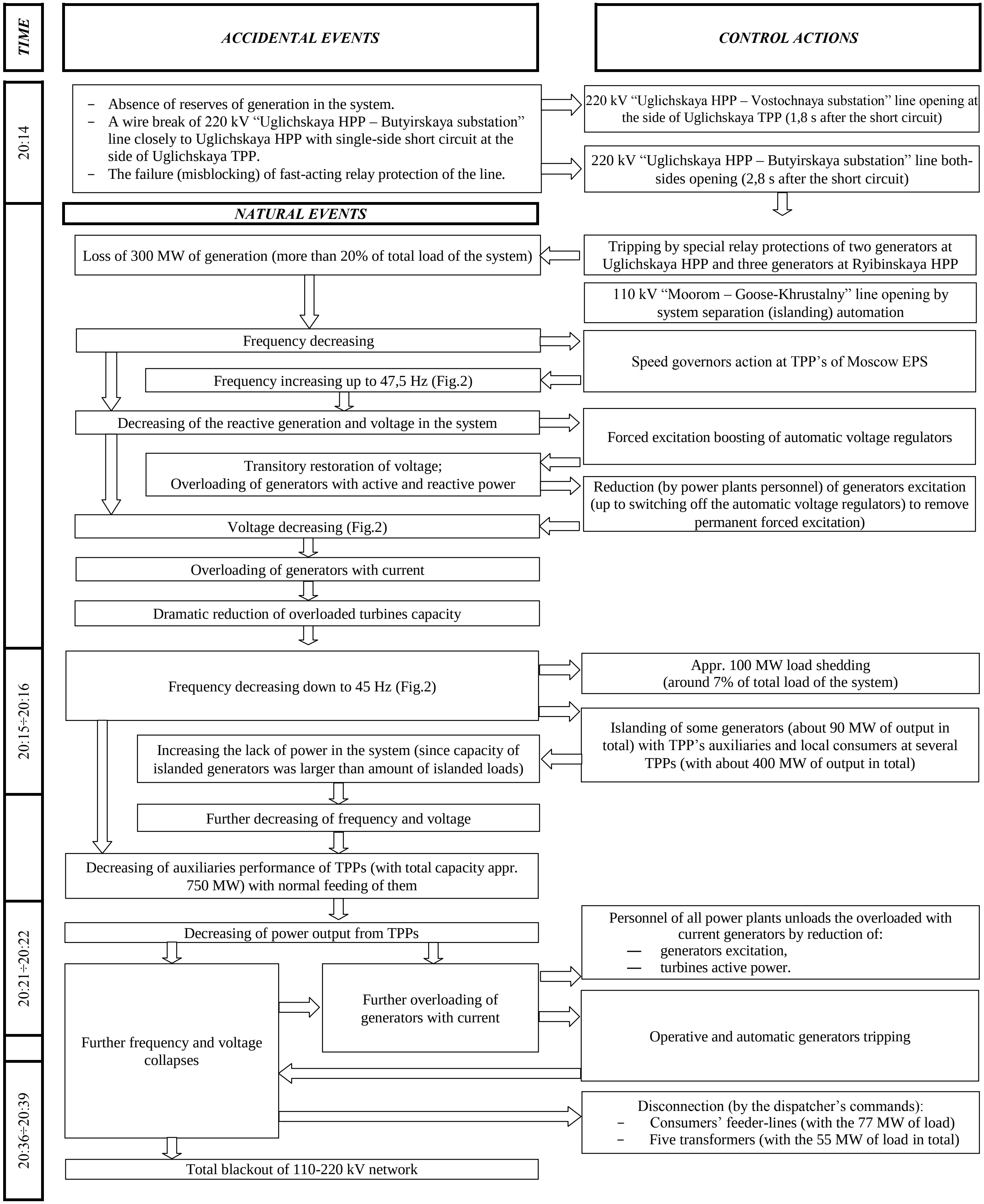

Figure 2. Blackout development: most significant events and cause-effect relationships between them.

V. CONCLUSION

The necessity to analyze the mechanisms of cascading blackouts is obvious. Along with specific pragmatic interest in the reasons and factors that lead to a catastrophic development of a certain emergency situation, knowing which it is possible to determine "bottlenecks" in the system and then eliminate them, generalization of system emergency development mechanisms allows one to make an attempt to reveal potentially possible ways of development of emergency processes by their modeling.

Such a representation facilitates an identification of bottlenecs of the EPS which provoked the initiation and development of blackout. These bottlenecs therefore shall be strengthened to avoid the repeating of such emergency scenarios.

In particular, the Moscow 1948 December 18 blackout had confirmed:

1. The importance of keeping the necessary amount of reserves of active and reactive power in the EPS.
2. The unacceptability of protracted operation of EPSs with the frequency of (and under) 48Hz.
3. The necessity of increasing the load available for automatic load shedding from 7% to at least 25%.
4. The necessity of improving the relay protection and automation of transmission lines, buses and transformers.
5. The necessity to equip the dispatcher centre of Moscow EPS with modern communication and remote control devices.

Moreover, the blackout essentially contributed to forcing the efforts to creation of Unified Electric System of the country.

REFERENCES

[1] Yu. V. Makarov, V. I. Reshetov, V. A. Stroev, and N. I. Voropai, "Blackout prevention in the United States, Europe and Russia," *Proceedings of the IEEE*, vol. 93, pp. 1942-1955, no.11, 2005.

[2] Management of bulk electric power interconnections / N. I. Voropai, V. V. Ershevich, Ya. N. Luginsky, etc.; Ed by S.A. Sovalov. M. Energoatomizdat, 1984, 256 p.

[3] R. C. Hardiman, M. Kumbale, Yu. V. Makarov, "An advanced tool for analyzing multiple cascading failures," in *Proc. of 8th Int. Conf. "Probabilistic Methods Applied to Power Systems"*, Ames, IA, USA, 2004, pp. 131-138.

[4] P. Pourbeik, P. Kundur, C. W. Taylor, "The anatomy of a power grid blackout," IEEE Power and Energy Magazine, 2006, Vol.4, No.5, pp. 22-29.

[5] E. D. Zeilidzon, "On the character of development of extremely severe system emergencies," Report at the 3rd All-Union scientific and technical meeting on stability and reliability of power systems in the USSR. L.: Energiya, 1973, pp.49-55.

[6] D. N. Kosterev, C. W. Taylor, and W. A. Mittelstadt, "Model validation for the August 10, 1996 WSCC system outage," IEEE Trans. Power Systems, 1999, Vol. 14, No. 3, pp. 967-979.

[7] I. A. Hiskens and M. Akke, "Analysis of the Nordel power grid disturbance of January, 1, 1997 using trajectory sensitivities," IEEE Trans. Power Systems, 1999, Vol. 14, No. 3, pp. 987-994.

[8] D. N. Efimov and N. I. Voropai, "Blackouts analysis and generalization," in *Proc. of Liberalization and Modernization of Power Systems: Risk Assessment and Optimization for Asset Management. The 3rd Int. Workshop*, Irkutsk, Energy Syst. Inst., 2006, pp. 139-148.

[9] N. I. Voropai and D. N. Efimov, "Mechanism of cascading emergencies in electric power systems," in *Proc. of 7th International World Energy System Conference (WESC-2008)*, June 30 – July 2, Iasi, Romania, 2008, 7 p.

[10] N. I. Voropai, D. N. Efimov, and V. I. Reshetov, "Analysis of mechanisms of system blackouts development in electric power systems," Electrichestvo, 2008, No.10, pp. 12-14. [in Russian]

[11] Yu. V. Makarov, N. I. Voropai, and D. N. Efimov, "Complex emergency control system against blackouts in Russia," *IEEE PES General Meeting*, Pittsburgh, USA, July 21-24, 2008, 8 p.

[12] A. F. Bondarenko, "On 1948 December 18 blackout in Moscow power system," Electricheskie stantsii, 2015, No.1, pp. 26-37. [in Russian]