ANALYSIS OF OPERATING MODES OF A FERRORESONANCE CURRENT STABILIZER WITH THREE-PHASE INPUT

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Abstract. *The paper considers the issue of a current stabilizer in case of a short circuit in one of the phases. The equations approximating the nonlinear magnetization of the ferromagnetic core of the inductor and describing the processes in abnormal operating modes of the current stabilizer are derived.*

Keywords: *current stabilizer, short circuit, approximation, magnetization, core, ferromagnetic, inductor.*

Introduction. A ferroresonance current stabilizer is a static device in which the phenomenon of ferroresonance currents is used to convert unstable mains voltage and load current into a current whose effective value is almost constant. It can be used in automatic installations, to power consumer electronics, to convert a single-phase voltage system into a symmetrical three-phase one [1].

One of the most important properties of ferroresonant current stabilizers is their almost inertia-free action. Changes in the load current within the operating range only lead to changes in the shape of the output voltage curve: the effective (or half-cycle average) value of the latter remains practically unchanged. They can be used for devices sensitive to sudden short-term (over several half-cycles) changes in the supply voltage. The disadvantages are: dependence of the stabilized current on the frequency of the power source, non-sinusoidal shape of the output current curve, sensitivity to the type of load, large weight per unit of output power [2]. The physical processes in such stabilizers can be compared to a swing. A swing that has been pumped up to a certain strength is difficult to stop or suddenly force to swing faster. When riding a swing, you don't have to push off every time - the energy of vibration makes the process inertial. It is also difficult to increase or decrease the oscillation frequency - the swing has its own resonance. In ferroresonant stabilizers, electromagnetic oscillations occur in the oscillatory circuit of capacitance and inductance [3].

Ferroresonant current stabilizer with three-phase input in single-phase short circuit mode, i.e. at ZA= 0, shown in Fig. 1. has certain advantages compared to analogues.

When analyzing the physical processes of a ferroresonant current stabilizer, we will make the following assumptions:

1. The magnetization curve of a nonlinear element is approximated by an incomplete third-order power function:

$$i = \mathrm{a}\psi + \mathrm{b}\psi^{3}$$

2. Losses in linear reactive elements are not taken into account;
3. The nonlinear element is represented by an equivalent circuit consisting of parallel-connected nonlinear inductance and constant active conductance, which takes into account losses in the core [4].

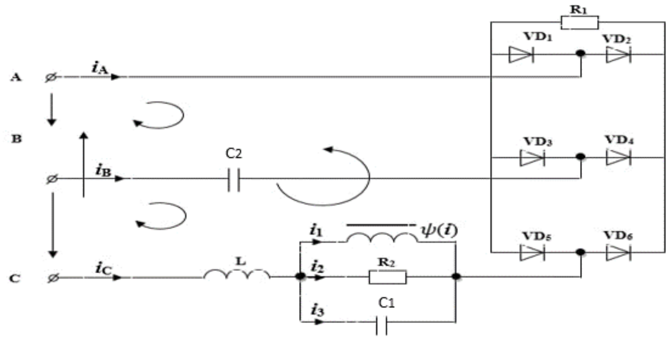

Fig.1. Schematic diagram of a ferroresonant current stabilizer

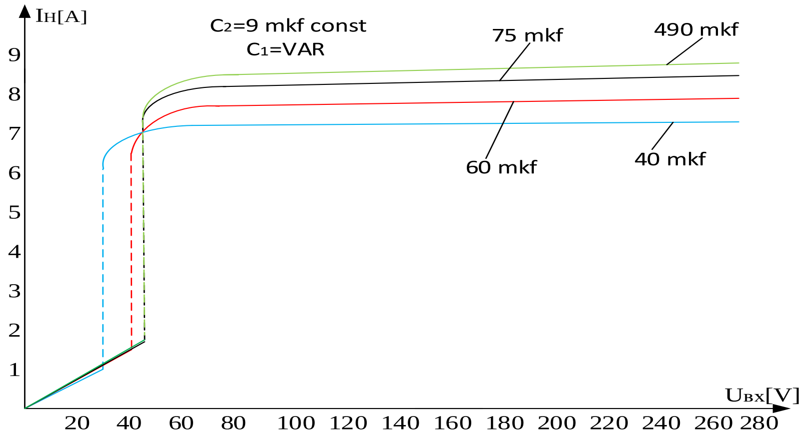

Fig. 1 Adjustment characteristics $I_{\text{H}}[A] = f(U_{\text{BX}})$

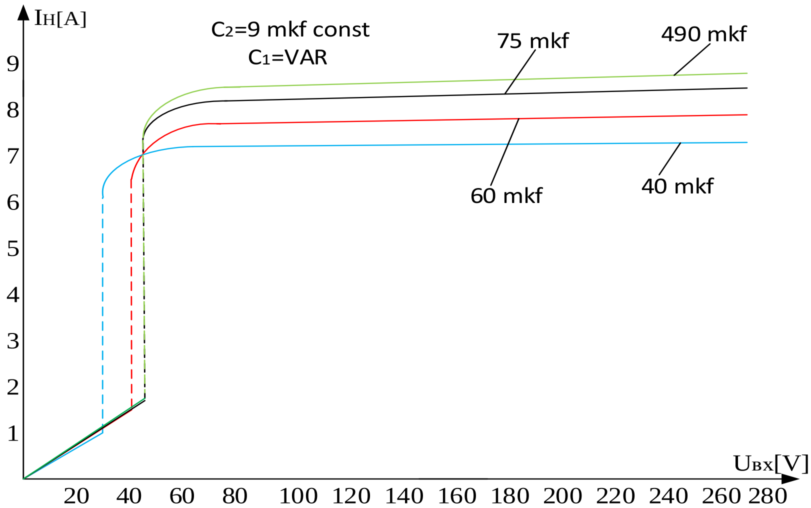

Fig 2 Adjustment characteristics $I_{\text{H}}[A] = f(U_{\text{BX}})$

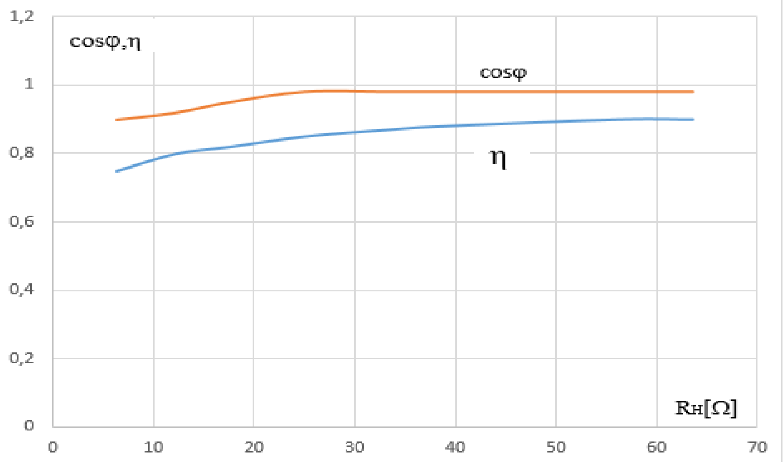

Fig. 3 Dependence of efficiency " η" and asymmetry coefficient " Ku" from load " Rн".

We use the following notation:

U_{AB}, U_{BC}, U_{CA} – external influence;

ψ- flux linkage in the core of a nonlinear element;

$i_A, i_B i_C$- currents flowing in each phase of a three-phase system;

$i_1, i_2 i_3$- currents flowing respectively through the windings of a nonlinear element through conductivity ***g*** and capacitor ***C***2.

For the scheme under consideration, the following relations are valid based on Kirchhoff's laws;

$$U_{AB} = -\frac{1}{C}\int i_B dt \quad (1.1)$$

$$U_{BC} = \frac{1}{C}\int i_B dt - \frac{d\psi}{dt} - L\frac{i_C}{dt} \quad (1.2)$$

$$U_{CA} = L\frac{di_C}{dt} + \frac{d\psi}{dt} \quad (1.3)$$

$$i_A + i_B + i_C = 0 \quad (1.4)$$

$$i_c + i_q + i_\psi = 0 \quad (1.5)$$

when

$$i_c = c_2\frac{d^2\psi}{dt^2}$$

$$i_q = q\frac{d\psi}{dt} \quad (1.6)$$

$$i_\psi = a\psi + b\psi^3$$

Taking (1.6) into account, we can write that

$$i_c = a\,\psi + b\psi^3 + q\frac{d\psi}{dt} + c_2\frac{d^2\psi}{dt^2} \quad (1.7)$$

From (1.2), (1.1) and (1.4) we obtain, respectively;

$$\frac{dU_{BC}}{dt} = -\frac{i_b}{c_1} - \frac{d^2\psi}{dt^2} - L\frac{d^2\psi}{dt^2} - L\frac{d^2 i_c}{dt^2}$$

$$\frac{dU_{AB}}{dt} = -\frac{i_b}{c_1} \qquad i_b = -c_1\frac{dU_{AB}}{dt}$$

$$\frac{dU_{BC}}{dt} = \frac{dU_{AB}}{dt} - \frac{d^2\psi}{dt^2} - 6bL\psi\frac{d\psi}{dt} + (a + 3b\psi^2)L\frac{d^2\psi}{dt^2} + qL\frac{d^3\psi}{dt^3} + Lc_2\frac{d^4\psi}{dt^4} \quad (1.8)$$

Let us accept the following assumptions:

$$U_{AB} = \sin(\tau)$$

$$U_{BC} = U_m\sin(\tau - 120^0)$$

$$\psi = \psi_m\sin(\tau + \psi_m), \quad (1.9)$$

when $\tau = \omega t$

Thus, we will consider the operating mode of the nonlinear inductance at the fundamental harmonic, taking into account (1.9) from (1.8) we obtain

$$U_m \cos(\tau - 120^0) = -U_m \cos(\tau) + \psi_m \omega \sin(\tau + \psi_m) -$$
$$-6bL\psi_m^2 \frac{d\psi}{dt} \sin(\tau + \psi_m) \cdot \cos(\tau + \psi_m) - [a + 3b\psi_m^2 \sin^2(\lambda + \psi_n)]$$
$$\omega L\psi_m \sin(\tau + \psi_n) - qL\psi_m \omega^2 \cos(\tau + \psi_n) + LC_2 \psi_m \omega^3 \sin(\lambda + \psi_n) \quad (1.10)$$

Whence it follows that

$$U_m(\cos(\tau) \cdot \cos(120^0) + \sin(\tau) \sin(120^0) = -U_m \cos(\tau) +$$
$$+U_m \omega \sin(\tau + \psi_m) - 3Lb\psi_m^2 \sin 2(\tau + \psi_n) - aL\omega\psi_m \sin(\tau + \psi_n) -$$
$$-3bL\omega\psi_m^3 \sin(\tau + \psi_n) - gL\psi_m \omega^2 \cos(\tau + \psi_n) + LC_2\omega^3\psi_m \sin(\tau + \psi_m) \quad (1.11)$$

From the last expression we get;

$$-\frac{U_m}{2} \cdot \cos(\tau) + \frac{\sqrt{3}}{2} U_m \sin(\tau) = U_m \cos(\tau) + \omega\psi_m(\sin(\tau)\cos(\psi_n) +$$
$$+\cos(\tau)\sin(\psi_n) - 3bL\psi_m^2 \sin 2(\tau + \psi_n) - aL\omega\psi_m(\sin(\tau)\cos\psi_n +$$
$$+\sin\psi_n) - 3Lb\psi_m^2 \sin 2(\tau + \psi_n) - aL\omega\psi_m(\sin\tau\cos\psi_n + \sin\psi_n\cos\tau) -$$
$$-3b\omega L\psi_m^3[(\frac{3}{4}\sin(\tau)\cos\psi_n - \frac{3}{4}\sin\psi_n\cos(\tau)) - (\frac{1}{4}\sin(3\tau)\cos(3\psi_n) -$$
$$-\frac{1}{4}\cos 3\tau \sin(3\psi_n))] - qL\psi_m\omega^2(\cos(\tau)\cos(\psi_n) - \sin(\tau)\sin(\psi_n)) +$$
$$+LC_2\omega^3\psi_m(\sin(\tau)\cos(\psi_n + \sin(\psi_n\cos(\tau)) \quad (1.12)$$

Without taking into account higher harmonics from (1.12), we obtain

$$\begin{cases} \frac{U_m}{2} = (\omega\psi_m - aL\omega\psi_m + \frac{9}{4}b\omega L\psi_m^3 + LC_2\omega^3\psi_m)\sin(\psi_n) + qL\psi_m\omega^2\cos(\psi_n) \\ \frac{\sqrt{3}}{2}U_m = qL\psi_m\omega^2\sin(\psi_n) + (\omega\psi_m - aL\omega\psi_n + \frac{9}{4}b\omega\psi_m^3 + LC_2\omega^3\psi_m)\cos(\psi_n) \end{cases}$$
(1.13)

By introducing the notation:

$$\omega\psi_m - aL\omega\psi_m + \frac{9}{4}bL\omega\psi_m^3 + LC_2\omega^3\psi_m = A$$
$$qL\psi_m\omega^2 = B$$
$$\frac{U_m}{2} = K: \qquad \frac{\sqrt{3}}{2}U_m = N:$$

Taking into account the notation we obtain:

$$\begin{cases} K = A\sin(\psi_n) + B\cos(\psi_n) \\ N = B\sin(\psi_n) + A\cos(\psi_n) \end{cases} \quad (1.14)$$

From system (1.14) it follows that

$$\sin\psi_т = \frac{KA - BN}{A^2 - B^2} \quad (1.15)$$
$$\cos(\psi_n) = \frac{AN - KB}{A^2 - B^2} \quad (1.16)$$

From (3.15), (3.16) we obtain:

$$\left(\frac{KA - BN}{A^2 - B^2}\right)^2 + \left(\frac{AN - KB}{A^2 - B^2}\right)^2 = 1 \quad (1.17)$$

Considering that $K = \frac{U_m}{2}$: $N = \sqrt{3}\frac{U_m}{2}$

Then from (1.17) we get:

$$\frac{U_m^2}{4}(A-\sqrt{3}B)^2+\frac{U_m^2}{4}(\sqrt{3}A-B)^2=(A^2-B^2)^2 \qquad (1.18)$$

$$\frac{U_m^2}{4}\left(A^2-2\sqrt{3}AB+3B^2+3A^2-2\sqrt{3}AB+B^2\right)=(A^2-B^2)^2$$

$$\frac{U_m^2}{4}4\left(A^2-\sqrt{3}AB+B^2\right)=(A^2-B^2)^2$$

Let us assume that (for a first approximation)

$$\left(A^2-\sqrt{3}AB+B^2\right)\approx(A-B)^2$$

$$\sqrt{3}=1.74\approx 2$$

Then

$$U_m=(A+B) \quad \text{т.е} \qquad (1.19)$$

$$U_m=\frac{9}{4}b\omega L\psi_m^3+\psi_m(\omega-aL\omega+LC_2\omega^3+gL\omega^2)$$

$$\psi_n=arc\tan\frac{KA-BN}{AN-KB}=arc\tan\frac{A-\sqrt{3}B}{\sqrt{3}A-B}$$

As a result of the analysis, equations were derived that approximate the nonlinear magnetization of the ferromagnetic core of the inductive element. In the event of a short circuit in phase A and the corresponding parameters of phase C, ferroresanance of currents occurs. Thus, the current is stabilized in phase C.

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