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doi:10.15199/48.2016.02.25

Magnetic Field Rotation Velocity of the Technological Inductor

Abstract. *Results of technological rotating magnetic field inductor rotation velocity investigation are presented. The analytical expression of rotation velocity in any point of active zone is obtained dependently on any phase magnetic flux density vectors amplitudes and directions. The mean rotation velocity throughout the one period is equal to the angular velocity of excitation current. The dependences of maximal instant rotation velocity deviation at mean value on non-equality of different phases magnetic flux density vectors values and directions are obtained.*

Streszczenie. *W artykule przedstawiono wyniki badań prędkości wirującego pola magnetycznego na potrzeby zastosowań technologicznych. Podano zależność na wartość prędkości kątowej pola magnetycznego w dowolnym punkcie strefy aktywnej. Średnia wartość prędkości w ciągu jednego okresu jest wymuszona przez częstotliwość prądu wzbudzenia. W pracy wyprowadzono zależność na wartość maksymalnego odchylenia wartości chwilowej prędkości wirowania pola magnetycznego od jej wartości średniej. (**Prędkość wirującego pola magnetycznego wzbudnika do celów technologicznych**).*

Keywords: rotating magnetic field; rotation velocity; non-uniformity of rotation.
Słowa kluczowe: wirujące pole magnetyczne; prędkość wirowania; nierównomierność wirowania.

Introduction

A long time the rotating magnetic field was used in induction electric motors, only. But the investigations of many researches ([1] – [5]) show that it can be used successfully for processing of different liquids, solutions or suspensions. The liquid under processing is supplemented commonly with some quantity of ferromagnetic particles. By action of rotating magnetic field with magnetic flux density equal to 0,1-0,2 T these particles move along the magnetic field lines and interact with other particles and with liquid substance. The vortex ferromagnetic layer forms. The crushing and mixing of liquid substance using this layer can be performed very effectively. The material is comminuted to less than 10 μm dimensions and became smooth, because the major particles are crushing more effectively. The stirring is performed perfectly in such reactor, too. The liquids which are immiscible in normal conditions can be stirred fine using vortex ferromagnetic layer. Processing with rotating magnetic field suits soundly for sewage processing.

The rotating magnetic field can be used for technological purposes without the vortex ferromagnetic layer, especially in such delicate industries, as electronics, foood, pharmacy or cosmetics [1,2]. By action of rotating magnetic field the chemical reactions are actived, the chemical and physical poperties of materials, its flavour and odour are changed.

The use of rotating magnetic field instead of traditional technologies can improve the quality of products, reduce the power consumption, accelerate a process, perfect the work conditions. The chemical pollution vanishes, the acustic pollution attenuates. The same results using traditional technologies can be obtained very expensive or cann‘t be obtained.

To obtain uniform rotating magnetic field the magnetic field created by any phase of exciting current must be distributed uniformly. Diference between the directions of magnetic flux density vectors of any two neighbouring phases must be 120° in any active zone point. It is difficult problem. Magnetic field created in the air gap of motor without the the rotor is essentially non-uniform. Therefore technological inductor must be designed especially. The investigation performed in [6] shows that the most uniform magnetic field can be created by the two pole inductor in which the magnetic field of any phase is created by one concentrated winding mounted in the magnetic circuit cavity. But this magnetic field is not uniform, too. The non-uniformity of magnetic field has influence to velocity of rotation. We evaluate analytically the rotation velocity when magnetic field is distributed non-uniformly.

Expression of total magnetic flux density

We investigate the vector of total magnetic flux density ***B*** in any point of perpendicular to axis *z* cross-section which includes the excitation windings axes. They are turned one to other by angle 120°. With the axes directions coincide the directions of unit vectors $\mathbf{e}_U$, $\mathbf{e}_V$ and $\mathbf{e}_W$, correspondingly (see Fig. 1). We suppose, that in the central point with coordinates $x=0$, $y=0$ the amplitude of magnetic flux density created by all windings is the same and equal to B_0. We express the values of magnetic flux density every phase B_U, B_V and B_W in the point of active zone with coordinates *x* and *y* as follows:

(1) $$B_U(t) = B_{\mathrm{Um}} \sin \omega t \ = aB_0 \sin \omega t,$$

(2) $$B_V(t) = B_{\mathrm{Vm}} \sin(\omega t - 120^\circ) \ = bB_0 \sin(\omega t - 120^\circ) \ = = -0{,}5bB_0 \sin\omega t - 0{,}5\sqrt{3}bB_0 \cos\omega t,$$

(3) $$B_W(t) = B_{\mathrm{Wm}} \sin(\omega t + 120^\circ) \ = cB_0 \sin(\omega t + 120^\circ) = = -0{,}5cB_0 \sin\omega t + 0{,}5\sqrt{3}cB_0 \cos\omega t,$$

where $a = a(x,y) = \frac{B_{\mathrm{Um}}(x,y)}{B_0}$, $b = b(x,y) = \frac{B_{\mathrm{Vm}}(x,y)}{B_0}$, $c = c(x,y) = \frac{B_{\mathrm{Wm}}(x,y)}{B_0}$.

The non-uniformity of total magnetic flux density ***B*** which is composed of three vectors $\mathbf{B}_U$, $\mathbf{B}_V$ and $\mathbf{B}_W$ directed by angle equal to 120° one to other was investigated in [5]. Now we evaluate additionally that the magnetic flux density vectors $\mathbf{B}_U$, $\mathbf{B}_V$ and $\mathbf{B}_W$ created by the suitable windings are turned in respect to the unit vectors by angles δ, ζ and η, correspondingly, as it is shown in the Fig. 1.

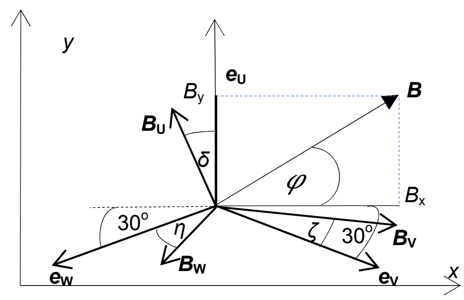

Fig. 1. The orientation of vectors ***B***, $\mathbf{B}_U$, $\mathbf{B}_V$ and $\mathbf{B}_W$ in respect to the unit vectors $\mathbf{e}_U$, $\mathbf{e}_V$ and $\mathbf{e}_W$ in any point of active zone

The components of magnetic flux density B_x and B_y are:

(4) $$B_x(t) = -B_U(t)\sin\delta + B_V(t)\cos(30° - \zeta) - $$
$$-B_W(t)\cos(30° + \eta) = (X_s\sin\omega t + X_c\cos\omega t),$$

(5) $$B_y(t) = B_U(t)\cos\delta - B_V(t)\cos(60° + \zeta) -$$
$$-B_W(t)\cos(60° - \eta) = B_0(Y_s\sin\omega t + Y_c\cos\omega t),$$

where

(6) $$X_s = -a\sin\delta - \frac{\sqrt{3}\cos\zeta + \sin\zeta}{4}b - \frac{\sqrt{3}\cos\eta - \sin\eta}{4}c],$$

(7) $X_c = -(\sqrt{3}/4)[(\sqrt{3}\cos\zeta + \sin\zeta)b + (\sqrt{3}\cos\eta - \sin\eta)c],$

(8) $Y_s = a\cos\delta + 0{,}25[(\cos\zeta - \sqrt{3}\sin\zeta)b + (\cos\eta + \sqrt{3}\sin\eta)c],$

(9) $Y_c = (\sqrt{3}/4)[(\cos\zeta - \sqrt{3}\sin\zeta)b - (\cos\eta + \sqrt{3}\sin\eta)c].$

By dependence of magnetic flux density components $B_x(t)$ and $B_y(t)$ on time we can express the dependence on time of magnetic field rotation velocity ω_r.

Rotation velocity

The angle position of vector ***B*** by Fig. 2 is:

(10) $$\varphi = \mathrm{arctg}\,(B_y/B_x).$$

The rotation velocity ω_r is derivative of angle φ at time:

(11) $\omega_r = d\varphi/dt = (B_y{}'B_x - B_yB_x')/[1 + (B_y/B_x)^2]\cdot B_x{}^2 = (B_y{}'B_x - B_yB_x')/(B_x{}^2 + B_y{}^2) = (B_y{}'B_x - B_yB_x')/B^2.$

B^2 of (4) and (5) can be expressed:

(12) $B^2 = B_x{}^2 + B_y{}^2 = B_0{}^2(X_s^2\sin^2\omega t + 2X_sX_c\sin\omega t\cos\omega t + +X_c^2\cos^2\omega t + Y_s^2\sin^2\omega t + 2Y_sY_c\sin\omega t\cos\omega t + Y_c^2\cos^2\omega t) = B_0{}^2(K_0 + K_C\cos 2\omega t + K_S\sin 2\omega t),$

where

(13) $K_0 = \frac{1}{2}(X_C{}^2 + Y_C{}^2 + X_S{}^2 + Y_S{}^2) = \frac{1}{2}\{a^2 + b^2 + c^2 + \frac{1}{2}ab[\sqrt{3}\sin(\delta - -\zeta) + \cos(\delta - \zeta)] + \frac{1}{2}ac[\sqrt{3}\sin(\eta - \delta) + \cos(\eta - \delta)] + \frac{1}{2}bc[\cos(\zeta - \eta) + \sqrt{3}\sin(\zeta - \eta)]\},$

(14) $K_C = \frac{1}{2}(X_C{}^2 + Y_C{}^2 - X_S{}^2 - Y_S{}^2) = \frac{1}{4}\{(b^2 + c^2) - 2a^2 + +2bc[\cos(\zeta - \eta) + \sqrt{3}\sin(\zeta - \eta)] - a[b(\cos(\delta - \zeta) + +\sqrt{3}\sin(\delta - \zeta)) + c(\cos(\eta - \delta) + \sqrt{3}\sin(\eta - \delta))]\},$

(15) $K_S = X_sX_C + Y_sY_C = \frac{\sqrt{3}}{4}\{(b^2 - c^2) + ab[\cos(\delta - \zeta) + \sqrt{3}\sin(\delta - \zeta)] - ac[\cos(\eta - \delta) + \sqrt{3}\sin(\eta - \delta)]\}.$

The numerator of expression (11) we express this way:

(16) $B_y{}'B_x - B_yB_x' = B_0{}^2\omega[(Y_s\cos\omega t - Y_c\sin\omega t)\cdot(X_s\sin\omega t + X_c\cos\omega t) - (Y_s\sin\omega t + Y_c\cos\omega t)(X_s\cos\omega t - -X_c\sin\omega t)] = SB_0{}^2\omega,$

where

(17) $S = X_cY_s - X_sY_c = \frac{\sqrt{3}}{4}\{ab[\sin(\delta - \zeta) - \sqrt{3}\cos(\delta - \zeta)] + ac[\sin(\eta - -\delta)] - \sqrt{3}\cos(\eta - \delta)] + cb[\sin(\zeta - \eta) - \sqrt{3}\cos(\zeta - \eta)]\}$.

Evaluating (12) and (16) we express ω_r as follows

(18) $$\omega_r = \omega\cdot S/(K_0 + K_C\cos 2\omega t + K_S\sin 2\omega t).$$

In symmetrical case, when *a*=*b*=*c*=1, δ=η=ζ, we obtain by (13-15) and (17): $S = -9/4$, K_0=9/4, K_C=K_S=0, $\omega_r = -\omega$. Therefore vector ***B*** will rotate evenly with the velocity equal to angle velocity ω of excitation current in the direction contrary to positive direction of the angle reading.

Now we calculate the mean value $\overline{\omega_r}$ of rotating velocity throughout the period of the expression (18) right part variation. We note in the (18) depending on time argument as *z*=2ω*t* and calculate the mean value $\overline{\omega_r}$ throughout the interval [0, 2π]:

(19) $$\overline{\omega_r} = S\omega/2\pi\int_0^{2\pi}[1/(K_0 + K_C\cos z + K_S\sin z)]dz = \frac{S\omega/2\pi}{\sqrt{K_0^2 - K_C^2 - K_S^2}}\mathrm{arctg}\frac{(K_0 - K_C)\mathrm{tg}^z/_2 + K_S}{\sqrt{K_0^2 - K_C^2 - K_S^2}}\Bigg|_0^{2\pi}.$$

In the equation (19) $\mathrm{arctg}\frac{(K_0 - K_C)\mathrm{tg}^z/_2 + K_S}{\sqrt{K_0^2 - K_C^2 - K_S^2}}\Bigg|_0^{2\pi} = 2\pi$, because the variation of *z* at 0 to 2π suites the minimal interval on which this ratio value is repeated. By (13) – (15) we can calculate the expression $K_0^2 - K_C^2 - K_S^2$:

(20) $K_0^2 - K_C^2 - K_S^2 = {}^1/_4[(X_C{}^2 + Y_C{}^2) + (X_S{}^2 + Y_S{}^2)]^2 - {}^1/_4[(X_C{}^2 + Y_C{}^2) - (X_S{}^2 + Y_S{}^2)]^2 - (X_SX_C + Y_SY_C)^2 = (X_cY_s - X_sY_c)^2 = S^2.$

Evaluating (20) and value of arctg we obtain $\overline{\omega_r} = \omega$.

Therefore in any point of active zone mean value of magnetic field rotating velocity during the period of excitation current variation is equal to the angular velocity of excitation current. But the instant value of ω_r will be different at ω by the factor $\frac{S}{K_0 + K_C\cos 2\omega t + K_S\sin 2\omega t}$, which depends on *a*, *b* ,*c*, δ, η and ζ. The quantity of arguments we can reduce including the variables:

(21) $D = b/a, C = c/a, \beta = \delta - \zeta, \gamma = \eta - \delta, \zeta - \eta = -(\beta + \gamma).$

By (20), (21), (13)-(15) and (17) we can express K_0, K_c, K_s, S:

(22) $K_0 = \frac{1}{2a^2}[1 + D^2 + C^2 + \frac{1}{2}D\{(\cos\beta + \sqrt{3}\sin\beta) + \frac{1}{2}C(\cos\gamma + \sqrt{3}\sin\gamma) + \frac{1}{2}[\cos(\beta + \gamma) - \sqrt{3}\sin(\beta + \gamma)]\},$

(23) $K_C = \frac{1}{4a^2}\{(D^2 + C^2) - 2 + 2DC[\cos(\beta + \gamma) - \sqrt{3}\sin(\beta + \gamma)] - D(\cos\beta + \sqrt{3}\sin\beta) - C(\cos\gamma + \sqrt{3}\sin\gamma)\},$

(24) $K_S = \frac{\sqrt{3}}{4a^2}[D^2 - C^2 + D(\cos\beta + \sqrt{3}\sin\beta) - C(\cos\gamma + \sqrt{3}\sin\gamma)],$

(25) $S = \frac{\sqrt{3}}{4a^2}\{D(\sin\beta - \sqrt{3}\cos\beta) + C(\sin\gamma - \sqrt{3}\cos\gamma) - -DC[\sin(\beta + \gamma) + \sqrt{3}\cos(\beta + \gamma)]\}$.

The denominator of (18) can be expressed as follows:

(26) $K_0 + K_C\cos 2\omega t + K_S\sin 2\omega t = K_0[1 + \Delta\sin(2\omega t + \varphi)],$

where

(27) $\Delta = \sqrt{K_C^2 + K_S^2}\,/K_0$, $\varphi = \mathrm{arctg}(\frac{K_C}{K_S})$.

Maximal and minimal values of rotation velocity ω_r are:

(28) $$\omega_{rmax} = \frac{S/K_0}{1 - \Delta}\omega, \qquad \omega_{rmin} = \frac{S/K_0}{1 + \Delta}\omega.$$

Rotation velocity deviation

The distribution in active zone of magnetic field created by one phase winding of two pole inductor has been investigated by modelling. JMAG package was used for modelling. This package is oriented for electric motors modelling and design.

The results of modelling show that ratio B/B_0 (*B* - magnetic flux density in any point of active zone) can vary between 0,8 and 1,8. Therefore, the ratios *D*=*b*/*a* and *C*=*c*/*a* can vary in the interval 1÷2,2. The angles β, γ and its sum β+γ are not exceed ±45°. Evaluating above-mentioned limits there were obtained some dependences for every *D*, *C*, β and γ values.

The dependences of maximal deviation *Δ* on β, γ or *D* in the cases when this deviation is maximal are obtained using MATLAB. They are presented in Fig. 2 – Fig.5. *Δ* can reach 0,8. In this case ω_r can increase 5 times. But the large deviation will be not always when the arguments *D*, *C*, *β* and *γ* have extremal values, really. In this moment when extremal values are reached the sinus can have any value in the interval [-1, 1]. Furthemore, the extremal values are reached on the periphery of the active zone in the inconsiderable part of the active zone volume.

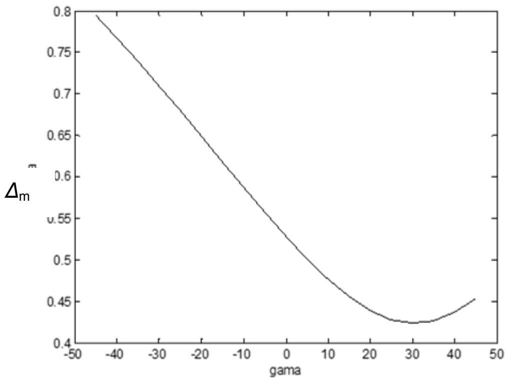

Fig.2. Dependence of maximal r(velocity deviation Δ_m on angle γ (*C*=1, β=0° *D*=2,2 and γ va the interval [-45°, 45°])

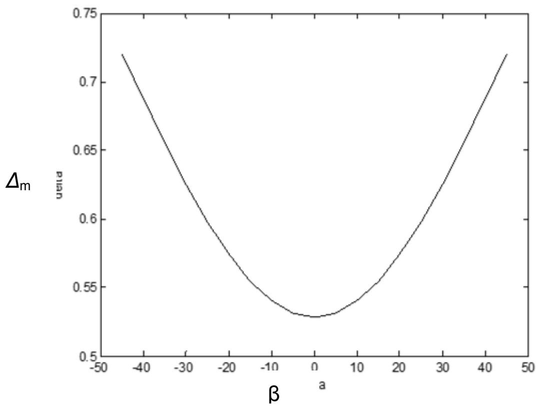

Fig.3. Dependence of maximal rotation velocity deviation Δ_m on angle β (*C*=1, γ =0°, *D*=2,2 and β varies in the interval [-45°, 45°])

Discussion

The variation of the rotation velocity acts to the material under processing differently in the case with ferromagnetic vortex layer and without the vortex layer. At first we discuss the case with vortex layer. The ferromagnetic particles move to the center when the rotation velocity decreases. In this area the rotation velocity is more even but when the particle concentration increases the probability of interaction increases, too. Therefore, the some part of particles will get to the peripheral part of active zone where rotation velocity is not even.

When the rotation velocity increases the particles move to the wall of pipe which limits active zone. If the particles strike against the wall its velocity decreases and they moves to the center. By the rotation velocity non-uniformity the quantity of particles which move in the both directions - to the wall ant to the center - increases. The intensity of the stirring raises, but the erosion of the wall raises, too, and the time of the reactor action without repair substantially decreases. Therefore, the uniformity of the rotation velocity must be main purpose of the designers of such inductors. When the vortex layer is not used the non-uniformity of the magnetic field rotation velocity has more delicate impact to the final product because the magnetic field acts in the cellular and molecular level. But it must be considered that flow is turbulent in the active zone, usually. The liquid particles will move in the different directions without vortex layer, too. Therefore, any particle of liquid will be relative small interval of all processing time in the areas with rotation velocity significantly different than mean value.

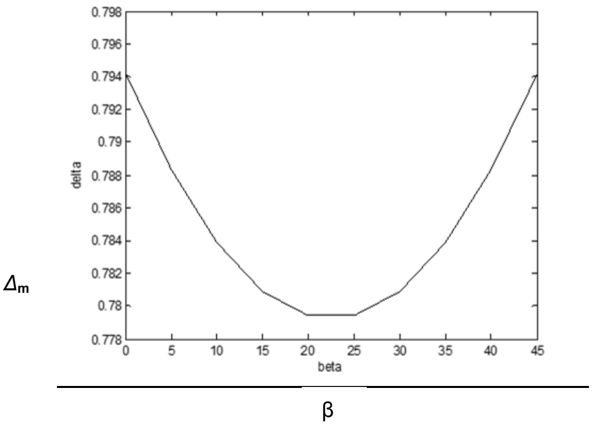

Fig.4. Dependence of maximal rotation velocity deviation Δ_m on angle β (γ =-45°, *C*=1, *D* =2,2 and β varies in the interval [0, 45°])

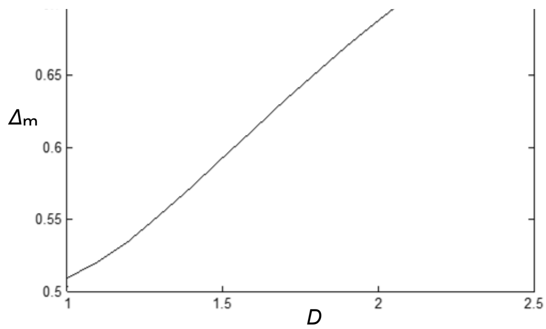

Fig.5. Dependence of maximal rotation velocity deviation Δ_m on the parameter *D*, when γ=-45°, β=45° *C*=1, *D* is in interval [0; 2,2].

When several separate areas are in the active zone some part of liquid will be acted permanently by magnetic field with rotation velocity different than mean value. In this case the special investigation is needed.

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