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ANALYTICAL EXPRESSIONS OF RELATIONSHIP TO CALCULATION OF AC STABILIZER WITH INDUCTION LEVITATION

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Abstract- In the presented work, an analysis of the calculation and design of an alternating current stabilizer with induction levitation is given. First of all, attention is drawn to the magnetic system, the main task is to obtain optimal performance characteristics for accurate stabilization of the load current. For this purpose, a symmetrical magnetic system was chosen for the stabilizer, and as a result, a uniform magnetic field was obtained in the working air gap. For this, the Ш-shaped core magnetic circuit is adopted as the most acceptable. In some cases, a stepped symmetrical Ш-shaped magnetic circuit is proposed. Such designs meet the requirements of simple and multi-rated AC stabilizers with induction levitation. Therefore, this design is used as a generalized design in the design of various stabilizers. The most difficult task of design is to determine the analytical relationships between the initial data and geometric dimensions. The solution of the problem requires the development of a mathematical model of the system of equations of electrical, mechanical, magnetic, thermal circuits. The solution of these equations contributes to the creation of analytical relationships between the initial data for the design, the course of the levitation winding X_M, the gravity force P_T, the cross-sectional area of the windings and the core (S_o, S_{02}, S_c), of the required power P_M.

Keywords: Current Stabilizer, Levitation Coordinate, Induction, Levitation Winding, Excitation Winding, Parameter, Size, Coefficient, Calculation, Design, Core.

1. INTRODUCTION

The initial data for calculating an AC stabilizer with induction levitation are: the range of mains voltage change ΔU_c, load currents I_{load1}, I_{load2}, ... $I_{load,n}$, mains voltage frequency ω, load resistance R_{load} (or power P_{load}), travel of the X_M moving part. As a result of the calculation, the geometric dimensions and overheating temperatures of the windings and the core are determined. Usually, the number of stabilizer parameters to be determined is greater than the number of equations. Therefore, when calculating the stabilizer, a number of well-known values of electrical, electromagnetic, and design parameters are used. The main task of designing an AC stabilizer with induction levitation is to determine the analytical relationships between geometric dimensions and initial data.

The main task in the calculation is to reduce the overall dimensions and weight. Therefore, it is necessary to increase the electromagnetic and electrical loads (magnetic induction B_M and current density in the windings j_1 and j_2). However, with an increase in magnetic induction, losses in the core increase, and with an increase in current density, copper losses in the windings increase. In some cases, the levitation condition $P_T = F_E$ is violated. With an increase in losses, it is possible, within certain limits, to increase the temperature rises of the core and windings, since the insulation period depends on the overheating temperature.

With a decrease in the geometric dimensions of the windings, the cooling surface decreases and the amount of heat increases. Therefore, in order to maintain a constant temperature of the windings, with a decrease in the power of the stabilizer, it is necessary to increase the calculated values of magnetic induction and current density. At the same time, it is not allowed to violate the levitation condition $P_T = F_E$ and exceed the overheating of the windings above the norm for these parameters [1-6].

Therefore, the stabilizer must be designed according to the superheat temperature of the windings, while the nominal values of magnetic induction and current density must be satisfied, as well as the fulfillment of the levitation condition. To achieve this goal, first of all, analytical relationships between the initial data, current density, winding overheating temperature, levitation winding stroke and geometric dimensions should be determined.

2. RELATIONS BETWEEN GEOMETRIC DIMENSIONS OF THE CORE AND WINDING

In most cases, according to the calculations, we have $h_1 >> c$ and $H >> c$, as a result of which the principle of proportionality is violated and the design of the stabilizer is inefficient. For example, with a large height of the stabilizer in relation to the width and thickness, it is difficult to ensure its vertical position and operation becomes more complicated, and in some cases the manufacturing technology. To ensure the principle of proportionality, it is necessary to analyze the range of certain ratios between the cross-section of the windings and the core, as well as the optimal ratios of mathematical expressions [7-8].

According to the expression for the maximum voltage value U_{1max}, the cross-sectional area of the core is determined [6]:

$$S = 2ab = \frac{k_u U_{1max}\sqrt{2}}{\omega k_{3c} W_{1min} B_M} = \frac{k_u U_{1max}}{\omega k_{3c} I_{1max} B_M}\sqrt{\frac{\lambda}{P_T}} \quad (1)$$

$$S_c = A_0 \frac{\sqrt{2}}{k_{3c} B_M} \quad (2)$$

where, $A_0 = \frac{k_u U_{1max}}{\omega W_{1min}}$; B_M is the maximum allowable value of the core induction. To define A_0 [2]:

$$h_{max} = \frac{A_0}{\sqrt{2P_T\lambda}} - \frac{h_1}{3n_\lambda}; h_{min} + \frac{h_1}{3n_\lambda} = \frac{X_M}{k_{cu}-1} \quad (3)$$

$$h_{max} = h_{min} + X_M \quad (4)$$

From mathematical expressions is determined [2]:

$$\frac{A_0}{\sqrt{2P_T\lambda}} = X_M\left(\frac{U_{1max}}{\Delta U_1}\right) \quad (5)$$

From here:

$$A_0 = X_M\sqrt{2P_T\lambda}\left(\frac{U_{1max}}{\Delta U_1}\right) \quad (6)$$

If the resulting expression is written in (2):

$$S_c = \frac{U_{1max}}{k_{3c}B_M}\sqrt{\frac{2k_u I_1 X_M \lambda}{\omega(\Delta U_1)}} \quad (7)$$

As the current I_1 increases, the cross-sectional area of the core increases, while X_M and λ should decrease. The decrease in specific magnetic conductivity λ is associated with a decrease in the ratio (b/c). To prevent violation of the principle of proportionality of geometric dimensions, it is necessary to determine the correct relationship between the cross-sectional area of the core and the windings. The current density of the excitation winding is defined as [5]:

$$j_1 = \frac{I_{1max}W_{1min}}{k_{31}S_{01}} = \left(\frac{I_{1max}U_{1max}}{B_{max}S_{01}S_c}\right)\left(\frac{k_u\sqrt{2}}{\omega k_{3c}k_{31}}\right) \quad (8)$$

From here:

$$(S_{01}S_c) = \left(\frac{k_u\sqrt{2}}{\omega k_{3c}k_{31}}\right)\left(\frac{U_{1max}I_{1max}}{j_1 B_{max}}\right) \quad (9)$$

This formula allows you to determine the smallest value of the product ($S_{01}\times S_c$) for given values U_{1max}, I_{1max}, B_{max}, j_1, but the relationship between ($S_{01}\times S_c$) and λ does not appear. Therefore, to determine the relationship between S_{01}, S_c, λ the following expressions are used [6]:

$$S_c = \frac{k_u U_{1max}\sqrt{2}}{\omega W_{1min} B_{c\,max} k_{3c}} \quad (10)$$

$$I_{1max}W_{1max} = j_1 k_{31} S_{01}; \quad I_2 W_2 = b_2 I_{1max} W_{1max} = j_2 k_{32} S_{02} \quad (11)$$

$$I_{1max}W_{1max} = \frac{k_u U_{1max}}{\omega W_{1min}\lambda\left(X_M + h_{min} + \frac{h_1}{3n_\lambda}\right)} = \frac{k_u \Delta U_1}{\omega W_{1min}\lambda X_M} \quad (12)$$

From here it is defined:

$$S_1^* = \frac{S_c}{S_{01}} = A_1 j_1 \lambda; S_2^* = \frac{S_c}{S_{02}} = A_2 j_2 \lambda \quad (13)$$

where, A_1 and A_2 are coefficients determined by the values of the parameters of the windings and the magnetic circuit:

$$A_1 = \left(\frac{k_{31}}{k_{3c}}\right)\left(\frac{X_M U_{1max}\sqrt{2}}{B_M \Delta U_1}\right); \quad A_2 = b_2\left(\frac{k_{32}}{k_{3c}}\right)\left(\frac{X_M U_{1max}\sqrt{2}}{B_M \Delta U_1}\right) \quad (14)$$

3. RANGES OF PARAMETER CHANGE FOR DIFFERENT VALUES OF X_M STROKE

Simple calculations: if X_M=20×10^{-3} m; B_M=1.6 Tl; U_{1max}=250 V; ΔU_1=92 V; b_2=98×10^{-2}; k_{3c}=95×10^{-2}; k_{31}=k_{32}=5×10^{-1}, then A_1=25.4×10^{-3}; A_2=25.38×10^{-3}. For values: j_1= (1.5÷4.0)×10^6 A/m^2; λ= (6÷20)×10^{-6} Hn/m, we have [5]: $S^* = S_1^* \approx S_2^* = \frac{S_c}{S_{01}} \approx \frac{S_c}{S_{02}} = 23\times10^{-2} \div 2.0$.

At X_M=8×10^{-3} m, A_1=9.88×10^{-3}; A_2=9.8×10^{-3}; $S_1^* \approx S_2^* \approx (9 \div 80)\times10^{-2}$. An analysis of these calculations shows that the generalized choice of values X_M, λ, j_1 leads to the following relations: $S_1^* = 9\times10^{-2}$ or $S_1^* = 23\times10^{-2}$. This violates the principle of proportionality of geometric dimensions. The results obtained when designing an AC stabilizer show: $S^* = S_1^* \approx S_2^* \approx (50 \div 150)\times10^{-2}$.

Table 1 shows the ranges S^*, j_1, λ for various X_M strokes [9]. For calculations, the use of data ensures that the principle of proportionality is maintained. Figure 1 shows the dependencies $S^*=f(X_M, j_1)$ and $\lambda_{min}=f(X_M, j_1)$, S^*=(50÷150)×10^{-2} according to which, as X_M decreases, the power S^* decreases and λ_{min} increases [10]. For the range S^*=(50÷150)×10^{-2}, we have: λ_{min}=12.5×10^6 Hn/m, j_1=(2.5÷4.0)×10^6 A/m^2, X_M= (8÷20)×10^{-3} m.

The data in Table 1 can be used to determine the geometric dimensions of an inductive levitation AC stabilizer [2-3]. For this purpose, the following sequence will be used: determining the course of the levitation winding X_M; current density based on stroke j_1; specific magnetic conductivity λ based on current density; product of sections of the core and windings ($S_{01}\times S_c$); determination of ampere turns, parameters A_1, A_2, S_1^*, S_2^*, S_{01} and S_{02}; dimensionless quantities m_a, m_c according to the value λ (from the table), geometric quantities [9-10].

Table 1. Variation range of j_1, S^*, λ parameters for different X_M strokes [6]

X_M×10^{-3} m	j_1×10^6 A/m^2	S^*×10^{-2}	λ×10^{-6} Hn/m
8	2.5	50	20
	3.0	50÷58	17÷20
	3.5	50÷68	14.8÷20
	4.0	50÷78	12.5÷20
10	1.5	-----	----
	2.0	50÷53	19÷20
	2.5	50÷65	15.2÷20
	3.0	50÷77	13÷20
	3.5	50÷93	11÷20
	4.0	50÷103	9.5÷20

14	1.5	50÷53	19÷20
	2.0	50÷73	13.8÷20
	2.5	50÷58	11÷20
	3.0	50÷90	9.5÷20
	3.5	50÷108	8÷20
	4.0	50÷127	7÷20
	-----	50÷144	-----
16	1.5	50÷60	16.5÷20
	2.0	50÷80	12.5÷20
	2.5	50÷100	10÷20
	3.0	50÷120	8÷20
	3.5	50÷140	7÷20
	4.0	50÷160	6.2÷20
18	1.5	50÷68	14.5÷20
	2.0	50÷93	11÷20
	2.5	50÷115	9÷20
	3.0	50÷138	7÷20
	3.5	50÷160	6.2÷20
	4.0	------	----
20	1.5	50÷78	13÷20
	2.0	50÷106	9.8÷20
	2.5	50÷126	7.8÷20
	3.0	50÷152	6.3÷20
	3.5	53÷150	6÷17
	4.0	56÷150	6÷15.8

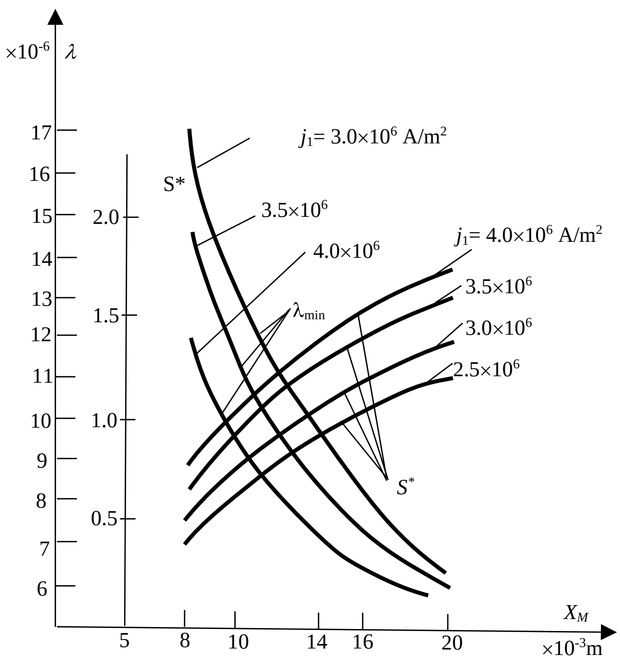

Figure 1. Dependencies $S^{*}=f(X_M, j_1)$ and $\lambda_{\min}=f(X_M, j_1)$

4. CHARACTERISTIC FEATURES OF CALCULATION AND DESIGN

We note the characteristic features of the calculation and design of a multi-rated AC stabilizer with induction levitation [8-9]:

1) The load is connected in series with the excitation winding of the stabilizer, which is the reason for the lower voltage at the winding terminals compared to the mains voltage. The range of voltage variation at the winding terminals ΔU_1 may be greater than the range of mains voltage variation ΔU_c. When the resistance R_{load} or load power P_{load} changes, the voltage U_1 at the terminals of the field winding changes.

Therefore, with a change in R_{load} and P_{load}, it is necessary to know the dependence of the voltage U_1 on the mains voltage U_c. The course of the levitation winding X_M depends on the excess voltage of the excitation winding $\Delta U_1=U_{1\max}-U_{1\min}$, then the dependencies $\frac{\Delta U_1}{X_M}=f(I_1)$; $\Delta U_1=f(\Delta U_c)$ are important characteristics of the current stabilizer. The relationship between ΔU_1 and ΔU_c is determined by the parameters R_{load} and P_{load} [1], [5].

2) The active resistance of the excitation winding is very small compared to the inductive resistance; the flowing current is constant. Therefore, the active resistance of the winding and its overheating temperature are constant; currents (I_1 and I_2), mains voltage and frequency, do not depend on the ambient temperature. The magnetomotive force (mmf) of the windings depends on the specific magnetic conductivity λ of the working air gap and the power of the force P_T [10]:

$$I_1W_1=\sqrt{\frac{2P_T}{\lambda}};\ I_2W_2=b_2\sqrt{\frac{2P_T}{\lambda}} \tag{15}$$

where, $b_2=(98\div99)\times10^{-2}$. From the windings to the environment, heat is mainly transferred through the surface of the sides, then:

$$\tau_1=\frac{I_1^2 r_1}{k_T S_{side1}};\ \tau_2=\frac{I_2^2 r_2}{k_T S_{side2}} \tag{16}$$

are marked here: $k=\frac{W_1}{W_2}$; $r=r_1+b_2^2k_2r_2$.

Usually, $\tau_1=\tau_2=\tau_{adm}$, therefore:

$$\frac{S_{side1}}{S_{side2}}=k_r\left(\frac{\tau_2}{\tau_1}\right)=k_r>1;\ k_r=1+\frac{1}{k^2b_2^2}\frac{r_1}{r_2} \tag{17}$$

To fulfill the condition $\tau_1=\tau_2=\tau_{adm}$ it is necessary to provide $S_{side1}>S_{side2}$.

3) For an AC stabilizer with inductive levitation, the ratio of the voltage at the terminals of the excitation winding U_1 to the inductive resistance of the winding X_1 is a constant parameter and is equal to the stabilized current I_1 [6]:

$$\frac{k_uU_1}{X_1}=\frac{k_uU_1}{\omega W_1^2\lambda\left(h+\frac{h_1}{3n_\lambda}\right)}=I_1=\text{const} \tag{18}$$

Levitation coordinate h is a linear function of voltage U_1:

$$h=\frac{k_uU_1}{\omega W_1^2\lambda I_1}-\frac{h_1}{3n_\lambda} \tag{19}$$

where, $n_\lambda=\lambda/\lambda_s$.

For a given constant current value, the maximum and minimum values of the levitation coordinate are determined by the voltages $U_{1\max}$ and $U_{1\min}$ [7]:

$$h_{\max}=\frac{k_uU_{1\max}}{\omega W_1^2\lambda I_1}-\frac{h_1}{3n_\lambda} \tag{20}$$

$$h_{\min}=\frac{k_uU_{1\min}}{\omega W_1^2\lambda I_1}-\frac{h_1}{3n_\lambda} \tag{21}$$

The maximum stroke of the levitation winding is determined by the expression:

$$X_M = h_{\max} - h_{\min} = \frac{k_u \Delta U_1}{\omega W_1 \lambda F_1} = \frac{k_u \Delta U_1}{\omega W_1 \sqrt{2 P_T \lambda}} \quad (22)$$

Thus, the course of the levitation winding is directly proportional to the voltage ΔU_1, but inversely proportional to the stabilized current I_1 or the power P_T [9-10].

4) The maximum value of the induction in the B_M core is limited by the grade of electrical steel and the currents of the three-section excitation winding are determined by the number of sections [2]:

$$I_{11} = I_{\min} = \frac{1}{W_{11}}\sqrt{\frac{2P_T}{\lambda}};\ I_{12} = I_{average} = \frac{1}{W_{12}}\sqrt{\frac{2P_T}{\lambda}}$$
$$I_{13} = I_{\max} = \frac{1}{W_{13}}\sqrt{\frac{2P_T}{\lambda}} \quad (23)$$

Given that the load currents $I_{load1}=I_{11}$, $I_{load2}=I_{12}$, $I_{load3}=I_{13}$ are given, then the number of turns of the sections is determined [1-3]:

$$W_{11} = \frac{1}{I_{11}}\sqrt{\frac{2P_T}{\lambda}};\ W_{12} = \frac{1}{I_{12}}\sqrt{\frac{2P_T}{\lambda}};\ W_{13} = \frac{1}{I_{13}}\sqrt{\frac{2P_T}{\lambda}} \quad (24)$$

For stabilizer:

$$\sqrt{\frac{2P_T}{\lambda}} = \text{const};\ I_{11} = I_{\min};\ I_{13} = I_{\max} \quad (25)$$

For the number of turns, you can write:

$$W_{13} = W_{\min};\ W_{11} = W_{\max};\ W_{11} > W_{12} > W_{13} \quad (26)$$

The cross-sectional area of the core is determined through $U_{1\max}$ and $W_{1\min}$ [6, 9]:

$$S = 2ab = \frac{k_u U_{1\max}\sqrt{2}}{\omega k_{3c} W_{1\min} B_M} = \frac{k_u U_{1\max}}{\omega k_{3c} I_{1\max} B_M}\sqrt{\frac{\lambda}{P_T}} \quad (27)$$

According to the expressions for the magnetomotive force (mmf) windings:

$$\frac{F_1}{F_2} = \left(\frac{j_1}{j_2}\right)\left(\frac{k_{31}}{k_{32}}\right)\left(\frac{S_{01}}{S_{02}}\right) = \frac{1}{b_2} \quad (28)$$

From here, for the ratio of the current density of the windings, we can write:

$$\frac{j_1}{j_2} = b_2\left(\frac{S_{02}}{S_{01}}\right)\left(\frac{k_{32}}{k_{31}}\right) < 1 \quad (29)$$

where, $S_{02}/S_{01}<1$; $b_2<1$; $k_{31}\approx k_{32}$.

As can be seen, the current density of the excitation winding j_1 is less than the current density of the levitation winding j_2. This ratio does not take into account the overheating temperature of the windings, which requires the definition of another mathematical expression.

Solving the problems of calculation and design for an AC stabilizer with induction levitation consists of several stages, namely: determination of the initial parameters, output characteristics for the criteria and analysis of the calculation, analytical expressions for the relationship between the initial data and output parameters, development of recommendations for improving the output parameters, choice of design, determination of criteria for optimizing parameters and calculating a multi-nominal stabilizer with a levitation winding. The task includes the value of the mains voltage U_c, the range of change $\Delta U_c=U_{c\max}-U_{c\min}$, U_{nom} and the load current I_{load}.

In accordance with the initial position of the levitation winding, the levitation coordinate h is calculated on the load current I_{load} and voltage U_{load}. The calculation takes into account the influence of the ambient temperature and the normal temperature of overheating, the contact of the levitation winding on the upper yoke, according to the difference $\Delta U=U_{\max}-U_{\min}$, the minimum working stroke of the levitation winding, the maximum induction limit in the core $B_{\max}$.

For this purpose, dependencies [5-6] are investigated: excess voltage at the terminals of the excitation winding $\Delta U_1=U_{1\max}-U_{1\min}$ on the change in mains voltage $\Delta U_c=U_{c\max}-U_{c\min}$; maximum travel X_M against overvoltage of the field winding ΔU_1; input S_{load}, output P_{load}, electromagnetic forces and winding powers (S_1, S_2) from the initial data; X_M stroke and stabilization current period from the initial data; load current I_{load} on ambient temperature θ_{ok} and overheating temperature of windings τ_1 and τ_2; main dimensions, power, electromagnetic loads (induction in the core B_c and current density j) on the overheating temperature of the windings; excess of the induction in the core ΔB_c, excess of the change in the mains voltage ΔU_c from the load power and the total power S_{load}.

5. CONCLUSIONS

The relationship between the ratio $\Delta U_1 / X_M$ and the load current $I_{load}=I_1$ shows that with an increase in the nominal values of the stabilized load current, the voltage drops ΔU_1 decreases. As a result, with an increase in the load current I_{load}, the increase in the stroke of the levitation winding of the X_M is large, which causes an increase in the height of the stabilizer. In order to limit the growth of the X_M travel, gravity must be sized for the maximum load current. With an increase in the voltage drop ΔU_c, the stroke X_M of the levitation winding increases.

Analytical expressions for the relationship between the coefficient n_λ characterizing the stepped shape of the core and the ratio $X_M^* = \frac{X_M}{h_1}$ are obtained. For straight cores $n_\lambda=1$, and for stepped cores $n_\lambda= (1.1\div 1.4)$. For the optimal size of the stabilizer $X_M= (133\div 265)\times 10^{-3}$, the dependence $X_M^* = f\left(\frac{U_{\max}}{U_{\min}}\right)$ is linear and the coefficient n_λ also increases with growth X_M^*. Therefore, to reduce the height of the stabilizer, a stepped core shape is necessary. For this reason, the ratio $n_{e1} = \frac{h_1}{c_1}$ should be as small as possible. A decrease in this ratio contributes to the creation of a magnetic neutral and causes a decrease in lift.

The equations of functional relationships between the cross section of the core and windings (S_c, S_o), conductivity λ, stroke X_M and current density j_1 are determined. The ranges of change defined for conductivity λ, current density j_1 and stroke X_M retain the principle of proportionality of the geometric dimensions used in the design of the stabilizer.

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