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Electromagnetic Process of Self-Excitation of Synchronous Generators

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ABSTRACT: In this thesis examines the self-excitation mode of synchronous generators when operating on a long transmission line. In addition, algebraic differential equations of synchronous generator stator voltages and currents during self-excitation are presented in this article. Self-excitation is a spontaneous increase of voltage and current in the elements of the system and generator coils, which makes the normal operation of the synchronous machine impossible and such a process cannot be controlled.

KEYWORDS: synchronous generator, self-excitation, synchronous self-excitation, asynchronous self-excitation, self-excitation zone, prerequisite for self-excitation to occur.

I. INTRODUCTION

Synchronous machines (SM) can operate on long power lines, as the power line is natural relative to the Ground. Capacitors can be connected to stators. When operating in a SM circuit, its phase changes inductively depending on the magnitude of the circuit's inductance, and fluctuations may occur in the circuit that change the current amplitude in a certain ratio of parameters. The presence of residual magnetic flux in the SM steel core is sufficient for self-excitation to occur. Therefore, SM can be self-excited even when operating in asynchronous mode.

To ensure the normal operation of SM on power transmission lines, it is necessary to know the relationship between the parameters of the "machine - capacitive load" chain, in which self-excitation occurs, which makes the normal operation of the SM impossible. Therefore, it is possible to consider only the conditions for the occurrence of the self-excitation process.

II. SIGNIFICANCE OF THE SYSTEM

To solve this problem, it is necessary to study the characteristic equation of the equilibrium differential equations of the SM voltages [1-3].

Self-excitation is an electromagnetic instability characterized by a spontaneous increase in voltage and current in the system elements and generator windings [4].

A necessary condition for the occurrence of self-excitation is the presence of a connected capacitance in the stator circuit, which creates an oscillating circuit with the inductive resistance of the machine. Due to the fact that the specific and mutual resistances of the machine windings vary over time as the rotor rotates, conditions may arise in which electrical oscillations in the circuit do not die out, but rather increase. This is called self-excitation.

This process is not advisable, because the values of voltages and currents can be very large, and most importantly, they cannot be controlled. Self-excitation is divided into synchronous and asynchronous types according to the nature of the voltage changes at the generator busbars and at the nodes of the system.

III. LITERATURE SURVEY

If the increase in current and voltage is relatively slow and smooth, then the self-excitation is called synchronous (Fig. 1,a). The rotational speeds of the stator and rotor magnetic fields are the same. Synchronous self-excitation can only occur in synchronous generators with salient poles.

If the increase in current and voltage is rapid and intermittent, then the self-excitation is called asynchronous (Fig. 1,b).

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The rotational speeds of the stator and rotor magnetic fields are different. Asynchronous self-excitation can occur in synchronous generators with visible and invisible poles. Under certain conditions, synchronous and asynchronous self-excitations can occur simultaneously.

Let us consider a circuit in which a capacitive resistance xc is connected in series with the stator winding of a synchronous generator. In this case, we will consider a synchronous generator without a damping winding. In this case, the rotational frequency of the synchronous generator will not change.

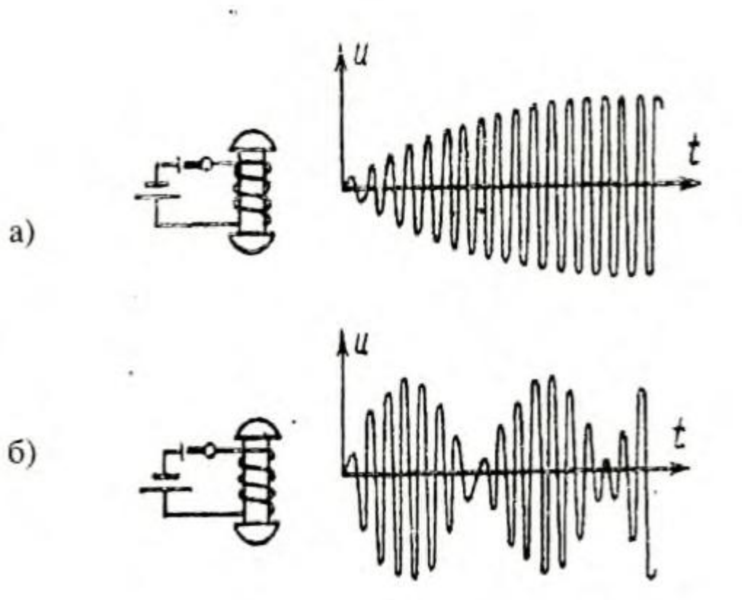

Fig 1. Self-excitation of a synchronous generator: a) synchronous, b) asynchronous

When constructing the differential equations of voltage balance, the voltage drop in the capacitance xc is determined by the following integral ∫ xc idt. To eliminate this integral, it is necessary to differentiate the equations of voltage balance in the stator winding. In this case, the voltage balance equations take the following form, based on [5]:

$$\frac{du_d}{dt} - \omega u_q = \frac{d}{dt}\left[\frac{d\psi_d}{dt} - \omega\psi_q + ri_d\right] - \omega\left(\frac{d\psi_q}{dt} + \omega\psi_d + ri_q\right) + x_c i_d;$$
$$\frac{du_q}{dt} - \omega u_d = \frac{d}{dt}\left[\frac{d\psi_q}{dt} + \omega\psi_d + ri_q\right] + \omega\left(\frac{d\psi_d}{dt} - \omega\psi_q + ri_d\right) + x_c i_q; \qquad (1)$$
$$U_{fd} = \frac{d\psi_{fd}}{dt} + r_{fd} i_{fd};$$
$$j\frac{d\Omega}{dt} = M_T - \frac{3}{2}\left(\psi_d i_q - \psi_q i_d\right).$$

If the rotor of a synchronous generator has two excitation windings, then the following equation is inserted into equation (1):

$$U_{fq} = \frac{d\psi_{fq}}{dt} + r_{fq} i_{fq}.$$

The characteristic equation of the system (system elements and generator) has the following form [1-3]:

$$a_0 p^5 + a_1 p^4 + a_2 p^3 + a_3 p^2 + a_4 p + a_5 = 0., \qquad (2)$$

where a_0, a_l, a_2, a_3, a_4, a_5 are the coefficients of the characteristic equation; r-operator.

The coefficients of the characteristic equation (2) are determined by the following parameters

$$\begin{aligned}
a_0 &= x_q x'_d T_{do};\\
a_1 &= r_1 (x_q + x'_d) T_{do} + x_d x_q;\\
a_2 &= (2 x_q x'_d + x_c x'_d + x_c x_q) T_{do} + r^2_1 T_{do} + r_1 (x_d + x_q);\\
a_3 &= r_1 (2x_c + x_q + x'_d) T_{d0} + x_c x_d + x_c x_q + 2x_d x_q + r^2_1);\\
a_4 &= (x_c - x_q)(x_c - x'_d) T_{do} + r^2_1 T_{do} + r_1 (2x_c + x_d + x_q);\\
a_5 &= (x_c - x_d)(x_c - x_q) + r^2_1.
\end{aligned} \qquad (3)$$

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The possibility of self-excitation is determined by the presence of roots with positive real parts in (2). This is achieved when, according to the Hurwitz criterion, $a5 < 0$; $\Delta 4 < 0$ (4)

The penultimate Hurwitz determinant of the characteristic equation is defined as follows:

$$\Delta_4 = \begin{vmatrix} a_1 & a_0 & 0 & 0 \\ a_3 & a_2 & a_1 & a_0 \\ a_5 & a_4 & a_3 & a_2 \\ 0 & 0 & a_5 & a_4 \end{vmatrix}$$

The fulfillment of condition 1 in (4) shows that the characteristic equation has one positive root and defines the zone of synchronous self-excitation.

The three-phase self-excitation currents in the stator generate a magnetic field that is stationary relative to the rotor and rotates at the synchronous frequency. The fulfillment of condition 2 in (4) shows that the characteristic equation has two positive roots and defines the asynchronous self-excitation zone.

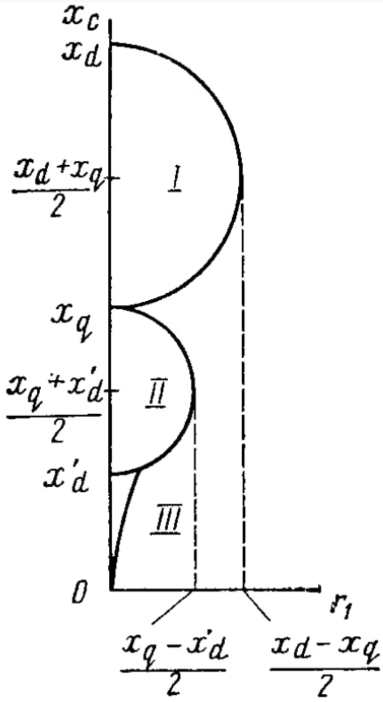

Fig.2. A clear pole without a damper coil

self-excitation zone of a synchronous machine

We can determine the self-excitation zones (Fig. 1) from the following conditions: when a_5=0, zone I (synchronous self-excitation zone); when Δ_4 =0, zones II and III (asynchronous self-excitation zone).

IV. METHODOLOGY

In the synchronous self-excitation zone, the characteristic equation has one zero root. In this case, the self-excitation condition

$$a_5 = (x_c - x_d)\,(x_c - x_q) + r^2_1 = 0 \tag{5}$$

or

$$(x_c - (x_d + x_q)/2)^2 + r^2_1 = [(x_d - x_q)/2]^2 . \tag{6}$$

(6) is the equation of a circle with radius (xd - xq)/2 and center xc = (xd + xq)/2, r1 = 0.

Figure 1 shows a half of the circle (I-zone), corresponding to positive values of active resistance. The circle intersects the coordinate axis at points $x_c = x_d$ and

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$x_c = x_q$, where $r_1 = 0$ is the synchronous self-excitation zone determined by the following inequality:

$$x_q < x_c < x_d . \quad (7)$$

The radius of the circle (a_5=0) is determined by the maximum value of the active resistance:

$$r_{1мак} = 0{,}5\ (x_d - x_q), \quad (8)$$

V. EXPERIMENTAL RESULTS

Synchronous self-excitation occurs. If $r_1 > r_{1max}$, synchronous self-excitation does not occur for any value of x_c.

The boundaries of the synchronous self-excitation zone do not depend on the time constant Td0, therefore synchronous self-excitation occurs when the excitation winding of the machine is short-circuited or open. Zones II and III (Fig. 1) with $\Delta_4 = 0$ are considered asynchronous self-excitation zones. In this case, the frequency of rotation of the stator magnetic field differs from the frequency of rotation of the rotor.

In these zones, self-excitation occurs only when the machine's ignition coil is short-circuited. Construction of asynchronous self-excitation zones can be done using various stagnation criteria, including the Hurwitz criterion [5-7].

Asynchronous self-excitation occurs at small values of r1 in the intervals $0 < x_c < x_q$ (Fig. 1).

For synchronous machines without a damping coil, zone III is shorter (narrower) and limited by small values of r_1, which are in the range of the values of the active resistance of the stator coil, so zone III can be ignored. In this case, the limits of asynchronous self-excitation are determined from the condition that the coefficient a_4 of the characteristic equation (2) is equal to zero:

$$a_4 = 0 . \quad (9)$$

Zone II in asynchronous self-excitation determined by condition (9) is limited by the arc of the ellipse.

If the value of the time constant Td0 in (3) is large (Td0 ≥ 4 s), then zone II is limited by half a circle.

The radius of this circle is $(x_q - x'_d)/2$, and its center is located at a distance $(x_q + x'_d)/2$ from the origin of the coordinate system relative to the xc axis. The maximum value of the active resistance of the stator winding in the event of asynchronous self-excitation is determined as follows:

$$r_{1мак} = (x_q - x'_d)/2. \quad (10)$$

At small values of the time constant T_{d0}, asynchronous self-excitation should be determined using the criterion $\Delta_4 = 0$.

VI. CONCLUSION AND FUTURE WORK

During synchronous self-excitation, the current and voltage rise slowly, so the self-excitation can be eliminated using an automatic rectifier.

In the process of asynchronous self-excitation, the current and voltage increase rapidly in a short period of time, so its excitation cannot be eliminated using an automatic adjustment device. In synchronous machines with longitudinal and transverse excitation windings on the rotor, the process of asynchronous self-excitation can be completely extinguished.

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