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A PARTICULAR OPERATION OF THE SYNCHRONOUS MACHINE AND ITS TECHNICAL IMPLICATIONS

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Abstract: *A mandatory condition for introducing a synchronous machine into the series manufacturing process is the long-term heating test at the nominal parameters. For medium and high power machines, the testing possibilities of the test stands are generally exceeded. In the paper, the parallel operation of two mechanically rigidly coupled synchronous machines is studied. The essential particularity consists in the fact that by simply varying the excitation currents, the active and reactive powers are modified within wide and controlled limits. The machine system works stably and recuperatively, so it absorbs from the network a power reduced by the amount of losses. The result is a new conclusive method of industrial testing for heating synchronous machines with powers that exceed up to 10 times the installed power of the test stands. In this way, the informative results of the synthetic methods known in the literature are eliminated. The method was used in factories in Romania and introduced in the Standard of the International Electrotechnical Commission.*

Key words: *synchronous machines, recovery operation, static stability, experimental tests, excitation currents.*

1. INTRODUCTION

Operating in parallel to the network of two mechanically coupled synchronous machines, with an electrical gap α of the rotors, has a theoretical and practical interest especially in terms of high powers.

Since the literature [1]-[5] does not provide any information, besides a brief reference [6], further on there is detailed the behaviour of the machines system in steady state.

The main feature refers to the possibility of modifying, in large and controlled limits, the active and reactive powers, by simply variation of the excitation currents.

This generally enlarges the possibilities of some factory experimental tests. From the active powers point of view, the operation is recoverable, the power taken from the network is reduced to the total losses.

The electric angle α is essential in establishing the loads of the two machines.

2. OPERATION EQUATIONS

There are established analytical expressions and phasor diagrams, which enable the quantitative control of this particular operation case.

The positive direction for the currents $\underline{I}_{i(i=1,2)}$ of the mechanically coupled machines and the terminals voltage $\underline{U}$ are according to the source.

Let it be θ the internal angle of the machine 1 supposed to be the generator; it results that (α-θ) is the internal angle of the machine 2, which is the motor in this recoverable operation.

For a α and a certain voltage $\underline{U}$, the currents $\underline{I}_i$, the network current $\underline{I}_r$, the electromagnetic powers P_{Mi} and the internal angles, are functions depending exclusively on the machines excitations.

Operating in parallel is defined by the following system of compact equations.

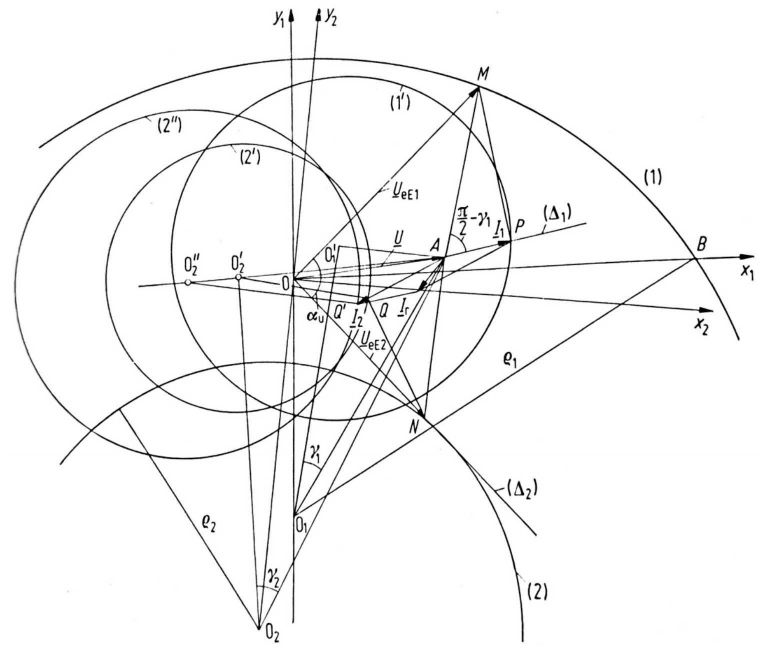

Fig. 1. Geometrical locus curves for two coupled synchronous machines at P_{M1}=const., α=const

$$
\begin{aligned}
&\underline{I}_i=\underline{I}_i\,(U_{eE1},\,U_{eE2})\\
&\underline{I}_r=\Sigma\underline{I}_i=\underline{I}_r(U_{eE1},\,U_{eE2})\\
&P_{Mi}=P_{Mi}\,(\,U_{eE1},\,U_{eE2})\\
&\theta=\theta\,(U_{eE1},U_{eE2})
\end{aligned}
\qquad (1)
$$

To (1) the relation between the electromagnetic powers is added $P_{M2}=-(P_{M1}+\sum p_{mec})$.

The notations used further on are the ones widely used in the literature; $\sum p_{mec}$ - sum of the mechanical loses in the system of the coupled machines.

It is difficult to solve analytically the system of equations (1) in the general case of the salient pole machines and by considering all the losses [7].

For this reason, in the first instance, the magnetic asymmetry will be neglected.

2.1 Considering sunken poles machines 1, 2

Further on, at the beginning, the magnetic asymmetry is not considered.

When all the losses are considered, the current of the machine 1 supposed to be the generator and $\underline{U}$=U, has the form.

$$\underline{I}_1=j\frac{U}{Z_{s1}}e^{j\gamma_1}-j\frac{U_{eE_1}}{Z_{s1}}e^{j(\theta+\gamma_1-\beta_1)} \qquad (2)$$

where

$\underline{Z}_{s1}=\underline{Z}_1+\underline{Z}_{m1}=jZ_{s1}e^{-j\gamma_1}$ - synchronous impedance,

$\underline{Z}_1=R_1+jX_1$ -leakage impedance and

$\underline{Z}_{m1}=R_{m1}+jX_{m1}=jZ_{m1}e^{-j\beta_1}$ - magnetization impedance.

According to [7]

$$\underline{Z}_{m1}=R_{m1}+jX_{m1}=jZ_{m1}e^{-j\beta_1}$$

$$R_{m1}=\frac{m}{2}K^{//}\omega^2L_{11m1}\qquad X_{m1}=\frac{m}{2}K^{/}\omega L_{11m1}$$

where

R_{m1},X_{m1} are the resistance and the magnetization reactance corresponding to the iron losses; L_{11m1}- the main own inductance (in alternating field) of a phase.

In the case of neglecting iron losses

$$R_{m1}=K''=0\,,K^{'}=1$$

(remember that in the presence of iron losses, K' is slightly subunit, and therefore the magnetization reactance is also affected). According to (1), the current I_1 is also a function of U_{eE2}, through the presence of the internal angle θ in the equation.

Analog, for machine 2

$$\underline{I}_2 = j\frac{U}{Z_{s2}} e^{j\gamma_2} - j\frac{U_{eE_2}}{Z_{s2}} e^{j(\theta-\alpha+\gamma_2-\beta_2)} \qquad (3)$$

and the network current

$$\underline{I}_r = \underline{I}_1 + \underline{I}_2 \qquad (4)$$

The following relation is obtained for the electromagnetic power P_{M1}

$$P_{M1} = \frac{mUU_{eE1}}{Z_{s1}} \sin(\theta - \gamma_1 + \beta_1) + mA_1 U_{eE1}^2 \qquad (5)$$

Analogue for machine 2

$$P_{M2} = \frac{-mUU_{eE2}}{X_{d2}} \sin(\alpha - \theta + \gamma_2 - \beta_2) + mA_2 U_{eE2}^2 \qquad (6)$$

The quantities in (3), (6), of the same form as for machine 1, are obtained by replacing indices 1 with 2.

So,

$$A_{i(i=1,2)} = \frac{R_i Z_{mi}^2 + R_{mi} Z_i^2}{Z_{mi}^2 Z_{si}^2}$$

To the equations (2)-(6) is added the necessary connection between the electromagnetic powers P_{Mi} of the form

$$P_{M2} = -(P_{M1} + \Sigma p_{mec}) \qquad (7)$$

The assembly of the equations (2)-(7) define by all the aspects, the synchronism operation of the machines 1, 2 system, connected to a common network, for different combinations U_{eEi} and α.

Fig. 1 shows the phasor diagrams for the considered machines at P_{M1}=const., α=const.

2.1.1 Analysis of the static stability

The equation (7) is considered; by computation it is obtained [7]

$$P_M = A_m \sin(\alpha - \theta - \beta)$$

$$A_m = mU\sqrt{\left(\frac{U_{eE1}}{Z_{s1}}\right)^2 + 2\left(\frac{U_{eE1}}{Z_{s1}}\right)\left(\frac{U_{eE2}}{Z_{s2}}\right)\cos\alpha_0 + \left(\frac{U_{eE2}}{Z_{s2}}\right)^2} = m\frac{UU_{eE}}{Z_s}$$

$$C = mA_1 U_{eE1}^2 + mA_2 U_{eE2}^2 + \Sigma P_{mec} \qquad (8)$$

$\alpha_0=\alpha_0$(α, losses in windings and iron)

$$\beta = \beta_0 - \gamma_2 + \beta_2$$

$\beta_0 = \beta_0(\alpha, U_{eE1}, U_{eE2}, Z_{s1}, Z_{s2})$

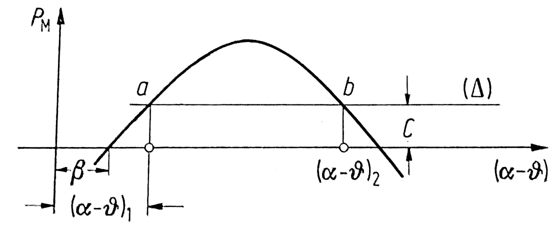

Fig. 2. The equivalent characteristic $P_M(\alpha-\theta)$

Plotting the equations (8) in Fig. 2 leads to the conclusion that the system of the two machines behaves, relatively to the network, as a single equivalent synchronous motor with the characteristic $P_M(\alpha-\theta)$, characterized by the polar e.m.f. U_{eE} and the synchronous impedance Z_s. From Fig. 2 there result two possible values $(\alpha-\theta)_1$, $(\alpha-\theta)_2$. From static stability reasons, only the solution $(\alpha-\theta)_1$ is valid.

All the quantities introduced in (8) are conditioned by the losses. These influence especially the value of C which represents the mechanical power at the shaft of the equivalent machine.

Since C is a power corresponding to the losses, in general $A_m >> C$. The equivalent synchronous machine appears practically unloaded and consequently it is characterized by a high static stability.

2.2 Considering salient pole machines 1, 2

In order to avoid phasor diagrams and equations in the two axes, much more complicated than those of the form (2)-(7), losses are neglected in the following.

This is acceptable especially for high power machines with high yields, most interested in the practical possibility of various experimental tests.

The phasor diagrams of machines 1, 2 are represented together in Fig. 3 for a terminal voltage U. The electric angle α between the lines was considered O_1A_1 and O_2A_2.

In the hypotheses introduced, the active components of the currents I_1 and I_2 are equal and of opposite signs. When changing the excitation currents, the variation limits of the induced currents and of the powers can be determined in a direct graphical way.

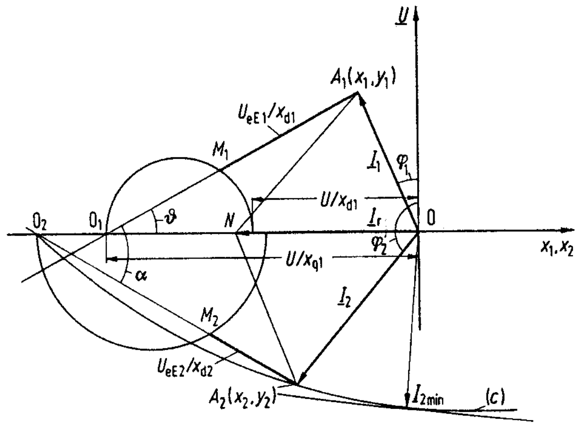

Fig. 3. Phasor diagram for synchronous machines with salient poles

For example, it is considered U_{eE1}=const., α=const., U_{eE2} variable. In this case, the point A_1 (the peak of $\underline{I}_1$) describes, in the complex plane, Pascal's snail; its place A_2 (the peak of $\underline{I}_2$) [curve (c)] is obtained point by point respecting the angle α and the equality of the active components of the currents $\underline{I}_1$, $\underline{I}_2$.

We observe that when moving the points A_1 and A_2 on the geometrically established location curves, the loads of the two machines change within wide limits.

The variations of the currents $\underline{I}_2$ and $\underline{I}_r$ are obtained directly graphically.

The shape characteristic $I_2 = f(U_{eE2})$ of a V-curve is obtained by comparing the segments A_2M_2~U_{eE2} and $OA_2 = I_2$.

The characteristic $I_r = f(U_{eE2})$ also takes the shape of a V-curve when comparing segments A_2M_2~U_{eE2} and $ON = I_r$.

For a given load for one of the machines, according to Fig. 3, the load of the other machine and the network can be established; changing it changes these loads.

2.2.1 Analysis of the static stability

For salient pole machines there is obtained an equivalent characteristic $P_M = P_M^{/} + P_M^{//}$ in which

$$P_M^{/} = A_m \sin(\alpha - \vartheta - \beta); \quad P_M^{//} = rU \sin[2(\alpha - \vartheta) - \varphi] \tag{9}$$

considers, as above, $P_M^{/}$ the contribution of the excited sunken pole machine, $P_M^{//}$ the contribution of the magnetic asymmetry and of the mechanical gap.

The values A_m, β are given by (8) in simplified form.

The characteristics I, II, III represent the curves $P_M(\alpha\text{-}\theta)$ for U_{eE1}=0 and three values U_{eE2}.

It results in several solutions for (α-θ).

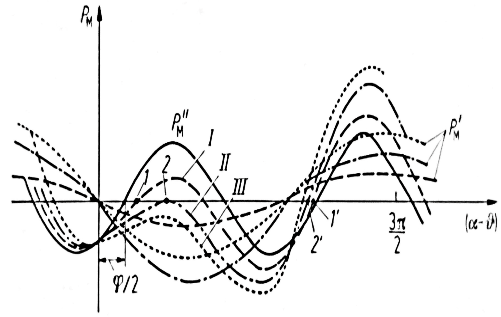

Fig. 4. The equivalent characteristics P_M(α-θ)

From the static stability condition for the equivalent machine, only the solutions $(\alpha\text{-}\theta)_i$ will be retained, for which $\left(\frac{dP_M}{d(\alpha-\vartheta)}\right)_{(\alpha-\theta)_i} > 0$.

In reality, the angles $(\alpha\text{-}\theta)_i$ which were evaluated as stable, are slightly different from the real ones, considering the losses and the fact that the torque is not zero on the shaft of the equivalent machine.

As in the case of machines with salient poles, the representations in Fig. 4 shows a large reserve of static stability for the system of machines 1, 2.

3. METHOD FOR DIRECT RECOVERY CHARGING AT NOMINAL LOAD OF A SYNCHRONOUS MACHINE

In [8] the need to create electric machines ensuring high efficiency, is emphasided.

The performances with rated load of a synchronous machine are conclusively confirmed only by the experimental test.

In case of middle and highpower synchronous machines, complicated methods become compulsory, with series of machines rated at important powers, ensuring electrical energy recovery in the network [9] a.o.

This option can become insurmountable on the industrial testing stands of which rated power does not generally exceed 1000-2000 kW.

The present method [9]-[11] overcomes these difficulties.

For the proposed test, there is used the system of machines 1, 2, rated practically at the same power, connected to the voltage network $\underline{U}$ (Fig. 5). Let us consider 2, the over-excited synchronous motor with the given values $I_2, \cos\varphi_2$ (particularly the rated ones). From the phasor diagram, there result more possible values for α and accordingly, different stator currents of the machine 1 and of the network.

The oscillating range of α depends on the admissible values I_1, I_r (so, for $\alpha=\alpha'$, in the simplified analysis considered, there result $\underline{I}_1'=\underline{I}_1=-\underline{I}_2$ and $\underline{I}_r=0$). The range narrows if a low power network is wanted (a low I_r).

It results that the machines 1, 2 must not necessarily be coupled with a rigorously established α.

Considering the losses in the analyzed system, $\underline{I}_r\neq 0$, even if the reactive power exchanged with the network becomes null (the machines 1, 2 ensure the magnetization powers).

The convenient electrical angle $\alpha=\alpha_1$, for the system of the machines 1, 2 and the network, is established graphically and analytically, by using the equations system (1).

The possible values for α_i, in case of a mechanical coupling with n bolts, are given by the relation (10).

$$\alpha_i = p\left(\alpha_{g0} + K_i\frac{2\pi}{n}\right) \pm \frac{2\pi}{3} \qquad (10)$$

where α_{g0} is the mechanical gap of the rotors axes.

The α_i closes to the value α_1 is chosen.

If a rated load long-duration test is intended for establishing the heating, for example of the machine 2 considered here, the convenient value α_1 corresponds to a minimum network current.

On this basis, the complicated solutions are removed [7]. There is also removed the limit solution accepted, of some synthetic tests, by using no-load or short-circuit operation, in which the high power synchronous machine heating is caused by an effects overlapping, a result only having an informative value.

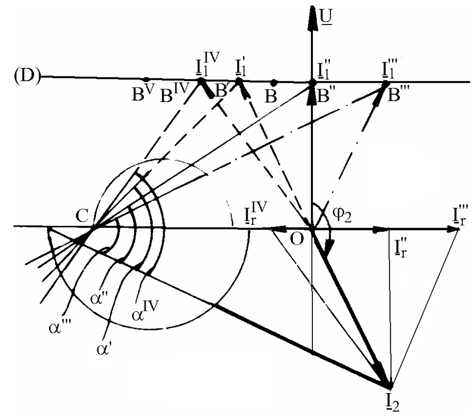

Fig. 5. Phase diagram for P_2=const., $\cos\varphi_2$=const., α=var

4. EXPERIMENTAL TESTS

4.1 Validation of theoretical considerations from 2.2.

Machines 1, 2 are two identical 150 kVA synchronous machines.

For a systematic study, different values were considered for I_{E1}=const., α=const.

In Fig. 6, the curves $P_1(I_{E2})$, $P_2(I_{E2})$ were represented, in Fig. 7 curves $I_2(I_{E2})$, $\cos\varphi_2$ (I_{E2}) and in Fig. 8 $I_r(I_{E2})$ curves.

The observations based on Fig. 3 are experimentally confirmed (it was taken into account that U_{eE1}~I_{E1}, U_{eE2}~I_{E2}).

4.2 Validation of the original recuperative test method

The testing machine was a synchronous motor rated at 630 kVA. The auxiliary machine was an identical one. As a network, there was considered a group of synchronous machines rated at 150 kVA.

The electrical angle α_1 was established analytically and graphically, taking into account and neglected losses.

The value $\alpha_1'=73^o$ was determined in the condition $I_{rr}=0$ and considering losses; the value $\alpha_1''=76^o$ was determined considering $I_r=0$; the angle $\alpha_i=69^o$ was the closet available according to [10], in which $n=8$, $\alpha_0=p\alpha_{g0}=39^o$.

Table 1

Experimental and calculate results (630 kVA)

		Electric angle α_1',α_1''	I_1 (A)	I_r (A)	Electric angle α_i=69°				
					I_1 (A)	I_{E1} (A)	I_{E2} (A)	I_r (A)	P_r (kVA)
Analitical method	Simpl.	76°	60,8	0	55,6	-	-	15	156
	Exact.	73°	54,9	6,5	51,5	122,5	224	10,25	106,5
Grafical method	Simpl.	76°	60,8	0	56,0	-	-	15,5	161
	Exact.	73°	55,0	7,0	51,5	124,1	224,5	10,5	109
Experimental results		U=6000V, I_2=60,8A, $\eta = 0{,}935$, P_n=630kVA (530 kW), $\cos\varphi_2 = 0{,}9$, p=3, α_i =69°			53,1	130,2	229,4	9,7	101 (P_{ra}=66 kW)

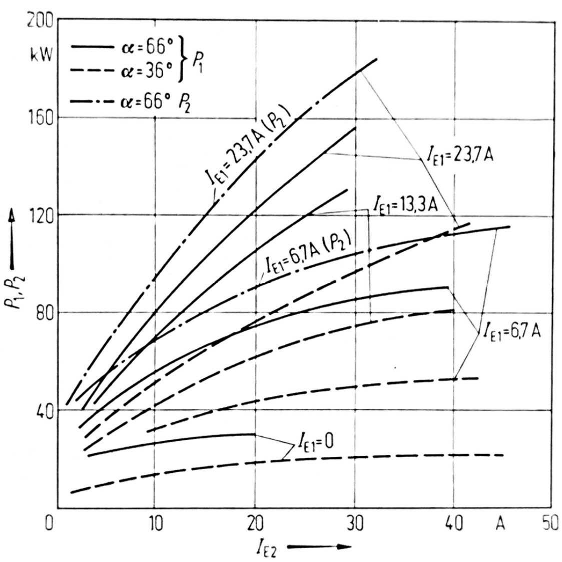

Fig. 6. Curves $P_1(I_{E2})$, $P_2(I_{E1})$ for I_{E1}=const., α=const

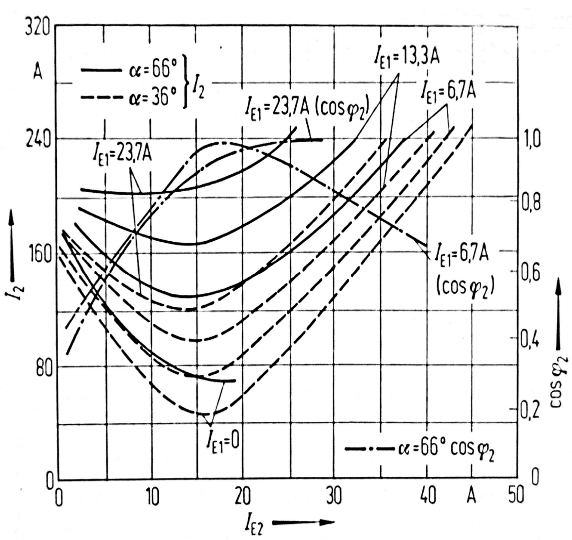

Fig. 7. Curves $I_2(I_{E2})$, $\cos\varphi_2(I_{E2})$ for I_{E1}=const., α=const

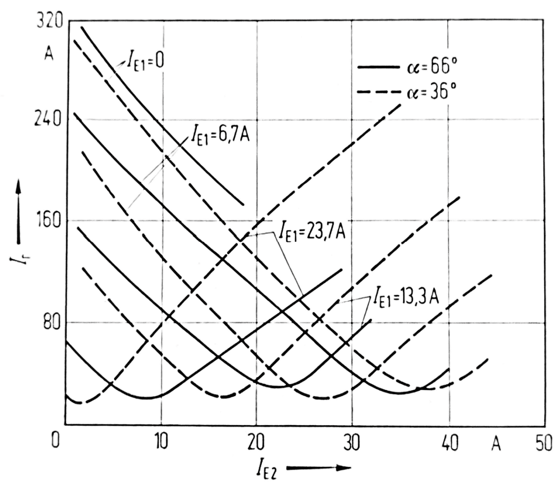

Fig. 8. Curves $I_r(I_{E2})$ for I_{E1}=const., α=const

It is noticed that:

-determining the loads for each machine and the main in different circumstances, especially in the case of considering the magnetic asymmetry it is complicated analytically and much simpler with the use of the graphic method;

-the value α_1' that takes into account the losses, must be retained;

-anticipated, an important ratio P_{2n}/P_r=630/101=6.23 is observed;

-this power ratio can be increased up to around 10, through a series of measures that do not involve practical difficulties (the use of couplings with a higher number of bolts).

5. CONCLUSIONS

This paper aims at a unitary analysis and synthesis of the physical processes from the system of two synchronous machines mechanically coupled and connected to the same network, investigated for the first time in the literature.

There result the following conclusions:

-in this case and only in this case, adjusting the excitation currents modifies in large and controlled limits the active and reactive powers;

-the machines system can be represented by a single synchronous machine, practically in no-load operation, characterized by an important reserve of static stability, independent on the electric angle between the rotors;

-the active powers are practically mutually compensated, so the active power required from the network corresponds to the total losses.

On this support, there is established a recuperative method, economic, for loading at rated parameters a machine from the system of machines. The mechanical gap of the rotors is essential in mentioning the reactive powers corresponding to the two machines and to the network.

This must be established so that the reactive power required from the network to be minimum (when the reactive powers from the synchronous machines system is mutually compensated).

This way, the electrical stresses from the auxiliary machine and from the network become minim. It results possible the industrial testing, without specific equipments, in direct rated load, of a middle or high power synchronous machine, compulsory in the international standards, for verifying the rated *parameters* and for mentioning the heating imposed by the insulation class of the machine.

The proposed testing method removes the evoked disadvantages of the series of high power machines, for recovering the energy in the network or of the synthetic insignificant tests.

Without special actions of establishing the possible mechanical gap according to (10), it is appreciated that it is possible to test experimentally synchronous machines rated up to ten times the rated power of the industrial testing stands.

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O funcționare particulara a mașinii sincrone și implicațiile ei tehnice

O condiție obligatorie pentru introducerea in procesul de fabricație serie a unei mașini sincrone, este încercarea de lunga durata la încălzire la parametrii nominali. Pentru mașini de puteri mijlocii si mari sunt depășite în general puterile instalate ale standurilor de proba. În lucrare se studiază funcționarea în paralel la rețea a doua mașini sincrone cuplate mecanic rigid. Particularitatea esențială consta in faptul ca prin simpla variație a curenților de excitație, se modifica in limite largi si controlate puterile active si reactive. Sistemul mașinilor funcționează stabil si recuperativ deci absoarbe de la rețea o putere redusa cat suma pierderilor. Rezulta o noua metoda concludenta de încercare uzinala la încălzire a mașinilor sincrone de puteri ce depășesc pana la de zece ori puterea instalata a standurilor de proba. Sunt eliminate astfel rezultatele informative ale metodelor sintetice cunoscute in literatura. Metoda a fost valorificata in uzinele din Romania si introdusa in Standardul Comisiei Electrotehnice Internaționale.

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