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Fundamentals of Electrical Safety Theory: Current State and Development Prospects

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Abstract—This article considers the current state and development prospects of the fundamentals of the electrical safety theory. The concept of electrical safety is refined. It is found out that, according to the system of labor safety standards, it coincides in content with the concept of an electrical safety assurance system. It is noted that this concept can be defined in various ways that describe electrical safety as a certain state in which human beings interact with areas of their life and activities. The list of fundamental tasks solved in the theory that has been laid out is formulated. Ten tasks are distinguished, and subtasks are distinguished in some of them. The attained solution level for each task is indicated. The current state of electrical safety theory allows setting up optimal engineering electrical safety assurance systems on particular sites and ensure the highest level of electrical safety at given costs.

Keywords: electrical safety, system approach, electrical injury rate, probabilistic approach, mathematical modeling of electrical safety, optimization of electrical safety assurance systems

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According to *GOST* (State Standard) *R 12.1.009-2009*, *electrical safety* is a system of organizational arrangements and engineering tools for protecting people and animals from the hazardous effects of electricity, voltaic arcs, electromagnetic fields, and static electricity [1]. This standard defines the concept in question for only one of the many areas of human life—the production industry. However, electrical hazards may show up in other areas as well. In such modules as *Fundamentals of Health and Safety* and *Noxology*, the more general term *safety* is defined as a certain state [2]. However, the standard being considered defines electrical safety as the means of reaching a certain state.

Despite the contradictory interpretations of this concept, we shall below rely on the interpretation provided in [1] and treat electrical safety as a specific electrical safety assurance system (ESAS).

The electrical safety theory can be presented as a system of connected and hierarchical tasks.

Let us consider the list of the theory's tasks in an order mostly compliant with the order of solving them in time. We shall characterize these tasks in brief and indicate their degree of solution, which will allow assessing the state and development prospects of the theory.

Task 1. Studying the Effects of Current on the Human Body and Creating Electrical Safety Criteria

The effects of current on the human body have been studied for quite a while. It is a characteristic feature of these studies that they take into account not only the physiological aspects of such effects, but also various characteristics of exposing current (physical characteristics, course of current, resistance of the human body, etc.). These studies were used to elaborate the primary electrical safety criteria as threshold currents that corresponded to certain responses of the human body. The list of such criteria includes threshold considerable current, threshold freezing current, and threshold fibrillation current. The values of these currents for different people differ and have been described, therefore, as random quantities with the help of various laws of distribution [3, 4].

Another form of setting primary electrical safety criteria takes the form of tables in which maximum permissible effective touch voltages and currents are indicated for various operation regimes of electrical plants. These criteria have a bivalent logic of decisions concerning electricity hazards. An international criterion developed later takes into account the negative effects of current accompanied by ventricular fibrillation [5]. This criterion allows defining the probability of fibrillation at target values of current and duration of exposure.

Task 2. Using the System Approach to Describing Electrical Safety

If we understand electrical safety as an electrical safety assurance system, the solution of this task must result in describing this system. The system is characterized by a multilevel structure. Its hierarchical levels are determined by the large number of people protected by the system. The top level in the hierarchy is nationwide. The lower levels that need to be considered may include electrical safety systems of particular branches of the economy (sectors), enterprises, etc. The bottom level corresponds to the protection of a single individual.

At present, the task in question has been solved for the farming sector [4, 6]. As a result of its solution, a set of system concepts has been formed to describe the functions, composition, elements, and structure of the branchwise ESAS, its hierarchical levels, and the external environment.

One should note the importance of considering systems for providing electrical safety at particular sites and facilities. At this level, one can take into account the interaction between a particular group of people and a particular group of electrical plants under the effect of particular ESAS components [7].

Task 3. Using the Probabilistic Approach to Describing Electrical Injuries and Injury Rates

This approach to electrical safety theory was proposed for the first time ever by A.I. Yakobs in the early 1970s. It started to be used abroad in that decade. The main contributors to the development of this concept were Soviet and Russian researchers in the field of electrical safety in mining and agriculture. This approach treats an electrical injury (electric shock) as a random event [4], which makes it possible to mathematically model such accidents using probability theory. That said, the *random event* mathematical scheme is used to describe particular electrical injuries and the *random quantity* and *random process* schemes are used to describe the electrical injury rate. The probability of a random event occurring can be indicated for a certain time range.

To mathematically describe electrical shocks suffered by many people, one uses the set of values of such probabilities (to find the so-called “electrocution risk level”) or the mathematical expectation of the number of people struck by current for a certain time range. The electrical injury rate for a certain number of people over several years is treated as a random process.

Task 4. Mathematical Modeling of Electrical Injuries (Electrical Shocks) and Electrical Injury Rate

This task is divided into several subtasks.

The first is general modeling of electrical injuries. This subtask is solved on the assumption that one can represent a random event called *electrical injury* as the product of certain elementary events and its probability as the product of probabilities of these events. Different sources provide different formulas to describe the product of these probabilities and interpret them in various ways [3, 4].

The second subtask is to calculate the conditional electrical injury probability. The most difficult component to define in the electrical injury probability formula is the conditional occurrence probability of electrical injury. This probability must be determined with a human being incorporated in the current circuit (when he is affected by voltage) and signifies the occurrence probability of a certain negative effect of current on his body (e.g., electrical shock), taking account the physical and topological characteristics of this impact. The electrical safety theory provides various techniques developed to calculate this probability. The technique most convenient in practice makes use of parametric distributions of current in the body of a person struck by current and the probabilistic description of effects of exposure of the human body to a current of certain value for a specific period [4]. The distributions of current were found by means of testing with the help of statistical modeling. The equation making it possible to find the conditional probability of electrical injury had an integral form.

The third subtask is to mathematically model the electrical injury of a human being as a random event that takes account the effect of a certain electrical protection technique (device). To accomplish this subtask, it is necessary to take account the characteristics of a particular device used to provide electrical protection of a particular person. These characteristics include the period for which the device disables the electrical plant, as well as the reliability of this device. The considered models are often referred to as “electrical protection efficiency models of specific electrical protection tools.”

The design formulas used in the considered kind of modeling are sums of products of probabilities of certain events. Various formulas have been proposed for several years by various electrical safety experts to make it possible to calculate electrical shock probabilities, taking account the role of various electrical safety tools. First of all, these formulas are intended for modeling electrical injuries to personnel who are not related to electrical engineering.

Analysis of the available models of this kind has made it possible to propose a model of assessing a neural wire grounding system for electrical protection efficiency, taking account the actual trip time of protective devices, the sequence in which personnel unrelated to electrical engineering touch exposed conducting parts of electrical plants that are not usually energized, and other characteristics [7, 8].

The fourth subtask is the mathematical modeling of electrical injury rates. This subtask is solved by describing the considered process as the Poisson stream of random events [4].

Task 5. Mathematical Modeling of the Operation of an Onsite ESAS and System Efficiency Assessment

The development of techniques for mathematically modeling electrical injuries (shocks) to people, taking account of the action of a separate electrical protection device, has paved the way for the efficiency assessment of onsite ESASs, taking account the synchronous action of all the protective devices installed on a certain site (e.g., its neutral wire grounding system). Electrical injury probabilities are calculated for all the workers on a given site.

The solution of this task involved solving two subtasks. The first was to choose the system efficiency indices. They were introduced for the first time ever in [6]. The ESAS was assessed for efficiency against the residual risk of electrical shocks that is encountered even with the ESAS installed. One of these indices was the average probability of electrical shock for a person in a certain time period.

The second subtask was to develop a modeling technology that would allow taking account the hierarchical structure of an onsite power supply system and the place in this system for protection equipment (fuses, automated circuit-breakers, leaked current creepage switches), as well as identifying locations of emergency condition sources (ECSs). In addition, it was necessary to take account a large number of people and the process in which they touched the ECSs. The specialized algorithm elaborated to solve this problem makes use of the hierarchical numbering of the onsite network sections [8, 9]. This algorithm allowed calculating the electrical shock probability for each person at the site.

The considered models were developed for farming facilities first and foremost; however, they can also be used for modeling electrical safety in other branches of economy, as well as in the household and civil area.

Note that the possibility of calculating the efficiency indices of onsite ESASs does the groundwork for onsite certification of these systems.

Task 6. Mathematical Modeling of Electrical Safety According to the Logical Probabilistic Approach

Modeling of this kind describes the occurrence of electrical shocks as a group of random events, each of which has its own probability. The condition for the occurrence of an electrical injury (shock) is described using the model elements function, on which basis it is possible to calculate the electrical injury probability and analyze the influence of particular events on this probability. The model allows not only taking account equipment failures, but also the actions of people who violate institutional or engineering norms. In this context, such models are used, first of all, to model electrical safety of electrical personnel employed at both manufacturing enterprises and power engineering facilities. It is another characteristic of the models that they allow calculating the electrical injury probability for one person only. Examples of using the considered modeling technique are currently provided in many publications, e.g., in [10].

Task 7. Optimization of the ESAS

This task is carried out on the basis of the completion of all the other considered tasks. In the late 1970s, A.I. Yakobs formulated the main scientific task the solution of which would allow the modern theoretical fundamentals of electrical safety to be completed. That task was formulated as a typical predictive optimization task: develop a technique for building the electrical safety system that would maintain electrical safety at a predetermined level and minimal reduced costs or maintain electrical safety at the maximum possible level at predetermined costs [4]. That said, it was noted that the main task had to do with several partial (auxiliary) subtasks, in particular, with the engineering efficiency assessment of specific electrical protection measures.

The task that has been laid out can be solved at various hierarchical levels of ESASs, taking account their different structures. The task as formulated by Yakobs was not restricted to any particular field of human life or branch of the economy. It can be supposed that this formulation can be implemented at the nationwide level in a certain branch of economy or in narrower areas of interaction between people and electrical plants (first of all, at particular sites).

The task that is being considered is divided into a number of specific subtasks:

—The first subtask is to describe the optimized system and potential ways to construct it.

—The second subtask is to mathematically model the operation of the dedicated system and, as a result, find the values of the efficiency indices of this system.

—The third subtask is to state the optimization task, including the establishment of optimality criteria and assignment of restrictions.

—The fourth subtask is to choose the optimal configuration of the system from a set of permissible configurations.

Thus, the possibility of optimizing the considered managerial and engineering systems is predetermined by the capabilities for modeling their operation. However, appropriate models have so far been developed only for engineering ESASs used at particular sites.

The ESAS optimization criteria were set up for the first time ever in [6], in which engineering and economic criteria were introduced. The engineering optimization criteria were derived on the basis of the ESAS efficiency indexes. The economic criterion of reduced costs of designing and operating the system was used for restrictions. The set of permissible ESAS configurations was established using sets of protective devices chosen according to the engineering techniques of their choice. Since a limited number of variants are considered in optimization, the optimal variant was chosen by means of an exhaustive search.

It should be noted that another task of ESAS optimization was stated and solved in [9]. It consisted in choosing optimal strategies for reconstructing the systems in question at a certain group of sites.

Task 8. Information Support of ESAS Modeling

To use the system approach to describing electrical safety in farming, an ESAS needs to have an information subsystem [3, 6]. This statement must be extended to other branches of the economy and areas of human life and activity. The mathematical modeling and optimization of the onsite ESAS make it necessary for this system to provide statistical information for evaluating the probabilities of certain elementary events (e.g., damage to electrical plant insulation, probabilities of protective device failure). To collect this information is very expensive. The specialized ESAS modeling and optimization techniques developed to cut these costs allow taking account the ambiguity of some of the initial data used for modeling. This led to the development of new techniques for optimizing the systems in question [11]. As a result, the costs of collecting necessary information were reduced.

Task 9. Using the Control Theory in the Field of Electrical Safety

An approach is currently in development in which the ESAS is treated as a controlled system. This approach necessitates that specialized electrical safety control systems be designed [12] and is used, first of all, to provide electrical safety of electrical personnel.

Task 10. Using the Concept of Technical Risks of Electrical Plants

In this concept, as applied to electrical safety, risk is understood as the combination of the probability of an electrical injury and the damage caused by this injury. The probability of electrical injury is defined by the logical probabilistic technique, which involves drawing an electrical injury risk tree. The use of fuzzy logic techniques is a characteristic feature of this concept. The most complete results of using the considered concept are presented in [13].

The considered list of the main tasks of the electrical safety theory includes those related only to one hazardous and adverse factor, i.e., current. Taking into the definition of electrical safety, its theoretical fundamentals must also involve considering electromagnetic and electrostatic safety tasks (exploration, normalizing, and elaboration of protection measures).

The development prospects of the electrical safety theory are exposed below:

—The first prospective trend is the continued study of effects of current on the human body.

Despite the large number of conducted investigations, this task cannot be considered completely solved, because the human body gives ambiguous responses to exposure to current. Thus, for example, one issue that is as yet unresolved is whether it is appropriate to take into account the physiological response of reflexively jerking back the hand, a response that is typical of a person who touches an energized conducting part the shape of which does not allow grabbing it with the hand [14]. Nevertheless, this interaction between people and electrical plants is precisely the one that is most typical in the case of an indirect touch by nonelectrical personnel.

—The second trend is toward expanding the field of application of the approach to describing electrical safety.

—The third trend is expanding the application of mathematical modeling of electrical injuries, including possible modifications of these techniques.

—The fourth trend is integration of the electrical safety theory with theories taking into account the negative effects of electrical plants on various facilities in their external environment.

—The fifth trend is the application of modern mathematical techniques in the electrical safety theory to model and optimize ESASs. These techniques differ from the conventional techniques of probability theory (in particular, soft math techniques, including the fuzzy set theory, fuzzy logic, and other areas).

—The sixth trend is continued application of new scientific concepts in electrical safety theory. These concepts include the control concept, risk management concept, process-based approach, etc.

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