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Assessment of the level of reliability of power supplies of the objects of critical infrastructure

M Krzykowski[1,*], **J Paś**[2], **A Rosiński**[3]

[1] University of Warmia and Mazury in Olsztyn, Faculty of Law and Administration, Warszawska 98, 10-702 Olsztyn, Poland
[2] Military University of Technology, Faculty of Electronic, gen. Sylwestra Kaliskiego 2, 00-908 Warsaw, Poland
[3] Warsaw University of Technology, Faculty of Transport, Koszykowa 75, 00-662 Warsaw, Poland

E-mail: m.krzykowski.mk@gmail.com

Abstract. In a document titled "The National Critical Infrastructure Protection Programme" developed by the Government Centre for Security in the Republic of Poland, 11 systems falling within the critical infrastructure were characterised. These systems are essential for proper functioning of the country. Their carried-out tasks provide the continuity of the administrative structure functioning, as well as protect citizens from different kinds of danger (both external and internal ones). The safety of critical infrastructure facilities depends not only on the applied individual technological and procedural solutions in these systems but also on their power supply systems' proper designing and operation (also including electromagnetic interferences). Therefore, in this article, the authors analysed the power supply systems that can be used in the critical infrastructure facilities. However, only supplying electricity to the device is not equivalent to provision of its operation continuity and the appropriate level of values of the reliability and exploitation indices. Therefore, redundant power supply systems are used. The power supply system composed of two independent power sources was subjected to the safety level assessment. The obtained results will make it possible, among others, to rationalise the energy system structures.

1. Introduction

„Critical infrastructure" is present in the Polish legal system e.g., in the:
- Law of 18.07.2001 – Water Resources Law,
- Law of 29.10.2010 on strategic reserves,
- Law of 18.03.2010 on the special powers of the minister competent for the matters of the State Treasury and their execution in certain capital companies or capital groups operating in the electricity, petroleum and gas sectors,
- Law of 24.08.2007 on the participation of the Republic of Poland in the Schengen Information System and the Visa Information System,
- Law of 29.11.2000 – atomic law,
- Law of 24.05.2013 on the use of force and firearms. However, a complete and legal definition of the above mentioned phrase can be found in the Law of 26.04.2007 on crisis management.In the light of cited act of law, "critical infrastructure" is understood as *"systems and mutually bound functional*

objects contained therein, including constructions, facilities, installations and services of key importance for the security of the state and its citizens, as well as serving to ensure efficient functioning of public administration authorities, institutions and enterprises " (art. 3 (2) of the law). In the same article, the legislator enlists systems (understood as a group of elements that constitute a complete system) included in the infrastructure, i.e.

- Energy, fuel and energy resources supply systems,
- Communication systems,
- Tele-information network systems,
- Financial systems,
- Food supply systems,
- Water supply systems,
- Health protection systems,
- Transportation systems,
- Rescue systems,
- Systems ensuring the continuity of public administration activities,
- Systems of production, storing and use of chemical and radioactive substances, including pipelines for hazardous substances.

In general, those systems have a fundamental meaning for proper functioning of the whole country in its entirety. Tasks that they execute provide continuous operation of administrative structures, as well as protect citizens from various types of threats (both internal and external) [35]. Detailed rules and goals of the critical infrastructure protection programme are described in "The National Critical Infrastructure Protection Programme" developed by the Government Centre for Security of the Republic of Poland [1].

Among the mentioned systems, transport is one of the most important. Its composition included [1]:

- railway transport,
- road transport,
- air transport,
- pipeline transport,
- inland shipping,
- maritime shipping.

At present, the safe transport of people and goods requires the provision of an appropriate level of safety to transport facilities (stationary [2,3] and mobile [4]). Therefore, electronic safety systems are used. They increase the safety level with respect to different types of threats (including terrorism). They are designed on the basis of the following systems distinguished depending on the detected hazards, as:

- intrusion detection systems (SSWiN),
- fire alarm systems (SSP),
- access control systems (SKD),
- CCTV systems,
- protection of external sites.

Nowadays, in view of a quite high risk of terrorist acts and other threats of a criminal nature, it is important to make the integrated safety system counter threats as broadly as possible in the transport process. At the same time, the reliability and exploitation indices of the applied systems should be rational [5,6], adequate to the protected transport facilities and the functions they implement. Therefore, the particular attention was paid to the power supply systems used in the electronic safety systems.

In terms of general considerations, the reliability and exploitation theory includes a literature base established for years [7,8]. In these publications, the authors carried-out a reliability analysis of systems, which makes it possible to include their structure: serial, parallel as well as serial and parallel ones. It allowed to develop the graphs of transitions between the distinguished technical states. By using a specified mathematical method (e.g. Kolmogorov-Chapman equation), it is possible to obtain the relationships that allow to determine the probability values of the system's staying in the assumed states [9,10]. This kind of the methodology can be applied to the reliability and exploitation analysis of the power supply system of the critical infrastructure facilities.

The issues related to reliability and exploitation of power supply systems have been considered in references for many years. Among them, the items [11,12] can be classified as the most important ones.

One of the most interesting includes the item [11], in which the issues related to the reliability of energy systems were presented. The relationship between the reliability and expenditure for its growth was shown. Furthermore, the systems' reliability models, including the damage and repair intensity, were also offered. The probability distribution of the analysed energy systems' reliability indices was also determined. The reliability graph containing the state of usability and unfitness as well as the graph additionally including the state of the device's exclusion from the entire system operation were also presented.

Another one that is interesting from the perspective of the scientific considerations includes the item [12], in which the deliberations within the scope of the electric power supply systems' reliability and quality were also demonstrated. The examples of different types of energy networks were given and the reliability and exploitation calculations were conducted for them. The values of the specific reliability indices, which can be taken into consideration in these types of power supply systems, were also characterized.

In order to increase the values of the systems' reliability indices, the reserve power supply systems [13-15] were used. In these developments, the emergency power supply systems, such as: uninterruptible power supply devices [UPS], generators, as well as environmentally friendly solutions in a form of solar panels or power generators propelled by the force of wind, were analysed. The conducted analyses allowed to explicitly state that their application makes it possible to increase the values of the reliability and exploitation indices. Of course, in this type of solutions, the appropriately designed systems controlling the transition between the applied electrical power sources as well as the systems managing the power grid are indispensable [16,17]. The optimization issues of power supply systems were described in the papers [18,19].

Despite the carried-out analyses in terms of reliability and exploitation of power supply systems, it seems to be necessary to conduct deliberations in the scope of the reliability and exploitation analysis of the power supply systems used in the critical infrastructure facilities. The safety of these facilities depends not only on the applied individual technological and procedural solutions [20,21] in these systems but also on their power supply systems' proper designing and operation (also including electromagnetic interferences [22-25], vibration [26], quality of information obtained from the systems [27,28]). Legal aspects are also very important [29,30]. The authors analysed the power supply systems that can be used in the critical infrastructure facilities. The electricity supply to the facility is a basis of its proper functioning. It means that the power supply, with required parameters for a given device, should be connected to individual electric receivers. However, only supplying electricity to the device is not equivalent to provision of its operation continuity and the appropriate level of values of the reliability and exploitation indices. Therefore, redundant power supply systems are used. The power supply system composed of two independent power sources was subjected to the safety level assessment.According to authors, this approach is justified because redundant power supply units are used in many structures of critical infrastructure.

2. Reliability and exploitation analysis of power supply systems

In order to reliably operate, the electronic safety systems, which are used in the critical infrastructure facilities, require providing appropriate power supply of individual devices included in their composition. Their damage constitutes a failure in the system operation, the result of which can be a downtime in operation of the entire system or its part [31-34]. Therefore, two independent sources of power supply are used for devices. The first one includes the basic power supply. In the event of its breakdown, the system automatically switches to the reserve power supply. It was demonstrated in Figure 1.

By analysing the operation of the electronic safety system's power supply used in the critical infrastructure transport facility, it is possible to illustrate the relationships in it, as shown in Figure 2.

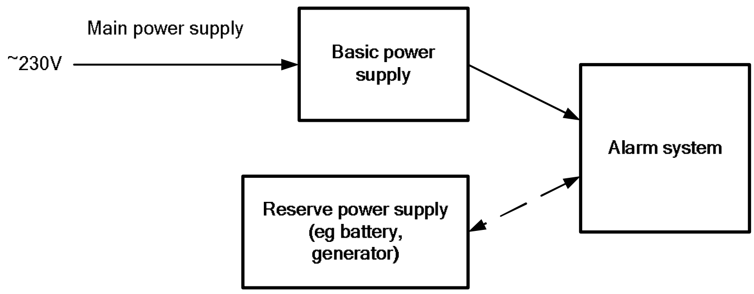

Figure 1. Example of the power supply from basic and reserve sources.

The damage to the basic power supply results in the transition from the state of complete usability S_{PZ} to the state of impendency over safety S_{ZB1}. The restoration of the state of usability to the basic power supply results in the transition from the state of impendency over safety S_{ZB1} to the state of compete usability $S_{PZ.}$ When the power supply system is in the state S_{ZB1} and the damage to the reserve power supply will occur, there is the transition to the state of unreliability of safety S_B.

The damage to the reserve power supply results in the transition from the state of complete usability S_{PZ} to the state of impendency over safety S_{ZB2}. The restoration of the state of usability to the reserve power supply results in the transition from the state of impendency over safety S_{ZB2} to the state of complete usability $S_{PZ.}$ When the power supply system is in the state S_{ZB2} and the damage to the basic power supply will occur, there is the transition to the state of unreliability of safety S_B.

It is also possible for the system to transit from the state of impendency over safety S_{ZB1} to the state of impendency over safety S_{ZB2} with the intensity λ_R. Such a situation occurs when there is a damage to the reserve power supply during restoration of the state of usability.

In their further considerations, the authors have accepted the exponential distribution characterized by constant intensity of damage over time. It is the consequence of using electronic devices in power supplies of electronic security systems. At the same time, other components of the power grid are also characterized by a constant parameter over time that is expressed by intensity of damage (according to values provided in scientific papers [14,15]).

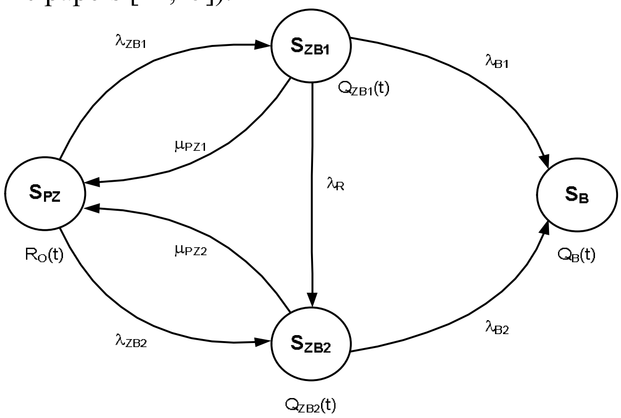

Figure 2. Relationships in the power supply system of the electronic safety system used in the critical infrastructure transport facility.

Markings in Figure 2:

- $R_O(t)$ – probability function in the system's staying in the state of complete usability S_{PZ},
- $Q_{ZB1}(t)$ – probability function of the system's staying in the state of impendency over safety S_{ZB1},
- $Q_{ZB2}(t)$ – probability function of the system's staying in the state of impendency over safety S_{ZB2},
- $Q_B(t)$ – probability function in the system's staying in the state of unreliability of safety S_B,
- λ_{ZB1} – intensity of transitions from the state of complete usability S_{PZ} to the state of impendency over safety S_{ZB1},
- λ_{ZB2} – intensity of transitions from the state of complete usability S_{PZ} to the state of impendency over safety S_{ZB2},
- μ_{PZ1} – intensity of transitions from the state of impendency over safety S_{ZB1} to the state of complete usability S_{PZ},
- μ_{PZ2} – intensity of transitions from the state of impendency over safety S_{ZB2} to the state of complete usability S_{PZ},
- λ_R – intensity of transitions from the state of impendency over safety S_{ZB1} to the state of impendency over safety S_{ZB2},
- λ_{B1} – intensity of transitions from the state of impendency over safety S_{ZB1} to the state of unreliability of safety S_B,
- λ_{B2} – intensity of transitions from the state of impendency over safety S_{ZB2} to the state of unreliability of safety S_B.

The system presented in Figure 2 can be described by the following Chapman–Kolmogorov equations:

$$\begin{aligned}
R_0'(t) &= -\lambda_{ZB1} \cdot R_0(t) + \mu_{PZ1} \cdot Q_{ZB1}(t) - \lambda_{ZB2} \cdot R_0(t) + \mu_{PZ2} \cdot Q_{ZB2}(t) \\
Q_{ZB1}'(t) &= \lambda_{ZB1} \cdot R_0(t) - \mu_{PZ1} \cdot Q_{ZB1}(t) - \lambda_{B1} \cdot Q_{ZB1}(t) - \lambda_R \cdot Q_{ZB1}(t) \\
Q_{ZB2}'(t) &= \lambda_{ZB2} \cdot R_0(t) - \mu_{PZ2} \cdot Q_{ZB2}(t) - \lambda_{B2} \cdot Q_{ZB2}(t) + \lambda_R \cdot Q_{ZB1}(t) \\
Q_B'(t) &= \lambda_{B1} \cdot Q_{ZB1}(t) + \lambda_{B2} \cdot Q_{ZB2}(t)
\end{aligned} \tag{1}$$

Assuming the baseline conditions:

$$\begin{aligned}
&R_0(0) = 1 \\
&Q_{ZB1}(0) = Q_{ZB2}(0) = Q_B(0) = 0
\end{aligned} \tag{2}$$

and applying the Laplace transform, the following system of linear equations is obtained:

$$\begin{aligned}
s \cdot R_0^*(s) - 1 &= -\lambda_{ZB1} \cdot R_0^*(s) + \mu_{PZ1} \cdot Q_{ZB1}^*(s) - \lambda_{ZB2} \cdot R_0^*(s) + \mu_{PZ2} \cdot Q_{ZB2}^*(s) \\
s \cdot Q_{ZB1}^*(s) &= \lambda_{ZB1} \cdot R_0^*(s) - \mu_{PZ1} \cdot Q_{ZB1}^*(s) - \lambda_{B1} \cdot Q_{ZB1}^*(s) - \lambda_R \cdot Q_{ZB1}^*(s) \\
s \cdot Q_{ZB2}^*(s) &= \lambda_{ZB2} \cdot R_0^*(s) - \mu_{PZ2} \cdot Q_{ZB2}^*(s) - \lambda_{B2} \cdot Q_{ZB2}^*(s) + \lambda_R \cdot Q_{ZB1}^*(s) \\
s \cdot Q_B^*(s) &= \lambda_{B1} \cdot Q_{ZB1}^*(s) + \lambda_{B2} \cdot Q_{ZB2}^*(s)
\end{aligned} \tag{3}$$

By transforming the system of equations (3), a record in the schematic view is obtained:

$$R_0^*(s) = -\frac{b_1 \cdot b_2}{b_2 \cdot \lambda_{ZB1} \cdot \mu_{PZ1} - a \cdot b_1 \cdot b_2 + b_1 \cdot \lambda_{ZB2} \cdot \mu_{PZ2} + \lambda_R \cdot \lambda_{ZB1} \cdot \mu_{PZ2}}$$

$$Q_{ZB1}^*(s) = -\frac{b_2 \cdot \lambda_{ZB1}}{b_2 \cdot \lambda_{ZB1} \cdot \mu_{PZ1} - a \cdot b_1 \cdot b_2 + b_1 \cdot \lambda_{ZB2} \cdot \mu_{PZ2} + \lambda_R \cdot \lambda_{ZB1} \cdot \mu_{PZ2}} \tag{4}$$

$$Q_{ZB2}^*(s) = -\frac{b_1 \cdot \lambda_{ZB2} + \lambda_R \cdot \lambda_{ZB1}}{b_2 \cdot \lambda_{ZB1} \cdot \mu_{PZ1} - a \cdot b_1 \cdot b_2 + b_1 \cdot \lambda_{ZB2} \cdot \mu_{PZ2} + \lambda_R \cdot \lambda_{ZB1} \cdot \mu_{PZ2}}$$

$$Q_B^*(s) = -\frac{b_2 \cdot \lambda_{B1} \cdot \lambda_{ZB1} + b_1 \cdot \lambda_{B2} \cdot \lambda_{ZB2} + \lambda_R \cdot \lambda_{B2} \cdot \lambda_{ZB1}}{b_2 \cdot s \cdot \lambda_{ZB1} \cdot \mu_{PZ1} - a \cdot b_1 \cdot b_2 \cdot s + b_1 \cdot s \cdot \lambda_{ZB2} \cdot \mu_{PZ2} + s \cdot \lambda_R \cdot \lambda_{ZB1} \cdot \mu_{PZ2}}$$

where:

$a = s + \lambda_{ZB1} + \lambda_{ZB2}$

$b_1 = s + \mu_{PZ1} + \lambda_{B1} + \lambda_R$

$b_2 = s + \mu_{PZ2} + \lambda_{B2}$

By conducting the further mathematical analysis, the relationships which allow to determine the probabilities of the power supply system's staying in the states of: complete usability S_{PZ}, impendency over safety S_{ZB1} and S_{ZB2} as well as unreliability of safety S_B, are obtained.

Owing to the use of the computer assistance, the calculations enabling determination of the probability value of the power supply system's staying in the state of complete usability can be made. Such a procedure is shown in the following example.

Example

The following values describing the analysed system are assumed:

- test duration – 1 year (value of this time is given in the units as hours [h]):

$$t = 8760 \; [h]$$

- intensity of transitions from the state of complete usability to impendency over safety I:

$$\lambda_{ZB1} = 0.000006$$

- intensity of transitions from the state of complete usability to impendency over safety II:

$$\lambda_{ZB2} = 0.000001$$

- intensity of transitions from the state of impendency over safety I to the state of impendency over safety II:

$$\lambda_R = 0.01$$

- intensity of transitions from the state of impendency over safety I to the state of unreliability of safety:

$$\lambda_{B1} = 0.000001$$

- intensity of transitions from the state of impendency over safety II to the state of unreliability of safety:

$$\lambda_{B2} = 0.000006$$

- intensity of transitions from the state of impendency over safety I to the state of complete usability:

$$\mu_{PZ1} = 0.1$$

- intensity of transitions from the state of impendency over safety II to the state of complete usability:

$$\mu_{PZ2} = 0.2$$

As a result of transformations, it is possible to obtain:

$$R_0(t) = 0.0000016669 \cdot e^{-0.2000063 \cdot t} + 0.9999377327 \cdot e^{-1.00900772 \cdot 10^{-10} \cdot t} +$$
$$+ 0.0000606002 \cdot e^{-0,11000766 \cdot t}$$

As a final result, it is possible to obtain: $R_O = 0.999936849$

In the presented model of the power supply of the electronic safety system used in the critical infrastructure transport facility, it was assumed that the state of unreliability of safety constitutes an absorbing state. By comparing all sorts of manufacturer solutions and their use in actual conditions, it is aimed at a failure to achieve this state by the system.

The presented model of the power supply of the electronic safety system used in the critical infrastructure transport facility can be used for determining the probability values of the analyzed systems' staying in the states of: complete usability S_{PZ}, impendency over safety S_{ZB1} and S_{ZB2} as well as unreliability of safety S_B. It will then make it possible to compare different types of solutions and to select a specific one, which meets the assumed criteria.

3. Conclusion

The article presents the reliability and exploitation analysis of the power supply systems of the electronic safety system used in the critical infrastructure transport facility. It allowed to offer a graph of relationships in the considered system, and then to create Chapman–Kolmogorov system of equations, which describes it. On this basis, it was possible to determine the relationships that allow to calculate the probability values of the power supply system's staying in the states of: complete usability S_{PZ} , impendency over safety S_{ZB1} and S_{ZB2} as well as unreliability of safety S_B. The presented approach allows, among others, to rationalise the structures of power supply systems. In the further studies, it is planned to carry-out analyses taking into account other types of power supply systems, and to develop a computer programme, which constitutes an exemplification of the obtained deliberations.Currently, commercial software of this kind is already available, nonetheless the authors are planning to develop their original software that could be used in the teaching process that concerns technical studies (majors: electronics and telecommunication, energetics).

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