PROBABILISTIC APPROACH FOR THERMAL AND ELECTRODYNAMIC STRESSES DISTRIBUTION FUNCTIONS

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1. INTRODUCTION

Thermal and electro-dynamic stresses can have a negative impact to the electrical equipment with immediate and/or long-term degradation effects. Electrical equipment failures can occur due to local degradation of the components as a consequence of the effect of the thermal or electro-dynamic stresses. Considering that the main cause which goes to the appearance of the thermal and electro-dynamic stresses in the electrical equipment is given by the short-circuit current in the electrical system, in the following, we will analyse the influence of the short-circuit current statistic character, on the thermal and electro-dynamic stresses.

The short-circuit currents and the thermal and electro-dynamic stresses represent important parameters that must be considered in the design of the system buses, breakers, the substation apparatus and, finally, in all aspects of the design of the electrical power sub-systems.

A fault may be appears anywhere in the system while the loads and the configuration of the network continuously changing, so the magnitude of the short-circuit currents has a statistic character, modelled as a random variable. Based on the analytic expressions of the thermal and electro-dynamic stress, depending on the amplitude and the distribution of the short-circuit current, the authors propose in this paper an original method to determine the analytic expressions of the thermal and electro-dynamic stress probability distribution functions.

2. THE PROBABILISTIC ANALYSIS OF THE SHORT-CIRCUIT CURRENTS

Based on the deterministic analysis of the three phase short–circuit currents and considering the fault's place as a random variable uniformly distributed, we presented in the other papers [1],[2] the way of changing of a random variable fault's place, in a random variable of the amplitude of the short–circuit current.

Generally, the probabilistic analysis of the short-circuit current, in the given point, is a function of the fault's place on the network line. This function is used together with the probability distribution function of the distance till the point of the fault on the line. Considering the impedance between the source and the fault location, as a function of the type of fault *(TF)* and the condition of the network *(C)*, the probability distribution function of the current using the theory of the total probability is given by:

$$P(A) = \sum P(A_i) P(A|A_i)\,, \tag{1}$$

applied to the probability distribution functions:

$$f_I(i) = \sum f_{I \mid C,TF}(i \mid C,TF) P_C P_{TF}\,, \tag{2}$$

where $f_{I \mid C,TF}(i \mid C,TF) = f_I(i)$ is the probability distribution function of the short-circuit current, conditioned by the type of particular fault and the system state.

For a network with a foregone configuration and with a certain type of fault, the size of the fault current is depending on the distance, *x*, from the source, this means $I=J(x)$. If the source – fault distance probability distribution function is $f_X(x)$, than the probability distribution function of the current may be calculated with the relation:

$$f_I(i) = \frac{dF_I(i)}{di} = \frac{d}{di}\left[F_X(J^{-1}(i))\right] = \frac{d}{di}\left[\int_{-\infty}^{J^{-1}(x)} f_X(x)dx\right]. \tag{3}$$

Derived from this change, in the mentioned papers, we developed the main expressions of the probability distribution functions of the short-circuit current, for different networks configurations.

The results of this analysis lead to the conclusion that, although the default place distribution is uniformly, the default has the same probability to appear for the whole line and the probability is as smaller as its length is bigger. The probability of appearance of the short-circuit current are very different, the probability distribution function of the short-circuit current have a different shape, directly influenced by the network configurations. For most of the analysed configurations, we demonstrated that the small values of the short-circuit current have bigger probability than the current with big values. In other words, the frequency of the small current appearance is bigger than the frequency of big currents, the values of the frequencies depending on the configuration, dimension and system parameters. This reality can be explained by the fact that the growth of the line length on which the fault appears, lead to the decrease of the probability of the fault appearance in one point and the domain of definition of the variable short-circuit currents amplitude, increases.

From the study of the analysed network configurations, we can assume that the growth of the number of parallel lines or loops connected to the same bus system, lead to the acquiring of some probability distribution functions of short-circuit currents, centred to the small values.

Considering the currents limiting methods and the possibility of presence of the currents limiting equipment within the electrical power system, the authors obtained the mathematical expressions of the probability distribution function of the short-circuit currents. Depending on the probability of working with associated currents limiting equipment, the growth of the efficiency of the currents limiting equipment involves a study that brings into discussion the short-circuit currents distribution with or without currents limiting equipment.

3. THE PROBABILISTIC ANALYSIS OF THE THERMAL AND ELECTRO-DYNAMIC STRESSES

To evaluate the probability distribution function of the thermal and electro-dynamic stresses, we will consider the deterministic analysis of the stress induced by three-phase short-circuit currents.

The Figure 1 shows the history of the short-circuit current, with and without the automatic voltage regulator (AVR), whereby the relationship is shown between the thermal stress, peak short-circuit current, I_p, the subtransient short-circuit current, I_k'' and the disconnecting short-circuit time, t_k. I_k'' changes into the steady-state short-circuit current $I_{k\infty}$. For faults located at a considerable distance from generators, it can be assumed that $I_{k\infty}$ is equal to I_k''. With faults close to generators, $I_{k\infty}$ is always less than I_k''.

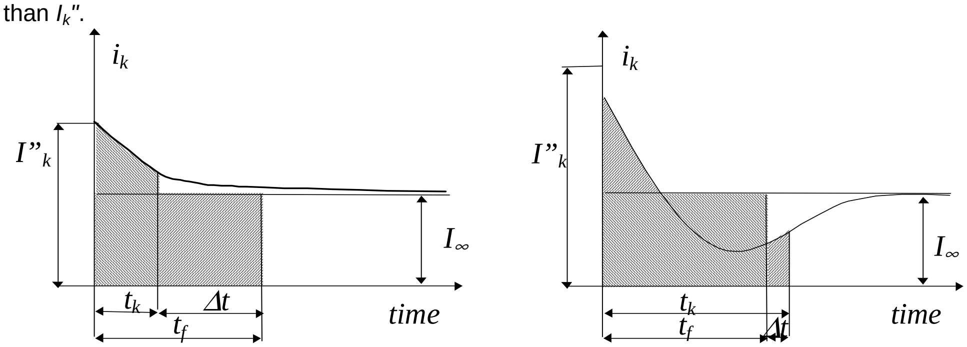

Figure 1. *The history of the short-circuit current, without and with the AVR*

The analytic expressions of the thermal and electro-dynamic stresses, depending on the short-circuit current are:

$$ST(t_k) = \int_0^{t_k} i_k^2(t)dt = \int_0^{t_k} i_{kp}^2 dt + \int_0^{t_k} i_{ka}^2 dt \approx I_{k\infty}^2 t_f \, , \tag{4}$$

and the peak short-circuit current I_p is determined from the subtransient short-circuit current I_k'' in accordance with the following relation:

$$I_p = \sqrt{2} \cdot k_p \cdot I_k'' \tag{5}$$

Considering also the distributions of the short-circuit current, we propose, in what follows, an original method to determine the analytic expressions of the distribution functions of the thermal $ST(t_k)$ and electro-dynamic I_p stresses [3].

$$f_{ST}(ST(t_k)) = f_I\left(\sqrt{\frac{ST(t_k)}{t_k}}\right) \cdot \left|\frac{1}{2\sqrt{ST(t_k) \cdot t_k}}\right| \tag{6}$$

and

$$f_{i_p}(i_p) = f_I\left(\frac{i_p}{\sqrt{2} \cdot k_p}\right) \cdot \left|\frac{1}{\sqrt{2} \cdot k_p}\right| \tag{7}$$

The main stress of electrical equipment means the thermal and electro-dynamic stress. Firstly, we consider the case of single line connected to a source, alike in Figure 2.

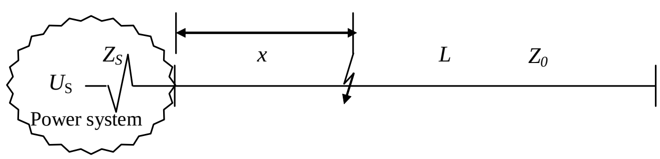

Figure 2 *The system with a single line to a source*

In the case of a fault located at the distance x from the source, the probability distribution function of the short-circuit current is given by:

$$f_I(i) = \frac{U_S}{LZ_0 i^2} \qquad for \quad \frac{U_S}{LZ_0 + Z_S} \le i \le \frac{U_S}{Z_S} \tag{9}$$

where:

U_S = is the phase-to-neutral system voltage;
Z_S = the impedance equivalent of the source;
Z_0 = the specific impedance of the line.

The probability distribution function of the thermal stress is given by:

$$f_{ST}(ST(t_k)) = \frac{U_S\sqrt{t_k}}{2LZ_0 ST\sqrt{ST}} \text{ for } \left(\frac{U_S}{LZ_0 + Z_S}\right)^2 t_k \le ST(t_k) \le \left(\frac{U_S}{Z_S}\right)^2 t_k \tag{10}$$

and the electro-dynamic stress distribution function is given by:

$$f_{i_p}(i_p) = \sqrt{2}k_p \cdot \frac{U_S}{LZ_0 i_p^2} \text{ for } \sqrt{2}k_p \frac{U_S}{LZ_0 + Z_S} \le i_p \le \sqrt{2}k_p \frac{U_S}{Z_S} \tag{11}$$

For the studied configuration, beside the analytic expressions of the distribution functions, the way to obtain them by practice, using the transformations of variables or the Monte Carlo simulation is presented. All these practical applications have the role to validate the acquired analytic models.

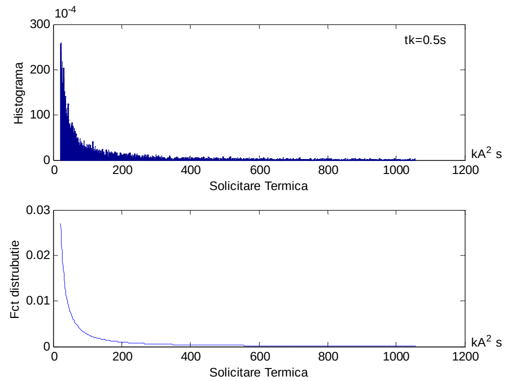

Figure 3 *The thermal stress pdf (simulation and analytical)*

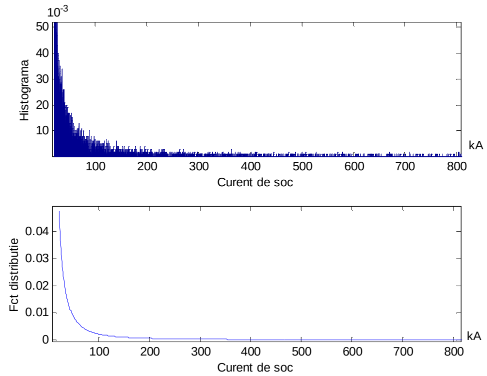

Figure 4 *The electro-dynamic stress pdf (simulation and analytical)*

Taking into account the real networks configuration the result is the idea to model the probability distribution functions of thermal and electro-dynamic stresses, in case of complex configurations. Therefore, in the following, the analysis of the distribution functions of thermal and electro-dynamic stresses was extended as well as for the case of a real complex system (a network of 110 kV), for which the authors established the distribution functions of short-circuit current using the analytic method and Monte Carlo simulation.

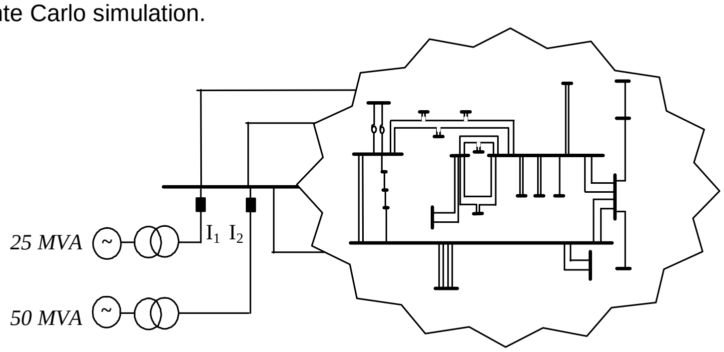

Figure 5 *A real complex system network - 110 kV*

To determine, in an analytic numerical way the distribution function, the analytic expressions obtained for the cases of the simple configurations were used and their combination, in common definitions intervals. To validate the obtained results, the function of the distribution in the case of the complex system was determined also by Monte Carlo simulation, both functions having a similar evolution. Both, the numerical calculations and the Monte Carlo simulation have been realised using Matlab software package with a view to determine and to combine the distribution functions, in common affiliation intervals.

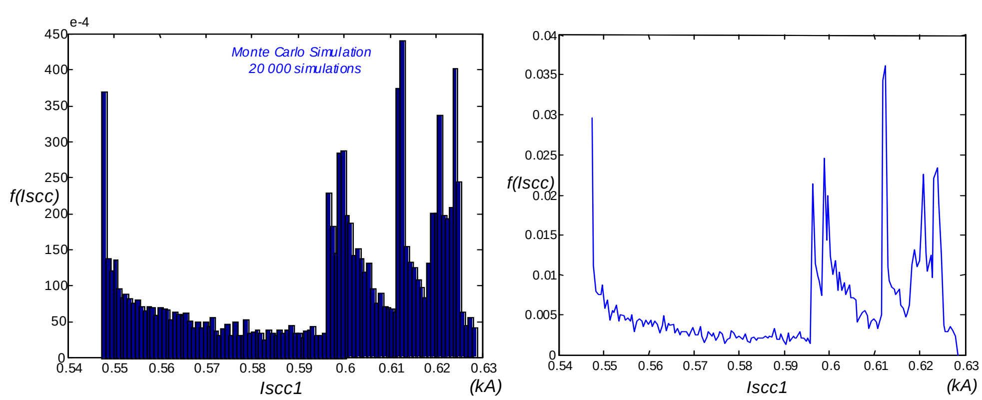

Figure 6 *Probability distribution function for the short-circuit currents I_1 (simulation and analytical)*

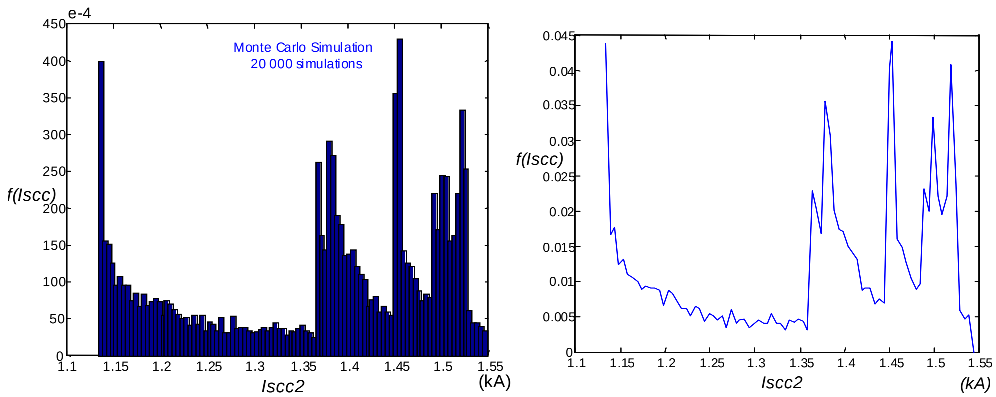

Figure 7 *Probability distribution function for the short-circuit currents I_2 (simulation and analytical)*

The intention was to obtain the distribution functions of the thermal and electro dynamic stresses, in the case of the complex system 110 kV. The expressions of the thermal and electrodynamics stresses probability distribution functions from the case of simple configurations were obtained, using a mathematical analysis and also using Monte Carlo simulation. For the considered system it was settled the distribution functions of the two stresses, in the case of two switches.

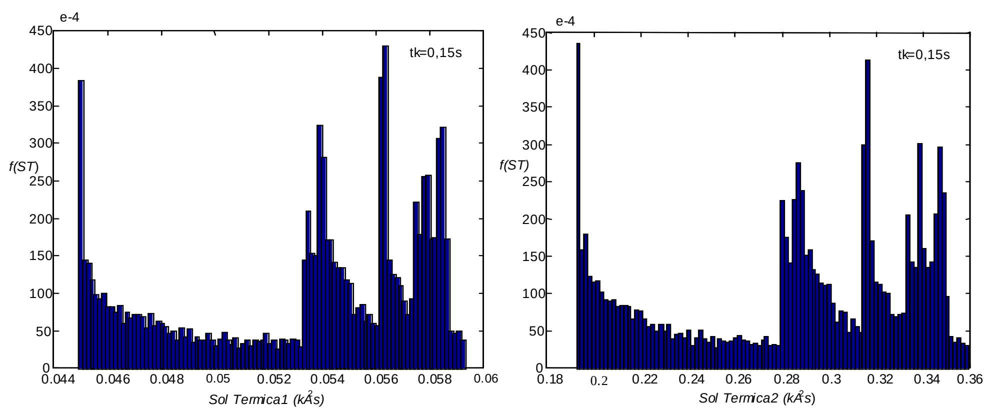

Figure 8 *Probability distribution functions for the thermal stress in the switches I_1 and I_2*

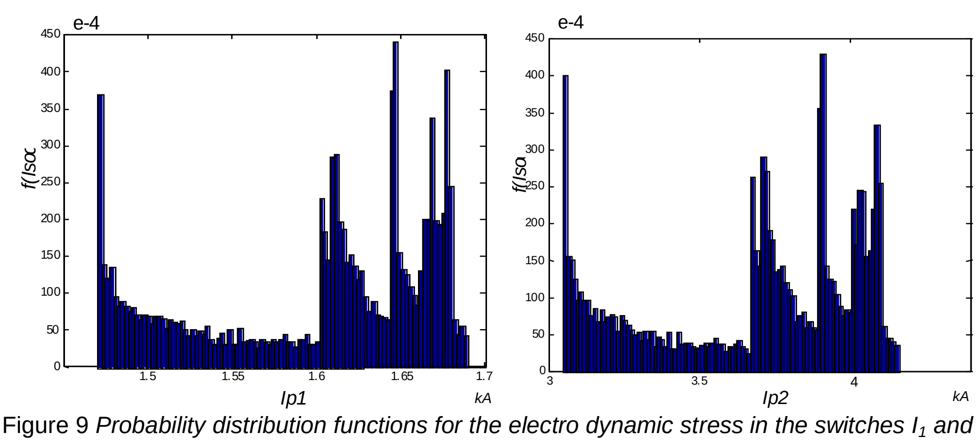

Figure 9 *Probability distribution functions for the electro dynamic stress in the switches I_1 and I_2*

4. CONCLUSIONS

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When analysing the thermal and electro dynamic stresses, the conditions of the system are prior and these values are calculated depending on the short-circuit currents for the different combinations, on the local power involved, the systems configurations and on the time of fault. Usually we consider the most unfavourable situations, in order to limit the number of the case studies. The stresses caused by the three-phase faults located to the system buses are usually considered. The equipment is chosen from thermal and electro dynamic stresses restrictions, calculated in these points.

If the amplitude of these stresses is considered as random variables so, the probabilistic methods become very attractive solutions to analyse the stress magnitudes caused by short-circuit currents.

The probabilistic concepts concerning the values of the thermal and electro dynamic stresses can be used for the power system design, by calculating a security coefficient taking into account that the maximal values of the thermal or electro dynamic stress, that appear with a smaller probability that their minimal values.

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