ANALYSIS OF ELECTRIC SYSTEMS' STRUCTURES IN NUCLEAR POWER PLANTS WITH EMPHASIS ON ENSURING OPERATIONAL RELIABILITY

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Key words: power plant's electric systems, auxiliary systems, nuclear power plant, reliability, EPR, ABWR, AP 1000

Summary. In this paper the analysis of electric systems' structures in nuclear power plants with emphasis on ensuring the operational reliability has been prepared. The authors focused on different issues regarding necessary conditions of a safe work of nuclear power plant. Based on authors research the auxiliaries' power supply systems must be designed to assure a maximal reliability level of the supply for the most important auxiliaries. In the nuclear power plant, it is necessary to remove the decay heat produced in nuclear fuel during the long time after the reactor shutdown. It is also necessary to supply the devices responsible for the radiation protection of people and environment. The authors analyzed the categories of the nuclear power plant auxiliaries and the standards for qualifying electrical equipment for nuclear power plants. Electric part of nuclear power plant is a set of electric power equipment, interconnected using the electric current paths, designed to leading-out energy from the power plant to the electric power system (power leading-out system) and to supply auxiliaries (auxiliaries' power supply system). The tasks of auxiliaries' power supply system in normal conditions differ significantly from the tasks that this system satisfies in the transient conditions: starts-up, shut-downs and failures. The other thing is presented review of solutions of auxiliaries' power supply in currently developed plants. The paper presents the solutions of auxiliaries' power supply system in chosen power plants, which are presently design and/or in construction process.

1. INTRODUCTION

One of necessary conditions of a safe work of nuclear power plant is to assure a reliable auxiliary power supply. Equally important is to transfer reliably generated power to the electric power system. The auxiliaries' power supply systems must by designed to assure a maximal reliability level of the supply for the most important auxiliaries. In the nuclear power plant, it is necessary to remove the decay heat produced in nuclear fuel during the long time after the reactor shutdown. It is also necessary to supply the devices responsible for the radiation protection of people and environment. How important is to ensure the auxiliaries power supply may be seen on the example of Fukushima Daiichi nuclear power plant accident. After the earthquake and tsunami on March 11th, 2011 the total loss of auxiliaries' power supply occurred. That caused loss of reactor core cooling. In effect three hydrogen explosions took place, partial core meltdown and results radioactive emission to the environment. For that reason, despite that auxiliaries used in nuclear power plants are like corresponding devices in conventional thermal plants, the auxiliaries' power supply systems in nuclear power plant should be much more expanded. They need to be more reliable and provide coverage of a broader scope of events. Also, the power leading-out systems (which transfer the electric power from generator to the power grid) in nuclear power plants have specific features related to specific expectations.

With the occurrence of the three major nuclear accidents (Three Mile Island, Chernobyl, Fukushima), nuclear safety issues have become the lifeblood for nuclear power development in the world. In the article [1], the histories of nuclear reactor safety development are reviewed in terms of the "birth of atomic energy", "birth of nuclear reactor safety", "development of nuclear reactor safety", "dilemma of nuclear reactor safety", "rebirth of nuclear reactor safety". Some authors paid attention on specific risk for nuclear power safety such as aircraft crush [2] or extreme earthquake [3].

Some specific issues of electric systems in nuclear power plants were also described in literature. Issue of cables used in auxiliaries' network of a nuclear power plant was researched in [4]. Author considered the effect of the resistance of the cable supplying power to the electric motor in the 0.4 kV auxiliaries' network of a nuclear power plant on the starting current and, hence, on the current set point for the circuit breaker, on its sensitivity to short-circuit current, and on the cable size.

Other aspects of auxiliary motors were analyzed in [5]. The existing technique of switching on the auxiliaries' reserve network of an NPP formulates the switch-on commands directly after a shutdown. Due to delay in activating the automatic switch, the command is completed with a certain time delay. It is proposed to determine, based on developed computer models of the actual equipment, the moments of formation of the reserve activation commands, thus ensuring smaller perturbations at the subsequent switch-on. Another reliability analysis of Diesel generator was led in [6]. Uncertainty analysis has been carried out through Monte Carlo simulations. Results of importance analysis and sensitivity study are used to identify significant contributors to unavailability.

However, the structural solutions of most frequently used electric systems ensuring high reliability level in nuclear power plants were not described there. That is why we present them below in this article.

2. CATEGORIES OF THE NUCLEAR POWER PLANT AUXILIARIES

The nuclear power plant auxiliaries can be divided onto three categories according to desired reliability level [7, 8, 9, 10, 11]. The first one category is equipment, for which power outage (longer than few seconds) is unacceptable, even in emergency conditions. Those are: control and measuring systems, control and protection systems of the reactor, valves actuators, emergency lighting, communication systems.

The second category includes equipment that require secure power supply. However, the short power outage, not longer than 3 minutes, is allowed. Those are devices providing the reactor and the main technological systems cooling, the reactor shutdowns and also the devices providing to locate a potential failure within the reactor building. Those are: equipment maintaining flow in the primary cooling circuit, emergency core cooling pumps, indirect primary pumps cooling equipment, auxiliary turbine-generator set shut-down systems, auxiliary ventilation systems, emergency feed water pumps, part of emergency lighting.

The third category includes other auxiliaries which require the reliability of power supply at the same level as corresponding devices in conventional thermal power plants. Those are, for example, condensate pumps and feed water pumps.

To assure a high reliability of power supply for the first and second category devices, the special secure power supply is used. Those systems should provide power supply even in case of total power loss on the generators terminals and power leading-out buses. The number of independent secure power supply sections corresponds to the number of emergency systems in the technological part of the nuclear power plant. In most cases three independent power sources and power supply systems are used: basic (primary), stand-by (secondary) and emergency. In normal conditions all AC devices are supplied from the auxiliaries' network and the DC devices are supplied from the battery directly or through the converters. In the emergency conditions the first category devices are supplied from the battery and the IInd category devices - from the independent autonomous source. Most frequently the Diesel generators units are used as such a source. The independent emergency power supply systems are designed as multiple and considering the adequate power reserve.

To achieve expected reliability of auxiliaries' power supply in nuclear power plants the following auxiliaries supply networks are used:

- 220, 110, 48 or 24 V DC network for supply Ist category devices;
- 400/230 V, AC network of secure supply for Ist category devices;
- 6 kV (or 10 kV) and 400/230 V, AC network of secure supply for IInd category devices;
- 6 kV (or 10 kV, sometimes two voltage levels 10 kV and 6 kV) and 400/230 kV, AC network for supply IIIrd category devices.

3. STANDARDS FOR QUALIFYING ELECTRICAL EQUIPMENT FOR NUCLEAR POWER PLANTS

All devices belonging to safety Classes shall go through the qualification process. Firstly, device is subjected to long-term loads corresponding to the normal environmental conditions and then comes to emergency loads. The most adverse conditions in which device could work are chosen for the qualification process. Design and qualification shall consider the effects of devices aging.

The qualification of nuclear power plant equipment as directly related to safety was described in the IEEE 323 Standards for Qualifying Class 1E Equipment for Nuclear Power Generating Substations from 1983 [12]. This is the standard for the qualification of Class 1E devices for nuclear power plants, currently existing as a common IEC/IEEE International Standard - 60780-323: 2016 - Nuclear facilities - Electrical equipment important to safety – Qualification [13]. It describes the basic requirements for the qualification of electrical equipment important for safety as well as interfaces (electrical and mechanical) to be used in nuclear facilities. Those rules, methods and procedures are used to qualify equipment, maintain and extend qualifications and update required qualifications, if the equipment is subjected to modifications.

The Class 1E of electrical equipment refers directly to devices and systems related to safety. This class includes power generators driven by Diesel engines, as well as measuring devices monitoring the neutron flux in the reactor core or the radiation level inside the containment. Class 1E for electrical equipment results from the functions performed by them in nuclear power plant systems, not in the technical specifications they meet. For example, a low voltage switch that is a spare part and meets all the requirements for use in nuclear power plant installations is not a 1E component if it stays in the warehouse not installed. When installed in a low voltage switchgear to separate Class 1E circuits from other circuits (non-Class 1E), it becomes a component of class 1E.

4. SOLUTIONS OF ELECTRIC SYSTEMS IN NUCLEAR POWER PLANTS

Electric part of nuclear power plant is a set of electric power equipment, interconnected using the electric current paths, designed to leading-out energy from the power plant to the electric power system (power leading-out system) and to supply auxiliaries (auxiliaries' power supply system).

The tasks of auxiliaries' power supply system in normal conditions differ significantly from the tasks that this system satisfies in the transient conditions: starts-up, shut-downs and failures. That's why it is necessary to separate the auxiliaries' power supply system: primary (basic) supply system, stand-by (reserve) supply system and emergency power supply system (safety system) [7, 8]. A functional diagram of the electric system in the nuclear power plant is shown in Figure 1.

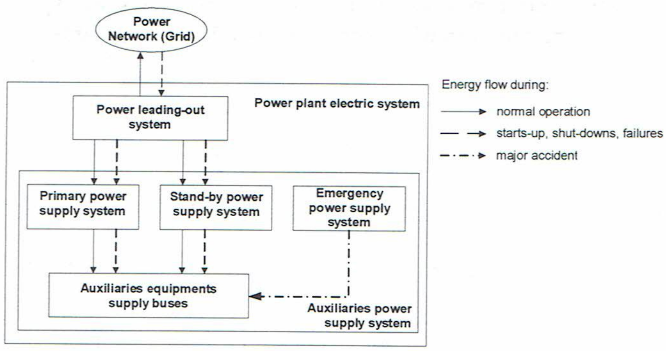

Fig 1. Functional diagram of the electric system in the nuclear power plant [7]

The power leading-out system include also plant substation but further discussion concerns power leading-out path only. At present two power leading-out path solutions can be found:

- single-unit power leading-out system, where each generator is connected to plant substation with a separated transmission line (block line);
- multi-unit power leading-out system (typically double-unit system), where several generators are connected to the plant substation with a single block line.

Two-unit systems are used only in older nuclear power plants. Compared to the single-unit systems they present a greater risk of unit "falling out" and they have less ability to fill various functions in case of emergency. In case of nuclear power plant equipped with the units (generators) at rated power above 1000 MW the solution with two power unit-transformers is also used. Currently the generator circuit breakers are commonly applied. Typical solutions of power leading-out systems in nuclear power plants are shown in Figure 2.

Solutions of power leading-out systems differ from each other functionally. This is due to the number and location of switches (circuit breakers). Choice of power leading-out system solution is a factor affecting the auxiliaries' power supply structure. When the generator circuit breaker is installed, it is possible to supply auxiliaries from the auxiliary transformer not only during the normal operation, but also during starts-up and failures. Then the separated stand-by supply system may be omitted, if it can shut-down unit using emergency sources.

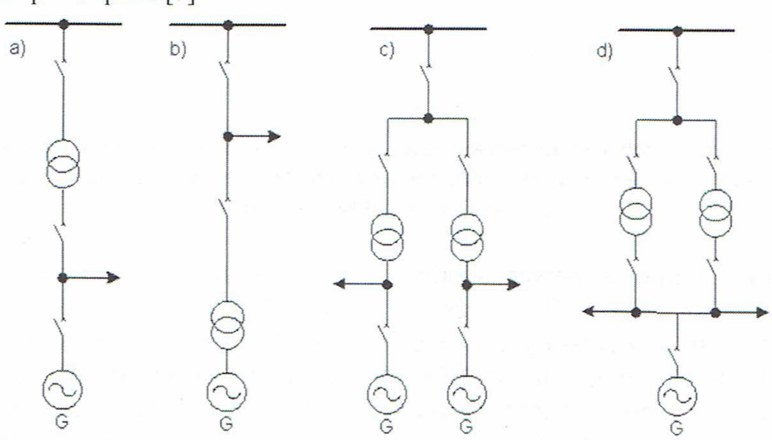

Fig. 2. Power leading-out systems used in nuclear power plants: a) single-unit system, b) single-unit system in EPR unit [14, 15], c) double-unit system, d) system used in plants, where units (generators) at rated power above 1000 MW are installed

The source of power for primary auxiliaries' power supply is commonly an auxiliary transformer. The task of this system is to provide auxiliary equipment supply during the normal operation, and if it is allowed by power leading-out system solution also during the starts-up and shutdowns. In the most widely used solutions the MV busbar is divided onto independent sections – usually 4. This results from approved redundancy rule. Auxiliaries are connected to proper sections in a way, that the scheduled start-up and shutdown were possible, using only one section supply. The most common primary auxiliaries' power supply systems in nuclear power plants are shown in Figure 3.

The task of the stand-by power supply system is to provide power supply for a nuclear unit technological load during the starts-up, shutdowns and failures, when it can't be executed by the basic (primary) supply system. Mostly this system is supplied from electric power network, independent from transmission network, to which nuclear unit is connected. It is also used the stand-by power supply powered from neighbour auxiliary's distribution switchboard. That solution reduces power supply reliability. The solution of stand-by auxiliaries' power supply systems used in nuclear plants are shown in Figure 4.

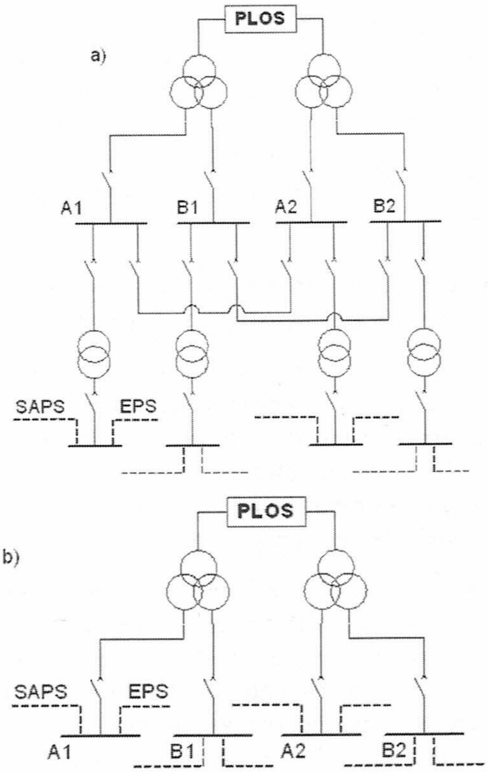

Fig. 3. Basic (primary) auxiliaries' power supply systems in nuclear power plants: a) system with two MV levels, b) system with one MV level: PLOS – power leading-out system; SAPS – stand-by auxiliaries' power supply system; EPS – emergency auxiliaries' power supply system; A, B – MV auxiliaries' distribution switchboard sections

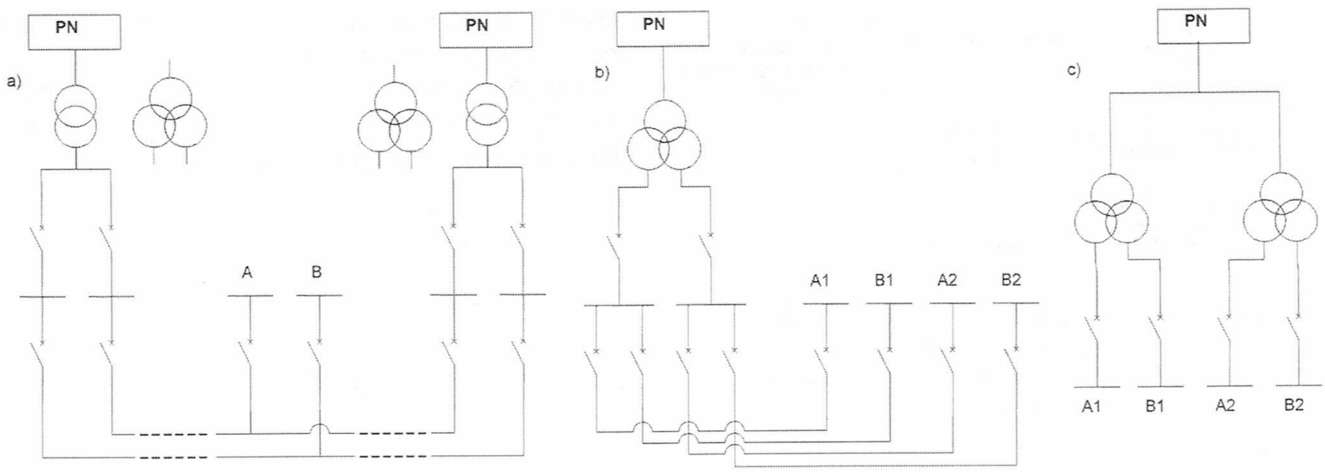

Fig. 4. Stand-by auxiliaries' power supply systems used in nuclear power plants: a) system with double bus bridge, b) system with one stand-by transformer, c) system with two transformers: PN – power network (power grid); A, B – MV auxiliaries distribution switchboard sections

The task of emergency auxiliaries power supply system, also known as safety system, is to supply those equipment, which work is necessary for safe nuclear unit shutdown in case of major failure. The configuration of the emergency power supply at the nuclear power plant must provide redundancy to increase the level of reliability. As a rule, at least two mutually recourse arrangements should be used, although three- or fourfold multiplexing is sometimes used. The source of power in this system are usually Diesel generators. The arrangement of the Diesel sets of the emergency supply system relative to the reactor building is also important for safety - individual units are placed at appropriate distances from each other on different sides of the reactor building, which provides additional protection against hazards coming from a particular direction – e.g. a large plane crash or wave impact tsunami to the area of the power plant. Such system should be able to start automatically in case of power failure on the safety busbars to which they are attached. Typical solution diagram is shown in Fig. 5.

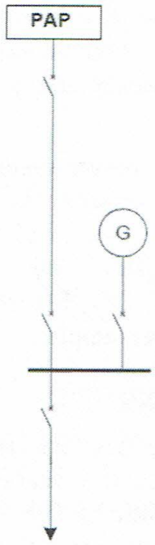

Fig. 5. Typical solution of emergency auxiliaries, power supply system: PAPS – primary (basic) auxiliaries' power supply system, G – Diesel generator unit

5. SOLUTIONS OF AUXILIARIES POWER SUPPLY IN CURRENTLY DEVELOPED PLANTS

The solution of auxiliaryies power supply system in power plants, which are presently designed, are result of many years of experiences using nuclear units. In the modern constructions the safety must by assured by the passive systems, which should work without on-site and off-site power supply. Despite of this the designs provide reliable power supply systems that minimize challenges to the passive safety systems.

The EPR is a third-generation pressurized water reactor (PWR) design. It's designed and developed by Areva, Electricité de France (EDF) and Siemens AG. Two of those units are under construction in Europe: Flamanville in France and Olkiluoto in Finland. The solution of auxiliaries power supply is shown in Figure 6.

The generator circuit breaker is given up – all switching operations take a place at HV side of step-up transformer. Power leading-out system is equipped with two circuit breakers, because of that is possible either: generation of power for own needs (captive) consumption purpose, island operation, also the unit start-up and shutdown using basic (primary) supply system. This system is supplied from power leading-out path through two three-winding auxiliaries transformers. Stand-by supply is executed using stand-by transformer, supplied from power network. The source of emergency supply are 4 independent Diesel generators attached to 10 kV network. Additional supply of security systems are two Diesel generators attached to 690 V secure network and set of batteries with converters. There are following auxiliaries' networks:

- 10 kV, AC power supply for general auxiliaries;
- 10 kV, AC guaranteed power supply;
- 690 V, AC networks guaranteed power supply;
- 400/230 V, AC general auxiliaries supply, 400/230 V, AC guaranteed power supply and 400/230 V, AC regulated power supply;
- 220 V DC guaranteed power supply.

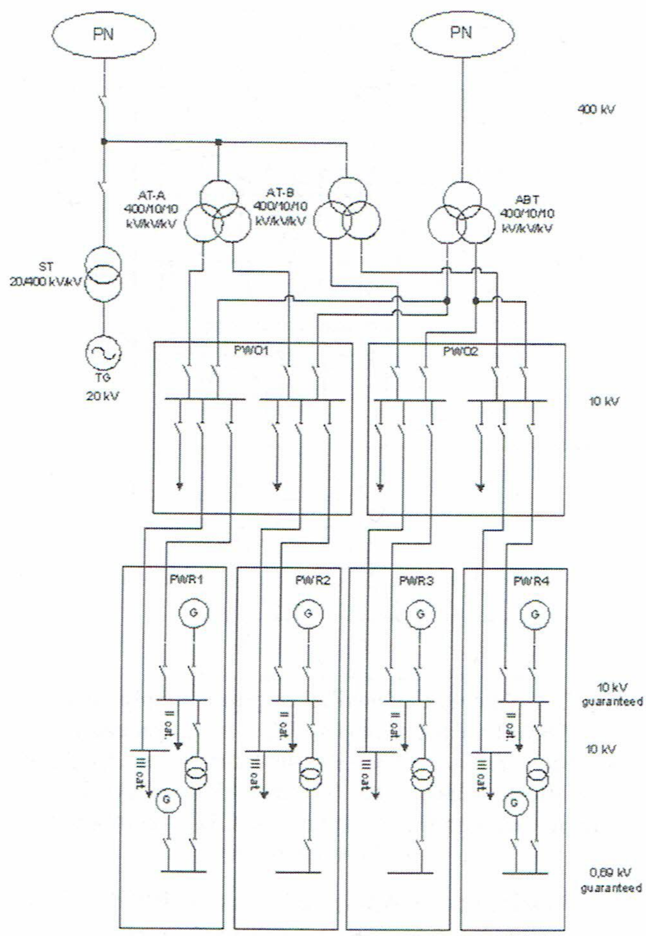

Fig. 6. Architecture of auxiliaries power supply system and arrangement of distribution boards in EPR nuclear unit [15], [16]: TG – main generator; PWO – general auxiliaries distribution board; PWR – reactor auxiliaries distribution board; PN – power network; ST – step-up transformer; AT-A, AT-B – auxiliaries transformers; ABT – auxiliaries stand-up transformer

Another third generation's unit is the Advanced Boiling Water Reactor (ABWR) currently offered by GE Hitachi Nuclear Energy (GEH) and Toshiba. The ABWR unit is the effect of evolution of boiling water reactor. Auxiliaries supply system is powered from power leading-out path through three three-winding auxiliaries transformers. Stand-by supply is executed using stand-by transformer, supplied from power network. Also, the combustion turbine generator is used as a source of stand-by power supply. The source of emergency supply are 3 independent Diesel generators attached to 4.16 kV network. The solution of auxiliaries power supply is presented in Figure 7.

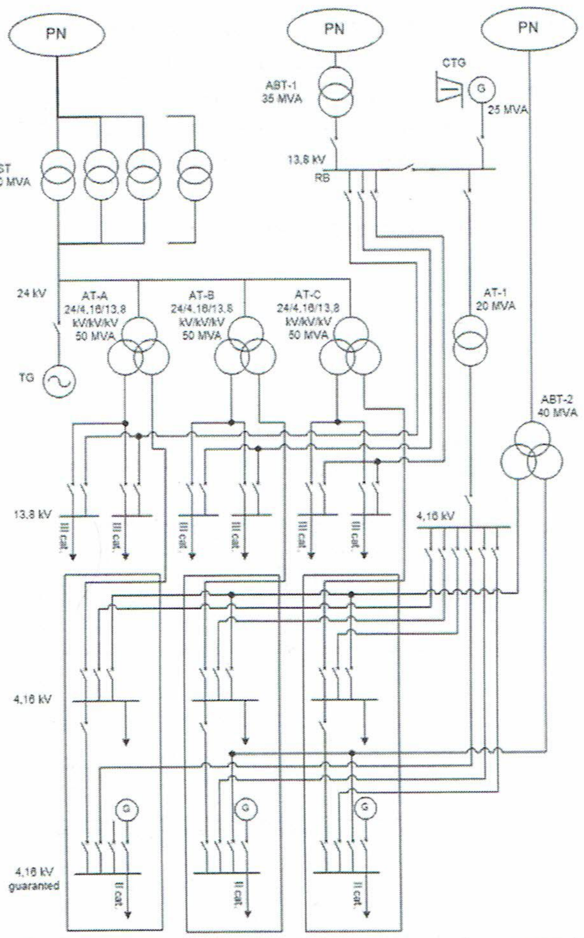

Fig. 7. Architecture of auxiliaries power supply system in ABWR nuclear unit [14]: TG – main generator; PN – power network; ST – step-up transformer; AT-A, AT-B, AT-C – auxiliaries transformers; ABT-1, ABT-2, AT – auxiliaries stand-up transformers; CTG – combustion turbine generator

The Westinghouse Advanced Passive PWR AP1000 is the third-generation pressurized water reactor (PWR) based on the earlier AP600 design [17].

The main generator is connected to the off-site power system via three single-phase main step-up transformers. The normal power source for the plant auxiliary AC loads is provided from the 24 kV generator buses through the two-unit auxiliary transformers. In case of a loss of the main generator supply, the power is maintained without interruption from the preferred power supply by an auto-trip of the generator breaker.

The emergency AC power system is powered by the two standby diesel generators. The plant DC power system comprises two independent DC power systems. Each system consists of ungrounded stationary batteries, DC distribution equipment and uninterruptible power supplies.

6. CONCLUSIONS

The work of the nuclear power plants cannot negatively influence the health of people and the environmental conditions. For that reasons the safety is of the first priority before the economic reasons in the construction and the operation of nuclear power plants. A prevention of hypothetical risk is based on two fundamental principles. The first one is "the defense in depth" based on the installation of multiple "defense lines" against the failure of devices or human errors. The second is security systems redundancy. This approach influences also the electric systems used in nuclear power plants. The auxiliaries power supply systems are desired to be reliable not only during the normal operation, reactor start-ups and shutdowns, but also during the major accidents. In comparison to the conventional thermal power plants of similar capacity the auxiliaries supply systems are characterized by the increased reliability of power supply and larger functional possibilities. In the structure of auxiliaries supply system of nuclear power plants all three basic subsystems are present: primary (basic), start-up and emergency power supply.

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ANALIZA STRUKTUR UKŁADÓW ELEKTRYCZNYCH W ELEKTROWNIACH JĄDROWYCH Z PODKREŚLENIEM ZAPEWNIENIA NIEZAWODNOŚCI OPERACYJNEJ

Słowa kluczowe: układy elektryczne elektrowni, układy potrzeb własnych, elektrownia jądrowa, niezawodność, EPR, ABWR, AP 1000

Streszczenie: W artykule dokonano analizy struktur układów elektrycznych w elektrowniach jądrowych, ze szczególnym uwzględnieniem zapewnienia niezawodności operacyjnej. Autorzy skupili się na różnych zagadnieniach dotyczących niezbędnych warunków bezpiecznej pracy elektrowni jądrowej. Układy zasilania potrzeb własnych muszą być projektowane tak, aby zapewnić maksymalny poziom niezawodności zasilania najważniejszych odbiorników potrzeb własnych. W elektrowni jądrowej konieczne jest usuwanie ciepła wytwarzanego w paliwie jądrowym przez długi czas po wyłączeniu reaktora. Konieczne jest również zasilanie urządzeń odpowiedzialnych za ochronę radiologiczną ludzi i środowiska. Autorzy przeanalizowali kategorie urządzeń potrzeb własnych elektrowni jądrowej oraz standardy kwalifikowania urządzeń elektrycznych dla elektrowni jądrowych. Część elektryczna elektrowni jądrowej to zespół urządzeń elektroenergetycznych, połączonych torami prądowymi, przeznaczony do wyprowadzenia energii z elektrowni do systemu elektroenergetycznego (układ wyprowadzenia mocy) oraz do zasilania potrzeb własnych (układ zasilania potrzeb własnych). Zadania układu zasilania potrzeb własnych w normalnych warunkach znacznie odbiegają od zadań, które spełnia ten układ w warunkach przejściowych: rozruchy, wyłączenia i awarie. Kolejnym elementem artykułu jest przegląd rozwiązań zasilania potrzeb własnych w obecnie budowanych elektrowniach jądrowych. W artykule przedstawiono rozwiązania układów zasilania potrzeb własnych w wybranych elektrowniach, które są obecnie projektowane i / lub budowane.

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