ASYNCHRONOUS RUNNING OF TURBO-ALTERNATORS*

By

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I. Introduction

During normal synchronous running of alternators it sometimes happens for purely electrical reasons (breakdowns, short circuit, etc.) the exciter becomes defective and consequently the alternator remains without excitation. Opinion is divided regarding the steps to be taken, both in the technical literature and in practice. There is no doubt that hydro-alternators should be disconnected from the network on account of their insufficient asynchronous torque. Certain authors are of the same opinion in regard to asynchronous running of turbo-alternators and they base their opinion on the fact that if the alternator works during asynchronous running in the neighbourhood of the nominal load, there will occur in the rotor — even where the slip only exceeds that which are generally accepted for asynchronous motors by a few percent — losses which can reach a number of times the nominal excitation power. In certain cases even it has been proposed to use a special protective device which in the case of loss of excitation would disconnect the alternator immediately from the network.

On the other hand, other authors (see for instance [1]) are of opinion on the basis of numerous tests carried out that asynchronous running of turbo-alternators with massive rotors is permissible. In effect it emerged from these tests that the value of the slip associated with the nominal torque is of the order of one-tenth of 1% and that consequently the losses in the rotor did not reach the losses of nominal excitation.

Asynchronous running of the turbo-alternator does not therefore involve any danger for the machine itself. It remains to be seen whether this regime is permissible or not from the point of view of the network. In effect, as soon as the excitation ceases, the alternator which up to that moment fed the network with reactive power, absorbs it and even in large quantities, which exceeds half of the apparent nominal output. However, in co-operative networks, where the majority of the alternators are provided with an automatic

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voltage regulator, the additional reactive power can generally be supplied without difficulty and without excessive overheating of the alternators. Generally the voltage drop does not itself reach values which would compromise the service.

II. The object of the test on Hungarian turbo-alternators during asynchronous running

The test of the turbo-alternators under asynchronous running is of considerable importance both from the theoretical and from the practical point of view. From the theoretical point of view it makes a contribution to the knowledge of certain transient characteristics of turbo-alternators with massive rotors (asynchronous torque, damping torque, etc.). In practice if the results of these tests give rise to favourable conclusions, it means that in the case of a breakdown to the exciter from electrical causes, the set can continue to run as an asynchronous generator and supply the network with a considerable amount of active power. Such possibilities increase the continuity of service and reduce the number of service outages. By running the turbo-alternator under an asynchronous regime, even for a relatively short time, one facilitates the changeover to stand-by excitation or where this does not exist, the distribution of the load over other alternators.

Asynchronous running therefore appears beneficial from the point of view of continuity of service and does not involve any danger for the turbo-alternators. It is only the necessity to satisfy the increased demand for reactive power which raises a problem of lesser importance.

A great deal of data on the behaviour of turbo-alternators under asynchronous running has appeared in different technical articles [1], [2]. But the results that can be found there do not apply directly to the turbo-alternators of Hungarian manufacture, because the design of the rotor differs essentially from those of other machines. Whereas in countries other than Hungary machines have been built with radial slots (Fig. 1), the old type of Hungarian turbo-alternator is built with slots of the so-called parallel type (Fig. 2) and those of more recent manufacture have been made with parallel slots and with a cross lap winding (Fig. 3). Furthermore, the section of the rotor is slightly elliptical. Consequently to know the behaviour during asynchronous running of the Hungarian type of turbo-alternators it was necessary to make direct measurements on this type of machine. On the basis of the results of our measurements the authors are in a position to reply to the following questions :

1. What is the asynchronous torque—slip characteristic curve of the Hungarian made turbo-alternators, that is to say, what are the values of slip corresponding to different loads on these alternators?

2. What rotor loss must be provided for during asynchronous running?

3. What is the limiting load that the turbo-alternators of different types can support? Is the load limited by the rotor losses or by the stator current?

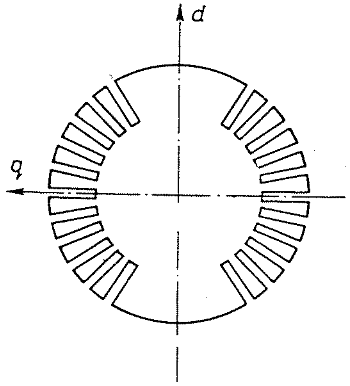


Fig. 1. Cross-section of rotor with radial slots

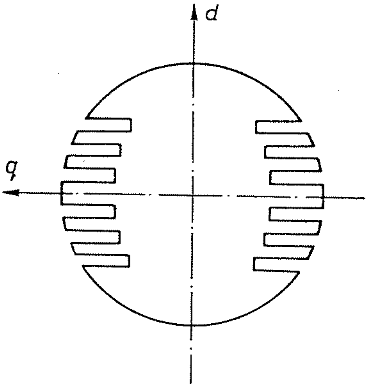


Fig. 2. Cross-section of rotor with parallel slots

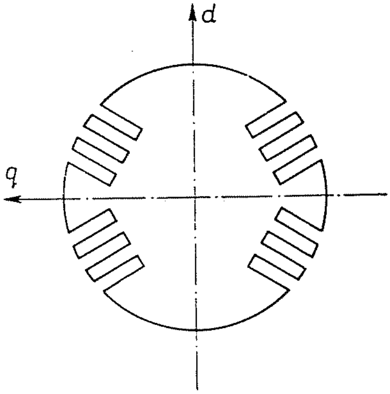


Fig. 3. Cross-section of rotor with parallel slots and with cross lap winding

4. On account of the difference in design of the rotor in the direct axis *d* and in the quadrature axis *q*, what will be the values of the fluctuations of stator current?

5. In view of the increased demand for reactive power and the possible voltage drops, is asynchronous running possible in the case of a given power station?

III. Turbo-alternator tests during asynchronous running

The measurements carried out in order to clarify the behaviour of turbo-alternators under asynchronous running have been carried out, on the one hand, with an alternator whose rotor was directly short circuited and, on the other hand, on this alternator with the rotor closed over a de-excitation resistance.

During synchronous running of the turbo-alternator a given load was adjusted by means of the turbine regulator. The automatic voltage regulator was taken out of circuit. The instruments were read and an oscillograph was run at a low speed. Without influencing the turbine regulator or the hand wheel of the excitation regulator rheostat the "open" button of the de-excitation circuit breaker was pressed (and when it was desired to take measurements on the alternator directly short circuited the short circuiting contactor especially provided was also operated). The de-excited alternator continued to run asynchronously. By carefully following the oscillations of the stator current and, respectively, the rotor current, a few cycles of slip were allowed. Then the short circuit was removed from the rotor and the closure button pressed on the de-excitation circuit breaker. The alternator then being excited pulled into synchronism. The instruments were read again and the oscillographs stopped.

During the test, the voltage and the current in the rotor, the voltage and the current in the stator, as well as the apparent, active and reactive powers were measured by means of the switchboard instruments and by laboratory instruments and with a bifilar oscillograph.

The mean value of the slip can be calculated by the following expression :

$$sf_0 : f_0 = \frac{1}{T} : \frac{1}{T_0},$$

where :

s, the slip ;
f_0, the frequency of the network ;
T_0, the duration of a network cycle ;
T, total duration of the oscillation of the rotor current.

If it is wished to calculate the slip in per cent, then taking into account the equality of $f_0 = 50$ cycles, therefore $T_0 = 0.02$ s, we have

$$s\,\% = \frac{2}{T\,(\mathrm{s})}.$$

IV. Main technical data of the turbo-alternators investigated

The turbo-alternators investigated during the series of measurements carried out up to the present, were of three different types. Their main technical characteristics are :

Set No. 1 Alternator: of an old type, 44 MVA, 10.6 kV, star connected, 2400 A, three-phase, 50 cycles, 3000 r. p. m., $(\cos \varphi)_n = 0.7$. Rotor with parallel slots and with steel slot wedges. Rotor resistance : 0.069 Ω. Synchronous reactance in the direct axis of the alternator : $x_d = 1.9$ relative units.

Exciter : 140 V, 1200 A, 3000 r. p. m.

Auxiliary exciter : 140 V, 11 A, 3000 r. p. m.

De-excitation resistance : 0.64 Ω (1000 A) and 110 Ω (1 A).

Set No. 2 Alternator : of a new type, 26.5 MVA, 10.5 kV, star connected, 1460 A, three-phase, 50 cycles, 3000 r. p. m., $(\cos \varphi)_n = 0.75$. Rotor with parallel slots with cross lap winding and bronze slot wedges. Rotor resistance : 0.0817 Ω. Synchronous reactance in the direct axis of the alternator $x_d = 2.2$ relative units.

Exciter : 140 V, 1000 A, 3000 r. p. m.

Auxiliary exciter : 165 V, 5 A, 3000 r. p. m.

De-excitation resistance : 0.3 Ω (600 A) and 30 Ω (3 A).

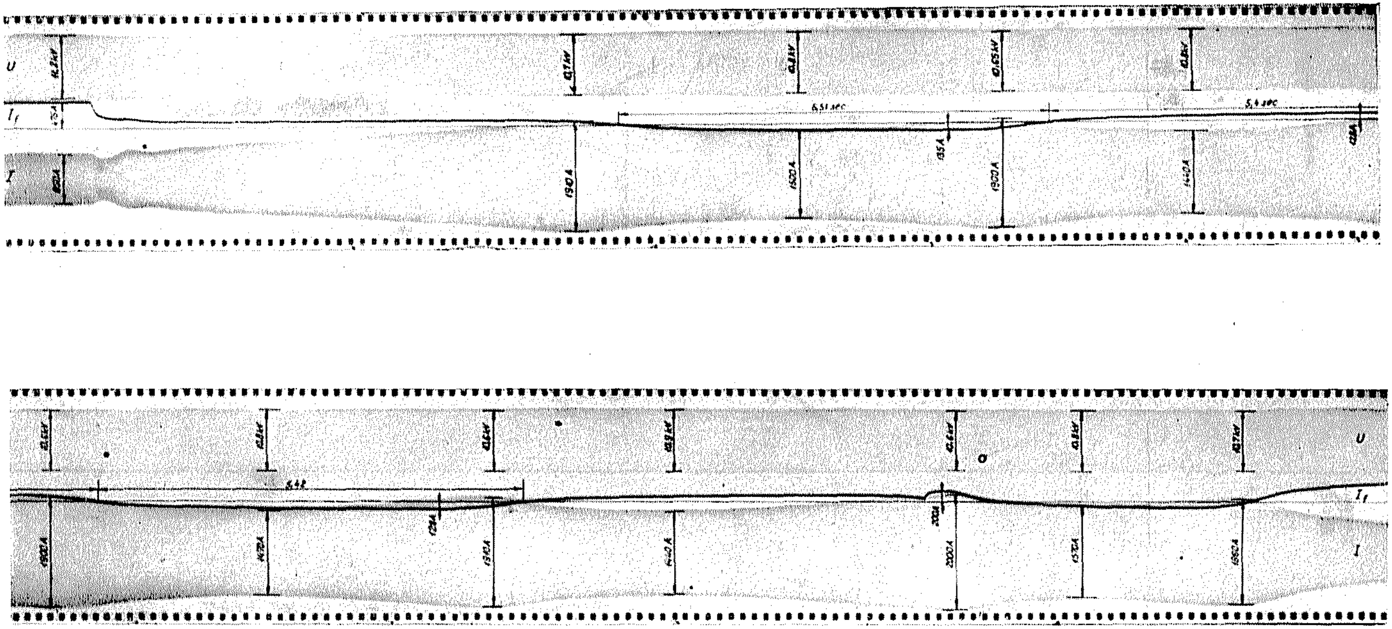
Set No. 3 : The characteristics were similar to those of Set No. 2 except that the rotor wedges were of steel.

V. Measurement results

The development during asynchronous running of some of the characteristic values is given for instance by oscillogram in Fig. 4. The stator voltage is represented by the upper curve, the rotor current by the middle curve and the stator current by the lower curve. The oscillogram refers to Set No. 2, the load was $P = 15$ MW. During the measurements the rotor was closed over a de-excitation resistance.

The main results of the measurements are given in Tables I, II and III. (It should be observed that where the loads are very small turbo-alternator No. 1 did not go over to asynchronous running but operated as a reluctance alternator.) The values in the tables are the figures rounded off to the nearest figure above. The data given on a same line do not with the exception of the average values, represent connex values; on the contrary, they represent the extreme values obtained during the course of the test at different moments.

The power output, during asynchronous running, by the three turbo-alternators is shown as a function of the average slip in Fig. 5. The curves



Figs. 4a and *4b*. Oscillogram of the asynchronous running of turbo-alternator No. 2. The rotor being closed over a de-excitation resistance. Load $P = 15$ MW

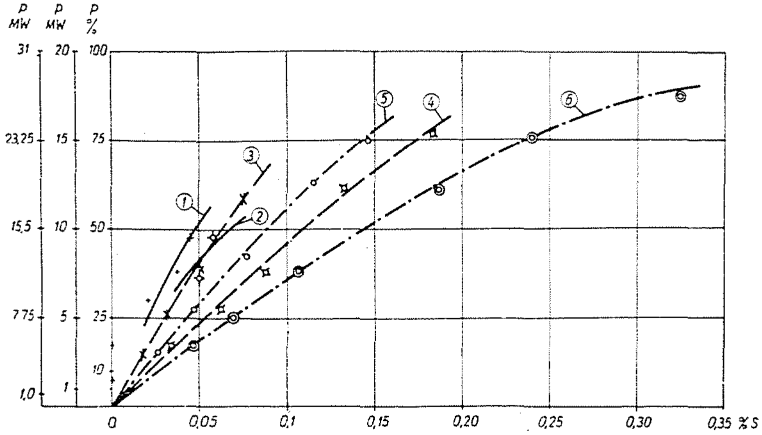


Fig. 5. Characteristic curves of asynchronous torque—slip (or output—slip)

can be identified by means of the data in Tables I, II and III. Because of the very small values of slip, the characteristic curves torque—slip represent at the same time the power—slip curves.

VI. Conclusions

On the basis of the results of the series of measurements that the authors have just given, they can now reply to the questions laid down in paragraph II by the following conclusions.

1. The torque—slip characteristic curve of the Hungarian made turbo-alternators has a very steep rate, that is to say, that the average slip does not reach even in cases of full load more than a few tenths of one per cent.

2. The rotor losses during asynchronous running are of no interest on account of the very small slip ; these losses represent but a fraction of the excitation losses which occur during synchronous running of the turbo-alternator.

3. The limiting output of the alternators is determined by the stator current and not by the slip. If the average current in the stator does not appreciably exceed its nominal current, machine No. 1 can be loaded up to half and machines No. 2 and 3 to three-quarters of their nominal active load.

4. Because the design of the rotor is different in the direction of the direct axis *d* and the quadrature axis *q*, fluctuations in the stator current and in the reactive power and the voltage at the terminals do occur.
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Table I

No. 1. Turbo-alternator: 44 MVA, 10.6 kV, 2400 A, $(\cos\varphi)_n = 0.7$, 3000 r. p. m. Rotor with steel wedges

P (MW)	Q (MVAr)	U (kV)	I (kA)	I_f (A)	P_m (MW)	$Q_{\max} - Q_{\min}$ (MVAr)	$U_{\max} - U_{\min}$ (kV)	$I_{\max} - I_{\min}$ (kA)	$I_{f\max}$ (A)	T (s)	s_m (%)	No. of the curve in Fig. 5.
Synchronous running					Reluctance running							
2.6	4.3	10.2	0.3	390	~ 2.6	21	9.7—9.5	1.3	—	—	0.00	—
5.3	6.8	10.3	0.5	462	~ 5.3	24	9.6—9.4	1.4	—	—	0.00	—
Synchronous running					Asynchronous running. Rotor short-circuited							
9.3	7.5	10.3	0.67	450	~ 9.3	31.5—26.0	9.7—9.1	2.1—1.6	143	90.0	0.0222	1
12.0	11.5	10.4	0.92	526	~ 12	36.7—27.8	9.5—9.1	2.5—1.85	190	55.2	0.0362	
15.0	11.0	10.4	1.03	529	~ 15	39.0—30.0	9.4—9.0	2.7—2.0	241	43.2	0.0463	
Synchronous running					Asynchronous running. Rotor closed over de-excitation resistance							
12.0	11.5	10.4	0.92	526	~ 12	32.0—25.0	9.3—9.0	2.2—1.75	66	40.0	0.0500	2
15.0	11.0	10.4	1.03	529	15—14.5	35.0—27.6	9.5—9.2	2.4—1.9	75	34.0	0.0590	

Table II

No. 2. Turbo-alternator: 26.5 MVA, 10.5 kV, 1460 A, $(\cos\varphi)_n = 0.75$, 3000 r. p. m. Rotor with bronze wedges

P (MW)	Q (MVAr)	U (kV)	I (kA)	I_f (A)	P_m (MW)	$Q_{\max}$ — $Q_{\min}$ (MVAr)	$U_{\max}$ — $U_{\min}$ (kV)	$I_{\max}$ — $I_{\min}$ (kA)	$I_{f\max}$ (A)	T (s)	s_m (%)	No. of the curve in Fig. 5.
Synchronous running					Asynchronous running. Rotor short-circuited							
3.0	4.0	11.1	0.27	360	~ 3.0	19.7—15.7	11.1—10.9	1.08—0.86	72	106.0	0.0189	3
5.1	3.3	11.2	0.35	360	~ 5.1	22.8—16.5	11.1—10.9	1.25—0.91	101	63.6	0.0314	
8.1	3.6	11.2	0.50	400	~ 8.1	27.6—17.4	11.0—10.8	1.56—1.04	170	39.6	0.0505	
12.0	6.9	11.2	0.72	465	~ 12.4	32.0—18.6	11.1—10.7	1.85—1.17	230	26.8	0.0746	
Synchronous running					Asynchronous running. Rotor closed over de-excitation resistance							
3.0	4.0	11.1	0.27	360	~ 3.1	19.4—16.0	11.1—10.9	1.05—0.89	29	70.0	0.0286	4
5.4	3.4	11.1	0.36	360	~ 5.4	21.8—17.2	10.9—10.8	1.20—0.99	54	33.8	0.0590	
8.4	3.6	11.2	0.51	380	~ 7.8	25.2—18.9	10.9—10.8	1.42—1.08	78	22.2	0.0900	
12.3	6.3	11.2	0.72	465	~ 11.8	28.8—21.0	11.0—10.7	1.67—1.28	101	15.6	0.1280	
15.3	4.7	11.2	0.85	475	~ 15.3	32.4—22.8	10.9—10.6	1.91—1.44	130	10.8	0.1850	

Table III

No. 3. Turbo-alternator: 26.5 MVA, 10.5 kV, 1460 A, $(\cos\varphi)_n = 0.75$, 3000 r. p. m. Rotor with steel wedges

P (MW)	Q (MVAr)	U (kV)	I (kA)	I_f (A)	P_m (MW)	$Q_{\max} - Q_{\min}$ (MVAr)	$U_{\max} - U_{\min}$ (kV)	$I_{\max} - I_{\min}$ (kA)	$I_{f\max}$ (A)	T (s)	s_m (%)	No. of the curve in Fig. 5.
Synchronous running					Asynchronous running. Rotor short-circuited							
3.0	2.4	11.1	0.24	330	~ 3.0	18.0—15.0	10.7—10.6	1.10—0.83	72	86.6	0.0231	5
5.6	1.8	11.1	0.33	320	~ 5.3	21.2—15.4	10.7—10.5	1.20—0.90	110	47.4	0.042	
9.0	1.1	11.1	0.48	340	~ 8.7	26.7—16.9	10.7—10.4	1.60—1.09	180	26.4	0.076	
12.3	4.8	11.2	0.68	430	13.5—11.5	31.2—18.8	10.6—10.3	1.90—1.23	240	18.0	0.111	
15.0	5.3	11.2	0.84	480	15.6—13.2	36.0—20.4	10.5—10.3	2.14—1.36	280	13.6	0.147	
Synchronous running					Asynchronous running. Rotor closed over de-excitation resistance							
3.3	0.6	11.1	0.24	290	~ 3.0	17.1—15.0	10.9—10.8	0.98—0.85	35	48.8	0.041	6
5.6	1.0	11.1	0.33	310	~ 5.0	19.5—16.2	10.9—10.7	1.18—1.00	50	29.2	0.068	
8.8	1.5	11.1	0.46	340	~ 8.2	22.4—17.7	10.7—10.5	1.32—1.08	70	18.0	0.111	
12.2	3.4	11.1	0.66	410	14—11.5	27.3—20.4	10.4—10.2	1.65—1.30	120	10.9	0.183	
15.1	5.3	11.2	0.84	470	16—13.5	30.6—22.2	10.6—10.3	1.89—1.50	140	8.24	0.243	
17.4	3.2	11.1	0.93	470	19—14.5	35.0—24.9	10.5—10.2	2.08—1.62	170	6.16	0.325	

Data regarding the fluctuations of current and of the reactive power with respect to their average value can be found in Table IV for short-circuited rotors, as well for rotors closed over his de-excitation resistance.

Table IV

Fluctuation of current and of reactive power

	$\frac{I_{\max}-I_{\min}}{I_{\max}+I_{\min}}$. Machine		
	1.	2.	3.
Rotor short-circuited (%)	±15	±22.5	±22.5
Rotor closed over de-excitation resistance (%)	±12	±13.5	±14.5

	$\frac{Q_{\max}-Q_{\min}}{Q_{\max}+Q_{\min}}$. Machine		
	1.	2.	3.
Rotor short-circuited (%)	±13	±26.5	±27.7
Rotor closed over de-excitation resistance (%)	±12	±15.5	±16

5. In the case where the rotor is closed over the de-excitation resistance, it is not only the stator current that is of lower value but also the rotor current, the voltage drop, the reactive power, the current fluctuations and the fluctuations of the reactive power and the voltage are also lower. However, the average slip increases but even in this case it is relatively small.

Asynchronous running is therefore more advantageous in practice with de-excitation resistance and in this case the active output can also be slightly higher than where the rotor is short circuited.

With an open-circuited rotor the conditions would be even more favourable although the slip would increase by a somewhat more considerable amount. However, asynchronous running with the rotor open is not to be advised on account of the possible transient phenomena which could cause harmful surges in the rotor winding and because the torque of the machine would decrease.

6. The voltage drops in the power stations investigated appear to be of acceptable value and do not have too much effect on the service.

7. From what has been stated above it can be concluded that asynchronous running is permissible in the cases investigated, not only from the point of view of the alternator but also from the point of view of the network (on the assumption that the load is less than the values specified under 3, or that it can be rapidly lowered below such values). In practice asynchronous running appears to be preferable by introducing the de-excitation resistance.

8. On the basis of published data [1], [2] and the results given by the authors, one can hope that asynchronous running can be introduced for

turbo-alternators of European manufacture (having a synchronous reactance of about 200%), but it would appear expedient to have these machines examined in the first place as explained in this paper.

9. For American made turbo-alternators (where one meets very small synchronous reactances, for instance of 100%), it is not possible to introduce asynchronous running because the reactive current alone reaches the nominal current and also the machine cannot be loaded with any active power without dangerous overheating of the machine.

10. In accordance with the above, the introduction of asynchronous running in the case of excitation breakdown can be recommended for European made turbo-alternators. The change over to asynchronous running can be carried out very simply, in particular by introducing a de-excitation resistance. The introduction of asynchronous running increases the continuity of service because by this means one can avoid or at least decrease the lack of active power, previously supplied by the turbo-alternator in question which should have been put out of service otherwise. Naturally asynchronous running requires the supply by the network of a quantity of reactive power exceeding that previously supplied by the machine during its synchronous running.

APPENDIX

Calculation of the torque—slip characteristic curves of turbo-alternators under asynchronous running

It is useful to check the results of measurement by also determining the asynchronous torque by means of calculation. (The method of calculation used to determine the asynchronous torque, assuming constant slip, can be found in several works [1], [5], [6], [7].)

For the purposes of calculation it is necessary to know the characteristic constants of the machine. Let us assume that they are known from the measurements carried out previously (for instance, the measurements of de-excitation). The characteristic constants of turbo-alternators vary with the saturation. In the calculation of asynchronous running one must substitute the values for an unsaturated state. Neglecting the value of the resistance of the stator, the asynchronous torque of a synchronous machine with a perfectly symmetrical rotor (which in practice does not exist because the presence of the excitation winding always causes differences in the directions *d* and *q*) can be calculated, as for an ordinary asynchronous motor, by means of the formula :

$$m = \frac{u^2}{(\cos\varphi)_n}\left(\frac{1}{x'} - \frac{1}{x}\right)\frac{s\,T'}{1 + (s\,T')^2}\,. \tag{1}$$

In this formula :

m, the relative torque (or the asynchronous power with respect to the nominal active power) ; for asynchronous running of the alternator of a negative value ;
u, the voltage at the terminals (in relative units) ;
x, the synchronous reactance (in relative units) ;
x', the transient reactance (in relative units) ;
T', the short-circuit transient time constant (in radians) ;
s, the slip (in relative units and not in percentage) ; for asynchronous running of the alternator of a negative value ;
$(\cos \varphi)_n$, the nominal power factor.

The reason why the power factor enters into the formula is that the calculation of reactances is made from the apparent output (MVA) and not from the active output (MW), whereas the torque (the output) is calculated with respect to the active torque (output).

In calculating the asynchronous torque of a synchronous machine with an asymmetrical rotor, the formula (1) can only give very approximate values. For a given slip, the value of the torque obtained by formula (1) exceeds the real value of it.

To determine the asynchronous torque—slip characteristic curve of a turbo-alternator with an asymmetrical rotor instead of using formula (1), one can use the following formula :

$$m = m_d' + m_d'' + m_q''. \tag{2}$$

In this formula :

$$m_d' = \frac{u^2}{2(\cos\varphi)_n}\left(\frac{1}{x_d'} - \frac{1}{x_d}\right)\frac{sT_d'}{1+(sT_d')^2}, \tag{2 a}$$

$$m_d'' = \frac{u^2}{2(\cos\varphi)_n}\left(\frac{1}{x_d''} - \frac{1}{x_d'}\right)\frac{sT_d''}{1+(sT_d'')^2}, \tag{2 b}$$

$$m_q'' = \frac{u^2}{2(\cos\varphi)_n}\left(\frac{1}{x_q''} - \frac{1}{x_q}\right)\frac{sT_q''}{1+(sT_q'')^2}, \tag{2 c}$$

where :

x_d, x_d', x_d'', the synchronous, transient and sub-transient reactances in the direct axis ;
x_q, x_q'', the synchronous and sub-transient reactances in the quadrature axis (all the reactances in relative units) ;
T_d', T_d'', the transient and sub-transient short-circuit time constants in the direct axis ;
T_q'', the sub-transient short-circuit time constant in the quadrature axis (all time constants are in radians).

It should be emphasized that by formula (1) the total torque is obtained for a constant slip whereas on the contrary formula (2) only gives the mean torque by assuming a constant slip. On account of the asymmetry of the rotor, there is in addition to the average torque, a pulsating torque of frequency $2\,s\,f_0$, that is to say, at a frequency double that of the slip. The integral of this pulsating torque for a half cycle of slip is equal to zero.

Formulae (1) and (2) cited above refer to turbo-alternators with short circuited rotors. In the case of an alternator with a rotor closed over a de-excitation resistance, the time constants T' and T_d' should be reduced by a suitable proportion, determined by the value of the de-excitation resistance.

It should be mentioned that in certain works [1] there is also another method of calculation which takes into account the variation of the parameters of the machine with the slip. However, if the slip is small, the difference between the results found from the two methods of calculation is negligible.

If, on the assumption of a constant slip it is desired to calculate the total relative torque, the following formula [3], [4], [5] appears to be the most appropriate :

$$m = \frac{u^2}{(\cos\varphi)_n}\,\mathrm{Re}\left[\frac{\overline{Y}_d + \overline{Y}_q}{2} - \frac{\hat{Y}_d - \hat{Y}_q}{2}\,e^{-j2st}\right], \tag{3}$$

where :

$\hat{Y}_d$ and $\hat{Y}_q$ are the conjugates of $\overline{Y}_d$ and $\overline{Y}_q$ and

$$\overline{Y}_q = \frac{1}{jx_q(js)} = \frac{1}{jx_q}\,\frac{js\,T''_{q0} + 1}{js\,T''_q + 1}, \tag{4}$$

$$\overline{Y}_d = \frac{1}{jx_d(js)} = \frac{1}{jx_d}\,\frac{js\,T''_{d0} + 1}{js\,T''_d + 1}\,\frac{js\,T'_{d0} + 1}{js\,T'_d + 1}. \tag{5}$$

Here T'_{d0}, T''_{d0} and T''_{q0} represent the time constants corresponding to no load. The latter formula was published by ADKINS [8] and applied to other problems [5] and [9].

In the formula (3) the component of the mean torque is represented by the first expression between the brackets and the component of the pulsating torque by the second expression. By substituting the expressions (4) and (5) in the relationship (3), one obtains precisely from the first expression the relationship (2).

A really clear and instructive picture of the variation of the torque of a machine with an asymmetrical rotor can be found [3] starting from the formula (3). To this effect, let us trace the geometrical locus of the extremity of the current vector :

$$\bar{i} = u \left[\frac{\overline{Y}_d - \overline{Y}_q}{2} - \frac{\hat{Y}_d - \hat{Y}_q}{2} e^{-j2st} \right], \tag{6}$$

expressed in a system of synchronously rotating co-ordinates. The result of this construction is represented in Fig. 6. Because the component of the torque m''_d in the formula (2) is of a relatively weak value, the time constants

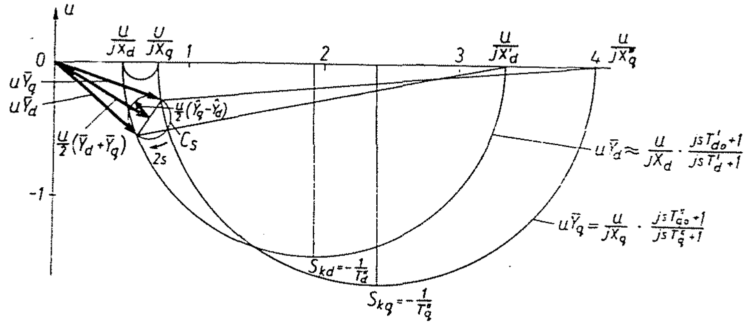

Fig. 6. Circle diagram of stator current

T''_d and T''_{d0} have been neglected in the expression (5). Thus with the variation of the slip s not only $u\overline{Y}_q$, but also $u\overline{Y}_d$ will describe a circle. If the beat slips s_{kd} and s_{kq} are known, one can determine on the two circles the terminal points of the vectorial value $u\overline{Y}_d$ and $u\overline{Y}_q$, associated with slip s supposed to be constant. It follows from the expression (4) that the extremity of the current vector $\bar{i}$ describes a circle C_s of which the centre and the radius can be expressed respectively by :

$$\frac{u}{2}(\overline{Y}_d + \overline{Y}_q) \quad \text{and} \quad \frac{u}{2}(\hat{Y}_q - Y_d).$$

The terminal point of the vectorial magnitude $\bar{i}$ of the current runs round the circle C_s with an angular speed of $2s$ (because $\omega_0 = 1$). The active output, and with a very good approximation the torque also, are proportional to the vertical sections measured from the abscissae.

As can be seen in Fig. 7, when the slip s is of a constant value, the active output P (as well as the reactive power Q and the stator current I) are not constant, but vary between certain maximum and minimum values.

During a complete cycle of slip these values each reach their extreme value twice.

If the slip is small, the regulator valve of the turbine (having an insensitivity coefficient of $\pm 0.1\%$) does not pick up the change of speed. Therefore, in practice it is not the slip, but the output of the turbine (or respectively its torque) which remains constant. On account of the smallness of the value and the slowness of the changes in speed, the effect of inertia being negligible, in the case of asynchronous running of turbo-alternators it will in practice be the active output P (or respectively the torque) which will be constant, whereas the slip will be subject to a variation [4].

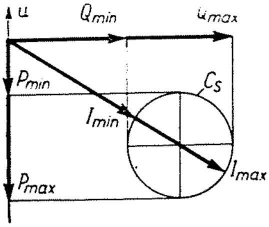

Fig. 7. Maximum and minimum of active output of the reactive power and of the stator current

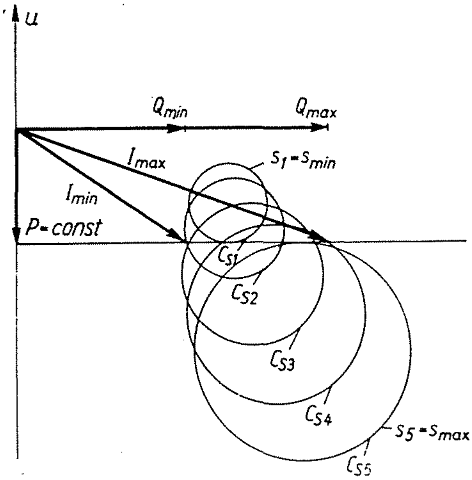

Fig. 8. Determination of the current and of the slip if the active output P = const.

It follows that the extremity of the current vector will not describe a circle but instead a straight line $P =$ const. (Fig. 8). The extremity of the current vector is determined by the point of intersection of this straight line and the circles constructed for different slips s. Consequently, although the active output P (and the torque) are constant, the reactive power Q, the current I and the slip s will vary between certain maxima and minima values.

It should be noted that in the case of variable slip, the formulae (3) and (4) are modified with particular reference to the factor e^{-j2st} should be replaced by $e^{j2\delta}$, where :

$$\frac{\mathrm{d}\delta}{\mathrm{d}t} = -s, \quad \text{respectively} \quad \delta = -\int_0^t s\,\mathrm{d}t. \tag{7}$$

If the slip is small, it becomes possible to calculate it as a function of time. Then expressions (4) and (5) can be written in the form

$$\left\{ \begin{aligned} \overline{Y}_d &= s\,k_d(s) - j\,b_d(s), \\ \overline{Y}_q &= s\,k_q(s) - j\,b_q(s), \end{aligned} \right. \tag{8}$$

where if s is small, one can consider k_d, k_q, b_d and b_q as constant.

Then from the expression (3) we have :

$$m = \frac{u^2}{(\cos\varphi)_n}\left[\left(\frac{k_d + k_q}{2} - \frac{k_d - k_q}{2}\cos 2\delta\right) s + \frac{b_d - b_q}{2}\sin 2\delta\right]. \tag{9}$$

For turbo-alternators one can assume approximately that $b_d \approx b_q$ and if the torque $m = \text{const.}$, then :

$$s(\delta) = \frac{\dfrac{m\,(\cos\varphi)_n}{u^2}}{\dfrac{k_d + k_q}{2} - \dfrac{k_d - k_q}{2}\cos 2\delta}, \tag{10}$$

and taking (7) into account :

$$t(\delta) = -\int_0^\delta \frac{\mathrm{d}\delta}{s(\delta)} = -\frac{u^2}{m\,(\cos\varphi)_n}\left[\frac{k_d + k_q}{2}\delta - \frac{k_d - k_q}{2}\,\frac{\sin 2\delta}{2}\right]. \tag{11}$$

Lastly, it becomes also possible to determine $s(t)$ from the functions $s(\delta)$ and $t(\delta)$. The determination of the functions $s(t)$ for a given case is represented in Fig 9.

It was derived from the numerical values rounded off as follows : $k_q = 1000$, $k_d = 333$, $m = -0.4$, $(\cos\varphi)_n = 0.75$, $u = 1$.

In spite of the simplification made during the calculations and the use of rounded off values, calculation agrees pretty well with the data in Table II. (Graphical construction gave $T \approx 44$ s whereas the measured value of $T = 39.6$ s.) It can be seen from Fig. 9 that the maximum slip is about double the value of the average slip.

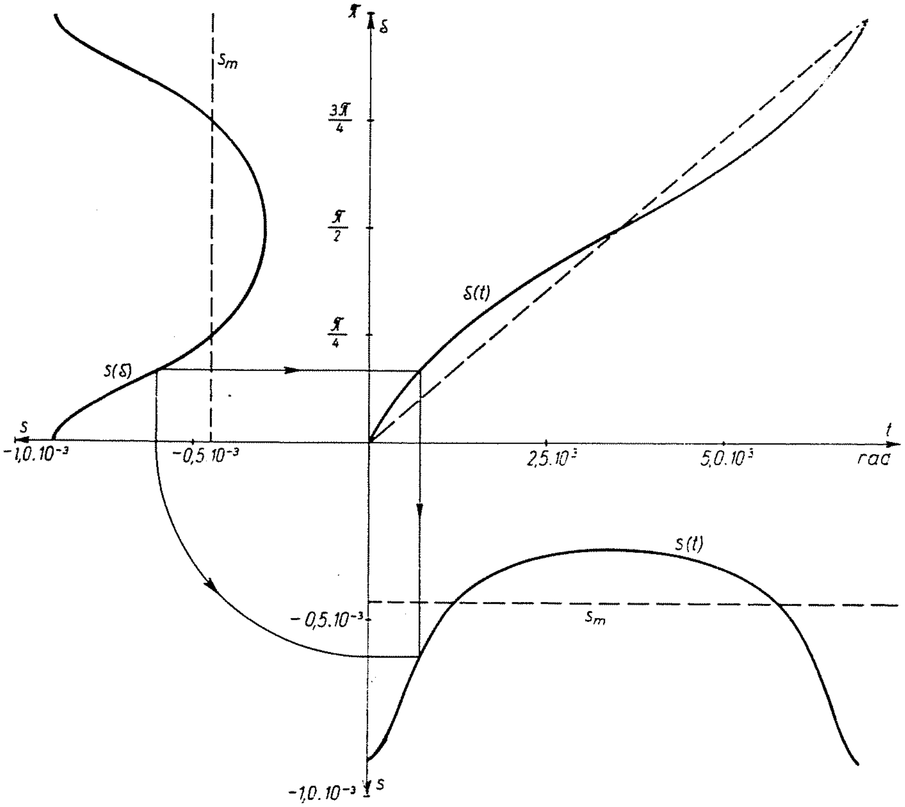

Fig. 9. Determination of the slip as a function of time

With the knowledge of the value of the functions $s(t)$ and $\delta\,(t)$ one can calculate the flow, as a function of time of the stator current as well as that of the reactive power and the rotor current.

If the assumption that $b_d = b_q$ cannot be accepted (Hungarian made turbo-alternators are most often of a type which do not permit this), but b_d, b_q can be regarded as constants, one obtains instead the expression (10) respectively (11) relations which are more complex (see [4]). It should be noted that in this case the shape of the change of slip will no longer be symmetrical.

If the functions k_d, k_q, b_d, b_q cannot be regarded as constants then, in order to determine the slip, the stator current, etc., one can use Fig. 8.

Finally, it should be emphasized that the validity of the calculations which have been exposed apply not only to Hungarian manufactured machines having rotors with parallel slots respectively with a cross lap winding, but to all turbo-alternators whatever be their type of rotor.

Summary

The present paper deals with asynchronous running of turbo-alternators, a problem which has considerable importance both from the theoretical and practical point of view. In effect the consideration of asynchronous running of turbo-alternators contributes on the one hand to the knowledge of certain transient characteristics of turbo-alternators with massive rotors, and, on the other hand, its practical introduction increases the continuity of service and reduces the number of outages.

The paper explains the object, the method and the results of measurements made on turbo-alternators of Hungarian make having a specially constructed rotor. The Appendix summaries the methods of calculation and formulae regarding asynchronous running.

In conclusion it can be stated that generally speaking asynchronous running is beneficial from the point of view of the continuity of service, that in most cases it does not involve any danger for turbo-alternators, the only disadvantage being the necessity of supplying a larger amount of reactive power.

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