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DYNAMICS OF ELECTRIC MACHINES ROTORS WITH UNBALANCED MAGNETIC PULL

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Abstract

The object of the study is Unbalanced Magnetic Pull (UMP) which arises in electric motors and generators and must be taken into account in rotor dynamics tasks. Review of existing methods of UMP determination is presented, its nonlinear nature is noted. The algorithm to solve the task of rotor dynamics behavior with UMP in nonlinear transient analysis is created. The hydraulic turbine generator model is taken as an example. Magnetic forces influence on hydraulic turbine generator dynamic characteristics is shown.

Key words: *Rotor dynamics, Unbalanced Magnetic Pull (UMP), electric machines , rotor eccentricity, Dynamics R4.*

Notations

F_{UMP} - force of unbalanced magnetic pull (UMP)

σ – Maxwell's stress tensor

S – surface area

n– surface normal vector

B - magnetic field induction

B_δ - magnetic field induction in air clearance (nominal value)

μ_0 – air magnetic permeability

k_c – Carter coefficient

R - rotor radius

l – active rotor part length

D - rotor diameter

φ - angular coordinate

R_s - inner stator radius

S_s - linear load in stator

p – number of ports

δ_0 - nominal air clearance

e – rotor eccentricity

ε - relative rotor eccentricity

r, θ - indexes of radial and tangential components correspondingly

Introduction

Mechanic vibrations in electric machines are typical due to the presence of changing magnetic field. In case of inequality of air clearance between a rotor and a stator, because of static and dynamic rotor eccentricity, electromagnetic field excites unbalanced magnetic force applied to the rotor centre and directed at the minimum air clearance. This force was called unbalanced magnetic pull (UMP).

Unbalanced magnetic pull is a source of forced oscillation in hydro generators and asynchronous motors. In hydro generators great influence of electromagnetic forces on the rotor vibrations takes place due to multipolarity and relatively small radial clearance between the rotor and the stator. In asynchronous motors of alternating current clearance between the rotor and the stator is small, so UMP is the same order of magnitude as unbalanced forces [1]. UMP influence on rotor dynamics takes place in other types of electric machines [2]. So UMP taking into account is an important task in rotor dynamics analysis of electric machines.

Nowadays the task of UMP complete taking into consideration in the rotor systems analysis and estimation of electromagnetic influence on the rotor dynamics of the electric machines is a complex one. Many investigations in rotor dynamics are devoted to study of the hydro generators rotors considering UMP [3]. Paolo Pennacchi presents nonlinear effects of UMP influence on a turbine generator. [2]. Z Song and Z Ma investigate UMP influence on natural frequencies of the rotor systems [4]. Mattias Nässelqvist uses UMP in investigation of rotor dynamics of hydro generators [5]. Arkkio A. investigates UMP and its influence on electric motors dynamics in works [6,7].

General theory

UMP value depends on many factors: the rotor eccentricity, geometrical machine sizes, magnetic field induction in air clearance, magnetic characteristics of the rotor material, presence of parallel winds in a winding. Taking into consideration of all factors is still complicated task.

There are analytical and numerical methods of UMP calculation. Numerical methods are based on joint solution of equation describing magnetic field and current circulation in winding. They provide high accuracy of the final solution, considering saturation and other complex nonlinear phenomena appearing in electric machines [8]. Nowadays to solve the task, the finite element method is used. However, even using modern powerful computers, FEM calculations of the models with complex 3-D geometry take a lot of time. So, magnetic field is often accepted to be 2-D; it means that the field is considered to be independent of the axis coordinate coinciding with the rotor axis of rotation. Such approach allows taking into consideration the majority of factors influencing UMP and obtaining quite accurate results [6], [8], [9].

The method presented in [7] should be highlighted. It is based on the results of modeling by numerical methods and theoretical analysis of an electric machine. The main point is that relation between UMP and the rotor eccentricity should be expressed by a simple parametric equation

$$F_{em}(s) = K(s)z(s), \quad (1),$$

where $F_{em}(s)$ - mutual electric force; $z(s)$ – function describing displacement of the rotor centre, $s = i\omega$ - Laplace variable, $K(s)$ - transfer function of the 2-nd order.

$$K(s) = k_0 + \frac{k_{p-1}}{s - a_{p-1}} + \frac{k_{p+1}}{s - a_{p+1}}, \quad (2)$$

where k_0, k_{p-1}, k_{p+1}, a_{p-1}, a_{p+1} - the model parameters obtained using numerical calculation, carried out on the basis of the electric machine analysis using FEM; p — the number of ports in the machine.

Application of the methods shown above gives the results with high accuracy, but to solve dynamics tasks, application of analytical methods has practical meaning. The advantage of analytical methods is operability of the results obtainment in the form that is simple for interpretation.

Analytical methods of UMP calculation are usually based on the use of Maxwell stress tensor [8], [3]. To obtain the force, it is necessary to calculate area integral of tensor.

$$F_{UMP} = \oint_S \sigma \cdot ndS \quad (3)$$

The main components of Maxwell tensor may be written as follows:

$$\sigma_r = \frac{1}{2\mu_0}(B_r^2 - B_\theta^2), \quad (4)$$

$$\sigma_\theta = \frac{1}{\mu_0} B_r B_\theta. \quad (5)$$

The value B_θ is insignificant, so it is accepted to be equal to 0. Finally we obtain integral, whose solution is UMP value [8].

$$F_{UMP} = \frac{lR}{2\mu_0} \int_0^{2\pi} B_r^2 nd\varphi, \quad (6)$$

There are a lot of the task solutions depending on assumptions. The simplest one is linear UMP relation to eccentricity [10].

$$F_{UMP} \approx \pi Dl \left(\frac{B_\delta}{5000} \right) \frac{\varepsilon}{2k_c}, \quad (7)$$

where $\varepsilon = \frac{e}{\delta_0}$.

Coefficient of magnetic stiffness k_e [11] can also be calculated.

$$k_e = \frac{\pi Dl}{4\mu_0} \frac{B_\delta^2}{\delta_0}. \quad (8)$$

Nonlinear relations give more accurate values [12]. For example, there is an analytic formula for UMP calculations in isotropic electric machines

$$F_{UMP} = \frac{l \cdot J(\varepsilon, p) \cdot 2 \cdot \pi \cdot R_s \cdot \left(\frac{B_\delta}{k_C} \right)^2}{2 \cdot \mu_0}, \quad (9)$$

where $J(\varepsilon, p)$ - function depending on the relative rotor eccentricity ε and the ports number p.

Here is the $J(\varepsilon, p)$ function

$$J(\varepsilon,p)=\frac{\varepsilon^2-\left(\frac{(1-\sqrt{1-\varepsilon^2})}{\varepsilon}\right)^{2p}\cdot\left(\varepsilon^2+2\cdot p\cdot\sqrt{1-\varepsilon^2}\right)}{2\cdot\varepsilon\cdot\left(\sqrt{1-\varepsilon^2}\right)^3}. \quad (10)$$

Calculation results with the use of this formula give high correlation with the experiment [12].

Hydro generators have a lot of poles. For them the UMP mean value may be written as following [13]

$$F_{UMP}=\frac{\mu_0 S_s^2 R_s^3 l\pi}{2(2p)^2\delta_0^2}\frac{\varepsilon}{\sqrt{(1-\varepsilon^2)^3}}. \quad (11)$$

Equations (9) and (11) represent the simplest nonlinear relations of UMP from eccentricity, so they are widely used.

Motion equations of rotor system

To take into consideration UMP in rotor systems dynamics, the algorithm and software module for modeling and analysis in the program system Dynamics R4 [14] were developed.

At nonlinear statement the matrix equation describing the nonlinear dynamic model of the rotor system, is presented below:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F(t)\}+\{R\}, \quad (12)$$

where $[M]$ – matrix of inertial coefficients, $[C]$ – matrix of damping coefficients, $[K]$ - matrix of stiffness coefficients, $\{\ddot{u}\},\{\dot{u}\},\{u\}$ – columns of vibration accelerations, vibration velocities and vibration displacements correspondingly; $\{F(t)\}$ - dynamic loads of any types – inner and outer; $\{R\}$ - reactions of a nonlinear link which considers magnetic force appearing between the rotor and the stator.

In Dynamics R4 the rotor system model is built from the bar subsystems connected by elastic links. The subsystem is a structural model element built from the standard elements – beams, shells, disks, etc. The link is a mathematical model of subsystems interaction between each other and the basement. The link is modeled by applying the same force to two interacting subsystems. According to the third Newton law, forces have different signs, but equal in value. They are called the link reactions.

The nonlinear link model is built on the basis of equations (9) and (11). In case of UMP modeling in an asynchronous machine, the equation (9) is used. In case of hydro generator - equation (11). It happens due to some peculiarities of the machine types presented above.

To integrate the equation (12), different methods may be applied, for example, Runge–Kutta methods, Adams method, difference methods, etc. Figure 1 presents the general calculations scheme.

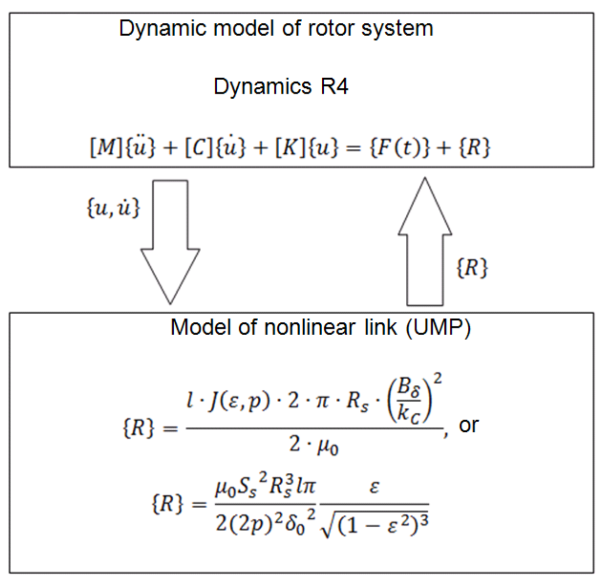


Figure 1 Interaction between models of rotor system and UMP model while integrating

At linear statement the equation (12) may be simplified, considering magnetic force through stiffness coefficient obtained from the equation (8).

Rotor system model

To investigate UMP impact on the rotor systems, the axis symmetrical hydro generator model is used. It is built in the program system for analysis of dynamic characteristics of rotating machines Dynamics R4, Figure 2. Initial data are presented in Table 1.

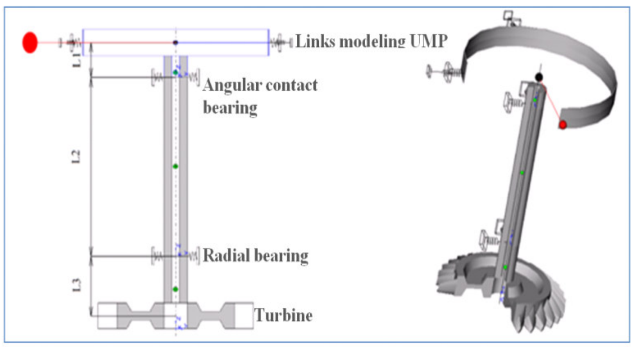


Figure 2 Generator model in Dynamics R4

Table 1

Shafting	
Length L1, m	1.32
Length L2, m	6.83
Length L3, m	2.286
Outer diameter, m	1
Inner diameter, m	0.35
Generator rotor	
Mass,kg	238898
Polar inertia moment, kgm^2	2.952e6
Diametral inertia moment, kgm^2	1.556e6
Diameter, m	8.066
Length,m	1.9
Poles number	60
Air clearance between stator and rotor, m	0.017
Linear load in stator, A/m	90000
Magnetic field induction in clearance, T	0.45
Turbine	
Mass, kg	50414
Polar inertia moment, kg*m^2	1.7619e5
Diametral inertia moment, kg*m^2	1.3757e5
Bearings	
Stiffness of angular contact bearing, N/m	4.905e8
Stiffness of radial bearing, N/m	6.54e8
Damping coefficient, Nsec/m	1e6

Magnetic stiffness coefficient is calculated using the equation (8) and equal $k_e = 1.168e8$ N/m. Unbalance load is applied to the rotor centre of gravity. It is calculated according to the standard GOST ISO 1940-1-2007 using the following equation:

$$U_{per} = 1000\frac{(e_{per}\Omega)m}{\Omega}, \qquad (13)$$

where U_{per} – acceptable residual unbalance [g·mm], $(e_{per}\Omega)$ – factor of the balance quality grade [mm/s], e_{per} - acceptable residual specific unbalance [m] , m – rotor mass[kg], Ω – angular rotor speed [rad/s].

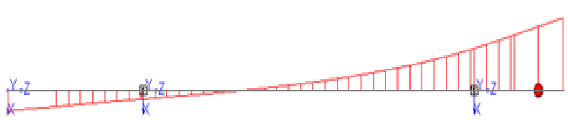
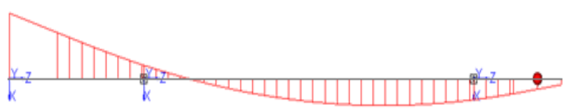
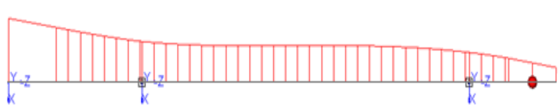
For this plant:

$$U_{per} = 1000\frac{(e_{per}\Omega)m}{\Omega} = 1000\frac{6.3 \cdot 340362}{25.13} = 85327520 \text{ g*mm}$$

Stationary analysis

The system frequencies and mode shapes are presented in Table 2.

Table 2

214.8 rpm (3.6 Hz) 
537.9 rpm (9.0 Hz) 
610.4 rpm (10.2 Hz) 

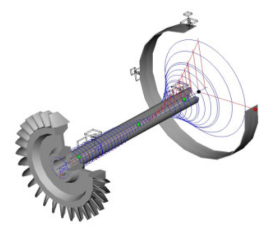
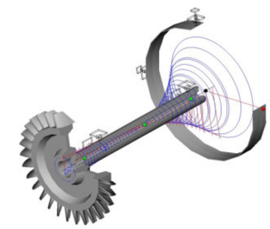
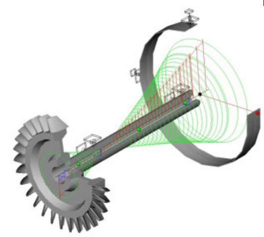
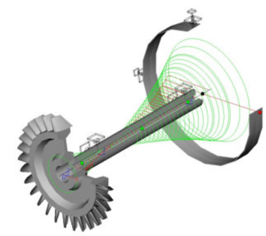
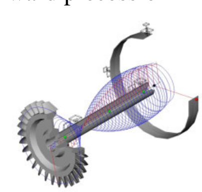
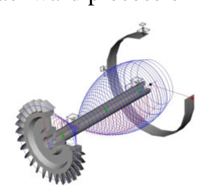
Distribution of potential energy on the system natural frequencies is presented in Table 3. The distribution knowledge allows highlighting the elements, by changing which it is possible to control natural frequencies.

Table 3

Subsystems and links	Natural frequencies, rpm		
	214.8	537.9	610.4
Generator rotor	8.983	8.974	7.289
Shaft	32.764	57.959	13.582
Turbine	0.026	7.196	5.486
Radial bearing	6.478	9.473	54.152
Angular contact bearing	115.446	17.429	21.677
UMP	-63.698	-1.031	-2.186

The UMP link has negative potential energy which contradicts physics. Negative sign appears in energy distribution, because stiffness of the link simulating electromagnetic force action is set as negative. Change in UMP value can influence natural frequency at first mode shape.

Table 4

Without taking UMP into account	With UMP taking into account
202.5 rpm (3.4 Hz) Backward precession 	166.9 rpm (2.8 Hz) Forward precession 
359.4 rpm (6.0 Hz) Forward precession 	283.8 rpm (4.7 Hz) Forward precession 
441.8 rpm (7.4 Hz) Backward precession 	421.4 rpm (7.0 Hz) Backward precession 

The system critical speeds and mode shapes are presented in **Ошибка! Источник ссылки не найден.** with taking UMP into account and without it.

Figure 3 presents the system amplitude-frequency characteristic. Without UMP taking into consideration, resonance appears at rotating speed of 359.4 rpm.

Oscillations amplitude at resonance is 5.1 mm. Considering UMP, simulated as a linear link with negative stiffness coefficient equal to 116800000 N/m, resonance takes place at rotating speed 283.8 rpm, and oscillations amplitude is 4.3 mm. UMP presence leads to decrease in critical speed of the rotor system. Reduction in oscillations amplitude is not the effect of UMP influence on the system; it is caused by decrease in unbalanced force.

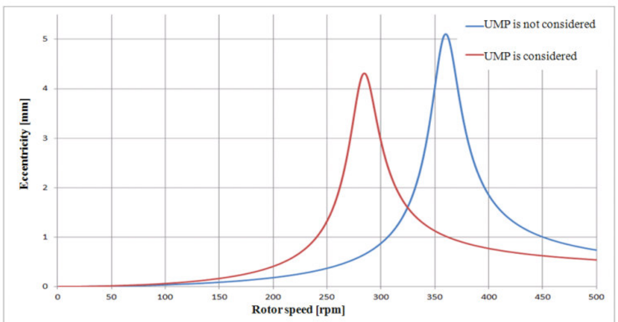


Figure 3 Amplitude-frequency characteristic of system with taking UMP into account and without it

Maximum operating rotor speed for the investigated hydro generator is 180 rpm, which is significantly lower than resonance frequency. However, UMP will influence vibration level even at frequencies which are lower than resonance. Figure 4 shows that UMP presence results in great amplitudes in operating speed range.

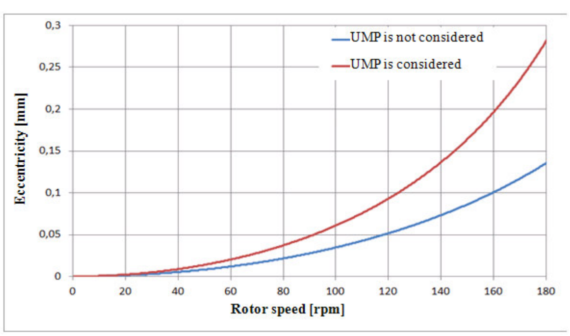


Figure 4 Amplitude-frequency characteristic in operating speed range

Transient response

At dynamic system analysis at unsteady statement, the generator's acceleration is simulated from 0 to 500 rpm. There is a critical speed of the system in this range. To take UMP into account, the non-linear model is used (11). As a result, time characteristic (Figure 5) is obtained during acceleration; its mean value is also found, Figure 6. Comparison of the results of the rotor model transient response with linear and non-linear UMP models shows that mean value plots almost match: difference between resonance peaks is only 1.2%, Figure 6.

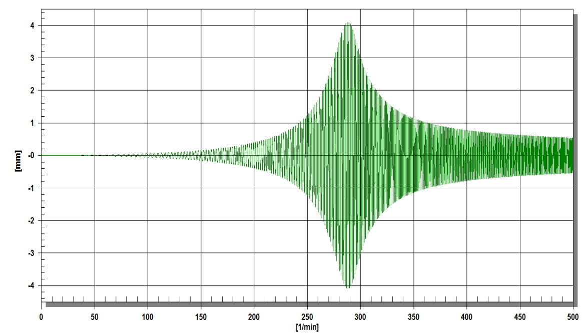


Figure 5 Amplitude-frequency characteristic of rotor system

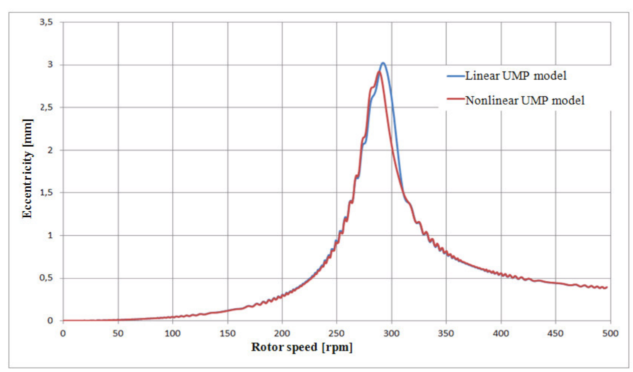


Figure 6 Mean value of amplitude-time characteristic of rotor system

There is a nonlinear relation between UMP and eccentricity [9, 10]. It is presented in Figure 7. UMP nonlinearity takes place at relatively big eccentricities $\varepsilon \geq 0.4$.

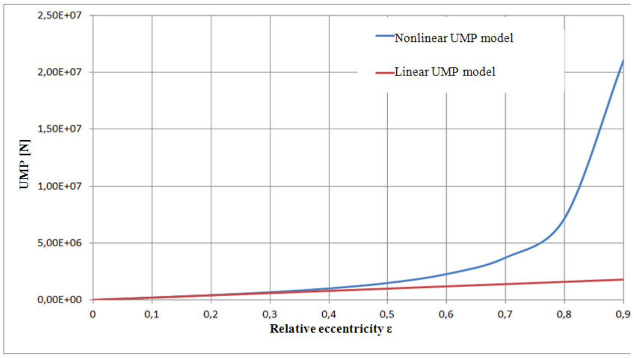


Figure 7 UMP vs eccentricity at linear and nonlinear statement

Figure 8 shows effect of big eccentricity and its influence on UMP. To reach relative eccentricity more than 0.4, the increased unbalance of 250000000 g*mm (three times bigger than the value calculated using (13)) is applied to the investigated model. Figure 8 shows that in case of nonlinear UMP calculation, resonance peak is lower than in case of linear one. Correspondingly, from previous results it may be confirmed that using the nonlinear model, we obtain bigger UMP values. This is corroborated by an experiment [12].

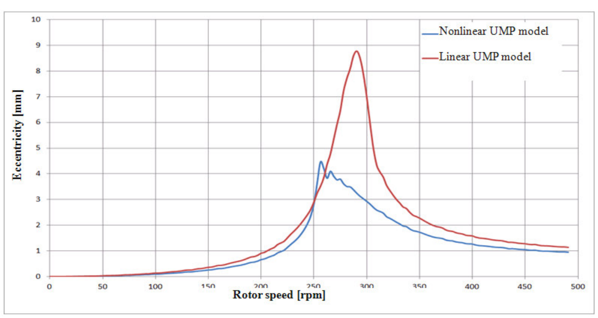


Figure 8 Mean value of amplitude-frequency characteristic of rotor system at big eccentricities (unbalance of 25000000 g*cm)

Conclusion

On the basis of the investigation, it may be concluded that UMP has a great influence on oscillations of electric machines rotors. UMP decreases critical speeds that results in resonance appearance at lower rotating speeds, changes oscillations amplitudes. Results show necessity of taking UMP into consideration in rotor dynamics tasks of electric machines. UMP may be calculated applying different methodologies. The main advantage of the presented methodology is relative simplicity and initial data minimum. Implementation of this algorithm in the Dynamics R4program system allows holding the most complete analysis of the rotor dynamics of electric machines. This enables engineers who do not have special knowledge in electro mechanics, taking UMP into account when solving dynamics tasks.

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