Current source converter into stabilized voltage source based on electromagnetic ferromagnetic circuit

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Abstract. The article considers a series ferroresonant circuit connected in parallel with a linear capacitance, having an "N" - shaped current-voltage characteristic with a wide zone of the incident section. By compensating this section with a linear inductance characteristic connected in series with the resulting circuit, it is possible to create a device that converts a current source into a stabilized voltage source.

1 Introduction

In a modern automation system, telemechanics and in the power circuit of various devices, electroferromagnetic circuits are widely used as current and voltage stabilizers, phase and frequency converters, they converted a current source into a stabilized voltage source, since devices created on the basis of electroferromagnetic oscillatory circuits have high reliability in operation, resistance to mechanical overload, rather high efficiency, power factor, manufacturing limit from several W to tens of kW, low cost [1-6, 12].

2 The current state of the investigated problem

With the rapid development of some branches of electrical engineering, there is an increasing need to create devices that convert a constant voltage system into a constant current system and vice versa.

The main part of the current source converter into a stabilized voltage source (CSCISVS) is a series ferroresonant circuit, the equivalent circuit of which is shown in Fig. 1. Consider the current-voltage characteristic of this circuit, shown in Fig.2. (curve 3) when powered from a voltage source. The value of the capacitance C1 is chosen such that its characteristic crosses the current-voltage characteristic of the nonlinear inductance in the saturation region. With an increase in the input voltage from U1=0 to the value U1=Umin, the current in the circuit increases in proportion to the voltage. The core of the non-linear coil is not saturated, and its voltage is greater than the capacitor voltage, the current in the circuit lags behind the input voltage by an angle π/2. When U1= Umin is reached, the current increases sharply, and its phase changes, and its phase changes by an angle π. The "ab" section of the characteristic is unstable. The voltage drop on the inductance leads, and on the capacitance C1 lags in phase from the current by an angle π/2. Therefore, the "oab" section of the circuit characteristic is inductive in nature, and "bs" is capacitive. A further increase in the input voltage leads to a proportional increase in the current in the circuit. This property of the circuit can be used to generate control signals for power thyristors [7-10, 13, 11, 14].

When a serial ferroresonant circuit is connected to a current source, the current-voltage characteristic of the circuit has the form of an “oabs” curve (Fig. 2). In this case, the section "ab" is stable. The form of this characteristic depends on the ratio of parameters in the circuit. If the falling section is observed in a small range of current changes, then in order to expand it, it is necessary to connect the capacitor C2 in parallel to the ferroresonant circuit with a characteristic passing tangentially to the “oa” curve. (curve 5) of such a circuit (Fig. 3) is built according to the characteristics of the resonant circuit (curve 3) and capacitance C1 (straight line 4) by summing the currents for the same values of the input voltage [15-20].

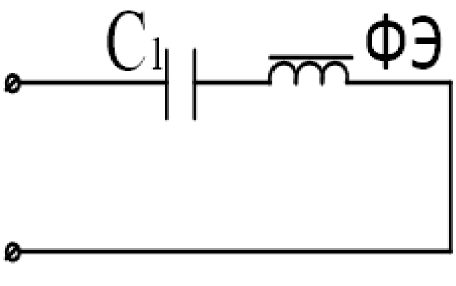

Fig.1. Series ferroresonant circuit

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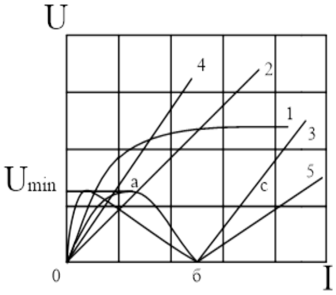

Fig.2. Volt-ampere characteristic of ferroresonant circuit

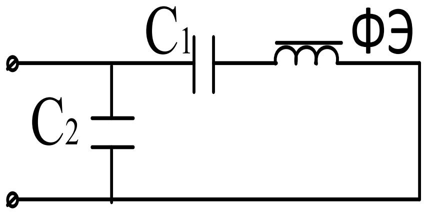

Fig.3. Series ferroresonant circuit with capacitor connected in parallel

This takes into account that in the pre-resonant mode the ferroresonant circuit is inductive, and in the post-resonant mode it is capacitive. As can be seen from Fig.2. with the inclusion of capacitor C1, the zone of the falling section of the characteristic expands in current. The length of the falling section of the characteristic strictly depends on the ratio of the parameters.

In order to compensate for the falling section and obtain the effect of voltage stabilization, we connect in series to the circuit shown in Fig.3., a linear inductance L0. The inductance characteristic must be strictly selected. The current-voltage characteristic of a two-coil ferroresonant circuit (Fig. 4.) is shown in Fig. 5. (curve 3) is obtained by summing curve 1 (current-voltage characteristic of a linear inductance) and curve 2 (volt-ampere characteristic of a ferroresonant circuit shown in Fig. 3). When constructing curve 3, it was taken into account that before resonance, the ferroresonant circuit (Fig. 3) has an inductive character, and after resonance, it is capacitive. As seen from Fig. 5, at certain ratios of the circuit parameters, a pronounced voltage stabilization zone appears. (av). The stabilization effect can also be achieved in the post-resonant mode, if the section "sun" of curve 2 is parallel to the linear inductance characteristic (curve 1). It is obvious that the overall dimensions and energy performance of the device will be better when operating in the pre-resonance mode, than in the post-resonance mode, since the effect of stabilizing the output voltage in the first case is obtained by summing, and in the second by subtracting the characteristics of the circuit elements [21-26, 18].

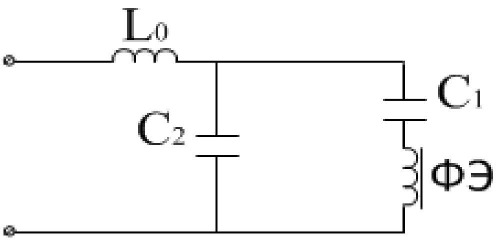

Fig.4. PITSIM scheme

In addition, the shape of the stabilized voltage curve in the pre-resonant mode is close to sinusoidal, and when the device is operated in the post-resonant mode, it is strongly distorted, since the ferromagnetic element is in the deep saturation zone [27-30, 15, 12].

Thus, connecting a series ferroresonant circuit to a current source calls the appearance of a stable falling section on the current-voltage characteristic, by compensating for which it is possible to achieve the transformation of a current source into a voltage source.

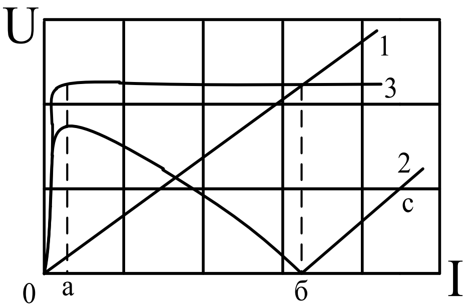

Fig.5. Volt-ampere characteristic of CSCISVS

In the theoretical analysis of ferroresonant circuits, their equivalent circuit plays an important role. Since the presence of a nonlinear ferromagnetic element in the circuit complicates the analytical solution, in order to obtain the basic mathematical expressions, it is necessary to make a number of assumptions that simplify the theoretical analysis. So, to analyze the static modes of the ferroresonant circuit (Rim. 4), we accept the following assumptions [31-33, 15, 1]:

1. The magnetization curve of a non-linear element is approximated by a power function in the form $i=K\psi 2$.
2. We neglect the active resistance and leakage inductance of the windings of a ferromagnetic element, since the effect on electromagnetic processes of ferroresonant circuits is not significant.
3. Losses in capacitances and in the core of the linear inductance are not taken into account due to their extreme smallness.
4. A non-linear ferromagnetic element is represented by an equivalent circuit consisting of a non-linear inductance and active resistance connected in series to it.

The PITSIN equivalent circuit is shown in Fig. 3-6. Accepted notation:

U is the circuit voltage;

I is the current flowing through Lo;

I1 is the current flowing through the serial ferroresonant circuit;

I2 is the current flowing through the capacitor C2;

Ψ is the flux linkage of the non-linear element.

For the circuit under consideration, the following relations are valid;

$$i = i_1 + i_2\,; \tag{1}$$

$$U = L_0\frac{di_1}{dt} + L_0\frac{dt_2}{dt} + \frac{1}{C_2}\int L_2 dt; \tag{2}$$

$$O = \frac{d\psi}{dt} + \frac{1}{C_1}\int i_1 dt - \frac{1}{C_2}\int i_2 dt + i_1 r; \tag{3}$$

There is

$$i_1 = K\psi^2 \tag{4}$$

From equation (3) we determine the current in C2

$$i_2 = C_2\frac{d^2\psi}{dt^2} + C_2 r\frac{di_1}{dt} + \frac{C_2}{C_1}i_1; \tag{5}$$

Then, taking into account (4), (5), we write the expression for the loop current as follows:

$$i = C_2\frac{d^2\psi}{dt^2} + C_2 rK\frac{d\psi^2}{dt} + K\psi^2(1 + \frac{C_2}{C_1}; \tag{6}$$

Introducing the replacement of the displaced

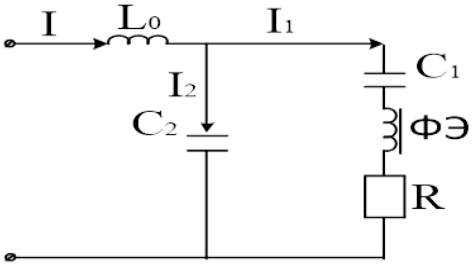

Fig.6. PITSIN equivalent circuit

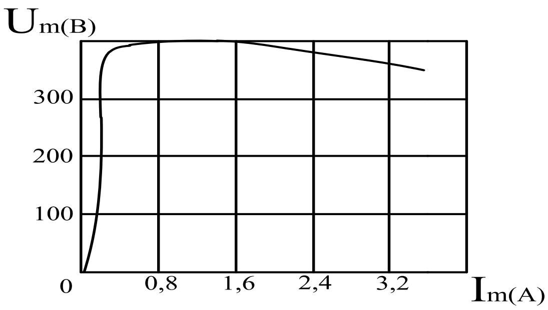

Fig.7. Volt-ampere characteristic of PITSIN

$$Y = \frac{i}{i_0}; \qquad x = \frac{\psi}{\psi_0}; \qquad \tau = \omega t$$

we will rewrite expression (6) in the form:

$$i_0 Y = C_2\omega^2\psi_7\frac{d^0 x}{d\tau^2} + C_2 rK\omega\psi_\delta^7\frac{dx^7}{d\tau} + K\psi_\delta^7 x^7(\frac{C_0}{C_1} + 1) \tag{7}$$

We multiply the right and left sides of equation (7) by $\frac{1}{C_2\omega^2\psi_0}$; and get:

$$\frac{i_\delta}{C\omega^2\psi_\delta}Y = \frac{d^2x}{d\tau^2} + \frac{rK\psi_\delta^6}{\omega}\cdot\frac{dx^7}{d\tau} + \frac{K\psi_\delta^6}{C_2\omega^2}(\frac{C_2}{C_1} + 1); \tag{8}$$

Let us introduce into equation (8) the notation

$$i_\delta = C_2\omega^2\psi_\delta; \quad d = \frac{64}{35}r\omega C_1; \quad \beta = \frac{64(C_1 + C_2)}{35C_2}; \quad \psi_\delta^6 = \sqrt{\frac{\omega^2 C_1 64}{35K}};$$

Taking into account the accepted notation, we rewrite equation (8) as follows [9]:

$$Y = \frac{d^2x}{d\tau^2} + d\frac{dx^2}{d\tau} + \beta x^7 \tag{9}$$

Solution (9) will be sought in the form:

$$x = x_m\sin(\tau + 4) \tag{10}$$

$$y = y_m\sin\tau \tag{11}$$

Derivatives of X have the form:

$$\frac{dx}{d\tau} = x_m\cos(\tau + \varphi) \tag{12}$$

$$\frac{d^2x^2}{d\tau^2} = 2\frac{dx_m}{d\tau}\cos(\tau + 4) - x_m\sin\tau + 2x_m\frac{d\varphi}{d\tau}\sin(\tau + \varphi) \tag{13}$$

$$x^7 = \frac{35}{64}x_m^7\sin(\tau + \varphi) \tag{14}$$

$$\frac{dx^7}{d\tau} = \frac{35}{64}x_m^7\cos(\tau + \varphi) \tag{15}$$

Substituting the values (11) - (15) into equation (9) and grouping the coefficients for the same trigonometric functions, we determine the value of Ym.

$$Y_m = \sqrt{(\beta\frac{35}{64}x_m^7 - x_m)^2 + (d\frac{35}{34}x_m^7)^2} \tag{16}$$

To build the current-voltage characteristic of the circuit, it is now necessary to determine the dependence U=f(ψ). Let us differentiate equation (2).

$$\frac{dU}{dt} = L_0\frac{di_1}{d\tau^2} + L_0\frac{di_2}{dt^2} + \frac{i_2}{C_2} \quad (17)$$

Taking into account (4) and (5), we rewrite the expression in the form:

$$\frac{dU}{dt} = L_0C_2\frac{d^4\psi}{dt^4} + L_0KC_2r\frac{d^3\psi^7}{dt^3} + (\frac{C_2}{C_1}+1)\cdot L_0K\frac{d^2\psi^7}{dt^2} + \frac{d^2\psi}{dt^2} + \quad (18)$$
$$+ Kr\frac{d\psi^7}{dt} + \frac{K}{C_1}\psi^7;$$

Let's make a change of variables

$$\upsilon = \frac{U}{U_\delta}; \quad x = \frac{\psi}{\psi_\delta}; \quad \tau = \omega t;$$

then (18) will take the following form:

$$\omega U_\delta\frac{d\upsilon}{d\tau} = L_0C_2\psi_\delta\omega^4\frac{d^4x}{d\tau^4} + L_0KC_2r\omega^\delta\psi_\delta^7\frac{d^3x^7}{d\tau^3} + \omega^2\psi_\delta\frac{d^2x}{d\tau^2} + \quad (19)$$
$$+ (\frac{C_2}{C_1}+1)\cdot L_0K\psi_\delta^7\omega^2\frac{d^2x^7}{d\tau^2} + K\psi_\delta^7r\omega\frac{dx^7}{d\tau} + \frac{K}{C_1}\psi_\delta^7x^7;$$

If we multiply the right and left parts of equation (19) by, then we can write $\frac{1}{L_1C_2\psi_\delta\omega^4}$

$$\frac{U_\delta}{L_0C_2\psi_\delta\omega^3}\cdot\frac{d\upsilon}{d\tau} = \frac{d^4x}{d\tau^4} + \frac{K\psi_\delta^6r}{\omega}\cdot\frac{d\ x^7}{d\tau^3} + (\frac{C_2}{C_1}+1)\cdot\frac{K\psi_\delta^6}{C_0\omega^2}\cdot\frac{d^2x^7}{d\tau^2} + \quad (20)$$
$$+ \frac{1}{L_0C_2\omega^2}\cdot\frac{d^2x}{d\tau^2} + \frac{K\psi_\delta^6r}{L_0C_2\omega^2}\cdot\frac{dx^7}{d\tau} + \frac{K\psi_\delta^6}{L_0C_1C_2\omega^2}\cdot K^7$$

We accept the notation $U_\delta = L_0C_2\psi_\delta\omega^6, \quad d = \frac{64}{35}C_1\omega r;$

$$\gamma = \frac{1}{L_0C_2\omega^2}, \quad \eta = \frac{64}{35}\cdot\frac{C_1r}{L_0C_2\omega}, \quad \delta = \frac{64}{35L_0C_2\omega^2};$$

Taking into account which (20) takes the form:

$$\frac{d\upsilon}{d\tau} = \frac{d^4x}{d\tau} + d\frac{d^3x^7}{d\tau^3} + \beta\frac{d^2x^7}{d\tau^2} + \gamma\frac{d^2x}{d\tau^2} + \eta\frac{dx^7}{d\tau} + \delta x\,; \quad (21)$$

Solution (21) will be sought in the form
Then

$$x = x_m\sin(\tau+\varphi); \quad \upsilon = \upsilon_m\sin(\tau+\theta); \quad (22)$$
$$\frac{d\upsilon}{d\tau} = \upsilon_m\cos(\tau+\theta)$$

Derivatives of x are equal

$$\frac{d^2x}{d\tau^2} = -x_m\sin(\tau+\varphi); \quad (23)$$

$$\frac{d^4x}{d\tau^4} = -x_m\sin(\tau+\varphi); \quad (24)$$

$$\frac{d^2x^7}{d\tau^2} = -x_m\sin(\tau+\varphi)\cdot\frac{64}{35}; \quad (25)$$

$$\frac{d^3x^7}{d\tau^2} = -\frac{35}{64}\cdot x_m^7\cos(\tau+\varphi); \quad (26)$$

Taking into account (14), (15) and (22) - (26), equation (21) for the steady state will take the form:

$$\upsilon_m\cos(\tau+\theta) = x_m\sin(\tau+\varphi) - d\frac{35}{64}x_m^7\cos(\tau+\varphi) - \beta\frac{35}{34}x_m^7\cdot \quad (27)$$
$$\cdot\sin(\tau+\varphi) - \gamma x_m\sin(\tau+\varphi) + \eta\frac{35}{64}x_m^7\cos(\tau+\varphi) + \gamma x_m^7\sin(\tau+\varphi);$$

We perform simple trigonometric transformations and group the coefficients for the same trigonometric functions, and after simple transformations we obtain

$$\upsilon_m = \sqrt{[x(1-\gamma 0 + x_m^7(x - \frac{35}{64}\beta)]^2 + [x_m^7\frac{35}{64}\cdot(\eta-\alpha)]^2}; \quad (28)$$

In Fig.7. the current-voltage characteristic of PITSIN is shown, built on the basis of expressions (16) and (28) for the following parameters: L0=1.4 H, C1=5 μF, C2=1 μF, r=100 Om. Here, at certain ratios of parameters, voltage stabilization is observed in a wide range of input current changes (0.2 ÷ 2A)

3 Conclusion

The proposed PITSIN scheme based on an electroferromagnetic circuit, which has a section on the amplitude characteristic, works without a trigger effect at a certain ratio of parameters. To expand the falling section "N" - a shaped current-voltage characteristic of a series ferroresonant circuit, it is proposed to use a capacitor, which must be connected in parallel to it.

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