UDC 681.518.5

V.F. Hraniak, PhD, V.V. Kukharchuk, D.S.
(Vinnitsa National Technical University, Ukraine)

New information coefficients of vibration signals for technical condition monitoring in rotating electric power machines

In the article the authors propose new high-information characteristics, in which capacity we used cross-correlation coefficients between vibration signals in space-distributed points of a rotating electric machine in combination with amplitudes of vibration signals in the same points.

As it was shown in papers [1-4], the systems for control of technical condition based on analysis of unit assemblies' vibration signals are highly promising in terms of solving the technical task assigned. However, the overwhelming majority of working hypotheses, based on which the methods for technical condition monitoring are based, consider the units of a rotating power machine separately, analyzing the obtained results, at the best, statistically only in an upper-level numeric converter [3, 4]. Such approach makes it impossible to evaluate the degree of disturbances' localization and the degree of their influence on the entire space-distributed structure of an electric machine. As a consequence, based on the measurement information obtained, it is impossible neither to imagine the geometrical location of the point of application of equivalent uncompensated force that causes vibration (which indirectly testifies to the reason of its origin), nor to make conclusions regarding the mechanical stiffness of the electrical machine's support structure (which is the parameter directly connected with mechanical strength).

Considering a rotating electric machine as a MO, one can imagine it as a relatively stationary distributed quasi-linearized inseparable elastic system having spatially variable coefficients of stiffness [5]. Another specific feature of MO lies in its being exposed to k spatially distributed uncompensated mechanical forces of various nature, amplitude and vector direction to change in a temporal function randomly. The structure of such MO may more simply be presented as follows (Fig. 1).

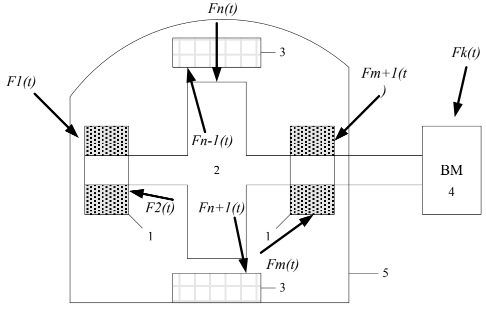

Fig. 1. Simplified flow diagram of a rotating electric machine: 1 – bearings; 2 – rotor; 3 – stator; 4 – actuating mechanism; 5 – outer case

In view of such system's non-separability, any of k external uncompensated disturbing forces will generate, in the system's randomly selected point (node), some vibration signal (response), the amplitude of which being other than zero [6]. That said, taking into account the system's stationary state, vector-identical force, the equivalent of which is applied to the electrical machine's one and the same point, will give rise to the system's identical response in any randomly selected assembly of the unit. Taking into account the foregoing, for a randomly selected controlled unit in relation to each of k possible disturbing forces, one can select a transient characteristic that will possess a relatively time-constant value on account of a high inertia of the process of change in the mechanical stiffness of the electric machine's units under acceptable operational conditions. In other words, for a randomly selected unit A being a part of the MO, the following system will be true:

$$\begin{cases} \psi_{A1}(t) = F_1(t) \cdot H_{A1}(t), \\ \psi_{A2}(t) = F_2(t) \cdot H_{A2}(t), \\ \dots\dots\dots\dots\dots\dots\dots\dots \\ \psi_{Ak}(t) = F_k(t) \cdot H_{Ak}(t), \end{cases} \tag{1}$$

where $F_1(t) - F_k(t)$ – the uncompensated forces affecting the electric machine; $H_{A1}(t) - H_{Ak}(t)$ – transient characteristics in relation to disturbing forces $F_1(t) - F_k(t)$, respectively; $\psi_{A1}(t) - \psi_{Ak}(t)$ – the system's response at A point to the effect of disturbance in the form of $F_1(t) - F_k(t)$ force, respectively.

Such being the case, the resultant vibration signal to be observed at A point may be obtained based on the superposition principle.

$$\psi_A(t) = \sum_{i=1}^{k} \psi_{Ai}(t) = \sum_{i=1}^{k} F_i(t) \cdot H_{Ai}(t). \tag{2}$$

Proceeding from similar reasoning, the described mathematical apparatus may be extended to any other random point B, which also belongs to MO and does not coincide with point A. Such being the case, for point B, dependence of vibration signal's response on disturbing forces will be written as follows:

$$\begin{cases} \psi_{B1}(t) = F_1(t) \cdot H_{B1}(t), \\ \psi_{B2}(t) = F_2(t) \cdot H_{B2}(t), \\ \dots\dots\dots\dots\dots\dots\dots\dots \\ \psi_{Bk}(t) = F_k(t) \cdot H_{Bk}(t), \end{cases} \tag{3}$$

$$\psi_B(t) = \sum_{i=1}^{k} \psi_{Bi}(t) = \sum_{i=1}^{k} F_i(t) \cdot H_{Bi}(t). \tag{4}$$

Taking into consideration (1) and (3), and the fact that MO is a quasilinear system, the dependence of the system's each response at point B on the system's response at point A will be written as follows:

$$\psi_{Bi}(t) = \frac{H_{Bi}(t)}{H_{Ai}(t)} \psi_{Ai}(t). \tag{5}$$

Hence, the system's general response at B point may be determined as

$$\psi_B(t) = \sum_{i=1}^{k} \frac{H_{Bi}(t)}{H_{Ai}(t)} \psi_{Ai}(t). \qquad (6)$$

Other points belonging to MO may similarly be connected between each other.

Obtaining instantaneous values of cross-correlation coefficients is a considerable challenge for the use of the approach proposed. As was shown above, since vibration processes in electrical machine's controlled units are of random nature, precise evaluation of linear connection between the two values $\psi_A(t)$ and $\psi_B(t)$ would require the use of the following expression [6]

$$K_\psi(t_1,t_2) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (\psi_1 - m_A(t_1))(\psi_2 - m_B(t_2)) \cdot f(\psi_1,\psi_2,t_1,t_2)\, d\psi_1 d\psi_2, \qquad (7)$$

where $m_A(t_1)$, $m_B(t_2)$ – mathematical expectations of $\psi_A(t)$ and $\psi_B(t)$ functions in t_1 and t_2 time moments, respectively; $f(\psi_1,\psi_2,t_1,t_2)$ – two-dimensional density probability of an occasional process ψ(t) that preconditions the appearance of vibration signals in A and B units that is determined at t_1 and t_2 time moments, in relation to which occasional process $\psi(t)$ may be considered as the system of two random values $\psi A(t)$ and $\psi_B(t)$, the values ψ_1 and ψ_2 of which being $\psi_A(t_1)$ and $\psi_B(t_2)$ values of occasional process realizations recorded at t_1 and t_2 time moments.

$$f(\psi_1,\psi_2,t_1,t_2) = \frac{\partial^2 F(\psi_1,\psi_2,t_1,t_2)}{\partial\psi_1 \partial\psi_2}, \qquad (8)$$

where $F(\psi_1,\psi_2,t_1,t_2)$ – two-dimensional function of distribution of occasional process probabilities $\psi(t)$ that assigns the value of probability of the fact that at t_1 time moment $\psi_A \le \psi_1$ in equation is implemented, and at t_2 time moment $\psi_B \le \psi_2$ in equation is implemented, that is

$$F(\psi_1,\psi_2,t_1,t_2) = P(\psi_A(t_1) \le \psi_1, \psi_B(t_2) \le \psi_2). \qquad (9)$$

Let us adapt the mathematical apparatus (7) – (9) to the MO under investigation. As was shown above, the disturbing forces $F_1(t)$ – $F_k(t)$ are distributed along the MO in such a way that points of application of their equivalents may be located at different conditional mechanical distances from A and B units. In this case, for some forces conditional mechanical distance from the point of application of the equivalent to unit A will exceed the conditional mechanical distance to unit B, for others – be equal, and for some others – be less. Hence, the rate of propagation of mechanical disturbance for each of k forces to controlled units will be different, which precludes from speaking about availability of time delay between system responses in the said points. Consequently, taking into account the specificity of MO, the autocorrelation coefficient between $\psi_A(t)$ and $\psi_B(t)$ signals will be advisable to determine for one and the same time moment, that is

$$t_1 = t_2. \qquad (10)$$

This results in the cross-correlation coefficient $K_\psi(t_1,t_2)$ transforming into $K_\psi(t_1)$.

Considering the vibration signal at stationary disturbing external influences $F_1(t) - F_k(t)$, which in physical terms will correspond to permanent qualitative composition and stationarity of laws of amplitude variation in uncompensated forces $F_1(t) - F_k(t)$, signals $\psi_A(t)$ and $\psi_B(t)$ may be considered ergodic. Such being the case, cross-correlation coefficient $K_\psi(t_1)$ of stationary occasional process $\psi(t)$ may with a slight error be considered equal to cross-correlation coefficient of certain temporal realization of $\psi_A(t)$ and $\psi_B(t)$ signals, for which the ergodic property will be implemented. In view of the fact that disturbing forces $F_1(t) - F_k(t)$ may only be deemed stationary during quite a short time period, while the value of vibration signal remains functionally dependent on angular position of electric machine's rotor [7, 8], in such case most admissible being the duration of realization of time series of $\psi_A(t)$ and $\psi_B(t)$ functions, which coincides with duration of rotation period of electric machine's rotor (for high-speed machines this may be divisible by period under acceptable value of duration). As a result, it would be entirely advisable and substantiated to proceed from calculation of instantaneous cross-correlation coefficients to calculation of quasiinstantaneous coefficients bound to the specified duration of temporal realization of $\psi_A(t)$ and $\psi_B(t)$ functions. On this basis, the unknown quasi-instantaneous cross-correlation coefficient may be calculated as follows:

$$K_\psi^*(t_1) = \frac{1}{T}\int_0^T (\psi_A^*(t_1) - m_A(t_1))(\psi_B^*(t_1) - m_B(t_1))dt_1, \tag{11}$$

where T – duration of temporal realization of $\psi_A(t)$ and $\psi_B(t)$ functions; $\psi^*_A(t)$ and $\psi^*_B(t)$ – temporal realizations of $\psi_A(t)$ and $\psi_B(t)$ functions.

And since oscillations of any elastic body occur in relation of some central (zero) position, then in the time period divisible by a rotation period of electric machine's rotor, a vibration signal of its any unit may be considered centered. Such being the case, the expression for calculation of cross-correlation coefficient between vibration signals of two distributed units will be written as follows:

$$K_\psi^*(t_1) = \frac{1}{T}\int_0^T (\psi_A^*(t_1))(\psi_B^*(t_1))dt_1. \tag{12}$$

Since the measurement of output vibration signals in real monitoring systems is frequently performed in a discrete way, then for discrete temporal realizations, taking into account the well-known Pearson equation (12) can be written as follows:

$$K_\psi^*(t_1) = \frac{\sum_{i=1}^{n} \psi_{Ai}^* \psi_{Bi}^*}{\sqrt{\sum_{i=1}^{n} \psi_{Ai}^{*2} \cdot \sum_{i=1}^{n} \psi_{Bi}^{*2}}}, \tag{13}$$

where ψ^*_{Ai} and ψ^*_{Bi} – i-th values of temporal realizations of $\psi_A(t)$ and $\psi_B(t)$ functions.

Conclusions

1.Proposed was the use of new high-information characteristics containing the information on not only the amplitude and spatial localizations of uncompensated disturbing forces (directly connected with the reasons of their origin), the influence of which gives rise to vibrations during operation of rotating electric machines. Theoretically proven and substantiated was the appropriateness of their functional connection and the advisability of use.

2.Determined and theoretically substantiated was the duration of vibration signal's temporal realizations, which is advisable to use when obtaining vibration signals' cross-correlation coefficients in the units under investigation. It was established that duration of such realizations must be divisible by the frequency of rotation period of electric machine's rotor.

3.Adapted was the mathematical model for calculation of cross-correlation coefficients, taking into account the specific features of vibration signal's origin and physical nature, which allowed significantly to simplify the analytical calculations required for obtaining the cross-correlation coefficients.

References

1. Kukharchuk V. V., Hraniak V. F., Vedmitskyi Y. G. (2015) Method of analytical calculation of vibration velocity in dispersal mode of hydro aggregate. Bulletin of the Engineering Academy of Ukraine, 2, 66-70.
2. Vedmitskyi Y. G., Kukharchuk V. V., Hraniak V. F. and other (2017) New non-system physical quantities for vibration monitoring of transient processes at hydropower facilities, integral vibratory accelerations. Przeglad electrotechniczny, 3, 69-72.
3. Kukharchuk V. V., Kazyv, S. S. Madjarov V. G. and other (2014) Monitoring, diagnosing, and forecasting of vibration state of hydraulic aggregates. Monograph. Vinnitsa, Ukraine: VNTU, 168.
4. Bilosova A., Bilos J. (2012) Vibration diagnostic. Ostrava, Czech Republic: Ostrava, 114.
5. Mokin B. I., Mokin O. B. (2004) Optimization of electric drives. Vinnitsa, Ukraine: UNIVERSUM-Vinnytsia, 250.
6. Broersen P. M. T. (2006) Automatic autocorrelation and spectral analysis. Landon, UK: Springer-Verlag London Limited, 298 p.
7. Kukharchuk V. V., Madjarov V. G., Nikolayev V. Y., Hraniak V. F. System for measuring and controlling the vibration parameters of electric machines. Patent of Ukraine for useful model. G01M 7/00, 7/02. № 102223; declared 01.04.2015; published 26.10.2015, № 20
8. Kukharchuk V. V., Madjarov V. G., Nikolayev V. Y., Hraniak V. F. System for measuring and controlling the vibration parameters of electric machines. Patent of Ukraine for useful model. G01M 7/00, 7/02. № 102700; declared 02.06.2015; published 10.11.2015, № 21