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Optimisation of Electromagnetic Components of a Parametrical Voltage Stabilizer with Magnetic Communications between the Nonlinear Coil and a Ballast Element

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ABSTRACT: Optimisation of electromagnetic components of a parametrical voltage stabilizer with magnetic connections between the nonlinear coil and a ballast element on the minimum volume of an electromagnetic element Is resulted. Suitability for optimisation of criterion of equality of losses in core and device windings is considered. Analytical expressions for restrictions in the form of density of a current and an admissible overheat are received. The comparative estimation of use of active materials in the given device and the optimum transformer is made.

KEYWORDS: a ferromagnetic element, approximation, core volume, current density, a magnetic induction, an overheat, losses in core, losses in the windings, full electromagnetic power, criterion function, restrictions, thermal balance.

INTRODUCTION

An integral part of almost any electronic device is secondary power sources (IVEP), which provide them with electrical energy of the required type and quality. Despite the circuitry variety of modern IVEP, the most reliable sources have proven to be based on ferromagnetic, Ferroresonant and auto-parametric circuits, which remain operational in conditions of high and low temperatures, increased radiation and cosmic radiation [1,4,5,11,12,14,15 , 16,18,19,20]. At the same time, parametric IWEP have higher weight and size indicators, therefore, increased attention is paid to the issue of their circuitry, economic, mode and weight and size optimization, and the research topic is relevant.

In light of the miniaturization of modern electrical equipment, the minimum volume of an electromagnetic element should be chosen as the main optimization criterion, and the optimization problem is reduced to finding the minimum of the objective volume function in the presence of a certain set of restrictions. The optimization criteria for the electromagnetic elements of linear transformers and chokes have been well studied [6,9,10,13], however, they cannot be fully transferred to the inductive elements of parametric IVEP because of the qualitative difference in the constraints. These constraints should be converted into analytical expressions reflecting the following mandatory relationships:

1) the electromagnetic element must transmit a given active or reactive power to the load;
2) the electromagnetic element must operate within a predetermined permissible overheating of its surface;
3) the electromagnetic element must operate under such mode parameters that known active materials can withstand for a long time;
4) the value of the induction in the rod of the oscillatory circuit should ensure its operation in a saturated mode, and the induction in the ballast elements should ensure their operation at the break point of the characteristic *B=f(H)*.

THE MAIN FINDINGS AND RESULTS

Let us estimate the suitability of the criteria for the equality of losses in the windings and the magnetic circuit of the electromagnetic element in relation to minimizing its volume for the stabilizer according to Fig. 1. From [6,10,17] it is known that the power losses in the magnetic circuit can be found from the expression

$$P_m = V_M * P_o * (\frac{f}{f^*})^{\alpha} * (\frac{B_m}{B_{m*}})^{\beta}, \qquad (1)$$

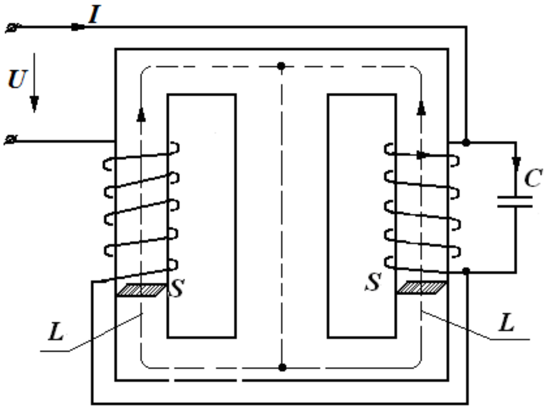

Fig. 1

Where is V_M – magnetic circuit volume; P_o, α, β – coefficients depending on the core material; f, f^* – operating and base frequencies; B_m, B_{m*} – respectively, the amplitudes of the working and base inductions.

The total losses for the investigated device can be found on the basis of (1) by the expression

$$P_m = P_o * (\frac{f}{f^*})^{\alpha} * (\frac{B_{1m}{}^{\beta} + B_{2m}{}^{\beta}}{B_{m*}{}^{\beta}}) * V_M \, . \qquad (2)$$

Where is V_M– the total volume of magnetic circuits of nonlinear inductance (NI) and ballast element (BE).

It is known from [6,9,10,17] that for the optimal electromagnetic element $V_{об} \approx V_m * 2$,

Where is $V_{об}$ – the volume of the windings, and the losses in the windings can be found from the expression

$$P_{об} = 2 * V_m * J^2 * \rho * K_m * K_d * K_t, \qquad (3)$$

Where is J– current density in windings; ρ – resistivity of the winding material; $K_м$ – Copper window filling factor; K_t – coefficient of increase in the resistance of the winding material due to an increase in its temperature; K_∂ – additional factor. Equating (2) and (3) after simplification, we obtain the relationship between the amplitudes of the magnetic inductions in the rods and the current density in the windings for the optimal electromagnetic element

$$B_{2m} = (\frac{4 * B_m{}^{\beta} * J^2 * \rho * K_m * K_\partial * K_t}{P_o * (\frac{f}{f^*})^{\alpha}} - B_{1m}{}^{\beta})^{\frac{1}{\beta}} \, . \qquad (4)$$

In fig. 2 shows the graphs of this dependence for the core made of steel 3114 (E330) with the value of the parameters (P_o=21*10^{-2}, α=1,3; β=1,6; f=50 Гц; $K_м$=0,25; $K_д$=2; K_t=1,4) and at different values of the current density in the windings. It can be seen from the graphs that in the range of possible changes in magnetic inductions $B_{1м}$=1,4-1,7Тл and $B_{2м}$=1,7-1,85Тл (shaded area in the graph), the current density in the windings should be 0,6-0,7 А/мм^2. Obviously, when using such values of the current density, it will be difficult to place the winding in the window of a standard magnetic circuit, and the criterion of equality of losses in the windings and the magnetic circuit is unacceptable for this class of stabilizers.

Let us find the function connecting the volume of the magnetic circuit V_M with the regime parameters of the stabilizer. Known dependencies

$$S = U * I; \; U = \frac{2\pi}{\sqrt{2}} * f * W * S * B_m * Коб; \;\; I_m = \frac{H_m * L}{W}$$

you can write expressions for the electromagnetic power in the rods of the magnetic circuit

$$S = \pi * f * Коб * B_m * H_m * V_M \quad ,$$

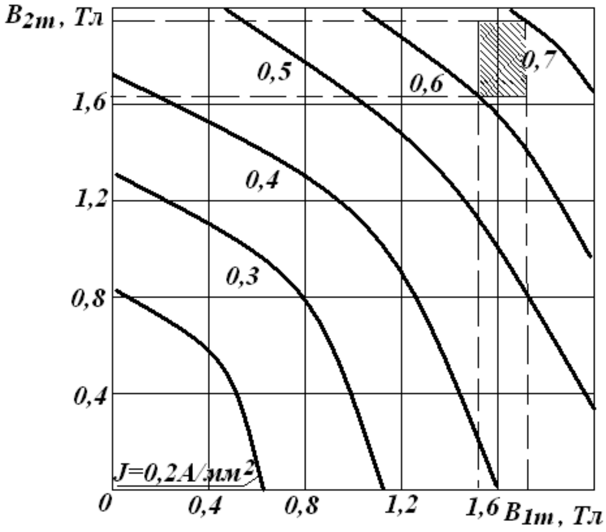

Fig. 2

Where is V_M=*S*L* – magnetic circuit volume, *К*об – winding factor, taking into account the filling of the magnetic circuit window with winding. We transform the expression for the electromagnetic power taking into account the approximation $H_M = k * B_M{}^9$ [2,3,7,8,13], and also bearing in mind that the electromagnetic power of the magnetic circuit must be determined by the maximum possible working induction B_{2m} in the NI, otherwise it will not be able to provide the specified stabilization quality. We get

$$S = \pi * f * Коб * k * B_{2m}{}^{10} * V_M$$

Whence the volume of the magnetic circuit of the electromagnetic element

$$V_M = \frac{S}{\pi * f * Коб * k * B_{2m}^{10}} \qquad (5)$$

In fig. 3 shows the graphs of the dependence at various electromagnetic powers S for a magnetic circuit made of steel Э330 (3414 It can be seen from the graphs that V_M most strongly depends on B_{2m} in the saturation region (B_{2m}>1,8Т*л*), , which for the circuit under study is the zone of nominal operation.

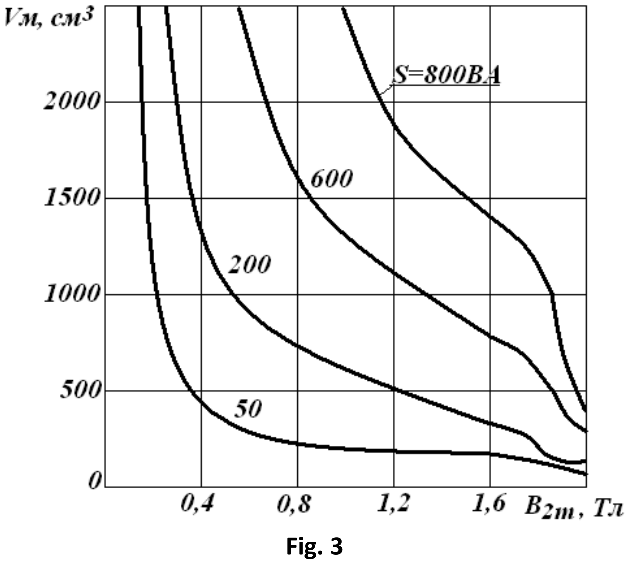

Fig. 3

The volume function of the magnetic circuit can serve as a starting point for the optimization procedure. Optimization in this case will consist in finding the minimum volume of the magnetic core VM, taking into account the previously mentioned limitations on current density and overheating. In expression (5) of the objective function, two of the above restrictions in the parameters (total electromagnetic power S and the maximum amplitude of magnetic induction in the saturated rod of NI B2m) are already taken into account. It is necessary to establish a connection between this function and the electrical parameters of the circuit, the main of which are the current density in the windings and overheating.

It is known from [10] that the cooling surface Coolant of an electromagnetic element and the volume of its magnetic circuit VM are related by an approximate ratio

$$\text{П}_{\text{охл}} \approx 13 * V_M^{\frac{2}{3}}\,, \qquad (6)$$

and the connection between losses in an electromagnetic element and its overheating is determined by the expression

$P_{\text{м}} + P_{\text{об}} = \text{П}_{\text{охл}} * \Delta T * A$, (7)

Where is ΔT overheating of the surface of the electromagnetic element, equal to the temperature difference between the environment and the surface of the magnetic circuit;

A – heat transfer coefficient. From expressions (6) and (7), we express the cooling surfaces $\text{П}_{\text{охл}}$, equate them and find VM from there. We get

$$V_M = \left(\frac{Pm + P\text{об}}{13 * \Delta T * A}\right)^{\frac{3}{2}} \qquad (8)$$

Substituting into (8) the expressions for $P_{\text{м}}$ (2) and the expression for $P_{\text{об}}$, (3), we obtain the dependence connecting the volume of the magnetic circuit VM, as well as the thermal and operating parameters

$$V_M = \left[\frac{P_o * (\frac{f}{f^*})^{\alpha} * (\frac{B_{2m}}{B_{m*}})^{\beta} * V_M + 2 * V_M * J^2 * \rho * K_m * K_d * Kt}{13 * \Delta T * A}\right]^{\frac{3}{2}}. \qquad (9)$$

We transform (9), for which we select $V_M^{3/2}$, from the right side of the expression, transfer it to the left side of the expression and after simple transformations we get

$$V_M = \left(\frac{13 * \Delta T * A}{P_o (\frac{f}{f^*})^{\alpha} * (\frac{B_{2m}}{B_{m*}})^{\beta} + 2J^2 \rho * K_m * K_t * K_d}\right)^3. \qquad (10)$$

In fig. 4 shows plotted on the basis of (10) dependences $V_M=f(J)$ for two values often used in superheat calculations – $\Delta T=50^{\circ}$C and $\Delta T=70^{\circ}$C and when using magnetic cores made of steel Э330 (3414).

It can be seen from the graphs that with an increase in the volume of the magnetic circuit, in order to ensure the thermal balance, it is necessary to significantly reduce the current density in the windings, and this property is manifested to a greater extent for large values of overheating. Thus, the curves in Fig. 4 limit the lower limit of V_M, which provides a heat balance in the electromagnetic element of the stabilizer for given J and ΔT.

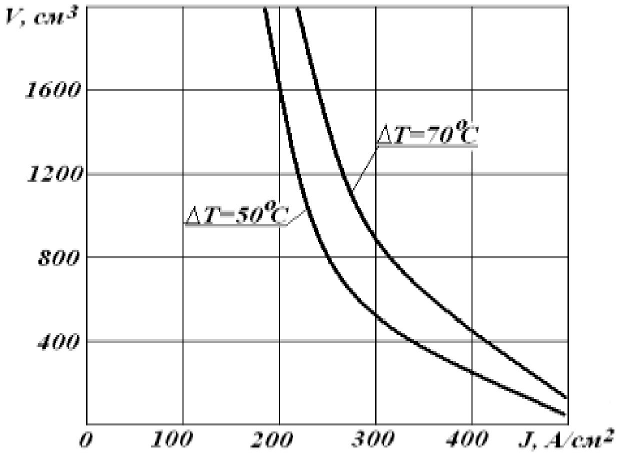

Fig. 4

To find the relationship between the electromagnetic power, the volume of the core of the electromagnetic element, thermal parameters and losses in the electromagnetic element of the stabilizer, the value VM from (5) is substituted into the left side of formula (9), and the value of VM from the right side of expression (9) is placed outside the brackets, we get

$$\frac{S}{\pi * f * \text{Коб} * k * B_{2m}^{10}} = \frac{V_M^{\frac{3}{2}}\left[P_o *(\frac{f}{f^*})^{\alpha} *(\frac{B_{2m}}{B_{m*}})^{\beta} + 2 * J^2 * \rho * K_m * K_d * K_t\right]^{\frac{3}{2}}}{13 * \Delta T * A} . \quad (11)$$

Solving (11) with respect to VM, after simple transformations, we obtain an expression for the target optimization function together with the constraints, which connects the electrical, magnetic and thermal parameters in the electromagnetic element of the circuit under study

$$V_M = (\frac{S}{\pi * f * \text{Коб} * k * B_{2m}^{10}})^{\frac{2}{3}} \frac{13 * \Delta T * A}{\left[P_o *(\frac{f}{f^*})^{\alpha} *(\frac{B_{2m}}{B_{m*}})^{\beta} + 2 * J^2 * \rho * K_m * K_d * K_t\right]} . \quad (12)$$

The graphs of the dependences $V_M=f(J,S)$ at a given B_{2m}=1,85Тл, ΔT=50^{0}C andΔT=70^{0}C (dashed lines) for a magnetic circuit made of steel Э330 (3414) are shown in Fig. 5. It can be seen from the graphs that the minimum of the objective function (and hence the volume of the electromagnetic element V_M with other parameters unchanged, is achieved at $J \to \infty$ and is equal to zero. However, it cannot be less than the value determined by (10) from the heat balance conditions. Joint graphical solution of equation (12) and equation (10), located at the intersection of the dotted lines of the thermal balance constraints for overheating ΔT=50°C and ΔT=70^{0}C at the points of intersection gives the values of the maximum current densities J and the minimum volumes of the magnetic circuit VM for the given electromagnetic powers *S*, at which the required electromagnetic power is provided and the thermal balance in the electromagnetic element of the stabilizer is ensured.

It is also seen from the graphical solution that with an increase in the electromagnetic power S, the volume VM required for its transmission increases significantly and the current density in the windings decreases. It is also obvious that with an increase in the power of the circuit under study above 1.2-1.5 kVA, a significant reduction in the current density required to maintain the thermal balance will lead to an irrational use of the materials of the electromagnetic element and windings, since it will be necessary to use a wire of significantly larger diameter.

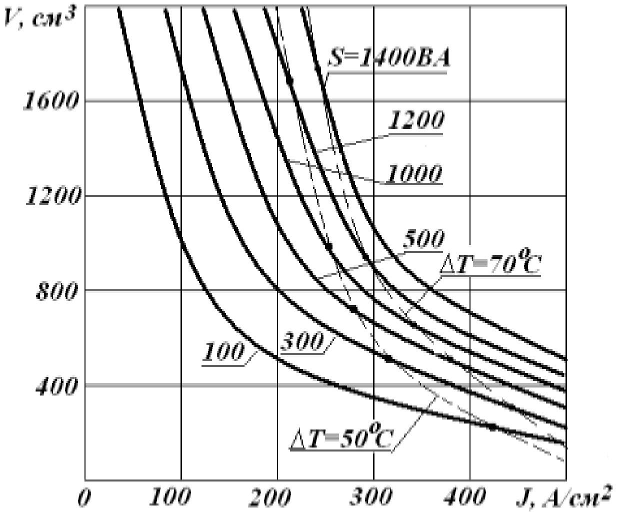

Fig. 5

For this reason, such stabilizers are practically not used at powers exceeding 1.5-2 kVA.

For the purpose of comparative assessment of the efficiency of using active materials, Fig. 6 shows the graphs of the dependences $V_M=f(S)$ for the optimal electromagnetic elements: the investigated circuit (V1) and the optimal two-winding linear transformer (V2), built on the basis of the well-known expression

$$V_m = \sqrt{\frac{A'^*K_d}{K_m}} * \frac{S}{f^{\frac{1}{4}} * \Delta T * T_1},$$

Where is *A'* coefficient depending on the material of the core (for steel 3114(Э320) *A'* =663 [6, 9,10]; *T1* – similarity criterion for optimal transformers (*T1*=0,7) [6, 9,10].

It can be seen from the graphs that in the range of power values of 20-1500VA, the V1 / V2 ratio is in the range of 1.2–2.0, which is significantly less than the similar ratio for classical schemes of ferroresonant stabilizers with separated magnetic cores of the FKK and the ballast element, for which it is equal to 2,1–2,5 [6,9].

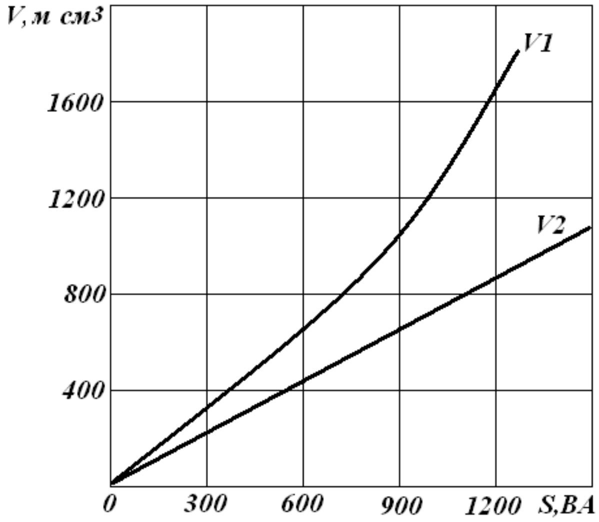

Fig. 6

Thus, we can consider a constructive method, which consists in combining a FKK and a nonlinear ballast element on a common magnetic circuit, as a method of circuit optimization.

CONCLUSION

1. The task of optimizing the volume of the magnetic circuit of the ferroresonant IVEP with the combined magnetic circuit of the NI and BE should be carried out at the maximum possible induction in the electromagnetic element of the NI;
2. The found expressions for the objective function of the volume of the magnetic circuit make it possible to minimize its volume, taking into account the operating electromagnetic and thermal limitations, and also to determine the optimal values of the main electrical parameters of the device;
3. It was found that with natural cooling of the electromagnetic element of the circuit under study, the most effective use of materials is possible in devices with an electromagnetic power of 20-1500VA.

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