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MODELLING RELIABILITY OF UNINTERRUPTIBLE POWER SUPPLY UNITS

MODELOWANIE NIEZAWODNOŚCI ZASILACZY BUFOROWYCH*

This paper discusses issues related to reliability of uninterruptible power supplies equipped with automatic protection mechanisms (short circuit protection – SCP, overload protection – OLP, overvoltage protection – OVP). Relationships for determining probability of system states: full operational capability, partial capability and failure were derived. The impact of time taken to restore the state of full operational capability on probability of different system states was also analysed.

Keywords*: reliability, power supply, maintenance.*

W artykule przedstawiono zagadnienia związane z niezawodnością zasilaczy buforowych wyposażonych w automatyczne zabezpieczenia (przeciwzwarciowe - SCP, przeciążeniowe - OLP, nadnapięciowe - OVP). Wyznaczono zależności pozwalające określić prawdopodobieństwa przebywania systemu w stanach: pełnej zdatności, niepełnej zdatności i niezdatności. Dokonano również analizy wpływu czasu przywrócenia stanu pełnej zdatności na wartości prawdopodobieństw przebywania zasilacza w wyróżnionych stanach technicznych.

Słowa kluczowe*: niezawodność, zasilacz, proces eksploatacji.*

1. Introduction

Uninterruptible power supplies are exposed to various external factors, which over time can cause the system to switch from the state of full operational capability into the state of reached operational capability (failure). In order to increase probability of the state of full operational capability, the following protection devices are often used: short circuit protection, overload protection, overvoltage protection. In this paper reliability analysis of uninterruptible power supplies equipped with those devices was presented.

The reliability theory in respect of general considerations has had sound footing for many years [5, 9, 19]. Approaches towards reliability analysis presented in those publications allow for factoring in system structure: serial, parallel and serial-parallel. It is then possible to create transition graphs for above-mentioned states of capability. By employing an adequate mathematical apparatus (e.g. Chapman–Kolmogorov equation) a relationship is obtained for determining probability of system in given state [11, 12]. This type of methodology may be used for reliability analysis of uninterruptible power supply.

For references on operating principle and engineering of power supplies, the following publications are noteworthy [6, 18, 23]. Some of them discuss applications in specific areas of rail transport in particular [10].

Reliability analysis of power supply systems in presented in item [1]. Emergency power supplies (both static and dynamic type) received substantial attention. Using this solution increases the availability rate of the entire system.

Issues concerning reliability of power supply systems have been discussed for many years by different authors. The papers of most significance are items [3, 16, 17].

The paper [3] presents issues related to reliability of power supply systems. The relationship between reliability and investment outlays for its improvement was proven. Models of system reliability factoring in failure rate and repair rate were also presented. Probability distributions of reliability parameters were defined. Reliability graph was displayed which depicted the state of full and reached operational capability and a graph depicting down times of device.

Papers [16, 17] discuss issues related to reliability and quality of electric power systems. Examples of different power networks were given, reliability calculations were made. Values of certain reliability parameters were also given, which could be applied to other electric power supply system of that type.

Optimization problem of power supply system were described in paper [15]. Theoretics of optimisation were discussed. Consequently deriving optimisation procedures for analysed systems factoring in economic factors was possible. Some of the publications describe practical applications of such solutions [4].

Redundant sources of power were elaborated on in publications [8, 24, 25]. Their focus was very much on emergency power supplies such as: uninterruptible power supplies UPS, generating sets and environmentally friendly solutions i.e. solar panels and wind powered generators. Conducted analysis of above solutions proves unequivocally that they increase reliability parameters. Of course, required is control equipment switching between on-line electricity supplies and electricity grid management systems [20].

Item [8] describes reliability of power supply systems on the scale of United States of America. Profile of the organisations handling those issues was given: North American Electric Reliability Corporation (NERC). It was concluded, that using wind farms, solar panels and power generators increases reliability and power generating efficiency of the entire power system should terrorist attacks or natural disasters strike (e.g. hurricanes, tornadoes).

Despite studies completed on reliability of power supply systems, it seems necessary to carry out a functional analysis of power supplies and protection devices. That approach was presented under subsequent items of this paper.

2. Power supplies

Direct current and alternating current power supplies are widely used in many devices, including computer equipment. Power supply directly from the power network is the most convenient, both on-line and via a transformer. Substantial amount of devices, however, re-

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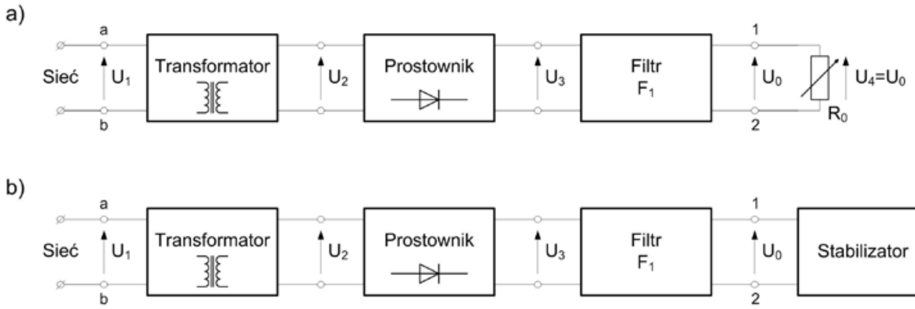

Fig. 1. Functional diagram of direct current power supply

quires direct current supply, hence direct current power supplies are used. They transform alternating current from the grid into stable direct current.

Figure 1. displays basic components of direct current power supplies. In general, they are equipped with the F_1 filter (fig. 1a) or - in more powerful versions - with additional voltage regulator (fig. 1b). The load marked as R_0 may have a variable value.

In order to protect the power supply from damage, the following protection devices are used:

- Short Circuit Protection – SCP,
- Over Load Protection – OLP,
- Over Voltage Protection – OVP.

Short circuit and overload protection devices protect the power supply's inputs and outputs from short-circuit over at the loaded side.

Overvoltage protection device protects units power by the power supply from overvoltage to maximum output voltage.

If power supply outputs were independent, neither short-circuit, overload nor overvoltage on any of the outputs should negatively affect functionality of other outputs.

Once the short-circuit, overload or the cause for overvoltage is removed, protection reset (either manually or automatically), the state of full operational capability should be restored on that output.

In general, power supplies interact with the broadly defined environment [14]. Therefore it is beyond doubt adequate reliability parameters have to be assured. Thus so important is the impact analysis of protection devices used in power supplies on selected reliability parameters [1, 7, 21, 22].

3. Reliability analysis of power supplies

The relationships occurring in power supply with protection devices (e.g. against short-circuit, overload and overvoltage) fitted to each of the two independent outputs have to be illustrated from the reliability perspective for purposes of the functional analysis. See figure 2 [13]. Those relationships do not cover all possible changes in system state of the power supply system (e.g. the transition from the state of full operational capability S_{PZ} to the state of reached operational capability S_N and reverse i.e. from S_N to S_{PZ} was ignored). Furthermore, failures on each output were assumed independent.

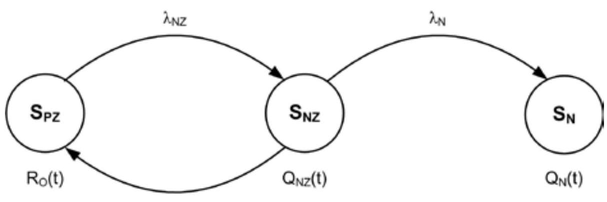

Fig. 2. Relationships occurring in uninterruptible power supply with protective devices

Denotations in figures:

$R_O(t)$ – the likelihood function of device in state of full operational capability,

$Q_{NZ}(t)$ – the likelihood function of device in state of partial operational capability,

$Q_{NZ}(t)$ – the likelihood function of device in state of reached operational capability,

λ_{NZ} – transition rate from the state of full operational capability into the state of partial operational capability,

μ_{PZ} – transition rate from the state of partial operational capability into the state of full operational capability,

λ_N – transition rate from the state of partial operational capability into the state of reached operational capability.

Failure of one output causes transition from the state of full operational capability S_{PZ} to the state of partial operational capability S_{NZ}. Removal of interference restores the state of full operational capability. Once the S_{NZ} state occurs (output failure), failure of the other, previously operational, output causes the power supply to switch into the state of reached operational capability S_N.

The relationship for determining probability of uninterruptible power supply unit in the state of full operational capability R_O (1), partial capability Q_{NZ} (2) and reached capability Q_N (3) is obtained from mathematical analysis (Chapman–Kolmogorov equation).

$$R_0(t)=\left[\begin{array}{l}\cos\left(\sqrt{2\cdot\lambda_{NZ}\cdot(\mu_{PZ}+\lambda_N)-4\cdot\mu_{PZ}\cdot\lambda_{NZ}-\lambda_{NZ}^2-(\mu_{PZ}+\lambda_N)^2}\cdot\frac{t}{2}\right)+\\ +\frac{\mu_{PZ}+\lambda_N-\lambda_{NZ}}{\sqrt{2\cdot\lambda_{NZ}\cdot(\mu_{PZ}+\lambda_N)-4\cdot\mu_{PZ}\cdot\lambda_{NZ}-\lambda_{NZ}^2-(\mu_{PZ}+\lambda_N)^2}}\cdot\\ \cdot\sin\left(\sqrt{2\cdot\lambda_{NZ}\cdot(\mu_{PZ}+\lambda_N)-4\cdot\mu_{PZ}\cdot\lambda_{NZ}-\lambda_{NZ}^2-(\mu_{PZ}+\lambda_N)^2}\cdot\frac{t}{2}\right)\end{array}\right]\cdot \cdot\exp\left[-\left(\frac{\lambda_{NZ}+\mu_{PZ}+\lambda_N}{2}\right)\cdot t\right] \quad (1)$$

$$Q_{NZ}(t)=\frac{2\cdot\lambda_{NZ}}{\sqrt{2\cdot\lambda_{NZ}\cdot\lambda_N-2\cdot\mu_{PZ}\cdot\lambda_{NZ}-\lambda_{NZ}^2-(\mu_{PZ}+\lambda_N)^2}}\cdot \cdot\sin\left(\sqrt{2\cdot\lambda_{NZ}\cdot\lambda_N-2\cdot\mu_{PZ}\cdot\lambda_{NZ}-\lambda_{NZ}^2-(\mu_{PZ}+\lambda_N)^2}\cdot\frac{t}{2}\right)\cdot \cdot\exp\left[-\left(\frac{\lambda_{NZ}+\mu_{PZ}+\lambda_N}{2}\right)\cdot t\right] \quad (2)$$

$$Q_N(t)=1-\left[\begin{array}{l}\cos\left(\sqrt{2\cdot\lambda_{NZ}\cdot(\mu_{PZ}+\lambda_N)-4\cdot\mu_{PZ}\cdot\lambda_{NZ}-\lambda_{NZ}^2-(\mu_{PZ}+\lambda_N)^2}\cdot\frac{t}{2}\right)+\\ +\frac{\mu_{PZ}+\lambda_N+\lambda_{NZ}}{\sqrt{2\cdot\lambda_{NZ}\cdot(\mu_{PZ}+\lambda_N)-4\cdot\mu_{PZ}\cdot\lambda_{NZ}-\lambda_{NZ}^2-(\mu_{PZ}+\lambda_N)^2}}\cdot\\ \cdot\sin\left(\sqrt{2\cdot\lambda_{NZ}\cdot(\mu_{PZ}+\lambda_N)-4\cdot\mu_{PZ}\cdot\lambda_{NZ}-\lambda_{NZ}^2-(\mu_{PZ}+\lambda_N)^2}\cdot\frac{t}{2}\right)\end{array}\right]\cdot \cdot\exp\left[-\left(\frac{\lambda_{NZ}+\mu_{PZ}+\lambda_N}{2}\right)\cdot t\right] \quad (3)$$

4. Modelling reliability of power supply units

Computer simulation and computer-aided analysis facilitate to relatively quickly determine the influence of change in reliability parameters of individual components on reliability of the entire system. Of course, the reliability structure of both the entire system and its components has to be known beforehand.

Computer aided-analysis enables to conduct impact analysis of the time taken to restore the state of full operational capability t_{PZ} on probability of the states of full operational capability R_O, partial capability Q_{NZ} and reached capability Q_N. That procedure is illustrated with below example.

Example

The following quantities were defined for the system:

– test duration - 1 year (values of this and the following parameters is given in [h]):

$$t = 8760\ [h]$$

– reliability of first power supply output track (including the receiver):

$$R_{NZ}(t) = 0{,}99$$

– reliability of second power supply output track (including the receiver):

$$R_N(t) = 0{,}999$$

Knowing the value of reliability $R_{NZ}(t)$, transition rate from the state of full operational capability into the state of partial operational capability may be estimated. Provided the up time is described by exponential distribution, the following relationship can be used:

$$R_{NZ}(t) = e^{-\lambda_{NZ} t} \text{ for } t \geq 0$$

thus

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

For $t = 8760\ [h]$ and $R_{NZ}(t) = 0{,}99$ we obtain:

$$\lambda_{NZ} = -\frac{\ln R_{NZ}(t)}{t} = -\frac{\ln 0{,}99}{8760} = 1{,}147298 \cdot 10^{-6} \left[\frac{1}{h}\right]$$

Knowing the value of reliability $R_N(t)$, transition rate from the state of partial operational capability into the state of full operational capability may be estimated. The following relationships are true for exponential distribution:

$$R_N(t) = e^{-\lambda_N t} \text{ for } t \geq 0$$

thus

$$\lambda_N = -\frac{\ln R_N(t)}{t}$$

For $t = 8760[h]$ and $R_N(t) = 0{,}999$ we obtain:

$$\lambda_N = -\frac{\ln R_N(t)}{t} = -\frac{\ln 0{,}999}{8760} = 1{,}142124 \cdot 10^{-7} \left[\frac{1}{h}\right]$$

transition rate from the state of partial operational capability to the state of full operational capability μ_{PZ} is – for exponential distribution – time inverse t_{PZ}:

$$\mu_{PZ} = \frac{1}{t_{PZ}}$$

The probability of analysed power supply in the above mentioned states of operational capability, assuming the time of restoring the state of full operational capability t_{PZ} falls within the interval $t_{PZ} \in \langle 12;168 \rangle\ [h]$ (i.e. after recalculation into days $t_{PZ} \in \left\langle 0{,}5\ ;\ 7 \right\rangle\ [day]$), is given by charts displayed in figures 3, 4 and 5. Values of time t_{PZ} were assumed based observation of actual systems.

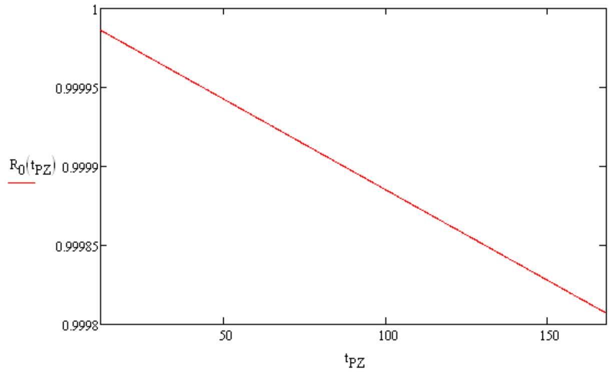

Fig. 3. The relationship between probability of power supply in the state of full operational capability R_0 as a function of time taken to restore full operational reliability t_{PZ}

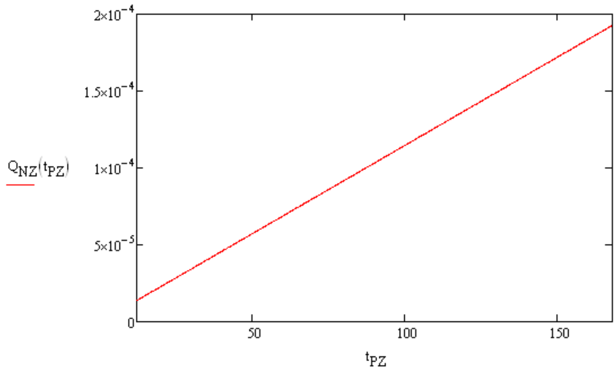

Fig. 4. The relationship between probability of power supply in the state of partial operational capability Q_{NZ} as a function of time taken to restore full operational reliability t_{PZ}

Figure 6 presents the relationship between probabilities of power supply being in the state of full operational capability R_O as a function of time taken to restore the state of full operational capability t_{PZ} on the assumption that t_{PZ} falls within the interval $t_{PZ} \in \langle 12;8500 \rangle\ [h]$ (i.e. after recalculation into days $t_{PZ} \in \left\langle 0{,}5\ ;\ 354{,}17 \right\rangle\ [day]$).

In charts presented in fig. 3, 4, 5, 6 and 7, denotations to the left of horizontal red lines mark the colour of analysed quantity line. Those are default denotations and colours used by computer-aided calculations software.

Analysis of relationships given in figures 3, 4, 5 and 6 concludes:

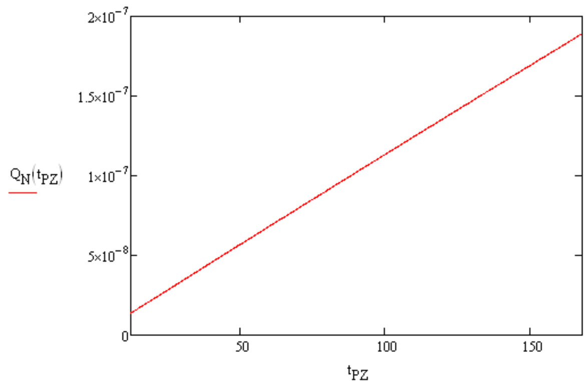

Fig. 5. The relationship between probability of power supply in the state of reached operational capability Q_N as a function of time taken to restore full operational reliability t_{PZ}

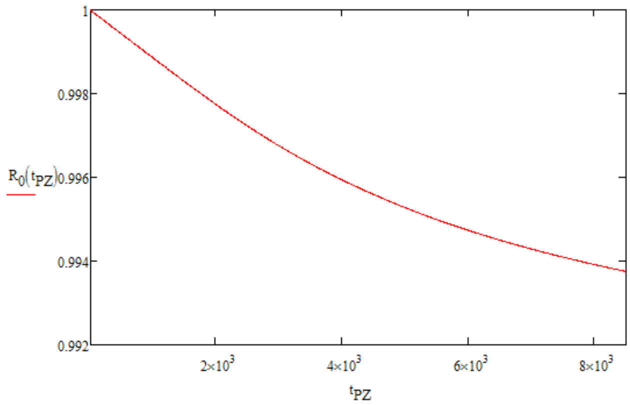

Fig. 6. The relationship between probability of power supply in the state of full operational capability RO as a function of time taken to restore full operational reliability $t_{PZ} \in \langle 0,5\ ;\ 354,17 \rangle\ [day]$

- the probability of power supply in the state of full operational capability R_0 as a function of time taken to restore full operational reliability t_{PZ} has maximum value for minimum value of t_{PZ} time,
- the probability of power supply in the state of partial operational capability Q_{NZ} as a function of time taken to restore full operational reliability t_{PZ} has maximum value for maximum value of t_{PZ} time,
- the probability of power supply in the state of reached operational capability Q_N as a function of time taken to restore full operational reliability t_{PZ} has maximum value for maximum value of t_{PZ} time,
- all three functions $R_0 = f(t_{PZ})$, $Q_{NZ} = f(t_{PZ})$, $Q_N = f(t_{PZ})$ are non-linear (according to relationships 1, 2 and 3; they resemble a straight line as per assumed t_{PZ}),
- the function $R_0 = f(t_{PZ})$ is a decreasing function,
- functions $Q_{NZ} = f(t_{PZ})$ and $Q_N = f(t_{PZ})$ are increasing functions.

Let us pose a question: how does the probability of either full of partial operational capability change relative to time taken to restore the state of full operational capability i.e. what is the shape of the function $\overline{Q_N} = f(t_{PZ})$. Respective calculations produced results presented in table 1 and in fig. 7.

Table 1. Value of the function $\overline{Q_N} = f(t_{PZ})$

$t_{PZ}\ [h]$	$\overline{Q_N} = f(t_{PZ})$
12	0.999999986244571
24	0.999999972527389
36	0.999999958848280
48	0.999999945207325
60	0.999999931604508
72	0.999999918039844
84	0.999999904513311
96	0.999999891024905
108	0.999999877574628
120	0.999999864162479
132	0.999999850788460
144	0.999999837452543
156	0.999999824154743
168	0.999999810895060

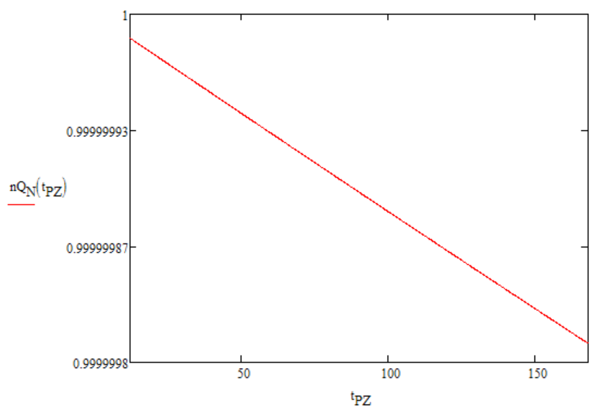

Fig. 7. The relationship between probability of power supply in the state of full or partial operational capability $\overline{Q_N}$ as a function of time taken to restore full operational reliability t_{PZ} (denotation in fig. nQ_N refers to the value of $\overline{Q_N}$).

What is clear, is that function $\overline{Q_N} = f(t_{PZ})$ has shape similar to function $R_0 = f(t_{PZ})$. However, for the same values of time taken to restore the state of full operational capability t_{PZ}, values of the function $\overline{Q_N}$ are greater than values of function R_0.

Graphs presented in fig. 3, 4, 5 and 7 seem to be straight lines, therefore suggest there is a linear relationship between analysed values of probability as a function of time taken o restore the state of full operational capability t_{PZ}. The reason being that the value t_{PZ} was assumed $t_{PZ} \in \langle 12;168 \rangle\ [h]$. By analysing the fig. 6 chart and assuming for purposes of the analysis solely the value $t_{PZ} \in \langle 12;168 \rangle \; [h]$, we obtain „roughly" straight lines. Actually they are curves, defined by non-linear relationships (formulae (1), (2) and (3)).

5. Conclusions

Reliability analysis of power supplies was presented in this paper. It focused especially on the influence of time taken to restore the state of full operational capability on probability of the states of full operational capability R_0, partial capability Q_{NZ} and reached capability Q_N. Analysis of results obtained proves that all four functions $R_0 = f(t_{PZ})$, $Q_{NZ} = f(t_{PZ})$, $Q_N = f(t_{PZ})$, $\overline{Q_N} = f(t_{PZ})$ are non-linear, functions $R_0 = f(t_{PZ})$ and $\overline{Q_N} = f(t_{PZ})$ are decreasing functions, whereas functions $Q_{NZ} = f(t_{PZ})$ and $Q_N = f(t_{PZ})$ are increasing functions. Hence reliability of power supplies improves when the time taken to restore the state of full operational capability – i.e. repair – is shorter. Of course, costs involved are higher. Further studies should aim to determine the relationship between financial outlays – incurred to improve the repair time – and the probability of predefined technical conditions.

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