The Investigation of Poles Shape of the Technological Rotating Magnetic Field Inductor

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Introduction

The use of the rotating magnetic field for technological purposes enlarges in the latter years. There is very wide area: sewage treatment, oilfield and petrochemistry, the crushing of different materials, pharmacological industry, food industry, production of cosmetic, chemical industry and other [1]. We name the processing of different materials by rotating magnetic field as process activating and the area in which the process activating performs as active zone.

The some concentration of ferromagnetic materials is used frequently in the active zone. It is named as vortex layer because there is proceeded intensive movement of the magnetic particles in different directions.

The electric machine stator is used usually for magnetic field creation in the process activating unit. It is not optimal solution with respect to the power consumption and the request to the field distribution.

The requests to the rotating magnetic field inductor are different in the process activating units used for different purposes. But there are some properties of technological rotating magnetic field common for all inductors:

1. The active zone is created in the tube with diameter not less then \( D = 50-100 \text{ mm} \), usually. Therefore the air gap is very big.

2. The magnetic flux density equal to 0.1-0.2 T must be created in this air gap. The considerable power for such magnetic field excitation is needed and solely the three-phase inductors are used [1].

3. The uniform value of the magnetic flux density is desirable in the all active zone. It is particularly important for process activating units without the vortex ferromagnetic layer. Such units can be used in the pharmacological industry, food industry, production of cosmetic, chemical industry, for creation of new material properties and other.

The problems of uniform rotating magnetic field creation are analyzed in [2] –[4]. Because the air gap bigness it is impossible to create uniform magnetic field in all air gap. The needed uniformity of field can be obtained narrowing down the active zone bounds.

The vortex ferromagnetic layer is strong factor of magnetic field action unification. Therefore, it is not essential to create the uniform magnetic field when ferromagnetic vortex layer is used.

The important influence to uniformity and intensity of field created by technological rotating magnetic field inductor has the shape and magnetic properties of poles. The rational choice of shape and dimensions of poles allows the electric power consumption needed for creation of necessary magnetic flux density in the active zone to diminish.

Investigation of influence of poles dimensions in the circumferential direction

The modeling using JMAG program package was performed. The investigated design is showed in Fig. 1.

Fig. 1. The view of the upper half-plane of the magnetic field inductor cross-section
The inductor of 6 poles with uniformly arranged windings was modeled. The parameters of every winding were: \( N=1250, R=13 \, \Omega \). These windings were connected to the current sources with amplitude equal to \( I_{m}=3 \, A \).

The 2D problem was performed in the cylindrical coordinate system. There was investigated the magnetic field distribution in the active zone for three different poles dimensions in the circumferential direction: for the non-salient poles, when the length of poles in the circumferential direction \( b_{d} \) is equal to the diameter of core of excitation winding \( d_{a} \), i.e., the ratio \( S=b_{d}/d_{a}=1 \), for the middle length poles, when the ratio \( S=b_{d}/d_{a}=2,17 \) and for the maximal length poles, when \( S=b_{d}/d_{a}=3,5 \).

The modeling result was rotating magnetic field, the mean values of which vary depending on relative active zone diameter \( D/D_{a} \) \( (D_{a} =\text{--distance between the contrary poles}) in limits between \( B_{\text{min}} \) and \( B_{\text{max}} \). The obtained results were processed for comparison the magnetic flux density \( B \) deviation from its value \( B_{0} \) in the active zone center. The value \( B_{0} \) was calculated, as the mean value of the magnetic flux density inside cylinder \( D/D_{a}=0,2 \) by expression

\[
B_{0} = \frac{B_{\text{max}}0,2 + B_{\text{min}}0,2}{2}.
\]  

The relative deviation \( \delta \) of magnetic flux density in every relative cylinder was calculated by expressions

\[
\delta_{\text{min}} = \frac{B_{0} - B_{\text{min}}}{B_{0}} \times 100\% ,
\]  

\[
\delta_{\text{max}} = \frac{B_{\text{max}} - B_{0}}{B_{0}} \times 100\% ,
\]  

\[
\delta = \frac{\delta_{\text{min}} + \delta_{\text{max}}}{2}. 
\]

The obtained results are presented in Table 1.

**Table 1.** The maximal and minimal values of magnetic flux density in the active zone cylinder, limited by relative diameter \( D/D_{a} \).  

<table>
<thead>
<tr>
<th>( D/D_{a} ) mm</th>
<th>Non-salient poles</th>
<th>Middle poles</th>
<th>Maximal poles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( B_{\text{max}} ) 10^4 T</td>
<td>( B_{\text{max}} ) 10^{-4} T</td>
<td>( B_{\text{max}} ) 10^{-4} T</td>
</tr>
<tr>
<td>0,2</td>
<td>1,351</td>
<td>1,355</td>
<td>0,17</td>
</tr>
<tr>
<td>0,3</td>
<td>1,336</td>
<td>1,369</td>
<td>1,25</td>
</tr>
<tr>
<td>0,4</td>
<td>1,310</td>
<td>1,401</td>
<td>3,4</td>
</tr>
<tr>
<td>0,5</td>
<td>1,244</td>
<td>1,466</td>
<td>8,2</td>
</tr>
<tr>
<td>0,6</td>
<td>1,127</td>
<td>1,598</td>
<td>17,9</td>
</tr>
<tr>
<td>0,7</td>
<td>0,844</td>
<td>1,832</td>
<td>36,3</td>
</tr>
<tr>
<td>0,8</td>
<td>0,520</td>
<td>2,300</td>
<td>65,7</td>
</tr>
</tbody>
</table>

We can see that the strongest field is obtained using the maximal length poles. In this case magnetic flux density arises on the average 45%, comparing with non-salient poles. Because the power consumption \( P \) is proportional to the second power of current \( I \) and \( B \cdot I \), for creation of 1,45 time major magnetic flux density it is needed two times major power. Therefore, we can two times diminish the power consumption by poles widening in circumferential direction.

Unfortunately, the maximal deviation of magnetic flux density was obtained using the maximal length poles. The deviation arises especially near the poles. In the cylinder with relative diameter \( D/D_{a}=0,5 \) the deviation \( \delta \) is not exceeded of 11% for all dimensions of poles. But this cylinder occupies only ¼ of maximal volume of the active zone. The cylinder limited by relative diameter \( D/D_{a}=0,7 \) occupies the half of the maximal volume, but the maximal deviation of magnetic flux density arises to (36 – 52)%, depending on the poles length.

**Magnetic field distribution along the active zone axis**

The 3D problem was modeled using JMAG program package to clear the distribution of magnetic field along the axis \( z \). The modeled design is showed in Fig. 2. The modeling was performed for maximal poles with \( S=b_{d}/d_{a}=3,5 \). The shape of pole was circle with diameter \( d_{p}=b_{d} \).

The distribution of the mean value \( B_{0} \) of the magnetic flux density inside the cylinder with relative diameter \( D/D_{a}=0,2 \) was investigated. There was accepted that the relative permeability all magnetic materials \( \mu_{r} \rightarrow \infty \). The relative deviation \( \delta \) of all values \( B_{0} \) in this cylinder was not exceeded 0,4%.

The dependence of relative magnetic flux density value \( \delta B = B_{0}(z')/B_{0}(0) \) on the relative distance \( z' = z/(d_{p}/2) \) is presented in Fig. 3. Axis \( z \) is directed along the active zone axis. The origin \( z=0 \) is in the plane which contains axes of the excitation windings.

We can see of Fig. 3 that the magnetic flux density on the zone bounds diminishes not more than 5% when the
length of active zone \( l_a \) is not exceeded the 0.7\( d_p \). When \( l_a = d_p \), the magnetic flux density on the zone bounds diminishes to 11\%. The raison of this diminution is the magnetic field lines deflection (Fig. 2).

### The possibility of active zone expansion along the axis

The poles length in circumferential direction is limited by poles of other phases. But in the axial direction the poles can be extended theoretically without restriction. If we could warrant the constant difference of scalar magnetic potentials on the poles we could be have approximately the same magnetic flux density between the poles. Therefore extending the poles we can extend the active zone of device. We clear restrictions of such expansion investigating the equivalent electric schema of the magnetic circuit, showed in the Fig. 4.

![Fig. 4. The equivalent electric circuit of the magnetic flux distribution](image)

The simplified circuit is presented in Fig. 4 supposing that poles are made of the ferromagnetic material with relative permeability \( \mu_r \to \infty \). In this figure there are presented \( R_{ma} \) – the total magnetic resistance of excitation windings core and magnetic screen, \( R_{ma} \) – the magnetic resistance of active zone, \( R_{ma} \) – magnetic resistance to peripheral flux \( \Phi_{per} \), which is situated outside active zone. The peripheral flux \( \Phi_p \) was equal to 12\% of total flux \( \Phi_a \) by modeling results of design, showed in Fig. 2. The ratio \( \Phi_p/\Phi_a \) can vary minutely extending the poles in \( z \) direction. The flux of active zone \( \Phi_a \) is generated by all area of poles and the peripheral flux is generated on the poles perimeter. But the poles area and perimeter are varied proportional in this case. The magnetic resistances \( R_{ma} \) and \( R_{ma} \) can be expressed as

\[
R_m = \frac{l}{S \mu_r \mu_0},
\]

where \( l \) – the mean length of the magnetic line; \( S \) – the area of cross-section of investigated part of magnetic circuit; \( \mu_r \) – the relative permeability; \( \mu_0 \) – magnetic constant.

Expressing magnetic flux \( \Phi_a \) in the active zone

\[
\Phi_a = B_a S_p = U_{ma} R_{ma}
\]

and evaluating (5), where \( l=l_a, \mu_r=1, S=S_p \), we can assure, that in active zone the magnetic flux density \( B_a \) is not depended on poles area \( S_p \). When magnetic voltage \( U_{ma} \) is constant

\[
B_a = \frac{\mu_0 l_a}{l}. \tag{7}
\]

Before the poles area \( S_p \) are not big the fall of magnetic voltage \( U_{ma} \) in magnetic resistance \( R_{ma} \) can not be evaluated. All voltage \( U_{ma} = F \) acts in the magnetic resistance \( R_{ma} \), i.e., in the active zone. With arising of poles area \( S_p \) the magnetic resistance \( R_{ma} \) decreases but the magnetic resistance \( R_{ma} \) rests the same and the fall of magnetic voltage \( U_{ma} \) becomes meaningful. For example, in the design, showed in Fig. 1 and 2, when radius of active zone is \( R_p = 50 \text{mm} \) and the pole length along axis \( z \) \( l_a = 100 \text{mm} \), the ratio \( R_{ma}/R_{ma} = (0.05-0.1) \mu_r \). Therefore if we want that the \( B_a \) could not be decrease meaningful the condition \( \mu_r \geq 1000 \) must be content.

![Fig. 5. Dividing of pole magnetic resistance and active zone magnetic conductance into elementary elements (a) and its equivalent electric circuit (b)](image)
the elementary magnetic conductance of the active zone \( d\Lambda_{ma} \) and the elementary magnetic resistance of the pole \( dR_{mp} \), evaluating that there are two poles (Fig. 6, a)

\[
d\Lambda_{ma} = \frac{\mu_0 dS_a}{h_a} = \frac{h_0 b}{h_a} d\varepsilon = \Lambda_{ma0} d\varepsilon, \quad (8)
\]

\[
dR_{mp} = \frac{2d\varepsilon}{\mu_{rp} \mu_0 S_p} = \frac{2}{\mu_{rp} \mu_0 h_p b} d\varepsilon = R_{mp0} d\varepsilon, \quad (9)
\]

where \( \Lambda_{ma0} \) – magnetic conductance of a unit of active zone length; \( R_{mp0} \) – magnetic resistance of a unit of pole length along axis \( \varepsilon \)

\[
\Lambda_{ma0} = \frac{\mu_0 b}{h_a}, \quad (10)
\]

\[
R_{mp0} = \frac{2}{\mu_{rp} \mu_0 h_p b}. \quad (11)
\]

The equivalent electric circuit of the elementary elements of the active zone and poles of length \( d\varepsilon \) is showed in Fig. 6, b. By Ohm law we can write

\[
dU_m = \Phi dR_{mp} = \Phi R_{mp0} d\varepsilon, \quad (12)
\]

\[
d\Phi = U_m d\Lambda_{ma} = U_m \Lambda_{ma0} d\varepsilon. \quad (13)
\]

We obtain differentiating the equations (12) and (13) by \( \varepsilon \) and expressing \( U_m \) via \( \Phi \)

\[
\frac{d^2\Phi}{d\varepsilon^2} = R_{mp0} \Lambda_{ma0} \Phi. \quad (14)
\]

It is the simplest variant of well-known wave equation which solution non-evaluating reflection is

\[
\Phi = \Phi_0 e^{-\sqrt{R_{mp0} \Lambda_{ma0}}} \cdot. \quad (15)
\]

By (10) and (11) we can write

\[
\Phi = \Phi_0 e^{-\sqrt{\frac{1}{\mu_{rp} (h_p/[2z]h_a/[z])}}}. \quad (16)
\]

Using this equation we can evaluate diminution of magnetic field and choose the design and materials of inductor. For example when \( h_a=100\text{mm}, \quad h_p=2\text{mm}, \quad \mu_{rp}=1000, \) on the distance \( z=100\text{mm} \) we obtain \( \Phi=0,74\Phi_0 \). Therefore, the flux diminishes 26% in the zone bound. Changing \( \mu_{rp}=1000 \) to \( \mu_{rp}=10000 \) we obtain \( \Phi=0,9\Phi_0 \). The flux diminishes 10%. If we will thicken the poles the diminution of field will decrease.

Conclusions

1. The magnetic field we can increase average 45% extending poles in circumferential direction.
2. Elongating the poles along inductor axis we can extend the active zone, but it is needed to thicken the poles and to increase its relative permeability.

References


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The inductor of technological rotating magnetic field must create the magnetic flux density equal to 0,1–0,2 T in the big air gap. The uniformity and intensity of created field strongly depend on the inductor poles geometry. The mean value of magnetic flux density can be increased about 45 % expending the poles in circumferential direction. The influence of pole magnetic resistance to the magnetic field distribution along axis can be evaluated, using the theory of distributed-parameter line. Elongating the poles along inductor axis the unit active zone can be extended, but the poles must be thickened and its relative permeability must be increased.


Индуктор технологического вращающегося магнитного поля должен создать плотность магнитного потока 0,1–0,2 T в большом воздушном промежутке. Однородность и интенсивность созданного поля очень зависит от геометрии полюсов индуктора. Влияние магнитного сопротивления полюса на распределение магнитного поля вдоль оси можно оценить, пользуясь теорией длинной линии. Значение плотности магнитного потока можно увеличить в среднем на 45%, расширяя полюса в радиальном направлении. Удлинение полюса в направлении оси индуктора можно удлинить активную зону устройства. Изл. 5, бб. 4, табл. 1 (на английском языке; рефераты на английском, русском и литовском яз.).


Technologinio suakmeninio magnetinio lauko induktorius turi sukurti 0,1–0,2 T tankio magnetinį srautą didelėme oro tarpe. Sukuriami lauko vienališkumas ir intensyvumas labai priklauso nuo induktorius polių geometrijos. Vidutinė magnetinio srauto tankio vertė galima padidinti vidutiniškai 45 % plečiant polius radialine kryptimi. Polių magnetinės varžos itaką magnetinio lauko pasiskirstymui ašies kryptimi galima nustatyti remiantis paskirstytų parametrų linijų teorija. Išlinkiant polių aktyvimmo įrenginio ašes kryptimi, galima praplėsti įrenginio aktyvų zonų šia kryptimi, tačiau būtina storinti polius ir didinti jų santykinę magnetinę škvarbą. Izl. 5, bbl. 4, lent. 1 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).