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Simulation research on hybrid electromechanical device - BLDC motor, torsion torque generator - for torsional vibration spectrum identification of drive systems

Streszczenie. *W artykule przedstawiono koncepcję hybrydowego przetwornika elektromechanicznego służącego do wytwarzania drgań skrętnych. Przedstawiono podstawowe własności przetwornika takie jak, np.: zależności generowanych częstotliwości momentów skrętnych od prędkości obrotowej wału generatora. Na drodze obliczeń symulacyjnych sprawdzono efektywność wyznaczenia charakterystyki modalnej układu napędowego na przykładzie zespołu prądotwórczego, złożonego z turbiny gazowej oraz generatora energii elektrycznej. (**Badania symulacyjne hybrydowego przetwornika elektromechanicznego - silnik BLDC, generator drgań skrętnych - do wyznaczania częstości drgań skrętnych układów napędowych**).*

Abstract. *In this article the general concept of hybrid electromechanical converter for torsion torque generation is presented. Fundamental properties of proposed electromechanical device, including dependence of frequencies of generated torsion torque on generator's rotor angular speed has been shown. Based on computer calculations the usefulness of proposed method for determination of modal characteristics of drive system is shown. As an exemplary drive system the set of gas turbine and electric energy generator were chosen.*

Słowa kluczowe: hybrydowy przetwornik elektromechaniczny, generator drgań skrętnych, silnik BLDC, drgania skrętne
Keywords: hybrid electromechanical device, torsion torque generator, BLDC motor, torsional vibrations.

doi:10.12915/pe.2014.07.11

Introduction

Ensuring appropriate ample excitations plays key role in modal analysis of mechanical devices, structural health monitoring (SHM), process identification and in design process of devices, which functionality is based on vibration generation, like vibration conveyors, or vibration separators and others drive systems. In real-life cases, exact determination of mechanical device parameters is often very problematic, impossible or uneconomic. Further more, parameters of mechanical devices will vary over time according to its durability, ageing process and fatigue process of devices parts. Generation of wide spectrum torsion excitation is also very problematic due to necessity of utilization numerous different actuators and/or complicated control systems. In this article the concept of relatively simple (from constructional point of view) and economically cheap hybrid devices, based on combination of electromagnetic torsion torque generator and BLDC motor, inextricably linked by their rotors shafts is presented. Such solution will be examined by means of numerical calculations, showing its usefulness in modal parameters estimation or enforcing work of investigated devices close to its natural frequencies.

Mathematical model of electromagnetic torsion generator

Electromagnetic torsion torque generator is a redesigned electric squirrel cage machine [1], [7, 8], in which some parameters are changed (like: number of rotors bars - Q_r= 28 were chosen, number of stator slots - Q_s = 36 were chosen and kind of stator windings - single layer, 2 pole pairs were chosen) in such a way, that machine starts producing high values of so - called parasitic torques [1, 4]. Electromagnetic torsion torque generator, besides the fractional asynchronous torque, generates torsion torques with different frequencies. Their frequencies, as well as amplitudes, depend on angular rotation speed of the rotor and also on supply frequency [1, 2]. The frequencies of generated torsion torques are described by so-called frequency-speed characteristics. As it was shown in [1, 2] frequency-speed characteristics can be described by following functions:

$$f_{(\nu,\rho)} = \left|\frac{\rho \pm \nu}{2\pi}\Omega_m \mp 2f_0\right| \quad (1)$$

$$f_{(\nu,\rho)} = \left|\frac{\rho \pm \nu}{2\pi}\Omega_m\right| \quad (2)$$

where: Ω_m - angular speed of generator shaft (in steady state), f_0 - frequency of supply network, ν, ρ - orders of space harmonics of magnetic fields in air - gap producing chosen torsion torque.

Exemplary frequency-speed characteristics of torsional torque for generator with following parameters: numbers of pole pairs p = 2, numbers of rotor bars Q_r = 28 are presented in figure 1, but its magnified region around small angular speed is presented in figure 2.

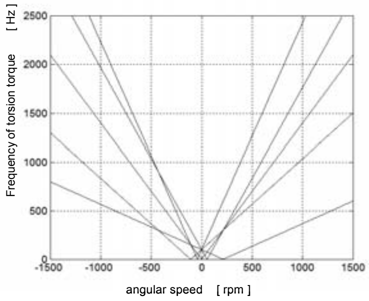

Fig.1. Frequency-speed characteristics of torsional torque for generator (p=2, Q_r =28)

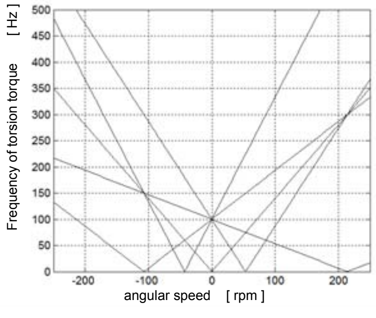

Fig.2. Magnified region of frequency-speed characteristics of torsion torque

Frequency-speed characteristics presented in figures 1 and 2 do not show the information about the amplitudes of generated torsion torques. In order to determine torsion torque amplitudes, it was necessary to formulate mathematical model of torsion torque generator, in which 15 space harmonics of magnetic field were taken into consideration. The selection of space harmonics it is not incidental, and it must be done accordingly with strict rules presented in [1, 4], rules which assures selection of only these harmonics that play most important role with torsion torque generation. Tools helpful for this purposes, are called diagrams of decomposition of induction machine into elementary machines [4], introducing graphical form of searching and selecting the space harmonics with most predominant influence of torsion torque generation. In the formulated mathematical model of torsion torque generator were taken into consideration space harmonics of magnetic field in air-gape with orders presented in table 1.

Table 1. Orders of space harmonics

2	26	58	82	86
22	34	50	62	116
10	38	46	74	94

Space harmonics situated in rows of table 1 establish pairs between them and each pair generate torsion torque. Formulated in two axes, clockwise coordinate systems $\alpha\beta dq$ ($\alpha\beta$ - coordinate system fixed with stator, dq - coordinate system fixed with rotor) mathematical model of torsion torque generator is given by following set of differential equations in matrix form:

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}^{\alpha\beta dq} = \boldsymbol{M}(\vartheta)^{-1}\left(\boldsymbol{u}^{\alpha\beta dq} - \boldsymbol{R}\ \boldsymbol{i}^{\alpha\beta dq} - \omega_m \frac{\partial}{\partial\vartheta}\boldsymbol{M}(\vartheta)\boldsymbol{i}^{\alpha\beta dq}\right) \tag{3}$$

where: $\boldsymbol{i}^{\alpha\beta dq}$ - vector of generator currents in $\alpha\beta dq$ coordinate system, $\boldsymbol{u}^{\alpha\beta dq}$ - vector of generator supply voltages in $\alpha\beta dq$ coordinate system, $\boldsymbol{M}(\vartheta)$ - block matrix of self inductances and mutual inductances, $\boldsymbol{R}$ - block matrix of resistances, ω_m - angular speed of the rotor.

Equation of electromagnetic torque generated by torsion torque generator is given by following equation:

$$T_e = \boldsymbol{i}_s^{\alpha\beta\mathrm{T}} \frac{\partial}{\partial\vartheta}\begin{bmatrix} \boldsymbol{M}_{sr2}(\vartheta) & \boldsymbol{M}_{sr10}(\vartheta) & \boldsymbol{M}_{sr22}(\vartheta) \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{i}_{r2}^{dq} \\ \boldsymbol{i}_{r10}^{dq} \\ \boldsymbol{i}_{r22}^{dq} \end{bmatrix} \tag{4}$$

where: $\boldsymbol{M}_{sr2}(\vartheta)$ - matrix of stator - rotor mutual inductances related with space harmonics presented in first row of table 1., $\boldsymbol{M}_{sr10}(\vartheta)$, $\boldsymbol{M}_{sr22}(\vartheta)$ - matrices of stator - rotor mutual inductances related with space harmonics presented in second and third row of table 1, $\boldsymbol{i}_s^{\alpha\beta}$ - vector of stator currents in its two axes coordinate system, $\boldsymbol{i}_{r2}^{dq}$, $\boldsymbol{i}_{r10}^{dq}$, $\boldsymbol{i}_{r22}^{dq}$ - vectors of rotor currents in its two axes coordinate systems.

Matrix of inductances $\boldsymbol{M}(\vartheta)$ occurring in equation (3) has a following block structure (due to the considerable size, dependencies of matrix elements on rotation angle has been omitted):

$$\boldsymbol{M} = \left[\begin{array}{c:c:c:c} \boldsymbol{M}_s & \boldsymbol{M}_{sr2} & \boldsymbol{M}_{sr10} & \boldsymbol{M}_{sr22} \\ \hdashline \boldsymbol{M}_{sr2}^{\mathrm{T}} & \boldsymbol{M}_{r2} & \boldsymbol{0} & \boldsymbol{0} \\ \hdashline \boldsymbol{M}_{sr10}^{\mathrm{T}} & \boldsymbol{0} & \boldsymbol{M}_{r10} & \boldsymbol{0} \\ \hdashline \boldsymbol{M}_{sr22}^{\mathrm{T}} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{M}_{r22} \end{array}\right] \tag{5}$$

where: $\boldsymbol{M}_s$, $\boldsymbol{M}_{r2}$, $\boldsymbol{M}_{r10}$, $\boldsymbol{M}_{r22}$ - diagonal matrices of stator and rotor self inductances (constant, unrelated with angular displacement), incorporating windings leakage inductances, $\boldsymbol{0}$ - zero filled matrix.

All of the matrices in block matrix (5) are 4 elements. The matrix of resistances $\boldsymbol{R}$, from equation (3), has a following block structure:

$$\boldsymbol{R} = \left[\begin{array}{c:c:c:c} \boldsymbol{R}_s & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \hdashline \boldsymbol{0} & \boldsymbol{R}_{r2} & \boldsymbol{0} & \boldsymbol{0} \\ \hdashline \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{R}_{r10} & \boldsymbol{0} \\ \hdashline \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{R}_{r22} \end{array}\right] \tag{6}$$

where: $\boldsymbol{R}_s$, $\boldsymbol{R}_{r2}$, $\boldsymbol{R}_{r10}$, $\boldsymbol{R}_{r22}$ - diagonal, 4 element stator and rotor windings resistances matrices.

Detailed representations of elements of inductance and resistance block matrices, in case of inclusion as much as 15 space harmonics, are very complex and will not be presented in this article. However, reader can restore them with [4], or directly from [1].

Determining amplitudes of torsion torques of a generator

In order to determine the amplitudes of generated torsion torques, mathematical model described in (3) and (4) has been implemented in MATLAB/Simulink environment. Right hand side of the equation (3) has been implemented as an m-function and put into "MATLAB Fcn" block. Graphic structure of the model is presented in figure 3. Block labelled as "(1)", contains a script function with a generator mathematical model. Variables of this function consist of supply voltages of stator and rotor (multiplexer "(2)" inputs "in_1", "in_2" and "in_4", "in_5"), stator and rotors currents (remaining inputs on Mux "(2)"), angular speed and angular displacement.

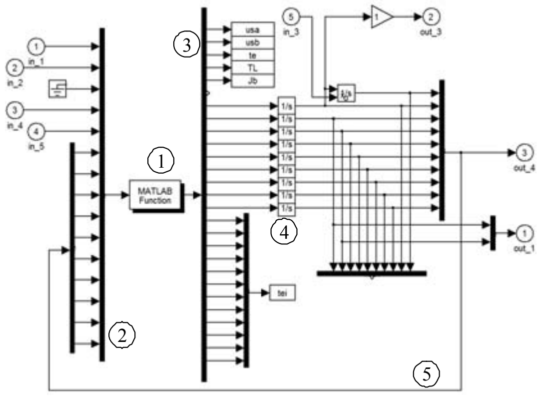

Fig.3. Block scheme representing mathematical model of torsion torque generator

Output of a script function is a vector, containing: stator voltage components, electromagnetic torque, stator and rotor currents derivatives, torque components related to considered harmonics of magnetic field. Current derivatives are being integrated in the block of integrators marked as "(4)". Calculated current values, combined with angular speed and displacement provide a feedback, labelled as "(5)", into the function script.

In simulations, a constant angular speed in range between -1500 to 1500 RPM (with a 30 RPM step) has been forced in a mathematical model. Each simulation lasted 5 seconds, and for calculations constant step ode5 method has been used (with a 50 μs step). Fast Fourier transformation has then been performed on sampled values of electromagnetic torque (20000 last samples were taken into account). Figure 4 represents consolidated enhanced, 3D frequency-speed characteristics of torsion torques in full range of investigated angular speeds, additionally picturing the amplitudes of generated torque.

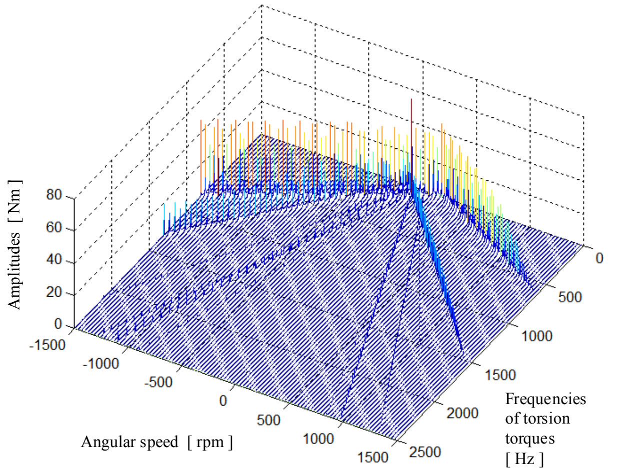

FIg.4. 3D frequency-speed characteristics of torsion torques

Magnified region of positive angular velocity, i.e. with a sense of rotation of a shaft same as of magnetic field in an air-gap of a generator, is presented in figure 5.

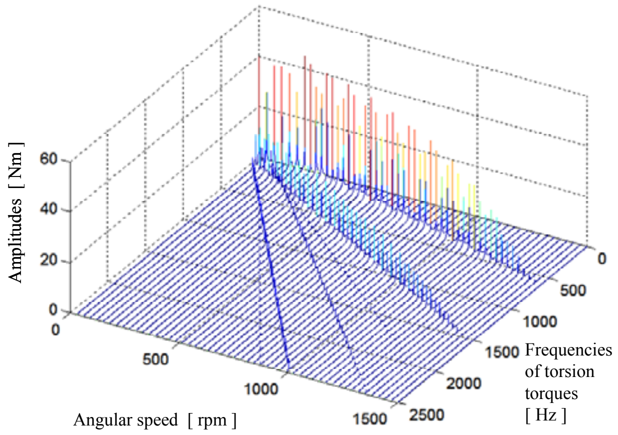

Fig.5. Magnified region of 3D frequency-speed characteristics for positive angular rotation speed of a shaft

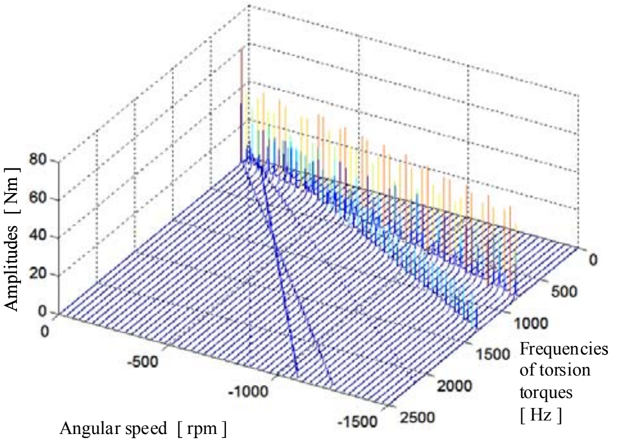

Fig.6. Magnified region of 3D frequency-speed characteristics for opposite angular rotation speed of a shaft

By contrast, figure 6 shows the opposite region of characteristics, with a sense of rotation of a shaft opposite to the rotation of magnetic field. Comparison of both figures allows to form a conclusion, that in a region of negative angular velocities, the amplitudes of generated torsion torques are reasonably even, unlike the positive region, where amplitudes are gradually decreasing, as the angular velocity moves closer to the synchronous speed. Highest amplitudes of torsion torques are generated by pairs of harmonics (2, 26), (10, 38), and (22, 34). Pair of space harmonics of magnetic field (2, 26) generates torques (in an investigated range) with a frequencies up to 800 Hz and amplitudes fluctuating around 45 Nm. Pair (10, 38) generates frequencies up to 1400 Hz and amplitudes roughly 20 Nm, finally pair (22, 34), generates torques in 3500 Hz range and amplitudes close to 5 Nm. Remaining pairs of harmonics generate torques of much lower amplitudes, but significant frequencies (up to 3 kHz).

Negative angular speed range is therefore beneficial for generating torque both from generated frequencies and amplitudes perspective, as well as their regularity.

Change of an operating point (angular speed), as presented above has a large influence on generated torsion torque. Hence hybrid generator, proposed in this paper is presented with additional BLDC motor which forces the desired angular rotation speed of generator shaft. The BLDC motor and its driving system have been modelled accordingly to the [5].

Mathematical model of the power plant drive system

As an example of mechanical system, to be examined regarding torsional vibration frequencies, consisting of an gas turbine and electric generator, as in [3] has been proposed. Assumed model of a power plant drive system is a kinematic chain comprised of seven rigid elements representing masses (representing among others mass moments of inertia of turbine, electrical power generator, torsional torque generator). Rigid elements representing masses are joined by six spring elements, representing rotational stiffness of shafts and clutches. Mathematical model of such a system has seven degrees of freedom and is described by following differential equations in matrix form:

$$(7) \qquad \frac{\mathrm{d}^2}{\mathrm{d}t^2}\vartheta = \boldsymbol{J}^{-1}(\boldsymbol{T}_e - \boldsymbol{K}\vartheta - \boldsymbol{B}\boldsymbol{\omega}_m)$$

where: $\boldsymbol{J}$ - diagonal matrix of mass moments of inertia, $\boldsymbol{K}$ - tridiagonal matrix of rotational stiffness, $\boldsymbol{B}$ - diagonal matrix of damping coefficients, ϑ - angular displacements vector of inertial masses, ω_m - inertial masses angular velocities vector, $\boldsymbol{T}_e$ – vector of driving torques.

Assumed (changed in relation to [3]) parameters from equations (7) are listed in table 2.

Table 2. Assumed parameters of investigated system

nodes i	1	2	3	4	5
J_i kgm^2	0.119	0.00454	0.0013	0.00025	0.00025
k_i Nm/rad	26013	34005	158528	300374	712153
nodes i	5	6	7	-	-
J_i kgm^2	0.00025	0.03188	0.0044	-	-
k_i Nm/rad	712153	164522	-	-	-

Determining appropriability of proposed torsional torque generator

In order to set a benchmark and examine capabilities of a theoretical wide spectrum torsional torque generator, mathematical model of a power plant drive system has been connected directly to the band limited white noise block, with a 50 μs sample time and noise power matched for a amplitudes of torque to not exceed +/- 6Nm. Input and output data from this simulation has been used to determine frequency response between respective nodes (point masses) of a system.

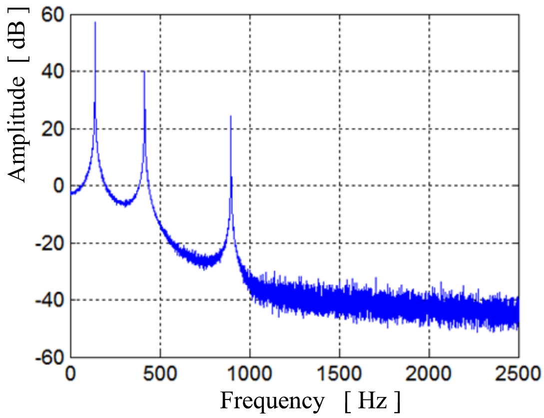

Fig.7. Vibration amplitudes characteristics of nodes 1-7

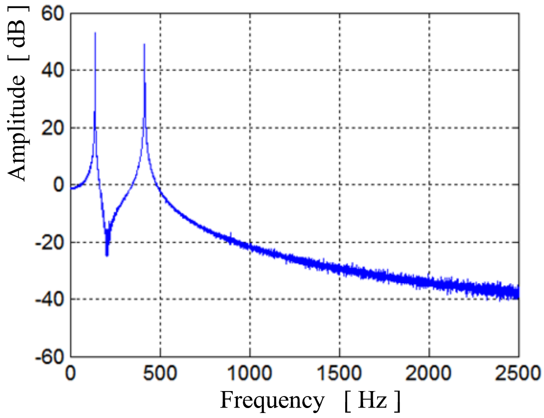

Fig.8. Vibration amplitudes characteristics of nodes 6-7

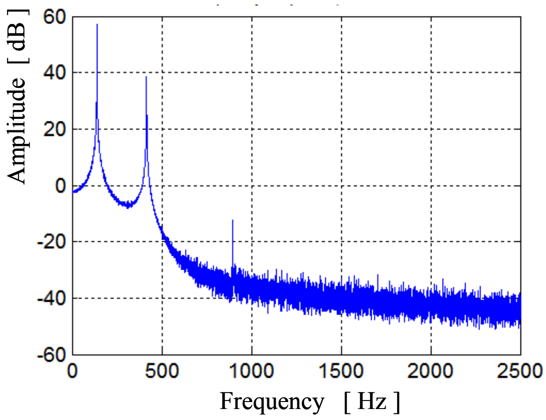

Fig.9. Vibration amplitudes characteristics of nodes 4-6

For selected node configurations, respectively 1-7, 6-7 and 4-6 characteristics has been presented in figures 7, 8 and 9. Conclusion can be drawn, that natural frequencies do not have the same magnitude between different rigid masses and in some configurations, certain modes don't occur at all. It has been also shown, that higher harmonics (in kHz range) for this system can be omitted in further analysis, due to their very small gain (in most cases, their magnitude hasn't exceeded the noise floor).

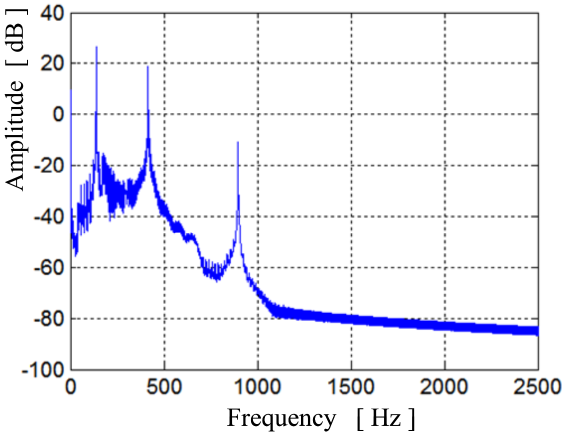

Fig.10. Estimate of power density spectrum of nodes 1-7, made using torsion torque generator

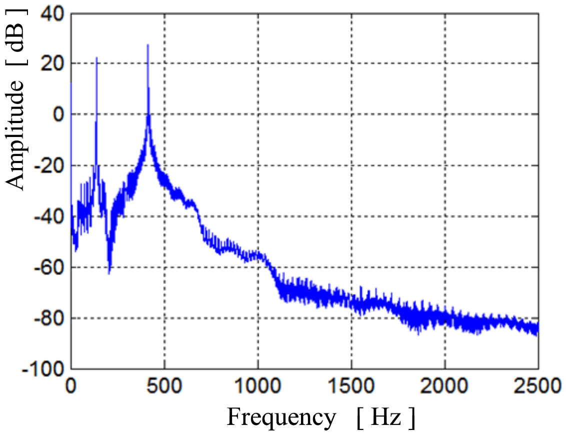

Fig.11. Estimate of power density spectrum of nodes 6-7, made using torsion torque generator

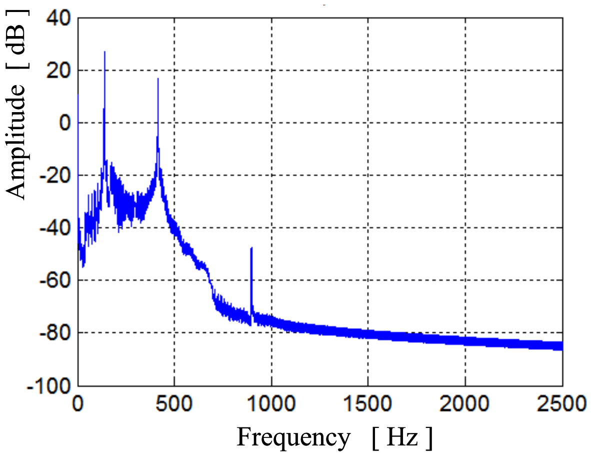

Fig.12. Estimate of power density spectrum of nodes 4-6, made using torsion torque generator

Proper appropriability experiment has been performed with a hybrid torsional torque generator connected to the first node (first mass) of the power plant. Despite many possibilities of accurate control of the torsional torque generator's behaviour and the fact, that exact natural frequencies of the investigated mechanical system are known, it has been assumed, as it would most likely have been in a real-life experiment, that it is imperative to treat the system as unknown and to generate very wide spectrum. Worst case, easiest to implement scenario from the hybrid generator's point of view has also been selected. To satisfy those assumptions, the experiment based on ramping the setpoint on BLDC motor's drive from 0 to 140 rad/s in 45 seconds has been simulated, with remaining parameters (i.e. torsional torque generator parameters) has been left unchanged. It has also been assumed, that input data (factual torque generated by the hybrid generator) may be unavailable in the real-world implementation. Due to this constraint, outcome of the experiment has been presented as power spectrum density plots, calculated with a Welsh method (8 windows with a 50% overlap), shown on figures 10 and 12, for a comparison needs for the same nodes, as in figures 7 and 10.

Direct comparison of presented data shows, that proposed hybrid torsional torque generator is an adequate excitation for a complex mechanical system, to expose its natural frequencies and can be a good estimator of a frequency response characteristics.

Performance of proposed generator can be further enhanced, with forcing negative angular velocities, BLDC motor and its drive choice or tuning generator construction or work parameters.

Summary

Proposed hybrid generator configuration, as a conjunction of two induction machines - electromagnetic torsion torque generator and BLDC motor, possess attributes, which allow it to be used to determine natural frequencies of complex drive systems. Furthermore, identification of those modes does not have to be performed on a stopped system, but also while it is running (for a range of different angular velocities). Electromagnetic generator in presented configuration can provide torsion torque of a significant frequency (up to 3.5 kHz) and amplitude (up to 45 Nm). Numerical calculations presented in this paper allow concluding, that evaluated system can be capable to generate torsion torque required to successfully perform modal analysis of a complex drive system.

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