Formation of the load graph for consumers of electric energy for the stabilizing work of electric energy system

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Abstract. Design and operation of electric energy system is being carried out with taking into account probable projected accidents. Thus, there are many prerequisites of developing accidents in electric energy systems, caused by impact of outer factors, which have random nature and can negatively influence the stability of operation of electric energy system. Problematic questions of functioning of electric energy systems in accidents, caused by various factors, which have both predicted and random nature are being considered in this article. There are actual ways of preventing development of accidents provided. A method of flexible regulation of consumption of electric energy had been suggested as one of the possible ways to stabilize the operation of electric energy system.

1. Introduction
Nowadays, the consumption of electric energy all over the world has a positive dynamic. The growth of consumption is provided by demand for electric energy in developing economics. So the small stagnation of electricity consumption of USA, Europe and Russia in crisis years has been fully compensated by the growth of electricity consumption in China, India and developing countries of Asia-Pacific region. In whole, in Russia the dynamic of consumption fits world trends of growth and decrease but the volume of production is stable.

The actual consumption of electric energy [1-4] in Russian Federation is growing in recent years (table 1).

| Year | Consumption, billions of kW per hour | Gain regarding the previous year, % |
|------|-------------------------------------|------------------------------------|
| 2015 | 1008.2                              | -                                  |
| 2016 | 1026.7                              | 1.8                                |
| 2017 | 1039.7                              | 1.3                                |
| 2018 | 1055.6                              | 1.5                                |

Firstly, growth of the consumption of electric energy is caused by increasing of production on the functioning industrial enterprises and also by commissioning the new factories. Mostly this gain is produced by factories of woodworking industry, metallurgical factories, and also by both oil and gas pipeline facilities and railway transport. Moreover, a household sector contributes to a growth of electricity consumption – therefore the power ratio of personal households is growing, very new
consumers and receivers of electric energy are appearing, rapid development of personal electric transport starts.

The installed capacity of Russian power plants increases every year [4], generally responding to the growing electric consumption. United energy system of Russia shows quite high stability of operation. Every year the number of accidents decreases [1]. At the same time, with the general decrease in the number of accidents at electricity facilities in general and the decrease in the number of major system accidents in particular, their scale becomes larger and they develop according to the cascade scenario.

2. Materials and methods
In the emergency and post-emergency conditions, the system is at a lower level of operation than normal operation. Any minor disturbance causing a decrease in the level of functioning with a high probability can turn into a cascade development of the accident and cause a mass disruption of the power supply to consumers. As systems become more complex, the number and severity of cascading system accidents increases, as well as the part of power shortage caused by these accidents increases. The reason is not only in the increase of the total number of dependent failures, but also in the complication of control in accidents, the difficulty of setting up emergency automation. The necessity and importance in ensuring the vitality of the electric power system, the reliability and quality of electric power supply to electric power users, as well as the power shortage reduces, makes it particularly relevant in the development of ways to prevent the development of accidents and the stable functioning of the electric power system with the impact of outer unfavorable factors of accidents.

In this regard, the aim of the research is to adapt the operation of the electric power system to accidents, resulting from negative outer factors.

To achieve this goal, the following tasks must be solved:

- To investigate features of functioning of an electrical power system in the accidents resulting from action of negative outer factors;
- To analyze the existing and perspective ways of prevention of accidents;
- To offer a possible way of stabilization of operation of an electrical power system.

The study was based on methods of statistical, historical, comparative, logical, economic-mathematical and system analysis, a method of expert assessments, which allowed to propose a method of flexible regulation of electricity consumption, as one of the possible ways to stabilize the operation of the electric power system.

3. Results
The analysis of daily reports of the Federal State Budget Institution "Situation and Analytical Center of the Ministry of Energy of Russia" on accidents that occurred at the facilities of the fuel and energy complex [5] shows that the occurrence of accidents of different scale and duration is coming out due to a number of main reasons.

The first reason is the occurrence of accidents at electric power facilities as a result of unfavorable weather conditions (heavy rain, wind gusts, storm). There is a large number of prerequisites for the occurrence of negative natural impacts, which are random and can negatively impact the operation of the elements of the electric power system. The territory of the Russian Federation is exposed to almost the entire spectrum of natural hazards and processes. The climate is changing rapidly, leading to widespread natural disasters. Among possible natural phenomena, earthquakes present the greatest risk (about 20% of the territory of Russia are exposed to earthquakes with intensity of more than 7 points) and floods (they occupy the first place in Russia among dangerous hydrological phenomena and processes in terms of area of spread and total average annual damage, and the second, after earthquakes, in terms of the number of victims and damage). The second reason comes due to the operation beyond the standard service life of more than half of the electric power equipment in
operation. According to the data of the technical inspection of EEC [6], the average service life of the main generating equipment of power plants in Russia in whole is:

- The steam turbines, gas turbines, water-wheels installed on power generation facilities which total established generating power in total exceeds 5 MW - 32.1 years;
- The package boilers providing the ferry the steam turbines installed on power generation facilities which total established generating power in total exceeds 5 MW - 44.7 years;
- The turbo generators and hydro generators installed on power generation facilities - 32.8 years;
- Transformers (autotransformers) power oil, established on power generation facilities, a class of voltage of 35 kV and above - 28.3 years.
- The average service life of the main electrical equipment, air and cable lines (hereinafter - power lines) of electrical networks in Russia in whole is:
  - The transformers installed on objects of electrical networks, a class of voltage of 35 kV and above - 31.7 years;
  - The power line a class of voltage of 35 kV and above - 39.7 years.

In 2019, 2969.9 MW of new capacity was introduced at power plants (including industrial power plants). 1746.03 inefficient and obsolete equipment has been decommissioned. At the same moment, the operation of a large number of equipment with unacceptably high wear and tear continues, operating at the border or outside the standard service life [2].

The next frequent reason of accidents is incorrect or false operation of emergency automation (EA). The fault is the technical incompatibility of devices of different manufacturers and inconsistency of algorithms of their operation. Besides, there are errors in adjustment of relay protection (RP) - protection settings do not take into account the possibility of operation of network elements with additional load, and its settings do not always meet the requirements under maximum loads and emergency modes. Failure of one element is accompanied by disconnection of the protection means of the network element taking over its load, which leads to cascade development of the accident and mass disruption of the consumers supply. In general, the reasons of accidents in electrical power systems can be conditionally divided into organizational, technical and accidents which have a random nature (figure 1).

There is a seasonal change in the number of accidents at electric power facilities of different voltage classes in the section of the year [3]. Seasonal accidents can be predicted, what helps to minimize their consequences by carrying out preventive measures by electricity grid organizations and utilities and bringing the forces and facilities of repair teams to full readiness. Accidents which have a random nature are not predictable and become an exceptional situation. The reasons of such accidents may come the effects of natural emergencies that are not typical for the region or have not previously occurred with such intensity. In addition, the current level of industrial development should involve a serious approach to assessing the man-made hazards that may arise in the operation of complex industries and technologies. One of the reasons for the accidents is the violation of the security zones of power transmission lines in the part of the non-coordinated construction works near the electric power infrastructure, non-compliance with the vertical dimensions of construction and heavy equipment when passing under the overhead line (OL) of power transmission. There are cases of light-powered aircraft, quadrocopters, drones and balloons falling on the OL. Vandalism, as well as deliberate deactivation of electrical network elements, is a rare but at the same time severe cause of accidents at electric power facilities.

The problem of operating a large number of electric power equipment outside the standard service life is exacerbated by the poor technical condition of the reserve equipment. This circumstance does not allow to put the reserve equipment into operation quickly in case of accidents. In addition, when new equipment is put into operation, there is often a problem of non-conformity of technical characteristics of the installed equipment with the parameters of that, which was already in operation.
All these lead to their inconsistent operation, incorrect adjustment of protection algorithms and failures.

Figure 1. Reasons, causing accidents.

A lot of the reasons of system accidents are coming due to organizational work. The situation is complicated by insufficient qualification of personnel and their errors in operational switching or interference with relay protection and automation. The organization of network and generating equipment outputs for repair is not always sufficiently thought out. This results in reduced reliability of power systems, especially in seasonal peak load conditions. There are also cases of inconsistent interaction of the system operator with electric power industry entities in terms of protection configuration, issuance of tasks and control of their execution.

The main direction of development of emergency control in the UES of Russia is improvement of emergency automation systems [7].

The emergency control solves the problems: prevention of power system operation stability failure, termination of asynchronous stroke, prevention of frequency, voltage and current exceeding permissible limits.

Modern types of emergency automation devices used in the operation of the UES of Russia are presented in table 2.

According to the regulatory documents [8-9], emergency control functions are implemented by AP by means of the following control actions:

- Short-term (pulse) and long unloading of power units of thermal power plant and NPP;
- Shutdown of generators;
- Shutdown of load of consumers of electric energy;
- Forsirovka of excitement of generators;
- Division of power supply system into nonsynchronously working parts;
- Automatic loading of generators;
- Electric braking;
- Change of topology of an electrical network;
- Change of operating modes and an operational condition of the operated elements of an electrical network.

**Table 2. Kinds of emergency automation devices.**

| A task, solved by an emergency automation | Kind of EA                        | Purpose                                                                                                                                                                                                 |
|------------------------------------------|-----------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| The prevention of stability violation    | SFPA Stability Failure Prevention Automation | Prevention of violation of static and dynamic stability of generating equipment of power plant, engine load assembly, controlled section, power area and prevention of unacceptable current overloads of power lines and equipment. |
| Terminations of the asynchronous course  | AATE Automatic Asynchronous Travel Elimination | Detection and elimination of asynchronous modes of individual generators, power plants and parts of power systems, detection and elimination of asynchronous full-phase and incomplete-phase modes of electric network.                  |
|                                          | AFIL Automatic frequency increase limitation | Prevention of unacceptable increase of frequency in the power system to the level, at which it is possible to activate the safety automatics of power plant and NPP turbines.                                        |
| The prevention of invalid frequency deviations | AFRL Automatic frequency reduction limitation | Prevention of frequency reduction and complete redemption of the power system or its part in case of active power deficit, including emergency allocation of the power system or its part for isolated operation, which is unacceptable by conditions of stable operation of generating equipment and power receiving plants of electric power consumers |
| Prevention of unacceptable voltage deviation | AVIL Automatic voltage increase limitation | Prevention of unacceptable value and duration of voltage increase on equipment of electric power industry objects.                                                                                     |
| Prevention of an unacceptable overloading of equipment | AVRL Automatic voltage reduction limitation | Prevention of voltage reduction unacceptable in terms of stability conditions of generating equipment and power receiving plants of electric power consumers.                                                 |
|                                          | EOLA Equipment overload limitation automation | Prevention of unacceptable current load value and duration of electrical equipment and power line.                                                                                                     |

One of the most common control actions of emergency automatics designed to prevent the development of emergency modes in the EES is to disable the load [10]. Disconnection of load (DL) of electric power consumers is used to prevent stability violations, limit reduction of frequency and voltage, eliminate overload of controlled sections, power lines and equipment. DL is performed by disconnection of all electrical connections of power receiving plants of electric power consumers with power system with prohibition of automatic entry of reserve of disconnected connections. At the same time, this effect is the least desirable because it reduces the main indicator of reliability of power.
supply to consumers. Both concentrated energy-intensive consumers and large distribution centers can be connected under DL. At the same time, in today’s conditions, it is almost impossible to abandon the DL in many cases, especially to solve the problems of sustainability of inter-system ties of the UES.

4. Discussion
The issue of stabilization of the operation of the electric power system, as well as preservation of the stability of its operation in case of power imbalances arising from accidents, is devoted to a lot of works of domestic and foreign authors.

One of the solutions to this issue can become the method of determining the value and placement in the system of reserve for consumers (power of short-term shut-down load) necessary to prevent the development of an accident caused by the shutdown of a large electric station in the EES [11].

An another way to prevent emergency situations can be to place the consumer-regulator in the system [12]. It is a consumer, whose technological process and mode of operation on a reimbursable contractual basis provide for the possibility to limit power consumption during the hours of maximum load of the electric power plant and increase the load during the hours of minimum. These measures are necessary to balance the daily load schedule of the power system.

There are developments on construction of adaptive automation of distributed load disconnection, as well as algorithms of formation of adaptive control actions in order to ensure stability of EES [13].

Currently, developments are under way to introduce Intelligent Energy Systems (IES) or Smart Grid. One such system is an intelligent system based on multi-agent technologies and machine learning algorithms for early warning and emergency prevention [14-18].

In 2011, at a joint meeting of the NTS of JSC "FSK UES" and the Russian Academy of Sciences, the Concept of Development of the Intelligent Electric Power System of Russia with an Active and Adaptive Network (IES AAN) was approved [16]. The intelligent electric power system with active-adaptive network is a new generation electric power system based on the multi-agent principle of organization and management of its functioning and development, based on modern technological means and a single intelligent hierarchical control system.

Load balancing is one of the factors of stable operation of the electric power system. One way to optimize daily load schedules is to use market mechanisms and develop digital technologies while encouraging consumers to actively manage their own consumption [19-21]. In this case, it is necessary to take into account the mismatch of interests of the power supply organization and consumers in the process of load balancing. In addition, the development of load schedules with the use of batteries as consumer regulators is under way [22].

Most existing approaches to maintaining the stability of the electric power system in case of power imbalances by switching off the load do not take into account the presence of different requirements for the reliability of electric power supply for individual consumers. In this regard, it is necessary to develop a method of stabilizing the operation of the electric power system, taking into account the requirements for reliability of electric power consumers and excluding their complete shutdown.

In order to solve this issue, the authors of the article propose flexible regulation of electricity consumption. [23] The main essence of this method is the possibility to generate a load graph, depending on the availability of free power in the system, taking into account the capacity of the electrical network elements.

The ability to generate a graph is achieved by:

- Temporary increase in capacity of a system of transfer and power distribution due to accounting of total thermal loading of separate elements of networks (transformers, air and cable lines);
- Transition from discrete regulation (shutdown of consumers of the electric power) to smooth (change of value of settings of devices of protection and the relay of priority loadings) on low-priority consumers of the electric power during the periods of lack of free power in a system.
• Preliminary start of reserve power sources of consumers of the I category of reliability of special group and transfer on them, as on the main source of the electric power, the specified consumers.

An example of load graph generation is shown in figure 2.

![Load Graph Generation](image)

Figure 2. The example of load graph generation.

Thus, load parameters are adapted to the generation capabilities and capacity of the electrical network.

At present, in order to implement the proposed method, the authors of the article are conducting studies aimed at preventing the development of emergency situations in the electric power system by using a set of technical means that provide flexible regulation of electricity consumption.

The set of technical means developed in the framework of this study [23-25] consists of several sets of devices, which are based on unique technical proposals to prevent the development of accidents:

- Set of devices increasing capacity of power transmission and distribution system due to taking into account total thermal load of individual network elements;
- Set of transmission power control devices in distribution networks in case of power shortage in the power system.

The proposed method of flexible regulation of electric power consumption can be used not only to prevent the development of emergency situations in the existing power system, but also for isolated power systems and power systems containing distributed generation to adjust the load schedule to the available free power in the system.

5. Conclusion

The article considers problematic issues of operation of electric power systems in emergency situations caused by various factors, which are both predictable and accidental. The current ways to prevent the development of emergency situations are presented. The authors propose a method of
flexible regulation of electric power consumption as one of the possible ways to stabilize the operation of the electric power system.

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