Determination of adverse events combinations in functioning of hydroelectric power plants

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Abstract. The article considers the development of algorithms and models for determining the probability of an adverse combination of events affecting the operational safety of a hydroelectric power plant. While developing the mathematical support, the formal apparatus of the Markov processes theory was used, thus making it possible to determine the occurrence probability of unfavorable combinations of events, each of which separately does not have a significant effect on the safety of the operation of the HPP from the solution of the Kolmogorov-Chapman system of differential equations. The results obtained can be used in the development of DSS.

1. Introduction

A hydroelectric power plant is a complicated and potentially dangerous control object characteristic for a plethora of parameters changing with time. The 2009 Sayano–Shushenskaya hydroelectric power plant accident that occurred on the 17th of August, 2009 has clearly demonstrated the possibility and consequences of a human mistake in the control circuit. A structure chart of that HPP is presented in Figure 1 below.

A set of HPP control systems has been already developed and tested: computer-aided process control systems (CAPCS) «Apogey» (“APOGEE”) “Micronica”, hardware-software complex «Ovatsiya» (“Applause”) and others. [1].
Meanwhile, as demonstrated by practice, the use of approaches, models and methods of Failure Modes and Effects Analysis (FMEA) alongside cause-and-effect theory allows one to increase safety of HPP operation by improving efficiency and quality of object control [1-7]. This article describes a mathematical model and an algorithm allowing one to evaluate the possibility of an alarm condition attributed to a failure in one or many HPP’s control elements.

2. Mathematical model

2.1. EVENT TREE

A worldwide-accepted methodology of a fault tree is used in this article for the purpose of developing systems reliability models. A fault tree is a logical model used to determine the occurrence of a basic or vertex event, meaning the system’s failure to perform its given functions due to the combinations of primary or elementary events that are the faults of system’s separate elements.
Figure 2 below gives an example of a fault tree for a hydropower unit safety accident. The symbols “G” mark the final states while the symbols “F” mark the initiating events.

2.2. CALCULATION OF A FAILURE PROBABILITY

The indicator used to describe a safety system’s reliability is probability $F_j(T,t_p)$ of system’s failure to exercise a given safety function after receiving one request for it. Along with this indicator, an “integral” indicator is also used, which is a probability of a failure to perform a given set of safety functions averaged over the initiating event:

$$F_j(T,t_p) = \frac{\sum_{i=1}^{l_j} \lambda_i F_{ij}(T,t_p)}{\sum_{i=1}^{l_j} \lambda_i}.$$  

$G_j$

\[ \begin{array}{c}
G_4 \\
\text{and} \\
G_6 \\
\text{of} \\
G_11 \\
G_12
\end{array} \]

$F_7$

\[ \begin{array}{c}
G_5 \\
\text{of} \\
F_1 \\
F_2 \\
F_3 \\
G_7 \\
G_1 \\
F_15 \\
F_1 \\
F_2 \\
F_3
\end{array} \]

$F_8$

\[ \begin{array}{c}
F_9 \\
F_10 \\
G_8 \\
F_11 \\
G_13 \\
F_12 \\
G_2
\end{array} \]

$F_16$

\[ \begin{array}{c}
F_13 \\
F_14 \\
F_1 \\
F_2 \\
F_3
\end{array} \]

Figure 2. A fault tree for a hydropower unit safety accident [9]

where $l_j$ is a number of initiating events types, in relation to which a safety system has a different structure; $\lambda_i$ - the intensity of occurrence of the $i$-th type initiating event.

A method used for calculating the aforementioned indicators is based on the fault trees method usage, by means of which the sets of inoperative states for the system are defined as minimum sections.

According to this method, the probability of system’s failure to operate a given function is expressed by the formula (so-called improved upper estimation):

$$F_i(T,t_p) = 1 - \prod_{l=1}^{l_j} [1 - F_l(T,t_p)],$$

where $l_j$ – a multitude of minimum sections of the system; $F_i(T,t_p)$ – a probability of the 1st minimal section occurrence.

Thus, a definition of the probability of a safety system’s fault in executing its functions comes down to defining a set of minimum sections, that is performed during the stage of qualitative analysis of reliability, and calculating $F_i(T,t_p)$ for the separate minimum sections.

The probability of determining the process in state 15 is the probability required for realizing the minimum section\(^1\) [2].

The Kolmogorov-Chapman system of differential equations for a given case has the form:

$$\frac{dp_0}{dt}(t) = -(1 + 2 + 3 + 4)p_0(t) + \mu_1 p_1(t) + \mu_2 p_2(t) + \mu_3 p_3(t) + \mu_4 p_4(t);$$

$$\frac{dp_1}{dt}(t) = -(2 + 3 + 4 + \mu_1)p_1(t) + \mu_2 p_2(t) + \mu_3 p_3(t) + \mu_4 p_0(t) + 1 p_0(t);$$

\(^1\)The probability of a system fault.
\[
\frac{dP_2}{dt}(t) = -(1 + 3 + 4 + \mu_2)P_2(t) + \mu_1 P_5(t) + \mu_3 P_7(t) + \mu_4 P_9(t) + 2 P_0(t);
\]
\[
\frac{dP_3}{dt}(t) = -(1 + 2 + 4 + \mu_3)P_3(t) + \mu_1 P_6(t) + \mu_2 P_7(t) + \mu_4 P_{10}(t) + 3 P_0(t);
\]
\[
\frac{dP_{14}}{dt}(t) = -(1 + \mu_2 + \mu_4 + \mu_3)P_{14}(t) + 2 P_{10}(t) + 3 P_9(t) + 4 P_7(t);
\]
\[
\frac{dP_{15}}{dt}(t) = 4 P_{11}(t) + 3 P_{12}(t) + 2 P_{13}(t) + 1 P_{14}(t).
\]

The system is based on a state diagram shown in Figure 3.

**Figure 3.** State diagram representing states of 4-element section

The graph of change in the minimum section occurrence probability in the time interval is shown in Figure 2.
Figure 4. The probability graph for a four-element section realisation in time $\lambda_1=0.05; \lambda_2=0.01; \lambda_3=0.03; \lambda_4=0.01; \mu_1=0.1; \mu_2=0; \mu_3=0.03; \mu_4=0.041$.

The probability for a realisation of a minimum section is decreased due to the restoration of elements. However, the common trend in safety system’s failure probability will have a monotonously increasing character. The results obtained may be used to enhance manufacturing process managing systems by the method developed in [1,2]

3. Conclusion
1. A mathematical model has been developed to determine the occurrence probabilities of adverse events combinations that affect the operational safety of the HPP.
2. An event tree has been made for the Sayano–Shushenskaya HPP accident case, making it possible to determine the minimum cross-sections that characterize various types of adverse combinations of events in the hydroelectric power station operating.

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$^1\mu_i$ is the restoration rate of the i-th element.