

## Control System Reliability for a Unified Power Part with a Thyristor Converter

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### Abstract

The problem of evaluation of the reliability and quality of packaging a unified power part with a solid state converter, on the example of thyristor control system, is studied by the methods of fault trees for the case when installed power is increased. Two types of defects are taken into account, namely, open circuits and short circuits. The example of the 'frequency converter - induction machine' system is discussed.

Keywords: control systems, reliability, converters, fault trees.

The progressive tendency for the development of thyristor control systems (TCS) is the elaboration of unified thyristor mono-blocks which include necessary functional constituents (resistive decoupling, built-in controls, a pulse-phase control system, logic and protection cells, and so on). Such a design approach make it possible to realize high indices of no-failure operation reaching the order of  $(6\div 8) \cdot 10^{-6}$  1/h for the systems based on the thyristor converters.

The modular thyristor converters developed up to now are the unified blocks providing a great scope for building different circuits of the power part of TCS with the numbers of pulsations of  $m = 3, 6, 12, \dots$ . With increasing installed power of control systems (CS), the pulse-phase control system (PPCS) of a driving block is the PPCS of all the driven blocks the power elements of which are connected in parallel and/or in series. The selection of TCS is governed by a complex of technological requirements to their power parts [1]. A block diagram for the  $n$ -phase  $m$ -pulse power part of a TCS is shown in Fig. 1, where OT1-OTN are the secondary windings of the power transformer PT, CT is the common tap of the transformer secondary winding, T1-TN are power thyristors, A and C are the anode and cathode groups of the thyristor converters, and SW1-SW3 are the stator windings of a three-phase short-circuited asynchronous engine (AE).

Three clearances of module thyristor converters allows packaging thyristor converter circuits with required power using series and parallel connections of power and information-control parts. They differ by pulsations and phase, which determine their power features and reliability. In addition, the reliability depends on the elements (thyristors) of the power part of a TCS. The selection of an optimal (by reliability) packaging version is associated with the research of the reliability of a parallel-series thyristor circuit.

The complexity of reliability evaluation for the power part of a TCS lies in the fact that the number of states increases very fast with increase of the number of elements in the binary behavior of elements and independent failures in TCS. However, the complexity of the problem is caused not only by the number of elements. There are two fundamental factors: the degree of redundancy which specifies the share of efficient states, and the density of connections between elements which specifies the number of the shortest paths from the input to the output of a system [2].

Thus, the power part of a TCS can be represented as the system of the "bridge" type of  $n$  elements with common duplication characterized by  $N_{es} = 2^{(n/2)+1} - 1$  efficient states. Their share in the total number of states is  $\delta_\tau = N_{es} / 2^n = 2^{-(n/2)+1} - 2^{-n}$ . Share  $n$  decreases with increasing  $\delta$ . The number of the shortest paths is two. The same system with separate (element-wise) duplication is characterized by a great share of efficient states determined by formula  $\delta_e = 3^{n/2} / 2^n$ . Then the number of the shortest paths is  $r = 2^{n/2}$ . In the duplication with integer multiplicity

$m_c=2/1$ , the same parameters can be calculated by formulas  $\delta_t = [3(2^{n/3}) \cdot (2^{n/3}-1)+1] \cdot 2^n$ ,  $\delta_e = 7^{n/3}/2^n$  and  $r = 3^{n/3}$ .

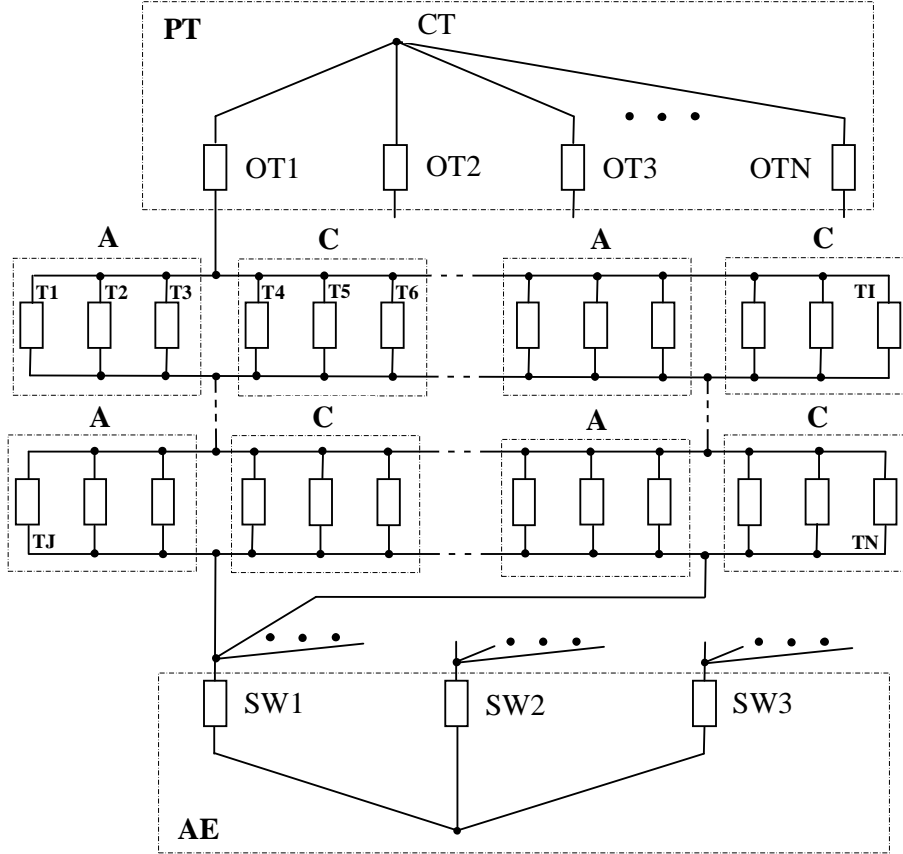


Fig. 1 A block diagram for the n-phase m-pulse power part of a TCS

The well-known bridge structure consisting of five elements is characterized by 16 efficient states (their share is  $\delta=0.5$ ) and by only 6 shortest paths. The system considered in [3] includes 15 elements and is characterized by 2410 efficient states within  $N=32768$  possible states  $\delta=7.35\%$  and by 92 shortest paths. In the series-parallel structure ( $n$  groups, a group includes  $m$  thyristor monoblocks), the share of efficient states is  $\delta_e = 2^{(m-1)n}/2^{mn}$ ;  $\delta_t = \delta_e(m-1) + 2^{-n}[1 - \delta_e(m-1)]$ .

Calculations show that with the increase of the complexity of a TCS with constant ratio  $n/m$ , the number of efficient states decreases relatively in the general duplication, and increases in the separate one. For example, in the circuit with the bridge structure consisting of five elements  $\delta=0.5$ , the share of efficient states lies between 0.438 and 0.563 for the circuits with  $m=n=2$ .

Analysis shows that in a TCS with constant relation between the width (the number of elements in the minimum cut) and length (the number of elements in the shortest path) of a network the value of  $\delta$  is sufficiently stable, i.e. it varies significantly more slowly than the total number of states in a TCS. Therefore, working time in evaluation of the probability of no-failure TCS operation can be determined by the total number of system states.

To estimate the probability of one of the states in a TCS consisting of N elements, it is required to perform N-1 multiplications and one addition. The total number of states is  $M \approx 10^{0.3N}$ . To calculate the reliability of the system consisting of 30 elements with the use of a last version IBM computer (Pentium), it is required approximately 40-50 minutes. For the boundary real structure of the control system to be synthesized, when the packaging of a TCS, for example, with power 1500 kW is realized on the basis of mono-blocks with power 12 kW, the time of reliability calculation becomes unacceptably large. However, there is a way to reduce working time by factor of thousands and more [4].

To do this, it makes sense to use the method of failure trees and the method of minimum paths and cuts, because they are based on Boolean algebra, and power TCS elements (thyristors) may take two states. It is necessary in this situation to distinguish the two types of malfunctions: a failure of operation of any power element, i.e. breakage with probability  $p_\tau$  and overloading (in particular, the mode of change of inverter state) or shorting in the circuits of power elements, i.e. a short circuit with probability  $p_{sc}$ . So, we can assume that element malfunctions are statistically independent.

By the malfunction of the power part of a TCS is meant both short-circuiting one of the circuitries or open-circuiting in all the parallel circuitries. It is true with sufficient redundancy of power elements, i.e. if the failure of any circuitry of the power part of a TCS occurs, switching from the failed power elements to reserve ones takes place.

Let us solve the following problem: it is required to determine the most reliable packaging (circuit) of the power part of an AE TCS consisting of n components and meeting the condition that the solution belongs to the packaging subset for which the requirements are met to the voltage-current characteristics of power elements.

The probability of the "open-circuit" malfunction for the circuit of  $n_j$  elements, which contains  $\zeta$  parallel circuitries with series connected  $x_i$ ,  $i = 1, m$  elements, can be described by the expression

$$P_{sc} = 1 - \prod_{i=1}^{\zeta} (1 - p_{sc}^{x_i}).$$

and the probability of the "short-circuit" malfunction for this circuit is

$$P_{oc} = \prod_{i=1}^{\zeta} (1 - (1 - p_{oc})^{x_i}),$$

The probability of reliable circuit operation can be written as

$$P = 1 - (P_{oc} + P_{sc}).$$

Minimizing function P by the possible versions of power circuitries and taking into account that  $x_i$  are integer variables, with the condition  $p_{oc} + p_{sc} < 1$ ,  $p_{oc} > 0$ ,  $p_{sc} > 0$ , we can obtain

$$P = \prod_{i=1}^{\zeta} (1 - (1 - p_{oc})^{x_i}) + 1 - \prod_{i=1}^{\zeta} (1 - p_{sc}^{x_i}) \rightarrow \min; \quad (1)$$

$$\sum_{i=1}^n x_i \leq n, x_i \in R^+, i = 1, \dots, n.$$

where  $R^+$  is the set of integer non-negative real numbers.

We can solve problem (1) as the problem of minimization using any iterative methods, for example on by Box-Wilson which allows a search for optimum in the conditions of indeterminacy or unexplorancy of the connections between the inputs and outputs of an object using a goal function. The goal function can be obtained in the form of the approximating polynomial the coefficients of which can be estimated with the help of experiments (physical or mathematical) carried out over the object or its model. The search for optimum is based on the

determination of maximum gradient (the direction of steepest descent for expenditure and steepest ascent for the goal function).

The distributions of failures of the open-circuit and short-circuit types for network transformers, the stator windings of an asynchronous engine and semiconductor devices (thyristors) [5] are: a)  $p_{oc}=31\%$ ,  $p_{sc}=69\%$ , b)  $p_{oc}=82\%$ ,  $p_{sc}=18\%$ , and c)  $p_{oc}=32\%$ ,  $p_{sc}=68\%$ , respectively. In the analysis of packaging reliability of the power part of the system a direct frequency converter - asynchronous engine realized by three-phase zero circuit, the following result has been obtained:  $P = 0.43$  with  $n=24$ ,  $\xi=18$ , and  $m=3$ . Analysis for the structure of the power part of the thyristor converter of the AE TCS demonstrated the fact that in order to obtain maximum reliability under proportional changes in power and reliability it is required to realize uniform parallel-series switching semiconductor monoblock devices.

So, the use of the method of steepest descent is the most efficient for the solution of this problem, because it allows the use of a linear arithmetic mean function determining reliability, capital investment, and period of assembling, and other criteria as a goal function.

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