INFLUENCE OF ECCENTRICITY ON SYNCHRONOUS REACTIVE FREQUENCY DOUBLER

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KEYWORDS
Finite element method, QuickField, frequency converter, frequency doubler.

ABSTRACT

This paper describes the influence of rotor eccentricity synchronous reactive frequency doubler's characteristics. Specifically, the research is concentrated on the influence of rotor eccentricity on increased frequency EMF E_2 value, that is induced it stator's secondary winding.

To clarify this question the simulations by using the finite element method implemented in QuickField software, are applied.

There are many reasons why does eccentricity occur:

- unbalance – an uneven distribution of a rotor's mass;
- bent shaft – damaged or curved shaft produces unequal air gap;
- bearing – a bearing that for some reason has lost it's lubrication, wear out fast (may also fail and damage remaining components;

loose foundation – the improper mounting of the machine without holding it rigidly to the ground causes the machine to vibrate and eventually leads to air gap's inequality (Rezig and Mekideche 2010).

Eccentricity is considered because of the influence of the air gap variance on the electromagnetic field distribution. Both the voltage and current sine waves can be altered, and when viewed in a fast Fourier-transform, they appear as harmonic sidebands of main eccentricity frequency.

INTRODUCTION

Eccentricity of a stator – ellipticity of inner lair of a stator with respect to rotor's rotation axis. This eccentricity arises due to improper bearing support mounting, bearing shield's defect or deformation of a stator.

Most common cause of eccentricity of a stator is laminated packages manufacturing defect. Very high possibility of stator's eccentricity occurrence is during electrical machine assembly, especially if the stator and bearing supports are mounted separately. This fault can arise in case of loose foundation or as a result of heat or other deformation.

Eccentricity of a stator (from electromagnetic process point of view) leads to periodic variation or pulsation of magnetic conductivity of an air gap. This pulsation has double the frequency of a supplying network.

Increased frequency pulsations with respect to supplying network arise due to alternatively passing, under a stator's inner surface position where the air gap width was changed, south and north poles. Increased frequency magnetic conductivities' pulsations lead to magnetic field pulsations with the same frequency.

Operating principles of all alternating current electrical machines is, approximately, the same – torque is produced due to stator's magnetic field interaction with:

1. rotor's magnetic field (synchronous machine);
2. current conductors in a rotor (asynchronous machine).

In synchronous machine energy is simultaneously supplied to rotor from direct current source, to stator from supplying network. In asynchronous machine energy is supplied only to a stator, because of that in order operate the machine a part of that energy must be transmitted through an air gap to a rotor, and only then the electromagnetic interaction can be started. Energy transfer through an air gap explains a smaller air gap's width in asynchronous machines, as well as sensitivity to nonlinearity of an air gap's width between stator and rotor.

Eccentricity of a rotor – inequality in distance between outer lair of a rotor and it's rotation axis. It is a very common cause of vibrations of electrical machines. If eccentricity of a rotor exist in particular electrical machine that leads to several peculiarities in electromagnetic field distribution. Electromagnetic field's density varies with the rotation of the rotor and leads to (due to inequality of air gap's width) uneven torque in motors, increased higher harmonics in generator's output voltage form (Rusov 1996; Intesar et al. 2011; Ebrahimi et al. 2011).

After clarifying possible eccentricity causes and variants, author concentrates on effects that arise due to eccentricity. The main concern for synchronous reactive frequency doubler is that eccentricity could lead to drastic output voltage (of EMF for no-load condition) drop or increase.

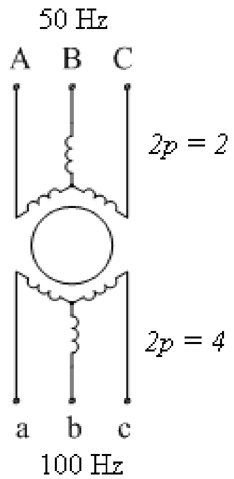
Proceedings 29th European Conference on Modelling and Simulation ©ECMS Valeri M. Mladenov, Petia Georgieva, Grisha Spasov, Galidiya Petrova (Editors)
ISBN: 978-0-9932440-0-1 / ISBN: 978-0-9932440-1-8 (CD)

SYNCHRONOUS REACTIVE FREQUENCY DOUBLER

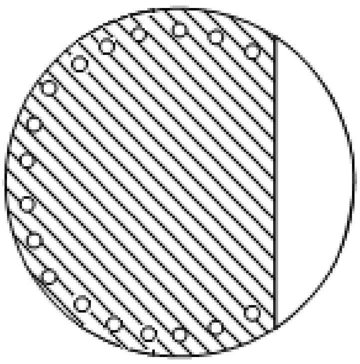
The synchronous reactive frequency doubler (SRFD) is the synchronous reactive machine, which uses the second harmonic - higher harmonics of the magnetic field. In slots of the SRFD, two windings are placed: the primary, which is connected to the industrial frequency AC network, and the secondary, which is used to receive the increased frequency. It is possible to note, that the synchronous reactive frequency converter is the one-machine aggregate, in which the synchronous reactive motor (stator's primary winding – salient pole rotor) and the inductor generator (salient pole rotor – secondary winding) are combined together.

The primary winding is consuming magnetizing current, which produces the rotating magnetic field in the air gap. From induction's distribution curve, the necessary (second) harmonic is used due to the specific form of the rotor's magnetic system and due to the appropriately selected width of the air gap.

This harmonic induces the increased frequency electromotive force (EMF) in the secondary winding. To achieve this, the secondary winding's step must be equal (or almost equal) to the higher harmonic pole pitch of the necessary field.



Figures.1. Stator Winding's Scheme



Figures.2. Rotor's Cross-Section View

Figure 2 schematically represents the rotor's cross-sectional view. The rotor's parts which are made of the ferromagnetic material are marked with stripes; the unmarked parts are made of the nonmagnetic material (aluminum, plastic). To star-up the SRFD in the rotor's magnetic part, the starting winding ("squirrel cage" shaped, made of aluminum bars and short-circuit rings) is placed.

Power with help of magnetic field is transferred from the primary winding to the secondary winding by means of specific transformation. In this case, the link between the primary and the secondary winding is not provided by the mutual induction flux, but by a part of it – the higher harmonic exuded flux. Power transfer is depending on the geometrical shape of the converter.

STATOR'S SECONDARY WINDING

Salient pole synchronous machines magnetic induction's distribution in air gap is not sinusoidal. That means, that magnetic induction curve contains not only fundamental harmonic, but also higher harmonics. Higher k harmonic's magnetic field in synchronous machines rotates with synchronous rotation frequency and its pole number $2p_k$ is k-times bigger than fundamental harmonic's pole number $2p$ (Zviedris 1984). So, to use k harmonic's energy in synchronous machines slots secondary winding with pole number

$$2p_k = 2kp \tag{1}$$

and winding pitch

$$y_k \approx \frac{\tau_z}{k} = \frac{Z_k}{2kp}, \tag{2}$$

where τ_z – fundamental harmonics pole pitch; Z_k – for secondary winding used slots number, must be inserted.

To use k harmonic's energy more efficiently it is important to choose secondary winding shame and parameters correctly. Constructively it is efficient to insert secondary winding in the same slots in which primary winding is placed. If secondary winding is organized as two lair loop winding, it will occupy all Z armature slots. Generally secondary winding can be organized with different phase number m_k (Mesņajevs et al. 2013).

EMF CALCULATIONS

As experience shows while studying the magnetic field, it can be assumed that the machine's magnetic field is plane-parallel (two-dimensional), the field characteristics vary only in radial and tangential direction. Furthermore, the machine's cross-section area can be chosen for calculations. This area is limited by the stator outer surface, on which, as it can be assumed, the normal component of the magnetic flux density is equal to zero.

It is appropriate to substitute the electromagnetic field equations system with one equation which depends on the magnetic vector potential, having only one (axial) component $A = A_z$ in a plane-parallel field (Mesņajevs and Ketnere 2014).

$$\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} - \mu\gamma\frac{\partial A}{\partial t} - \mu\gamma\nu\frac{\partial A}{\partial x} = -\mu j_a \quad (3)$$

where μ - magnetic permeability, γ – medium electric conductivity; ν – medium's relative velocity comparatively to the magnetic field and j_a – the external field source's current density.

In this equation, A is spatial coordinates x, y and time t function, which means that the Equation (3) describes space and time alternating magnetic field. Solving this type of equation is rather difficult, therefore, it is appropriate to reduce it to number of simpler tasks, in which the electromagnetic field described by the equation

$$\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} = -\mu j_a \quad (4)$$

In this case, the task is based on the fact that in time varying process ($\partial/\partial t \neq 0$) can be viewed as a single fixed process set of different consecutive time points t_1, t_2, ... ,t_i, ... ,t_n. So, for example, if the field source current density is in time varying sinusoidal function $j_a(t) = j_{am}\sin\omega t$, then Equation (4) must be solved n times, each time in the right side of that equation define moment of time t_i that corresponds to current densities moment value $j_a(t_i) = j_{am}\sin\omega t_i$. Solving such a task as the results receive vector potentials, which are essentially a table formed functional dependence $A = f(t)$. A similar approach is used solving non-stationary field equations, when $\nu \neq 0$. In this case, it is possible to solve a number of magnetostatic field equations. Each of them corresponds to different consecutive rotor positions related to stator.

The instantaneous value of current in armature windings phases may be determined by the following formulas:

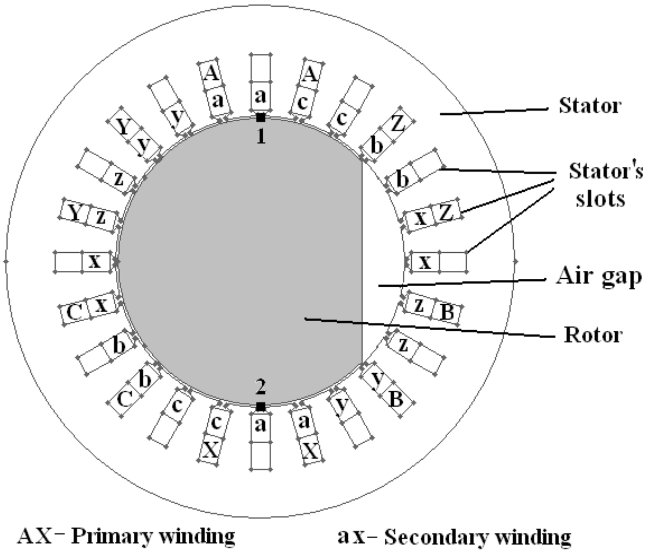
$$\left.\begin{aligned} i_A &= I_m \cdot \cos(\omega t - \alpha) \\ i_B &= I_m \cdot \cos(\omega t - 120^\circ - \alpha) \\ i_C &= I_m \cdot \cos(\omega t - 240^\circ - \alpha) \end{aligned}\right\} \quad (5)$$

where $I_m = \sqrt{2}I$ - the armature current as the peak value of the field source; α_i - rotor position angle (Mesņajevs and Zviedris 2010).

To determine the magnetic flux $\Phi_d(\omega t_i)$ with sufficient accuracy, it is preferably that the time step is chosen small enough. The magnetic flux of one pole can be obtained with different armature current instantaneous values according to Equation (5) with the rotor position angle α_i. After a series of magnetic field calculations for time moments t_i

$$\Phi_d(\omega t_i) = \Phi_d(\alpha_i) = (A_{1i} - A_{2i})l \quad (6)$$

where A_{1i} and A_{2i} - the vector potential values on the surface of the armature in points 1 and 2 (Fig.3.) w - number of turns per phase, l - the machine length in axial direction.



Figures 3. SRFC's Model

Numerical harmonic analysis of the function $\Phi_d(\omega t_i)$ allows to obtain the fundamental harmonic amplitude value Φ_{1md} and higher harmonics (second) amplitude value Φ_{2md}, which are required for determination of EMFs E_{1d} and E_{2d}.

Similarly the EMFs E_{1q} and E_{2q} can be obtained if α is replaced with $\alpha - 90^\circ$ while simulating quadrature axis magnetic field in Equation (5).

The fundamental harmonic's effective value of the EMFs E_{1d} and E_{1q} can be determined using the following formulas

$$E_{1d} = 4{,}44 f_1 k_{w1}\frac{2pqw_{sp}}{a}\Phi_{1md} \quad (7)$$

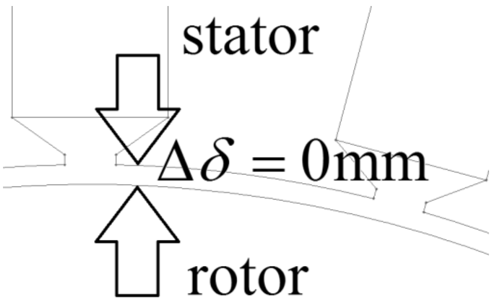
or

$$E_{1d} = 4{,}44 f_1 k_{w1} \frac{2pqw_{sp}}{a} 2A_{1md} l \qquad (8)$$

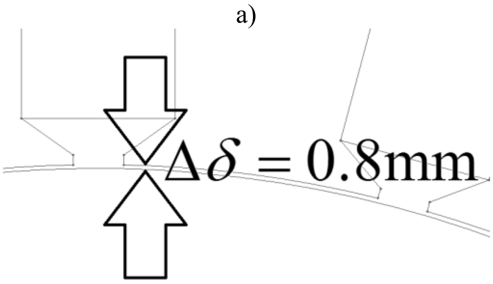
where f_1 – fundamental harmonic's frequency; k_{w1} – winding's distribution coefficient; q – slot number per pole and phase; p – pole number; w_{sp} – coil's turn numbers; a – parallel branch number; A_{1md} – direct-axis VMP's amplitude value; Φ_{1md} – direct-axis magnetic flux's amplitude value (Mesņajevs and Zviedris 2010).
In the same way the higher harmonics EMF are determined. In last two equations winding's data and corresponding VMP amplitude value must be inserted.

SRFD'S SIMULATION

In order to evaluate eccentricity of a rotor the air gap's width (Fig. 4) was increased on one side and, respectively, decreased on diametrically opposite side by $\Delta\delta$ from 0 to 0,8 mm with a step of 0,1 mm (total width of an air gap is 1 mm). The task is solved by using the finite element method implemented in QuickField software.



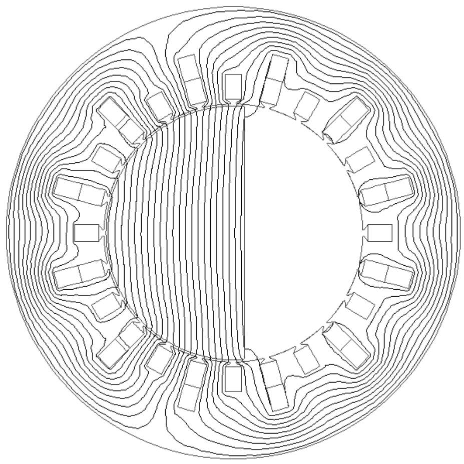
a)



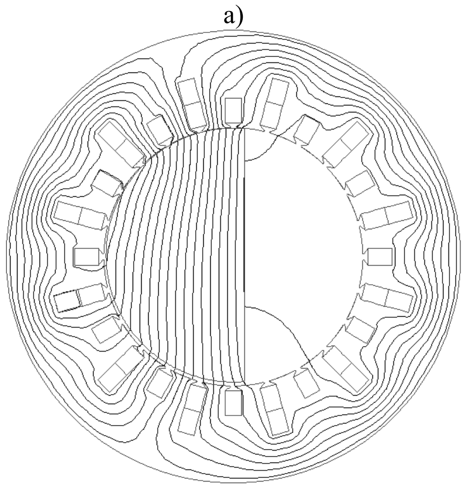
b)

Figures 4. SRFD`s rotor different positions
a) – rotor is centered; b) rotor is shifted

On Fig. 5a and Fig. 5b SRFD's magnetic field picture are presented. On Fig. 4a the rotor is centered, on Fig. 5b rotor is shifted by 0,8 mm.



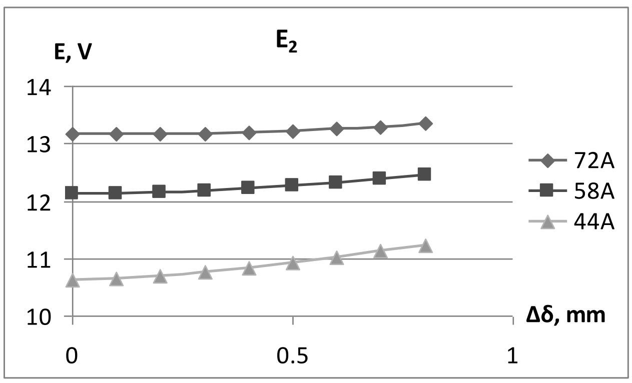
a)



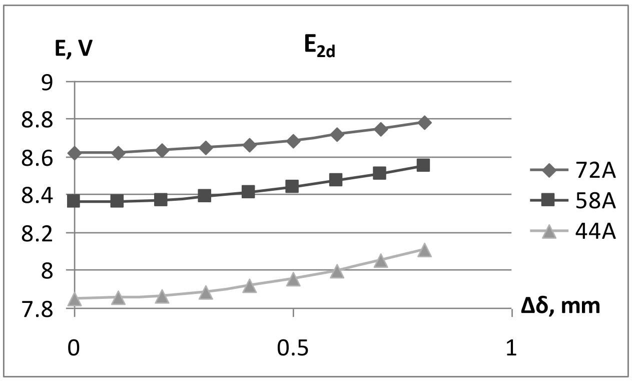
b)

Figures 5. Magnetic Field`s Picture For Different Rotor Position
a) – centered rotor; b) - shifted rotor

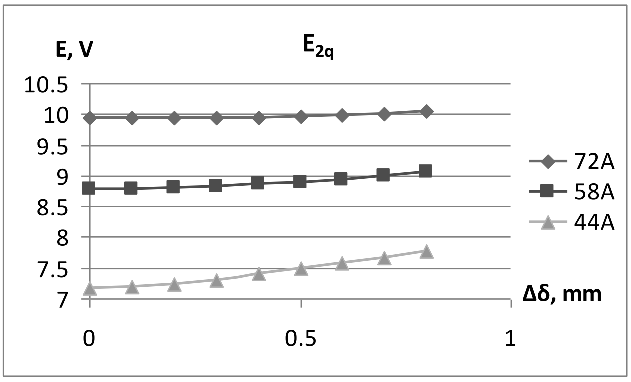
Magnetic field mathematical simulations were conducted for idle running ($I_2 = 0$ A) and for different armature currents $I_a = 44,\ 58,\ 72$ A. Results are presented on Fig. 6, Fig. 7, Fig. 8.



Figures 6. Increased Frequency EMF E_2



Figures 7. Increased Frequency EMF E_{2d} (Direct-axis $I_a = I_d$ and $I_q = 0$)



Figures 8. Increased Frequency EMF E_{2q} – Quadrature-axis ($I_a = I_q$ and $I_d = 0$)

As it can be seen from last three figures eccentricity of a rotor has greater impact on EMF effective value at lower currents. Also at lower currents the influence is bigger on direct-axis EMF.

CONCLUSION

Eccentricity of a rotor in SRFD has positive influence on increased frequency EMF, but the influence is decreased at higher armature currents. However, it should be noted that eccentricity of a rotor is a cause of electrical machines vibration that can lead to malfunction. In addition it can be stated that this is not an appropriate method of eccentricity's determination; it is much easier done, for example, by sensing the vibration of electrical machine.

ACKNOWLEDGEMENTS

This paper was supported by the European Social Fund project "Assessment of wind energy potential in Latvia and environmental impact from wind energy installations",
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