Novel approaches to analysis of transition processes identification error by probability-statistical methods during sudden symmetric short-circuit tests of synchronous machines

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***Abstract*—The article is devoted to the development of probabilistic and statistical methods (PSM) of researching long transient processes in synchronous machines (SM), occurring under the influence of various random factors. In particular, a new authentic method is explained that is oriented at minimizing the mean square error of approximation of the discrete statistical model of the transient component to the experimental data on a relatively long section of the discrete transition process. The model allows representing the found error in the form of a discrete surface in three dimensions.**

Keywords*—synchronous machine; transition process; research; identification; time constant; mean square error.

Artificial disruption of normal operation of synchronous generators by sudden symmetric short-circuit (SSC) of all phases during bench tests at electrical engineering enterprises is one of the most common practices providing with a wide range of electro-magnetic parameters of powerful synchronous machines.

Accuracy and validity in identifying transition processes by the methods codified in national standards of SMs tests have not been completely assured until now because of *a.* significant variation of time constants (TCs), *b.* initial values of armature current components, *c.* inaccurate exploitation of the armature's steady current value, *d.* different random factors etc.

This results in sensible deviation of SMs parameters x_d, x'_d, x''_d, initial short-circuit current and certain important intermediate values – for instance, initial shift of the first peak (ΔT) and consequent 5 to 6 peaks with strong sub-transient effect in the transition process – from their precise values.

Therefore, designing an accurate and reliable method for transition process identification errors during the SSC is a topical issue.

From [1, 2] it follows that this issue cannot be solved analytically, for which reason the authors detail an original probability-statistical method (PSM) for the transition process identification during the SSC, drawing on probability theory and mathematical statistics. The method is based on the universal time constant parameter τ_{kj} found via logarithmic decrement of sine oscillations damped in accordance with exponential law of transition processes presented in a discrete manner [1]:

$$\tau_{kj} = \frac{(t_j - t_k)}{\ln\left|i_k / i_j\right|}, \quad (1)$$

where $k = \overline{1,K}$ is the variable modification in specifying the lower boundary t'_{L}, $j = \overline{k+1,K}$ is the variable modification in specifying the upper boundary t'_{U}, K is the number of elements i_k between the lower and upper boundaries. By element we mean here the armature's discretely specified current between the lower and upper envelope curves of the transition process at every stage.

The random parameter described allows redundancy of the information processed, guaranteeing full integrity of the input data, while identifying transition processes of any duration. It also makes possible to construct the general population of the random parameter and samples from it needed for the further investigation involving the transient component.

Effective point samples selected from the general population of the random parameter with the lowest relative deviation from the mathematical expectation (ME) enable producing effective formulas to determine TCs with initial values of all components of the armature's total current defined discretely during the SSC tests.

In order to build up validity in identifying the transient component and minimize an amount of the input data, for the first time a sample of minimum acceptable size was selected, obtained by Poisson distribution from four effective point samples ($n_{\text{ef}} = 4$) [1]:

$$\tilde{\tau}'_{\text{ef}} = \frac{1}{4}\sum_{\substack{k=1 \\ j}}^{4} \frac{\left(t'_j - t'_k\right)_{\text{ef}}}{\ln\left|i'_k / i'_j\right|}\,,\; 2\tilde{I}'_{\text{ef}} = \frac{1}{4}\left(\sum_{k=1}^{4} i'_k\left(t_k\right)\cdot \mathrm{e}^{\frac{t_k}{\tilde{\tau}'_{\text{ef}}}}\right), \quad (2)$$

where $k = 1, 2, 3, 4$ is the variable to define the lower boundary, i.e. $k = 1\left(t'_{\text{L1ef}}\right)$, $k = 2\left(t'_{\text{L1ef}} + \Delta t\right)$, $k = 3\left(t'_{\text{L1ef}} + 2\Delta t\right)$, $k = 4\left(t'_{\text{L1ef}} + 3\Delta t\right)$ with corresponding elements i'_{L1ef}, i'_{L2ef}, i'_{L3ef}, i'_{L4ef}; j is the variable to specify the upper boundary $t'_{\text{U.ef}}$ in accordance with condition (16) in [2], $i'_{\text{U1ef}} = 0.33 i'_{\text{L1ef}}\left(t'_{\text{U1ef}}\right)$, $i'_{\text{U2ef}} = 0.33 i'_{\text{L2ef}}\left(t'_{\text{U2ef}}\right)$, $i'_{\text{U3ef}} = 0.33 i'_{\text{L3ef}}\left(t'_{\text{U3ef}}\right)$, $i'_{\text{U4ef}} = 0{,}33 i'_{\text{L4ef}}\left(t'_{\text{U4ef}}\right)$ are always smaller than the ultimate boundary $(t')^*$ of the transient component analyzed within the boundaries $t'_{\text{L.ef}} - (t')^*$.

The study suggests **a nonconventional approach to minimize a mean-square error of approximation in the form of 3D discrete surface for a section of the discrete process with a single transient component.**

The mean-square error of approximation $\overline{\Delta'}$ is defined as a difference between a discrete model of the transient component and test data at discretization nodes with 0.01 s interval within the section of the transition process with a single transient component [1,3]:

$$\overline{\Delta}'_K\left(t_k\right) = \sqrt{\frac{1}{K}\sum_{k_{\text{н}}}^{k_{\text{в}}}\left(i_{k.\text{mod}}\left(t_k\right) - i_{k.\text{ob}}\left(t_k\right)\right)^2}\,, \quad (3)$$

where K is the number of the elements between the upper and lower boundaries within the range $t'_{\text{L.ef}} - (t')^*$; $i_{k.\text{mod}}\left(t_k\right) = 2\tilde{I}'_{\text{ef}} \cdot \mathrm{e}^{-\frac{t_k + \Delta T}{\tilde{\tau}'_{\text{ef}}}} + 2I_\infty$ is the model of transition process according to (2) for the section $\left(t'_j - t'_k\right)_{\text{ef}}$ in identifying the transient component within the range studied $t'_{\text{L.ef}} - (t')^*$; $i_{k.\text{ob}}\left(t_k\right)$ is the observation value of the section of transition process for the same range as the model defined by the formula [1]:

$$\begin{aligned} &i_{\text{i}k} = \left|0{,}375\left(\pm I_{\text{m}(k\text{-}1)}\right) + 0{,}75\left(\pm I_{\text{m}(k+1)}\right) - 0{,}125\left(\pm I_{\text{m}(k+3)}\right)\right| \\ &\text{if } \left(\left|\pm i_{\text{i}k}\right| > \left|\pm I_{\text{m}k}\right|\right) \text{or} \left(\left|\pm I_{\text{m}k}\right| > \left|\pm i_{\text{i}k}\right|\right) \text{then} \\ &\qquad i_{k.\text{ob}} = \left|\pm i_{\text{i}k} - \left(\pm I_{\text{m}k}\right)\right|, \end{aligned} \quad (4)$$

where 0.375, 0.75, 0.125 are the factors calculated by the Aitken interpolation which allow specifying the additional values $i_{\text{i}k}$ of the current envelope curves between the peaks, using the three armature's amplitude current values $I_{\text{m}(k\text{-}1)}$, $I_{\text{m}(k+1)}$, $I_{\text{m}(k+3)}$, showing an forward-running interpolation.

In terms of probability theory and mathematical statistics this error may be represented by a statistical function of the armature's steady current value, lower boundary $t'_{\text{L.ef}}$, and the transient component's upper boundary $t'_{\text{U.ef}}$ rigidly bound with the latter.

In doing so, one should note the ultimate boundary $(t')^*$ of the whole transition process in order to control the area of practical constancy of minimum error approximation $\overline{\Delta'}$ of effective point samples towards the mathematical expectation within the $t'_{\text{L.ef}} - (t')^*$ range.

A minimization of the discretely defined statistical function is performed by simultaneous variation of the armature's steady current value, lower boundary t'_{L} with modeling the transient component (2) discretely defined at each interval to calculate the error.

The 3D discrete surface clearly demonstrates a groove-like minimum error level.

The original method of minimizing the mean-square error of approximation is programmed into LabVIEW using the 50 MW SM's test data for three different voltage levels and nonsaturated operation mode, which made possible automatic visualization of the results of identification and discrete mean-square error of the transient component in the form of 3D surface.

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