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A RELIABILITY-EXPLOITATION ANALYSIS OF A STATIC CONVERTER TAKING INTO ACCOUNT ELECTROMAGNETIC INTERFERENCE

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The paper presents issues associated with the impact of electromagnetic interference on static converters, which exploitation in a railway transport environment. The measurements of an electromagnetic field emitted by a static converter were shown. Designs of this kind are exploitation in railway facilities, therefore, they should not disturb the functioning of other equipment, the rail traffic control systems, in particular. As a result of the EMC tests, it was concluded that the permissible values of conducted interference emissions were exceeded. An analysis of the obtained results enabled developing a research model, and a further reliability and exploitation analysis, taking into account electromagnetic interference. This, in turn, enabled determining a relationship allowing to determine the probability of a static converter staying in a state of full ability. The presented discussions regarding a static converter, taking into account electromagnetic interference, allow for the numerical assessment of different types of solutions (technical and organizational), which can be implemented in order to mitigate the impact of electromagnetic interference on a system's functioning.

Keywords: exploitation, reliability, electromagnetic interference, modelling, static converter

1. Introduction

Static converters exploitation in railway transport (especially in moving objects), most often function in diverse exploitation conditions. The observations of their exploitation process in a railway environment (Siergiejczyk *et al.*, 2016; Sunitha and Thomas, 2018) confirm the dependency of their correct exploitation on the reliability of their components, and an efficient exploitation management process (Chrzan, 2018; Dyduch *et al.*, 2011; Paś, 2015; Urbaniak *et al.*, 2019). Therefore, a thorough analysis of static converters should take into account not only their reliability but also the efficiency of exploitation management (Siergiejczyk *et al.*, 2015a). For this purpose, the authors imitated the phenomena undergoing in reality (taking into account electromagnetic interference) in a research model of a static converter.

Static converters are currently very often used in transport systems. Their task (in a railway vehicle) is to convert the constant traction voltage of 3000 V DC to low three-phase voltage 400 V AC and constant 24 V DC. The 400 V AC voltage is used to supply, i.e., auxiliary devices with high power demand (e.g. compressor drive motor). The 24 V DC voltage is used to supply, i.e., lighting system, signalling system, as well as onboard computers and control systems. The correct exploitation of a converter has a significant impact on the safety and efficiency of a transportation process. The state of unreliability of safety of these devices may lead to safety hazards. The theory of reliability deals with, among others, the analysis of damage impact on specified reliability indicators (Billinton and Allan, 1996; Girón *et al.*, 2018; Piegdoń *et al.*, 2018). The area of interest of the theory of safety includes the results of damages, which may lead to safety hazards (especially important from the point of view of a passenger and good transport process). Therefore, the issue of correctly defining, which state can be deemed permissible or unacceptable from the point of view of safety (the impendency over safety states) is very important.

Increasing the safety level of transport systems can be achieved by, among others, improving their reliability parameters. The reliability of a converter is impacted by both the reliability of its components, as well as the use of redundant structures. The first solution is aimed at preventing damage. In the second

case, the use of redundancy, although leading to an expansion of the converter, enables tolerating the occurring damage (through the introduction of the impendancy over safety states) (Caban and Walkowiak 2019). The quality of information (Siergiejczyk *et al.*, 2017; Stawowy and Kasprzyk, 2015; Stawowy and Siergiejczyk, 2017; Stawowy *et al.*, 2017) obtained by systems from the sensors (Dabrowski *et al.*, 2012; Kaniewski *et al.*, 2017; Łabowski and Kaniewski, 2015; Reddig *et al.*, 2018; Bednarek *et al.*, 2019) is also important during a reliability-exploitation analysis. Certain scientific papers propose that scientific discussions apply the principles of artificial neural networks (Duer, 2012; Krzykowska and Krzykowski, 2019) or fuzzy logic (Losurdo *et al.*, 2017). Functioning of static converters is also significantly impacted by the vibrations generated as a result of vehicle movement (Burdzik *et al.*, 2013; Kostrzewski, 2018; Kukulski *et al.*, 2019) but they are not taken into account in this article.

The impact of electromagnetic interference on the exploitation of various electrical and electronic devices used in transport has been attempted by scientists and engineers for a long time (Melit *et al.*, 2014; Niknejad, 2007; Piersanti *et al.*, 2018; Matyszek *et al.*, 2019). The analyses concern not only mobile means of transport but also stationary facilities (Kolarovszki *et al.*, 2013). However, there are still no detailed elaborations containing both the deliberations in the field of electromagnetic compatibility measurements, as well as the reliability-exploitation analysis of static converters.

Among others, the evaluation of electromagnetic compatibility taking into account the impact of atmospheric discharges on the exploitation of electronic devices has been, so far, discussed in regard to railway transport. The electronic devices used in transport are, i.a., rail traffic control systems, systems installed at level crossings, GSM-R (Global System for Mobile Communications – Railway), visual monitoring systems, etc. The analyses in that field were presented in the paper (Vašata and Doleček, 2016). The authors described various implemented methods of protection against adverse phenomena of this type. They also suggested solutions increasing the efficiency of the protection against discharges (i.a., through arrangement of electronic devices adequate to the environmental conditions already at the engineering stage of protection systems and elements).

The paper (Lheurette, 2013) should be cited among the most interesting scientific positions in the field of ensuring electromagnetic compatibility of electrical systems and devices. The elaboration describes issues associated with using various materials for the construction of mobile means of transport and their impact (including screening) on satisfying the requirements of electromagnetic compatibility.

A separate group of papers include the deliberations in the field of electromagnetic interference and electromagnetic compatibility of static converters. The authors of these positions present a generic approach towards this issue, not always taking into account the specific nature of rail transport and the requirements therein.

The paper (Nicolae *et al.*, 2010) presents issues regarding electromagnetic interference generated by static converters. It was shown that the permissible values of electromagnetic interference were exceeded, which is why the use of a filter was suggested. Repeated measurements confirmed the lack of exceeding limit values, hence, the validity of the adopted concept.

The issue of studying static converters in terms of electromagnetic interference was described in (Gharbi and Hasnaoui, 2014). In order to meet the EMI requirements, the authors suggested the use of passive filters. They conducted computer simulations with the use of a SPICE computer environment, confirming that the guidelines in standards 55016-2-1, EN 50121-3-2 were met. Next, they conducted experimental tests, which confirmed the validity of the conducted computer simulations.

The previous considerations (presented above) in the field of electromagnetic compatibility of static converters, taking into account electromagnetic interference, and the suggestions of solutions decreasing the level of electromagnetic interference, do not take reliability-exploitation modelling into account. This is why, the authors of this article decided to adopt such an approach, while bearing in mind the specificity of rail transport and the applicable normative requirements (RajaPriyanka *et al.*, 2017; White *et al.*, 2006; Wróbel, 2018).

The paper presents the measurements of an electromagnetic field emitted by a static converter. Solutions of this kind are installed in mobile railway objects, therefore, they should not disturb the functioning of other equipment, the rail traffic control systems, in particular. An analysis of the obtained results enabled developing a research model, and a further reliability-exploitation analysis, taking into account electromagnetic interference.

2. Reliability-Exploitation Analysis of a Static Converter Taking into Account the Electromagnetic Interference

The electromagnetic compatibility studies of a static converter were conducted with the use of a test bench (Figure 1). An EMI receiver of the ESCI3 type and a TK 9420 HV measuring probe were used. The used measuring equipment satisfied the requirements of the standard (PN-EN 55016-4-2:2011 + A1:2014).

The measurements were conducted as per the methodology presented in the standard (PN-EN 55016-2-1:2014). Electromagnetic radiation limit values were adopted as per the guidelines included in the standard for railway object (PN-EN 50121-3-2:2017).

Figure 1. Measuring system block diagram

A static converter with the following technical parameters was tested:

- supply voltage 3 kV DC,
- power 120 kVA,
- output AC voltage: 3x 400 V,
- output DC voltage: 24 V,
- overall efficiency: > 90%,
- exploitation temperature: $-40^{\circ}\text{C} \div +50^{\circ}\text{C}$.

The conducted interference emission measurement was conducted on a 3 kV DC input port.

The tests started with measurements of the static converter, with reported incorrectly selected input filter parameters (i.e. frequency band and rejection value for unwanted out-of-band signals)

Measurement of an asymmetric component between the + 3kV cable and the static converter casing is shown in Figure 2. Measurement of an asymmetric component between the + 3 kV cable and the static converter casing is shown in Figure 3. The limit values specified in relevant standards are exceeded in both cases.

Figure 2. Measurement of an asymmetric component between the + 3 kV cable and the static converter casing

Table 1 shows the values of frequencies where the limit levels of conducted interference emissions were exceeded.

Table 1. The values of frequencies with reported exceeded limit levels of conducted interference emissions between a +3 kV cable and a converter casing, and a -3 kV cable and a converter casing

Frequency value [kHz]	Interference signal amplitude value U[dBμV] for: + 3 kV cable and converter casing	Frequency value [kHz]	Interference signal amplitude value U[dBμV] for: - 3 kV cable and converter casing
322	101	258	101
390	103	382	102
400-500 /entire band/	max 110	400-500 /entire band/	max 110
500-600 /entire band/	max 98	500-600 /entire band/	max 98
3130	94	3182	95
4014	95	3978	96

Figure 3. Measurement of an asymmetric component between the - 3 kV cable and the static converter casing

The studies concerning the electromagnetic compatibility of conducted interference emissions of railway devices are in accordance with the methodology set out in the standard PN-EN 55016-2-1 for an asymmetric component of radioelectric disturbance voltage over a frequency range from 150 kHz to 30 MHz, divided into two frequency sub-ranges:

- 150 kHz ÷ 500 kHz,
- 500 kHz ÷ 30 MHz.

The limit levels of conducted interference emissions included in PN-EN 50121-3-2 are shown in Figure 4.

Figure 4. The permissible conducted interference emission values for a selected frequency band

In order to decrease the electromagnetic interference and meeting the requirements set out in the standards for railway equipment, it was decided to correct the filter parameters through adding capacitance of a specific value. Measurement of an asymmetric component between the +3 kV cable and the static converter casing is shown in Figure 5. Measurement of an asymmetric component between the +3 kV cable and the static converter casing is shown in Figure 6. The limit values are not exceeded in any of the two cases. Table 2 shows the values of interference signal amplitudes prior to and after using the filter with capacitance, and the differences resulting from attenuation introduced by the electronic system.

Figure 5. Measurement of an asymmetric component between the +3 kV cable and the static converter casing (after correcting filter parameters)

Figure 6. Measurement of an asymmetric component between the -3 kV cable and the static converter casing (after correcting filter parameters)

Table 2. Values of interference signal amplitudes prior to and after using the filter with capacitance, and the differences resulting from attenuation introduced by the electronic system

Frequency value [kHz]	Interference signal amplitude value U[dBμV] for: + 3 kV cable and converter casing, rejection value U[dBμV]			Frequency value [kHz]	Interference signal amplitude value U[dBμV] for: - 3 kV cable and converter casing, rejection value U[dBμV]		
	no filter	filter	rejection		no filter	filter	rejection
322	101	81	20	258	101	75	26
390	103	81	22	382	102	81	21
400-500 /entire band/	max 110	max 94	16	400-500 /entire band/	max 110	93	17
500-600 /entire band/	max 98	max 82	16	500-600 /entire band/	max 98	84	14
3130	94	77	17	3182	95	76	19
4014	95	82	13	3978	96	77	19

In the course of analysing the measurement results, it can be concluded that a static converted exploitation in a transport environment (with electromagnetic interference) can stay in defined states (Siergiejczyk *et al.*, 2015). Therefore, it was decided to conduct a reliability-exploitation analysis (Siergiejczyk *et al.*, 2017; Wasiak *et al.*, 2019; Klimczak and Paś, 2019). Conducting the analysis will provide relationships, which allow the determination of the probability values of the system being in the distinguished exploitation states.

The external electromagnetic field penetrates into the circuits of the static converter through the coupling mechanism producing interference. The electronic components of the static converter (Figure 7) are exposed to an external, unintentional electromagnetic field (PEM) from a specific frequency band. In this case, the transmission bus connecting the devices with the static converter is an unintentional receiving antenna that picks up the interference generated by the interference current. This coupling arises as a result of the PEM effect on the cable that transmits useful signals. The interference signal induced in the bus is suppressed by the shield of the transmission bus cable. The attenuation of the cable does not reach a large value, so part of the interference signal gets along with the useful signal to the static converter. It causes the changes of the reference potential (ground) of the static converter as a result of coupling through common impedance Z and ground loop. In a static converter (as a railway device) two types of coupling can be distinguished, series coupling (PEM) and parallel (through elements Z , C at the output operational amplifier OA). The following elements implement the coupling with PEM: it is the reference impedance Z , capacity C in relation to the metal cover of the entire railway device. These couplings can be minimized by reducing the parasitic capacity, or by reducing the rapid voltage changes occurring at C . Additional interference voltage also occurs in the ground loop for the entire device. This can also cause feedback through so-called crosstalk (inductive or capacitive). Especially in electrical wires that are near interference sources, i.e. U_{zak} voltage, the occurrence of a static voltage drop in the static converter may generate an alternating electric and magnetic field around this conductor. The alternating electric and magnetic field generates current and voltage, causing interference in cables near the transmission bus through capacitive crosstalk interference that affects other devices. Interference values are proportional to the rate of change of voltage (effect through capacitance - C) or current (effect through inductance – ground loop) over time.

Figure 7. Input circuits of the electrostatic converter subject to unintended electromagnetic interference

By conducting an exploitation analysis regarding a static converter, it is possible to illustrate the relationships occurring in such a structure, in terms of reliability and exploitation, as presented in Figure 8.

When determining the intensity of transitions between the distinguished states, the factor of electromagnetic interference Γ on the analyzed static converter was taken into account. Its value is in the range:

$$\Gamma \in \langle 0,1 \rangle. \quad (1)$$

We assume that:

- $\Gamma = 0$ in the absence of electromagnetic interference (the protection measures used completely eliminate the influence of electromagnetic interference on the static converter),
- $\Gamma = 1$ for the impact of electromagnetic interference (no protective measures are in place to reduce the effects of electromagnetic interference on a static converter).

The electromagnetic interference factor Γ on the analyzed static converter can be used to select rational solutions that reduce the impact of electromagnetic interference (Paś *et al.*, 2020).

Figure 8. Relations in a static converter, taking into account electromagnetic interference

Marking in the Figure 8:

- $R_O(t)$ – the probability function of the system staying in the state of full ability S_{PZ} ,
- Q_{ZB1} – the probability function of a system staying in a state of the impendency over safety I S_{ZB1} ,
- Q_{ZB2} – the probability function of a system staying in a state of the impendency over safety II S_{ZB2} ,
- $Q_B(t)$ – the probability function of a system staying in a state of unreliability of safety S_B ,
- λ_{ZB1} – intensities of transition from a state of full ability I S_{PZ} to a state of the impendency over safety I S_{ZB1} ,
- Γ_{ZB1} – the electromagnetic interference factor for the transition intensity λ_{ZB1} ,
- λ_{ZB2} – intensities of transition from a state of full ability II S_{PZ} to a state of the impendency over safety II S_{ZB2} ,
- Γ_{ZB2} – the electromagnetic interference factor for the transition intensity λ_{ZB2} ,
- μ_{PZ1} – intensities of transition from a state of the impendency over safety I S_{ZB1} to a state of full ability S_{PZ} ,
- μ_{PZ2} – intensities of transition from a state of the impendency over safety II S_{ZB2} to a state of full ability S_{PZ} ,
- μ_{B0} – intensities of transition from a state of the impendency over safety I S_{ZB1} to a state of full ability II S_{PZ} ,
- Γ_{B0} – the electromagnetic interference factor for the transition intensity μ_{B0} ,
- μ_{B1} – intensities of transition from a state of full ability S_{PZ} to a state of unreliability of safety S_B ,
- λ_{B1} – intensities of transition from a state of the impendency over safety I S_{ZB1} to a state of unreliability of safety S_B ,
- Γ_{B1} – the electromagnetic interference factor for the transition intensity λ_{B1} ,
- λ_{B2} – intensities of transition from a state of the impendency over safety II S_{ZB2} to a state of unreliability of safety S_B ,
- Γ_{B2} – the electromagnetic interference factor for the transition intensity λ_{B2} ,
- λ_B – intensities of transition from a state of full ability I S_{PZ} to a state of unreliability of safety S_B ,
- Γ_B – the electromagnetic interference factor for the transition intensity λ_B .

The state of full ability S_{PZ} is a state, in which a static converter functions correctly. The impendency over safety I S_{ZB1} is a state in which a static converter is partially fit (parallel coupling through mutual impedance). The impendency over safety II S_{ZB2} is a state in which a static converter is

partially fit (parallel coupling through board capacity relative to the casing). Unreliability of safety S_B is a state in which a static converter is unfit (electromagnetic interference exceed limit values).

If a static converter is in a state of full ability S_{PZ} and the interference appears in the form of parallel coupling through common impedance, then the system switches to a state of the impendancy over safety I S_{ZB1} with the intensity of λ_{ZB1} . If a static converter is in the state of the impendancy over safety I S_{ZB1} , then it is possible to switch to the state of full ability S_{PZ} , provided that actions are taken aimed at restoring the fitness state.

In the event of a state of the impendancy over safety I S_{ZB1} and the interference exceeding permissible values, the a static converter moves to a state of unreliability of safety S_B with an intensity of λ_{B1} .

If a static converter is in a state of full ability S_{PZ} and the interference appears in the form of parallel coupling through board capacitance relative to the casing, then the system switches to a state of the impendancy over safety II S_{ZB2} with the intensity of λ_{ZB2} . If a static converter is in the state of the impendancy over safety II S_{ZB2} , then it is possible to switch to the state of full ability S_{PZ} , provided that actions are taken aimed at restoring the fitness state.

In the event of a state of the impendancy over safety II S_{ZB2} and the interference exceeding permissible values, a static converter moves to a state of unreliability of safety S_B with an intensity of λ_{B2} .

If a static converter is in a state of the impendancy over safety I S_{ZB1} and the interference changes from parallel coupling through common impedance to interference in the form of parallel coupling through board capacitance relative to the casing, a static converter switches to a state of the impendancy over safety II S_{ZB2} with the intensity of μ_{B0} .

If a static converter is in a state of full ability S_{PZ} and the arising electromagnetic interference exceed the limit values, it moves to a state of unreliability of safety S_B with the intensity of μ_{B1} .

A static converter illustrated in Figure 8 can be described by the following Chapman–Kolmogorov equations:

$$\begin{aligned} R_0'(t) &= -\Gamma_{ZB1} \cdot \lambda_{ZB1} \cdot R_0(t) + \mu_{PZ1} \cdot Q_{ZB1}(t) - \Gamma_{ZB2} \cdot \lambda_{ZB2} \cdot R_0(t) + \mu_{PZ2} \cdot Q_{ZB2}(t) - \Gamma_B \cdot \mu_B \cdot R_0(t). \\ Q_{ZB1}'(t) &= \Gamma_{ZB1} \cdot \lambda_{ZB1} \cdot R_0(t) - \mu_{PZ1} \cdot Q_{ZB1}(t) - \Gamma_{B1} \cdot \lambda_{B1} \cdot Q_{ZB1}(t) - \Gamma_{B0} \cdot \mu_{B0} \cdot Q_{ZB1}(t). \\ Q_{ZB2}'(t) &= \Gamma_{ZB2} \cdot \lambda_{ZB2} \cdot R_0(t) - \mu_{PZ2} \cdot Q_{ZB2}(t) - \Gamma_{B2} \cdot \lambda_{B2} \cdot Q_{ZB2}(t) + \Gamma_{B0} \cdot \mu_{B0} \cdot Q_{ZB1}(t). \\ Q_B'(t) &= \Gamma_{B1} \cdot \lambda_{B1} \cdot Q_{ZB1}(t) + \Gamma_{B2} \cdot \lambda_{B2} \cdot Q_{ZB2}(t) + \Gamma_B \cdot \mu_B \cdot R_0(t). \end{aligned} \quad (2)$$

Given the initial conditions:

$$\begin{aligned} R_0(0) &= 1, \\ Q_{ZB1}(0) &= Q_{ZB2}(0) = Q_B(0) = 0 \end{aligned} \quad (3)$$

and Laplace transform yields the following system of linear equations:

$$\begin{aligned} s \cdot R_0^*(s) - 1 &= -\Gamma_{ZB1} \cdot \lambda_{ZB1} \cdot R_0^*(s) + \mu_{PZ1} \cdot Q_{ZB1}^*(s) - \Gamma_{ZB2} \cdot \lambda_{ZB2} \cdot R_0^*(s) + \\ &+ \mu_{PZ2} \cdot Q_{ZB2}^*(s) - \Gamma_B \cdot \mu_B \cdot R_0^*(s). \\ s \cdot Q_{ZB1}^*(s) &= \Gamma_{ZB1} \cdot \lambda_{ZB1} \cdot R_0^*(s) - \mu_{PZ1} \cdot Q_{ZB1}^*(s) - \Gamma_{B1} \cdot \lambda_{B1} \cdot Q_{ZB1}^*(s) - \Gamma_{B0} \cdot \mu_{B0} \cdot Q_{ZB1}^*(s). \\ s \cdot Q_{ZB2}^*(s) &= \Gamma_{ZB2} \cdot \lambda_{ZB2} \cdot R_0^*(s) - \mu_{PZ2} \cdot Q_{ZB2}^*(s) - \Gamma_{B2} \cdot \lambda_{B2} \cdot Q_{ZB2}^*(s) + \Gamma_{B0} \cdot \mu_{B0} \cdot Q_{ZB1}^*(s). \\ s \cdot Q_B^*(s) &= \Gamma_{B1} \cdot \lambda_{B1} \cdot Q_{ZB1}^*(s) + \Gamma_{B2} \cdot \lambda_{B2} \cdot Q_{ZB2}^*(s) + \Gamma_B \cdot \mu_B \cdot R_0^*(s). \end{aligned} \quad (4)$$

Transforming it, a record in the schematic (Laplace) view is obtained:

$$\begin{aligned} R_0^*(s) &= -\frac{b_1 \cdot b_2}{b_2 \cdot \Gamma_{ZB1} \cdot \lambda_{ZB1} \cdot \mu_{PZ1} - a \cdot b_1 \cdot b_2 + b_1 \cdot \Gamma_{ZB2} \cdot \lambda_{ZB2} \cdot \mu_{PZ2} + \\ &+ \Gamma_{B0} \cdot \mu_{B0} \cdot \Gamma_{ZB1} \cdot \lambda_{ZB1} \cdot \mu_{PZ2}} \cdot \\ Q_{ZB1}^*(s) &= -\frac{b_2 \cdot \Gamma_{ZB1} \cdot \lambda_{ZB1}}{b_2 \cdot \Gamma_{ZB1} \cdot \lambda_{ZB1} \cdot \mu_{PZ1} - a \cdot b_1 \cdot b_2 + b_1 \cdot \Gamma_{ZB2} \cdot \lambda_{ZB2} \cdot \mu_{PZ2} + \\ &+ \Gamma_{B0} \cdot \mu_{B0} \cdot \Gamma_{ZB1} \cdot \lambda_{ZB1} \cdot \mu_{PZ2}} \cdot \\ Q_{ZB2}^*(s) &= -\frac{b_1 \cdot \Gamma_{ZB2} \cdot \lambda_{ZB2} + \Gamma_{B0} \cdot \mu_{B0} \cdot \Gamma_{ZB1} \cdot \lambda_{ZB1}}{b_2 \cdot \Gamma_{ZB1} \cdot \lambda_{ZB1} \cdot \mu_{PZ1} - a \cdot b_1 \cdot b_2 + b_1 \cdot \Gamma_{ZB2} \cdot \lambda_{ZB2} \cdot \mu_{PZ2} + \\ &+ \Gamma_{B0} \cdot \mu_{B0} \cdot \Gamma_{ZB1} \cdot \lambda_{ZB1} \cdot \mu_{PZ2}} \cdot \end{aligned}$$

$$Q_B^*(s) = - \frac{b_1 \cdot b_2 \cdot \Gamma_B \cdot \mu_B + b_2 \cdot \Gamma_{B1} \cdot \lambda_{B1} \cdot \Gamma_{ZB1} \cdot \lambda_{ZB1} + b_1 \cdot \Gamma_{B2} \cdot \lambda_{B2} \cdot \Gamma_{ZB2} \cdot \lambda_{ZB2} + \Gamma_{B0} \cdot \mu_{B0} \cdot \Gamma_{B2} \cdot \lambda_{B2} \cdot \Gamma_{ZB1} \cdot \lambda_{ZB1}}{b_2 \cdot \Gamma_{ZB1} \cdot \lambda_{ZB1} \cdot \mu_{PZ1} - a \cdot b_1 \cdot b_2 + b_1 \cdot \Gamma_{ZB2} \cdot \lambda_{ZB2} \cdot \mu_{PZ2} + \Gamma_{B0} \cdot \mu_{B0} \cdot \Gamma_{ZB1} \cdot \lambda_{ZB1} \cdot \mu_{PZ2}}, \quad (5)$$

where:

$$\begin{aligned} a &= s + \Gamma_{ZB1} \cdot \lambda_{ZB1} + \Gamma_{ZB2} \cdot \lambda_{ZB2} + \Gamma_B \cdot \mu_B, \\ b_1 &= s + \mu_{PZ1} + \Gamma_{B1} \cdot \lambda_{B1} + \Gamma_{B0} \cdot \mu_{B0}, \\ b_2 &= s + \mu_{PZ2} + \Gamma_{B2} \cdot \lambda_{B2}, \\ c &= s. \end{aligned} \quad (6)$$

By conducting further mathematical analysis, we obtain relationships, which allow the determination of probabilities of a static converter staying in states of: full ability S_{PZ} , the impendency over safety S_{ZB1} and S_{ZB2} , and unreliability of safety S_B .

3. Modelling the Exploitation Process of a Static Converter, Taking into Account Electromagnetic Interference

Simulation and computer methods and studies give an opportunity to determine influence of the reliability and maintenance parameters of particular elements on reliability of the entire system relatively fast.

Thanks to the computer assistance (mathematical program), it is possible to conduct the calculations enabling the determination of the probability R_O of a static converter staying in a state of full ability S_{PZ} . Such a procedure is shown in the following example (it was assumed that no dedicated solutions were used to reduce the effects of electromagnetic interference on a static converter, and therefore $\Gamma = 1$).

Example

Let us assume the following values describing the analysed a static converter:

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

$$t = 8760 [h];$$

- intensity of transitions from a state of full ability to a state of the impendency over safety I λ_{ZB1} :

$$\lambda_{ZB1} = 0.000001 [1/h];$$

- intensity of transitions from a state of full ability to a state of the impendency over safety II λ_{ZB2} :

$$\lambda_{ZB2} = 0.0000001 [1/h];$$

- intensity of transitions from a state of the impendency over safety I to a state of unreliability of safety λ_{B1} :

$$\lambda_{B1} = 0.0000001 [1/h];$$

- intensity of transitions from a state of the impendency over safety II to a state of unreliability of safety λ_{B2} :

$$\lambda_{B2} = 0.000001 [1/h];$$

- intensity of transitions from a state of the impendency over safety I to a state of full ability μ_{B0} :

$$\mu_{B0} = 0.00000001 [1/h];$$

- intensity of transitions from a state of full ability to a state of unreliability of safety μ_{B1} :

$$\mu_B = 0.00000001 [1/h];$$

- intensity of transitions from a state of the impendency over safety I to a state of full ability μ_{PZ1} :

$$\mu_{PZ1} = 0.1 [1/h];$$

- intensity of transitions from a state of the impendency over safety II to a state of full ability μ_{PZ2} :

$$\mu_{PZ2} = 0.2 [1/h].$$

The above values of damage intensity (marked with the symbol λ) were estimated on the basis of observation of the operation process of real systems (Chmielińska *et al.*, 2016, Klimczak and Paś, 2019). Railway equipment is subject to a pre-aging process in production plants. Therefore, an exponential distribution model of airworthiness was used.

Knowing the value of the integrity $R_{ZB1}(t)$, there can be estimated the intensity of the transition from the state of full ability to the state of the impendency over safety I λ_{ZB1} :

$$\lambda_{ZB1} = -\frac{\ln R_{ZB1}(t)}{t}.$$

For $t = 8760$ [h] and $R_{ZB1}(t) = 0.991278$ we get:

$$\lambda_{ZB1} = -\frac{\ln R_{ZB1}(t)}{t} = -\frac{\ln 0.991278}{8760} = 0.000001 \left[\frac{1}{h} \right].$$

Other damage intensities were calculated similarly.

The intensities of recovery of exploitation potential (marked with the symbol μ) were also estimated on the basis of observation of the process of exploitation of real systems (Paś, 2015, Klimczak and Paś, 2019). In the case of exponential distribution, these are the inverse of time.

The following is obtained for the above input values, using the equation (5):

$$R_0^*(s) = \frac{1.11 \cdot 10^{16} \cdot s + 1 \cdot 10^{16} \cdot \mu_{PZ1} + 1.1 \cdot 10^{15} \cdot \mu_{PZ2} + 1.1 \cdot 10^{22} \cdot s^2 + 1 \cdot 10^{22} \cdot s \cdot \mu_{PZ1} + 1 \cdot 10^{22} \cdot s \cdot \mu_{PZ2} + 1 \cdot 10^{22} \cdot \mu_{PZ1} \cdot \mu_{PZ2} + 1.1 \cdot 10^9}{1.3421 \cdot 10^{10} \cdot s + 1.1 \cdot 10^9 \cdot \mu_{PZ1} + 1.011 \cdot 10^9 \cdot \mu_{PZ2} + 1 \cdot 10^{22} \cdot s^2 \cdot \mu_{PZ1} + 1 \cdot 10^{22} \cdot s^2 \cdot \mu_{PZ2} + 2.22 \cdot 10^{16} \cdot s^2 + 1 \cdot 10^{22} \cdot s^3 + 1.11 \cdot 10^{16} \cdot s \cdot \mu_{PZ1} + 1.12 \cdot 10^{16} \cdot s \cdot \mu_{PZ2} + 1 \cdot 10^{14} \cdot \mu_{PZ1} \cdot \mu_{PZ2} + 1 \cdot 10^{22} \cdot s \cdot \mu_{PZ1} \cdot \mu_{PZ2} + 1221}. \quad (7)$$

As a result of transformations, we obtain:

$$R_0(t) = 0.9999895 \cdot e^{-1.000139 \cdot 10^{-8} \cdot t} + 5.00004299 \cdot 10^{-7} \cdot e^{-0.2000011 \cdot t} + 0.0000099998 \cdot e^{-0.1000011 \cdot t}.$$

As a final result, we obtain: $R_0 = 0.99990189$

If, for the data adopted in the above example, we assume the use of dedicated solutions reducing the effects of electromagnetic interference on the static converter, which result in a change in the value of all coefficients of the impact of electromagnetic interference on the value $\Gamma_{ZB1} = \Gamma_{ZB2} = \Gamma_{B0} = \Gamma_{B1} = \Gamma_{B2} = \Gamma_B = 0.5$, then the calculations will result in:

$$R_0(t) = 0.9999947 \cdot e^{-1.000032 \cdot 10^{-8} \cdot t} + 2.5000096 \cdot 10^{-7} \cdot e^{-0.2000005 \cdot t} + 0.0000049999 \cdot e^{-0.1000005 \cdot t}.$$

As a final result, we obtain: $R_0 = 0.99990715$

The presented reliability-exploitation analysis of a static converter, taking account of electromagnetic interference, enables numerical evaluation of different types of solutions (technical and organizational). This enables their implementation in order to mitigate the impact of internal and external electromagnetic interference (including the lack of a filter and the functioning of a filter matched to the extent of present interference) on the exploitation of a static converter.

It is also possible to use the developed model to determine the curves representing the dependencies of the probabilities of the static converter staying in the designated states as a function of the intensity of transitions between individual states. These issues will be explored by the authors in further research.

To sum up the considerations, it can be concluded that if the designers of static converters exploitation in rail transport are aware of the conditions of an electromagnetic environment (i.e., through measurements and reliability-exploitation analysis presented above) in which a system is to be probably functioning, then EMC requirements, which are usually known and can be taken into account at the device engineering stage, have to be met.

4. Conclusions

The current, very frequent use of static converters in numerous rail transport objects results in the necessity of their functioning in variable systems, located in close proximity. The effect of such technical and system solutions might be a case of increased level of electromagnetic interference, which impact the

system. The lack of ensured external (interaction of, e.g., two devices) and internal (interference inside a given device) electromagnetic compatibility in a railway device means a possibility of exploitationally unacceptable transitions between specified states. This may cause incorrect functioning of a static converter, hence, it can stay in the states of the impendency over safety or unreliability of safety. This is why, designing static converters should include planning their functioning in actual conditions, that is, in an environment with other electronic and electric devices, which satisfy the requirements regarding the permissible emission levels for conducted and radiated electromagnetic interferences in defined conditions. The presented reliability-exploitation analysis of a static converter, taking into account electromagnetic interference, may become helpful in that matter. It enables to numerically determine the value of probabilities of a converter staying in distinguished states in the course of electromagnetic interference, within a selected frequency range.

In further research concerning this issue, the authors plan to further develop reliability-exploitation models, which will differentiate between the states of the impendency over safety. This will allow a more accurate mapping of static converter functioning in an electromagnetic railway environment.

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