RELIABILITY OF ENERGY SYSTEMS

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Introduction. Depending on the goals of studies, the object of studies may be either an energy complex as a whole, or individual energy systems it includes, or separate elements of the systems. The studied object may perform different functions.

The main specified functions include:

a) *purpose* of the object;
b) the fact of its *creation* [1].

Ability of the object to perform the function associated with its *purpose* is referred to as power supply reliability (Fig. 1). *Power supply reliability as applied to energy systems is ability of the facility to supply the target product of the required quality to consumers following the given schedule of consumption.* An energy complex unites power systems, systems of gas, oil, coal and heat supply, and nuclear energy systems. Purpose of the electric power system (EPS) in particular is power supply for consumers. *Power supply reliability of EPS is its ability to supply power of the required quality following the given power consumption schedule.* Power supply reliability is reliability in "narrow sense" as consideration is given to the specified function only (a function related to the object purpose) [2].

Power supply reliability is a complex property that may include several unit properties: failure-free operation, maintainability, survivability, stability, controllability, durability and conservability. Durability and conservability are characteristic of the system's elements rather than of the system as a whole.

Another specified function of the object conditioned by the fact of its *creation* is avoidance of situations hazardous for people and environment that are caused by failures during the object operation [1]. *Ability of the object to avoid situations that are hazardous for* people and environment is referred to as safety (Fig. 1).

Reliability is ability of the object to perform all the specified functions in the required scope under certain operating conditions (Fig. 1). Reliability is a complex property. Difference between reliability and power supply reliability lies in the fact that reliability includes *safety* as additional unit property.

The notion of reliability is being shaped. Should one compare the first (1980) and second (2007) editions of glossaries on the energy systems reliability he would notice that the definition of reliability and of its unit properties has changed [3, 4]. At the moment there is a need to change (clarify) the content of such unit properties as failure-free operation, controllability and survivability.

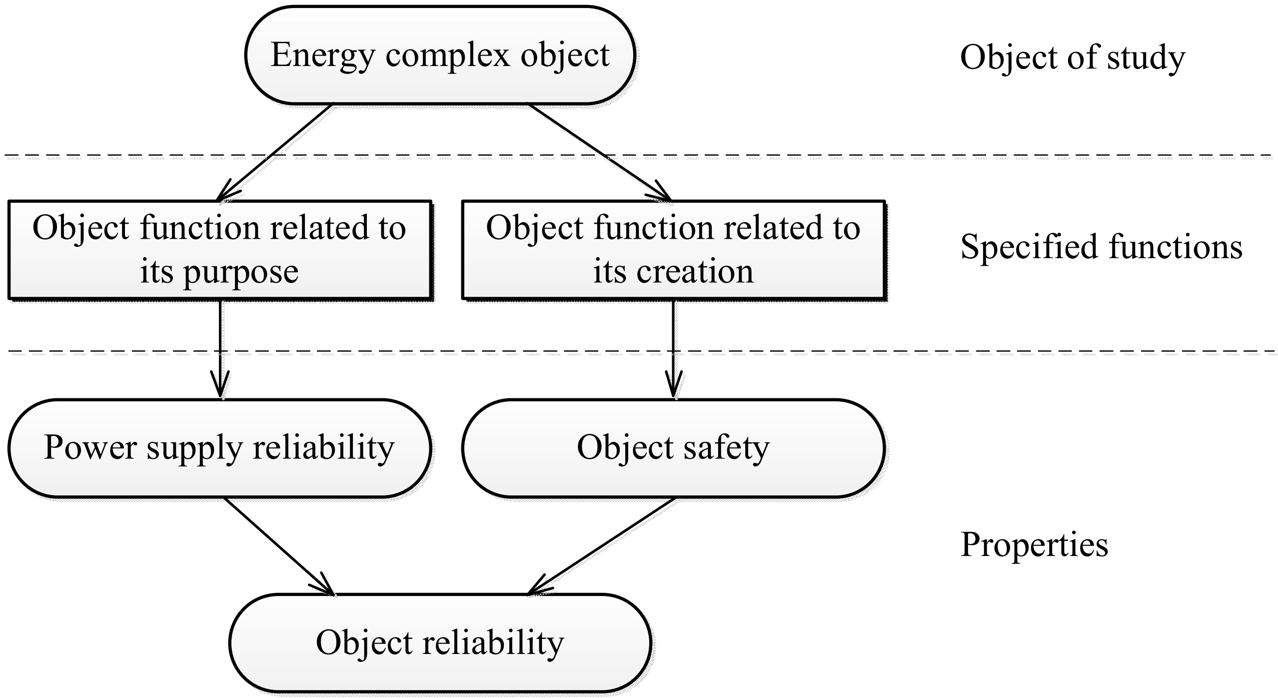

Fig. 1. The ratio of notions: an object, its specified functions and properties

(Object of energy complex; Object function related to its purpose; Object function related to its creation; Power supply reliability; Object safety; Object reliability. Object of studies. Specified functions. Properties)

Failure-free operation *is ability of the object to continuously maintain operability or operable state during a certain period of time [1, 3].* The facility is subjected to different disturbances. All the disturbances effecting the facility can be divided into two main groups: whether they are *external* with respect to the object or they are of *internal* origin. It was recommended that assessment of failure-free operation should take into account all the disturbances irrespective of the fact whether they are major or minor, internal or external with respect to the object [1].

A different approach is also possible that is more constructive and, therefore, more preferable as it allows one to pay special attention to extreme disturbances, to principles (criteria) of decision-making and to reliability support activities in the extreme conditions. The essence of the method lies in that the disturbances are identified and considered separately, within the survivability property rather than within the failure-free operation property. Such approach to accounting different disturbances is preferred by well-known specialists in the field of reliability of technical systems [5-7].

Therefore, in the study of the failure-free operation it is sufficient to take into account all the disturbances of the *internal* origin, i.e. equipment failures (drawbacks of operation, maintenance defects, manufacturing defects, and end of service life); and errors of operating personnel [1]. As to external disturbances, one should take into account only the disturbances the object is designed for (thunderstorms, earthquakes (but within the design seismicity of the area) etc.).

The effect of factors reducing failure-free operation ability and, hence, reliability could be fully or partially balanced by [8]: selection of the appropriate design of the system; higher reliability and enhanced equipment performances (including equipment and devices of control means and systems); redundancy in all the elements of the system; perfection of the system operation management.

Controllability is ability of the object to maintain normal operating conditions [1,3,4]. Such a definition does not give a comprehensive idea of the term. It does not take into account that an object can be controlled in different operating conditions, including control in emergency conditions. It does not take into account requirements to control in different operating conditions. For example, the object control in emergency conditions at high controllability shall not result in cascade emergency with large-scale interruption of power supply for consumers.

The main requirements to the definition of controllability could be:

- the object control at high controllability in emergency shall not result in cascade emergency with large-scale interruption of power supply for consumers;
- high controllability shall ensure parameters control and their input into the feasible region [6];
- high controllability of the object shall allow maintenance of normal operating conditions using by control [1].

Those requirements being taken into account, the following definition of controllability could be proposed: *Controllability is ability of the object: not to allow cascade development of emergencies with large-scale interruption of power supply for consumers; bring the operating conditions back into the allowable region and maintain the specified parameters by control.*

Controllability is ensured by: sufficient control range and mobility of the main equipment; mobility of standby capacity; redundancy of transfer capability of the network; selection of the architecture and parameters of the automatic control devices, and of automatic emergency and on-line control.

Survivability is ability of the object to resist to disturbances avoiding their cascade propagation resulting in large-scale interruption of power supply for consumers. This definition of 'survivability' term is given in the first and second editions of Reliability of Energy Systems glossary [3,4]. Nevertheless, 'cascade propagation' does not mean survivability failure. As it has already been noted, it is a feature of insufficiently high controllability. Large-scale interruption of power supply for consumers is not an indicator of survivability failures either. It can be caused, for example, by technological process breakdown in the system that (as evidences the analysis of major emergencies) can be promptly mitigated and the object continue operation in normal conditions.

The main indicator of survivability failure is a failure at extreme external impact on the system. Extreme *external* disturbances include [5]:

- External impacts on the object that were not considered during its design (hurricanes, earthquakes, tsunami, etc.);
- Deliberate actions (sabotage attacks, acts of terror, military actions, etc.).

Such disturbances result in partial or even complete destruction of the object. Let 'survivability' denote the reliability in extreme conditions [1]. *'Survivability' is ability of the object to resist to external disturbances it is not designed for in normal operating conditions.* 'To resist' means that the level of the system operation at extreme external impact shall not be lower than the minimum feasible one.

Minimum feasible level of operation at extreme external impact could be ensured by: emergency power backup; selection of the system structure and operating regimes (preventive reduction of the system operating level); automatic and on-line control; reserve stock of the main equipment and consumables and their optimum location in the system; anti-terrorism activities.

Safety is a unit property of reliability. As a matter of fact, assessment of the relevancy of safety problems for energy systems is noted to be interpreted in different ways by the same authors. On the one hand, "research in this field has become more intense" [9]; on the other hand, "the main reason why safety was excluded from the list of reliability properties of energy facilities is the fact that this property has not been in demand for 27 years" [4]. *Firstly, such wording does not contain a substantial justification for exclusion of this property, and, secondly, with account of major* *emergencies that occurred at energy systems in the past 30 years, it is evident that the problem of safety assurance needs to be more thoroughly considered [2].*

As opposed to power supply reliability, safety is a multi-aspect property. For assessment of power supply reliability, it is sufficient to control supply of the target product for the customers, while it is not sufficient for safety analysis. Situations causing hazards to people and environment may not be related to supply of the target product to the customers. It is thus advisable to review a ratio between safety, failure-free operation, controllability and survivability (particularly in view of the fact that the content of the notions for unit properties of power supply reliability has been revised).

Ratio between failure-free operation, survivability and controllability Figure 2 shows a set of disturbances (denote it as A) which may upset failure-free operation. Some of the disturbances are associated with cascade propagation of emergencies and massive interruption of power supply for consumers due to insufficiently high controllability of the object. Let *B* be a set of disturbances that upset failure-free operation and were associated with cascade propagation of emergencies and massive limitation of power supply to consumers due to insufficiently high controllability (Fig. 2).

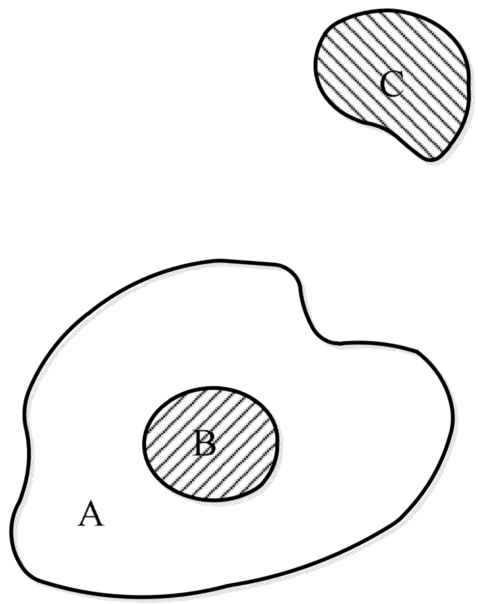

Fig. 2. Ratio between sets of disturbances that upset failure-free operation and survivability: *A* is a set of disturbances that upset failure-free operation; *B* – is a set of disturbances that upset failure-free operation and are associated with cascade propagation of emergencies due to insufficiently high controllability; *C* is a set of disturbances that upset survivability.

$$B \subset A. \tag{1}$$

Cascade emergencies, for instance at EPS, may occur due to the following causes [1]:

- Short circuit in elements of the system (about 10 per cent of all the failures of elements in the main 400-750 kV networks are accompanied by failures of other elements);
- Overload or power jump in power transmission due to capacity disbalance in the interconnected parts of the system.
- False tripping of power line, buses or transformers by relay protection or automatic emergency devices.
- Non full-phase regime due to failure of breakers at operative switching-overs.
- Erroneous shut down of power supply by the operating personnel.

Disturbances that result in survivability failure are not considered in studies of failure-free operation. As it has already been said, extreme disturbances may be the consequence of floods, tsunami, typhoons, earthquakes, snowfalls of deliberate external acts. Therefore, a set of disturbances resulting in survivability failure has no elements common with a set of disturbances that upset failure-free operation. Let C be a set of extreme disturbances that may result in survivability failure then

$$A \cap C = \emptyset \,. \quad (2)$$

Survivability failures are, as a rule, associated with the cascade propagation of emergencies. For this reason the set C in Fig. 2 is shaded.

Ratio between survivability, controllability, and safety . All the disturbances that may cause survivability failures will also be the cause of safety failures (Fig. 3) as survivability failures are associated with the target product shortage, destruction of the object, and situations hazardous for people and environment. Studies on the object safety shall be preceded by analysis of their survivability. Higher survivability of the facility enhances its safety.

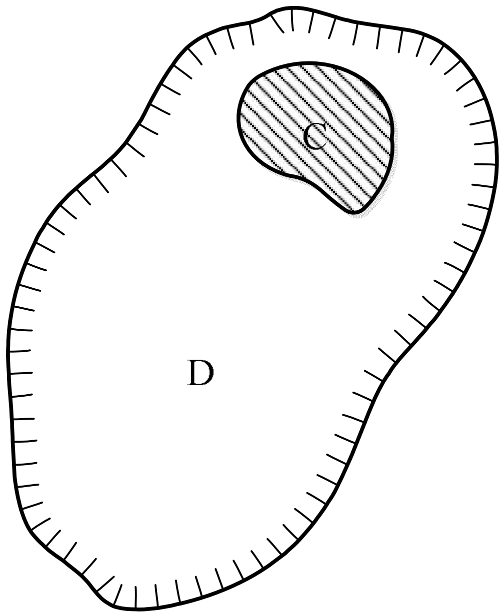

Fig. 3. Ratio between sets of disturbances that upset survivability and safety. *C* is a set of disturbances that cause survivability failure; D is a set of disturbances that cause safety failures.

But, on the other hand, not all the disturbances that cause safety failure would cause the survivability failure. For example, the emergency at Sayano-Shushenskaya Power Plant that caused considerable destruction and death of people was an upset of failure-free operation, but it was not a survivability failure. Failure of electric precipitators at thermal power plants that may cause higher emission of pollutants with flue gases and, hence, safety failure, is not a survivability failure.

Not all the activities used to raise safety enhance survivability. Location of some or other EPS facilities (of power plants, in particular) impacts EPS safety, but it has no impact on the EPS survivability and failure-free operation. Therefore, higher safety does not always result in higher survivability. Let D be a set of disturbances that may result in safety failures. then

$$C \subset D \,. \quad (3)$$

Ratio between failure-free operation, controllability, and safety. Disturbance of failure-free operation may be at the same time the cause of safety failures. First, safety failures may be caused by failure-free operation disturbances associated with cascade propagation of emergencies and notable shortage of the target product supply to consumers.

Then

$$B \subset D \,. \tag{4}$$

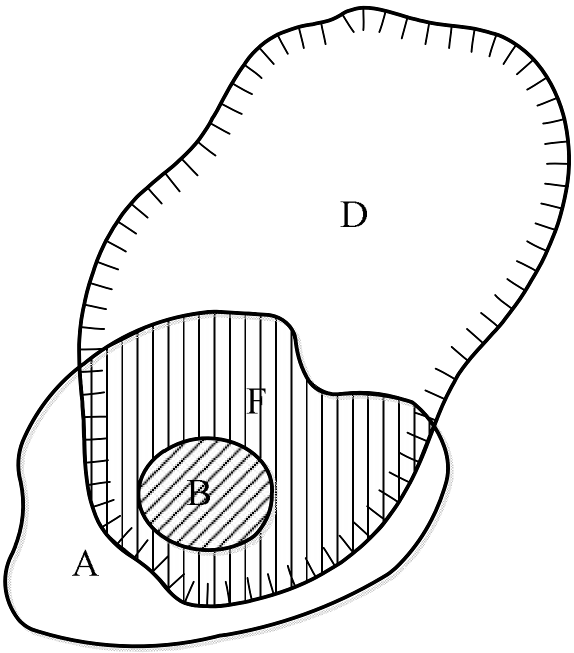

Fig. 4. Ratio between sets of disturbances that upset failure-free operation and safety: A is a set of disturbances upsetting failure-free operation; D is a set of disturbances causing the safety failures; B is a set of disturbances upsetting the failure-free operation associated with the cascade propagation of emergencies due to insufficient controllability; F is a set of disturbances that cause the safety failures and upset the failure-free operation, but do not cause the cascade propagation of emergencies.

Such emergencies are frequent at EPS of different countries. They occur on the average once in two years (there were 20 major emergencies in the 40-years period between 1965 and 2005). Some emergencies were major ones. Hundreds of thousands and even millions of people had no power supply. Thousands of people were 'prisoned' in lifts and metro trains, there were fires, robbery, etc. Examples of such emergencies are: emergency in the USA on November 9-10, 1965; emergency at EPS of the USA and Canada in 2003, Moscow systems emergency in 2005, systems emergency in St.- Petersburg on August 20, 2010; emergency in Canada on January 23, 2005, and emergency in Brazil in 2009. Such emergencies are in the focus of attention of the countries' authorities.

Secondly, safety failures without cascade propagation of emergencies are also possible, for example, due to emergency disconnection of certain consumers of Grade 1 or due to emergency shut down of electric pumps in the sewage system. It would result in emergency discharge of wastes, pollution of the area and water reservoirs. Let F be a set of disturbances that upset safety and failure-free operation without cascade propagation (Fig. 4). Then

$$A \cap D - B = F \,. \tag{5}$$

Ratio between failure-free operation, controllability, survivability and safety of EPS. Not all the disturbances that cause safety failure would cause the survivability failure and upset failure-free operation. The non-shaded area in Fig. 5 corresponds to the set of disturbances D.

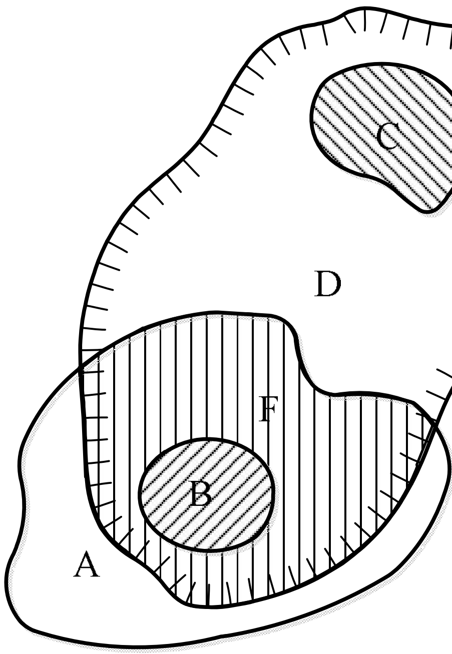

Fig. 5. Ratio between sets of disturbances that upset failure-free operation, survivability, and safety: A is a set of disturbances upsetting failure-free operation; D is a set of disturbances causing the safety failures; B is a set of disturbances upsetting the failure-free operation associated with the cascade propagation of emergencies due to insufficient controllability; F is a set of disturbances causing the safety failures and upsetting the failure-free operation, but they do not cause the cascade propagation of emergencies; C is a set of disturbances causing the survivability failures.

They include, for example, disturbances caused by destruction of ash dumps of Thermal Power Plants that is followed by destruction of other facilities, pollution of the area, water reservoirs, etc. Let L be a set of such disturbances. Then

$$D - A \cap D - C = L. \quad (6)$$

Safety failures can be replaced by disturbances of failure-free operation. For example, at a stage of EPS design it is not always possible to avoid the excess of maximum permissible concentrations of hazardous substances. Sometimes for a short period of time the concentration of hazardous substances in the surface air may rapidly increase, for example, under availability of raised inversions located immediately over the stacks of thermal power plants, and in windless conditions. For avoiding the rapid growth of hazardous substances concentrations in the surface air the regimes of power plants are varied, up to complete shut down of boilers fired by fuel with high content of sulphur and ash in highly dangerous periods.

Therefore, higher safety does not always enhance failure-free operation. In some instances higher safety may cause some reduction in failure-free operation. For instance, failures of safety systems of nuclear power plants may cause emergency tripping of power generating equipment.

Therefore, causes, affecting factors and activities to ensure failure-free operation and survivability, failure-free operation and safety, safety and survivability, respectively, may differ from one another.

CONCLUSIONS

1. Consideration is given to the ratio between notions: an object, its specified functions and properties

2. Content of such notions as power supply reliability, failure-free operation, controllability, survivability and safety is discussed.

3. Definitions of such terms as power supply reliability, controllability and survivability are given.
4. The ratio between such unit properties of reliability as failure-free operation, controllability, survivability and safety is discussed.
5. Causes, affecting factors and activities to ensure failure-free operation, survivability and safety may differ.
6. New edition of glossary on "Power System Reliability. Terminology" should, firstly, take into account changes in the essence of such terms as failure-free operation, controllability, and, secondly, bring back the 'safety' term and include it into the unit properties of power systems reliability.

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