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Determination of the Fail-Safety of Multichannel Voltage Converters with Power-Channel Rotation

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Abstract—One promising trend in making voltage converters more reliable is to design them on the basis of backbone modular architecture, combined redundancy, and rotation of main and backup power channels. A technique is proposed for this converter for calculating the upper and the lower failsafe operation probability estimates that is based on using the standardized model for the *sliding loaded redundancy* group. It is shown that the session rate of failures can be used as the channel fail-safety indicator in the rotation of channels. The proposed technique allows finding these estimates as time functions and considering the rate of channel failures not only in the converter's running mode, but in the standby mode as well. An example of calculating the converter's failsafe operation estimates is presented; a similar calculation by imitative modeling is provided to confirm the obtained results. It is shown that a shortened full channel rotation cycle makes the channels spend the resource in a more even manner, has no effect on the converter's fault-free performance figures at an *absolutely reliable* switch, and reduces them in the case of an *unreliable* switch.

Keywords: multichannel voltage converter, backbone modular architecture, power channel, rotation, reliability, redundancy, failsafe operation probability, residual life, failure rate

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One of the tasks in the process of designing power electronics products consists in attaining a required level of their fail-safety. One of the most popular ways of achieving this level in practice is redundancy. As was shown in [1], for example, voltage converters for attaining high fail-safety figures must be based on backbone modular architecture, including the combined redundancy of their power channels.

In the early phases of designing multichannel converters, fail-safety figures are found by calculation. It is obvious that, the more accurate the estimation of these figures, the higher the probability that the created specimen will meets the necessary requirements. In practice, however, the estimation procedure is often confined to finding the bottom fail-safety estimates, which in some cases can make the products unjustifiably complex and expensive provided that the estimates are very different from the true values.

The voltage converter reliability estimation is considered in works [1–3]; however, the techniques provided therein have a large number of serious restrictions. For this reason, this paper is aimed at improving the estimation of the bottom and upper boundary probabilities of failsafe operation of multichannel voltage converters.

TECHNIQUE FOR CALCULATING PROBABILITY OF FAILSAFE OPERATION OF A MULTICHANNEL VOLTAGE CONVERTER WITH ROTATION OF POWER CHANNELS

For the architecture of the central part of a multichannel voltage converter with rotation of power channels taken from [1], see Fig. 1.

It is seen from Fig. 1 that the converter has N main power modules (PM_1—PM_N) backed up by one redundancy module (PM_{N+1}) in the on mode and K redundancy modules (PM_{N+1+1}—PM_{N+1+K}) in the off mode. For the basic reliability diagram for this kind of backing up power modules (channels), see Fig. 2.

The peculiarity of the considered redundancy technique is that in the standard *sliding unloaded redundancy* group the backup channels (BUCHs) in off mode are connected only when one of the main channels (MCHs) fails, whereas, in the case in question, the BUCHs are also connected upon failure of backup channel $BUCH_1$ in the on mode.

The proposal made in work [1] to improve the converter's efficiency when using the above described redundancy technique is to apply *rotation of power channels*. This method consists in multiple disconnection of the functional channel running on load and

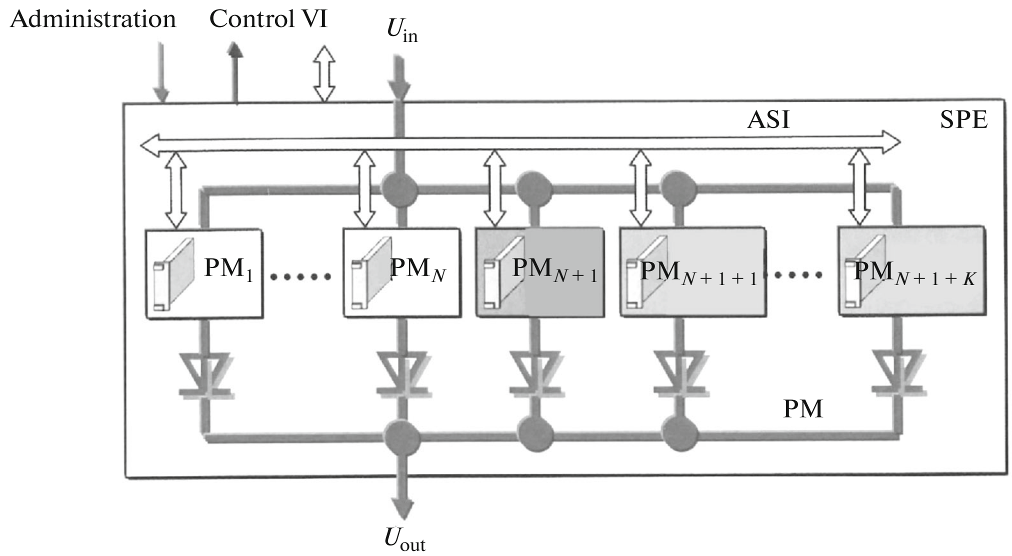

Fig. 1. Central part of the multichannel voltage converter with backbone modular architecture and combined redundancy.

connecting a functional backup channel in off mode instead.

The design ratios for estimating bottom limit W_{bt} and upper limit W_{up} of the probability of the converter's failsafe operation in the steady-state rotation mode of its channels provided in [2, 3] have been derived under the following conditions, assumptions, and restrictions:

• the power channels have an exponential reliability model;

• all the power channels have identical reliability characteristics;

• the power channel reliability characteristics are

failure rate in operational mode $\lambda = \text{const}$ and failure rate in standby mode $\lambda_{stb} = 0$;

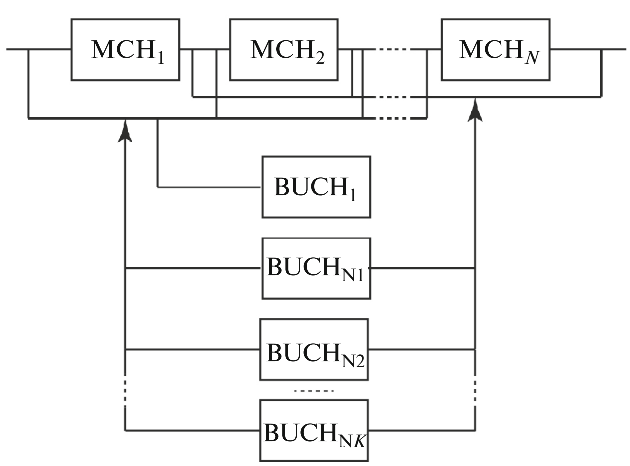

Fig. 2. Basic reliability diagram of the power channels of a backbone modular multichannel voltage converter.

• the switch failure probability is $Q_{0swh} = 0$;

• the channel rotation period is $\tau = \text{const}$;

• only one power channel in operational mode can be exposed to rotation at the end of each period;

• the design operation period, within which the converter's failsafe operation probability will at least be equal to preset value, is t_{fsop} (in [3] it is accepted equal to a year);

• the voltage converter's operation mode is uninterrupted operation in the design operation period;

• power channel failures are detected in an instant;

• power channels do not recover for the voltage converter's design operation period; and

• the voltage converter's failure criterion is the failure of any $K + 2$ power channels.

In addition, works [2, 3] provide the plot of the distribution of the runtime of a voltage converter with its power channels engaged in periodical operation (Fig. 3a) and work [3] provides the relations to $\lambda\tau$ and K of the converter's W_{bt} and W_{up} in the steady-state rotation mode of its power channels (Fig. 3b).

It is seen from Fig. 3a that the values of W_{bt} and W_{up} do not depend on time, whereas a reduction in τ increases W_{bt} while W_{up} remains constant. In addition, the conclusion drawn in [2, 3] is that a reduction in τ also increases W_{up} (Fig. 3b).

It should be noted that this way of making products more reliable (rotation of components) is not new and its efficiency has been shown, for example, in [4] as applied to the calculation of initial reserve levels in SPTA kits and in [5] as applied to improving the radiation durability of automation tools as parts of onboard equipment of airspace vehicles.

As shown below, the proposal from work [4] to calculate intensities (λ_{rpl}), with which the constituents are replaced upon adopting their rotation between the product and the SPTA kit, also allows estimating W_{bt} and W_{up} for backbone modular multichannel converters with rotation of power channels for the given way of their redundancy and upon the conditions, assumptions, and restrictions proposed in [2, 3].

Since the use of rotation sees each channel found interchangeably in the operational or standby mode, in this context the word “rotation” means “multiple (cyclical) application,” which is more correct according to the terminology from [6]. For the peculiarities of designing the reliability of objects with a periodical piecewise constant failure rate and in cyclically used electronic modules, see [7] and [8], respectively.

The channel’s reliability indicator in the case of cyclical (session) application is its session failure rate λ_{SSN} found by the formula from [9] as

$$\lambda_{SSN} = K_{OPIN}\lambda + (1 - K_{OPIN})\lambda_{stb}, \quad (1)$$

where K_{OPIN} is the channel operation intensity coefficient in the operational mode, λ is the channel failure rate in the operational mode, and λ_{stb} is the channel failure rate in the standby mode.

The value of K_{OPIN} in (1) is found as

$$\mathrm{K}_{OPIN} = \frac{t_{\Sigma_{op}}}{t_{fsop}}, \quad (2)$$

where $t_{\Sigma_{op}}$ is the channel’s aggregate operation time for t_{fsop} and t_{fsop} is the design operation period.

If we proceed from the equal reliability principle, then all the channels of the multichannel voltage converter must have equal λ_{SSN}, whereas it follows from (1) and (2) that the values of their $t_{\Sigma_{op}}$ must be equal as well:

$$t_{\Sigma_{opMCH_1}} = \ldots = t_{\Sigma_{opMCH_N}} = t_{\Sigma_{opBUCH_1}} = t_{\Sigma_{opBUCH_{H1}}} \ldots = t_{\Sigma_{opBUCH_{HK}}}. \quad (3)$$

To meet this condition, it is necessary to ensure at least one cycle of full rotation of all the channels. The minimal number of rotations (switchings) for each channel is found on the basis of their operation time schedules.

The Table 1 below presents the operation time schedules of the channels *sequentially* switched for a converter with two main channels—one backup loaded channel and one backup unloaded channel.

One such schedule is a cycle of full rotation of the converter’s channels; in this case, $\tau_{op} = 3\Delta_{op}$ and the standby time is $\tau_{stb} = \Delta_{stb}$. The length of one cycle of full rotation is then

$$\tau_{full} = \tau_{op} + \tau_{stb}. \quad (4)$$

It follows from this that the rotation of the channels means that they will have equal application conditions (there will be no difference between the main and the backup channels) and, from this point on, equal λ_{SSN}. In this case, the basic diagram of the converter’s reliability will be a standard *sliding loaded redundancy*

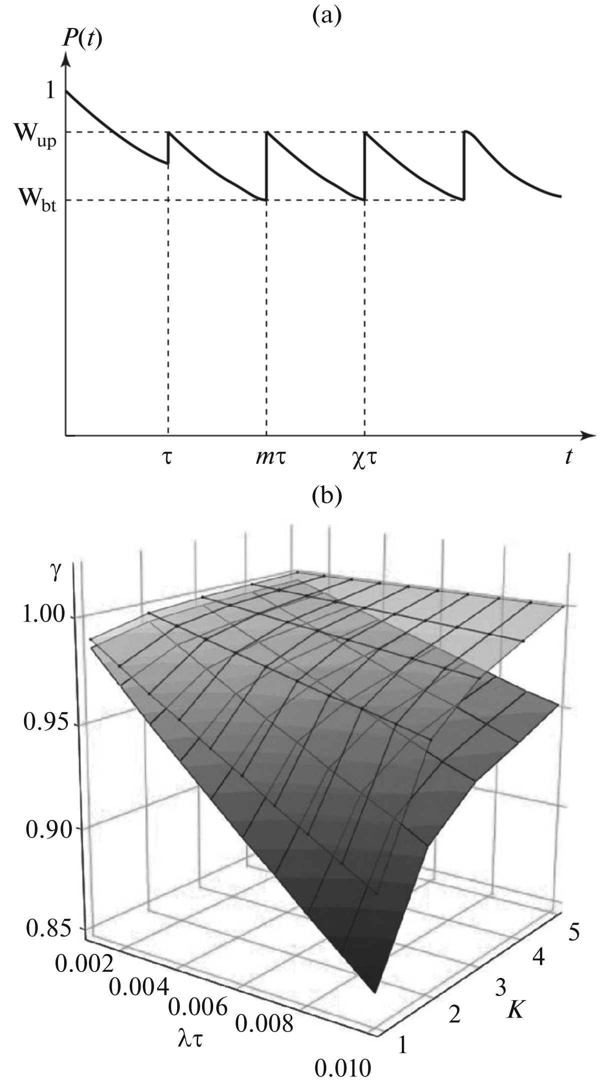

Fig. 3. (a) Distribution of the runtime of a voltage converter with its power channels used in periodical operation. (b) Relations to $\lambda\tau$ and K of the converter’s W_{bt} and W_{up} in the steady-state rotation mode of its power channels.

Table 1. Operation time schedules of the converter’s power channels. Δ_{op} is the operation time; Δ_{stb} is the standby time

Channel number	Channel mode number			
	1	2	3	4
1	Δ_{op}	Δ_{stb}	Δ_{op}	Δ_{op}
2	Δ_{op}	Δ_{op}	Δ_{stb}	Δ_{op}
3	Δ_{op}	Δ_{op}	Δ_{op}	Δ_{stb}
4	Δ_{stb}	Δ_{op}	Δ_{op}	Δ_{op}

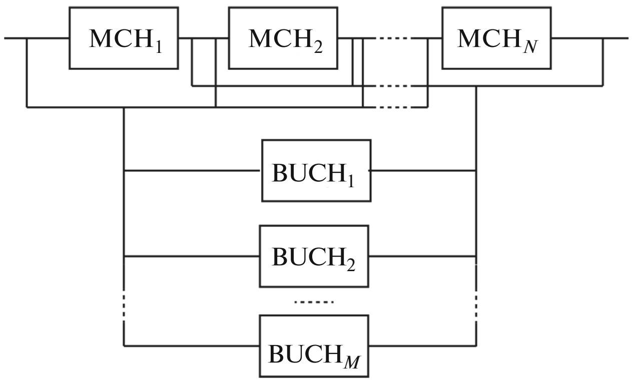

Fig. 4. Basic reliability diagram of a backbone modular multichannel voltage converter with its power channels rotated.

group with N main and $M = (K + 1)$ backup channels (Fig. 4).

The probability of failsafe operation of this group is determined according to the formula from [10] recorded as

$$P(t_{\text{fsop}}) = \sum_{m=0}^{M}\left[C_{(N+M)}^{m}\left(e^{-\lambda_{\text{SSN}}t_{\text{fsop}}}\right)^{(N+M)-m}\left(1-e^{-\lambda_{\text{SSN}}t_{\text{fsop}}}\right)^{m}\right], \quad (5)$$

where $C_{(N+1)}^{m}$ is the number of combinations, λ_{SSN} is the channel failure rate in the cyclical (session) operation mode, t_{fsop} is the design period of operation, N is the number of main channels, and M is the number of backup channels.

As was shown in [4], K_{OPIN} at the rotation of the product's component parts and spare parts from the SPTA is found as

$$K_{\text{OPIN}} = \frac{m_i}{m_i + n_i}, \quad (6)$$

where m_i is the number of type i component parts in the product and n_i is the initial level of type i reserves in the SPATA kit.

Thus the formula that can be used for finding K_{OPIN} instead of (2) and, similarly to (6), is

$$K_{\text{OPIN}} = \frac{N+1}{N+M}, \quad (7)$$

where N is the number of main channels and M is the number of backup channels.

If follows from (5) that the calculation of $W(t_{\text{fsop}})$ includes summing failsafe operation probabilities at the failure of 0, 1, 2, ..., M channels. In SPATA systems, the resources are replenished, for which reason K_{OPIN} and, henceforth, λ_{SSN} can be taken as constant for replacement intensity calculations [4]. A similar assumption (λ = const) is made in [2], where *steady-state rotation* of power channels is considered. The power channels do not recover upon failing within t_{fsop}, which reduces the number of remaining functional channels and, therefore, increases their K_{OPIN} and λ_{SSN}.

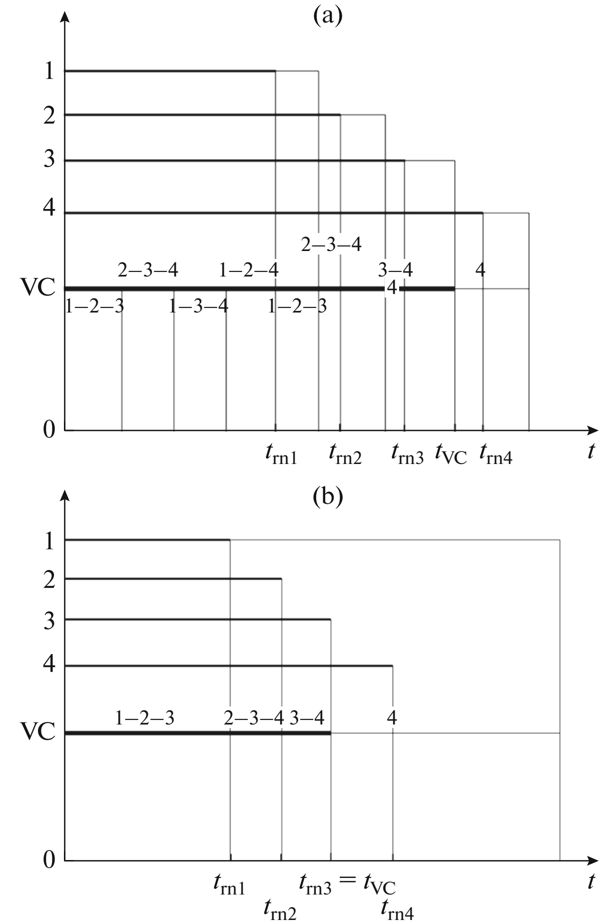

Fig. 5. Voltage converter (VC) runtime spent (a) with and (b) without rotation of power channels.

Figure 5 shows examples of runs spent (t_{rnVC}) in a converter with two main channels, one backup loaded channel, and one backup unloaded channel: the main, loaded backup, and unloaded backup channel runs are t_{rn1} and t_{rn2}, t_{rn3}, and t_{rn4}, respectively.

It follows from Fig. 5a that, to meet (3) when finding the estimate of W_{up}, it can be assumed that the channels fail in the converter's final operation period, i.e., that the converter's channels undergo full rotation for t_{fsop} (the best case for this example is $t_{\text{fsop}} = t_{\text{rn1}}$). Then K_{OPIN} can be taken equal for all the channels, and its value found from (7), whereas λ_{SSN} and $W_{\text{up}}(t_{\text{fsop}})$ can be found from (1) and (5), respectively.

To find the estimate of the converter's $W_{\text{up}}(t_{\text{fsop}})$ for meeting (3), it can be assumed that the channels fail in the converter's initial operation period, i.e., the time that passes for these channels from the start of the converter's operation to their failure is much shorter than t_{fsop} (the worst case). In particular, the channels full rotation may not occur at all (Fig. 5b).

With this assumption, K_{OPIN} will increase depending on the number of failed channels as

$$K_{\text{OPIN}} = \frac{\sum_{m=0}^{M} K_{\text{OPIN}m}}{M+1}, \tag{8}$$

where $K_{\text{OPIN}m}$ is the channel operation intensity coefficient at the failure of the converter's m backup channels:

$$K_{\text{OPIN}m} = \begin{cases} \dfrac{N+1}{N+(M-m)} \text{ at } m < (M-1) \\ 1 \text{ at } m \geq (M-1) \end{cases}. \tag{9}$$

Let us calculate W_{bt} and W_{up} for the above-considered case of the converter with its operation time schedules borrowed from the table. We shall assume that $\lambda = 1.9 \times 10^{-5}$ h^{-1}, $\lambda_{\text{stb}} = 1.9 \times 10^{-7}$, and $t_{\text{fsop}} = 9000$ h.

The calculation results are $K_{\text{OPIN}} = 3/4$, $\lambda_{\text{SSN}} = 1.42975 \times 10^{-5}$ h^{-1}, and $W_{\text{up}}(9000) = 0.994$ and, respectively, $K_{\text{OPIN0}} = 3/4$, $K_{\text{OPIN1}} = K_{\text{OPIN2}} = 1$, $K_{\text{OPIN}} = 11/12$, $\lambda_{\text{SSN}} = 1.74325 \times 10^{-5}$ h^{-1}, and $W_{\text{bt}}(9000) = 0.989$.

These results were checked by finding $W(t_{\text{fsop}})$ for the above0considered converter's case by imitative modeling in the ASONI-KA-K-RES system [11]. The calculation results were that $W(9000) = 0.9915$, which fell within the analytically derived range of from 0.989 to 0.994.

For the relations of the converter's W_{bt} and W_{tp} in the above-considered case at t_{fsop} varying from 0 to 9000 h and M from 2 to 5, see Fig. 6.

It follows from Fig. 6 that W_{bt} and W_{up} depend on t_{fsop}, which contradicts the results provided in Fig. 3. Since the *power channels' steady-state rotation mode* Fig. 3a) corresponds to the above-considered *best case*, it is obvious that, in this mode,

$$t_{\Sigma_{\text{pOK}_1}} \simeq \ldots \simeq t_{\Sigma_{p\text{MCH}_N}} \simeq t_{\Sigma_{p\text{BUCH}_1}} \simeq t_{\Sigma_{p\text{BUCH}_{\text{rn1}}}} \ldots t_{\Sigma_{p\text{BUCH}_{\text{HK}}}} \Rightarrow P(t_{\text{fsop}}) \simeq P_{\text{B}}(t_{\text{fsop}}), \tag{10}$$

where $W(t_{\text{fsop}})$ is the converter's failsafe operation probability and $W_{\text{up}}(t_{\text{fsop}})$ is the upper boundary of this probability.

The equality sign in (10) means that $W_{\text{up}}(t_{\text{fsop}})$ is affected by τ_{c}, or, being more precise, the channel switching algorithm. It follows from Fig. 5a that it is appropriate to rotate the channels in the converter's initial operation period. It is obvious that a higher number of full channel rotation cycles will mean that

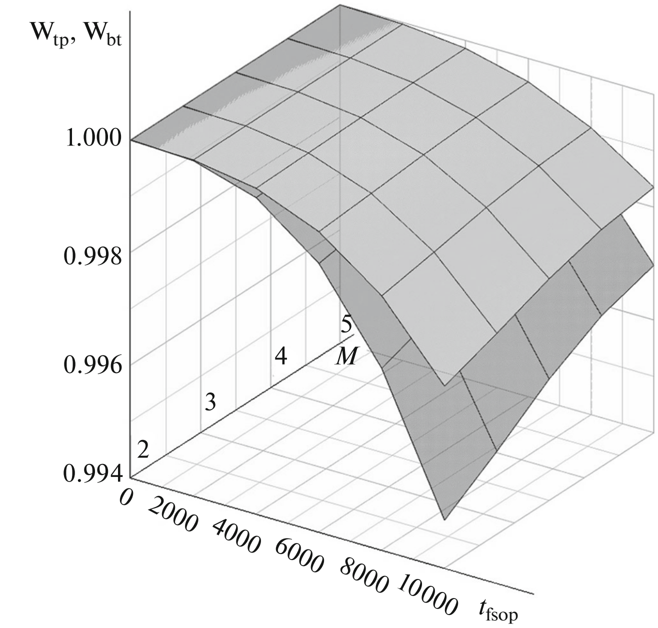

Fig. 6. Relation of the converter's W_{bt} and W_{tp} to t_{fsop} and M.

their duration with reduce in correspondence with the number of channels as

$$\tau_{\text{c}}(L) = \frac{\tau_{\text{c}}}{L}, \tag{11}$$

where L is the number of cycles of the converter channels' full rotation.

For example, if we assume that $\tau_{\text{c}} = \text{const}$, it will be hard to ensure at high τ_{c} an equal number of rotations for each of the channels, because it is necessary to meet the following condition:

$$\tau_{\text{c}}(L)\, L = t_{\text{fsop}}. \tag{12}$$

Since the channel run values are not known beforehand, condition (12) will be met only at $\tau_{\text{r}} \to 0$. In this case, $t_{\Sigma_{\text{r}}}$ of each channel for t_{fsop} will be constant, which will ensure equal λ_{SSN} and, therefore, the fulfilment of (10).

It should also be noted that, according to the classification from [6] and proceeding from the peculiarities of using the channels and the model of running them in voltage converters, these channels are referred to multiple cyclical application objects (MCAOs) unrecoverable and unmaintainable for t_{fsop}. The fail-safety indicators of these objects also include probability $P_{0\text{on}}$ of their failsafe actuation.

In [2, 3, 10], however, it is assumed for deriving the formulas of calculating fail-safety levels that "the probability of a switch's failure is negligibly small", i.e., $P_{0\text{on}}$ is taken to be 1. It is obvious that, with an increase in L, the number of switchings S and, henceforth, $P_{0\text{on}}(S)$ will increase as well. Then, if $P_{0\text{on}}(S)$ increases too much, this will require repeated calculations taking into account the reliability of the switch(es) of the converter's channels [12].

Within this framework, the step necessary to improve the converter fail-safety is not to reduce τ_{rn} of channels (increase L), as recommended in [2], but reduce L to 1. At the same time, it is impossible to reduce S to 1 for all the channels by synchronously switching two and more channels, for no more than one running channel can be switched at each time instant.

At the same time, in addition to the range of normalizable fail-safety indicators, work [6] also sets the range of longevity indicators for MCAOs. Since a channel spends its resources faster in the operational mode than in the standby mode [13], equal residual resources will be ensured at $L \to \infty$ for all the power channels at any time instant of the converter's operation period.

For this reason, if the converter's design fail-safety indicators are much higher than required, it will be appropriate to increase L, which will reduce $W(t_{fsop})$ but make the channels spend their resources in a more even manner.

Thus, it can be concluded that using the failure rate in cyclical (session) operation mode of power channels allows applying standard formulas for the *sliding loaded redundancy* group when calculating fail-safety figures of multichannel voltage converters based on backbone modular architecture with rotation of power channels. This allows finding time-dependent failsafe operation probability boundary estimates.

The number of full rotation of power-channel cycles does not affect the converter's fail-safety under the assumption that the switch is *absolutely reliable*. At the same time, an increase in the number of full channel rotation cycles makes the power channels spend their resources in a more even manner but aggravates the converter's fail-safety because, if there are a large number of channel connections and disconnections, the channels can also be heavily affected by the switch's reliability.

However, neither the proposed technique of estimating failsafe operation probability boundaries nor imitative modeling can guarantee 100% accuracy of the results, for which reason they must be corrected according to the test results and control use of multichannel voltage converters.

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