REDUCTION OF PULSATIONS IN THE ASYNCHRONOUS OPERATION OF TURBOGENERATORS

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One of the most important problems of power system operations is that of service safety, assuring the continuity of the power supply. Important interests are tied up with the consumers energy-supply being undisturbed, so it is not surprising that the researchers all over the world dealing with the problems of energetics are trying to find and develop methods and possibilities permitting to hinder the service disturbances due to the machine outages caused by unexpected faults, that is, to quickly eliminate the disturbances which had already arisen. Within the scope of the respective research work several methods have been elaborated and successfully adopted in practice during the last fifteen years, that had been found too risky previously to apply from the machine, or network, or from point of view of both, as e.g. the different self synchronizing methods, or quick overexcitation. To these belongs the asynchronous operation of turbogenerators, the problem referred to in the title will be discussed in the present paper.

In connection with the asynchronous operation of turbogenerators several publications have appeared during the last few years. In the literature the works by SIROMYATNIKOV and CSÁKI are the most remarkable. SIROMYATNIKOV on the basis of extensive experiments proved the permissibility of the asynchronous operation, while CSÁKI elaborated a calculating method suitable for the precise study of the asynchronous operation. Based on publications the fundamental theoretical and practical problems of the turbogenerators asynchronous operation may be regarded as solved. As a result of the many experiments made on machines of different manufacture and capacity, it has been stated that the asynchronous torque-slip characteristics of the great majority of turbogenerators are in the initial section to be considered very steep from the asynchronous operational point of view; the slip is extremely small with respect to which the loss appearing in the rotor is only a fraction of the excitation loss permitted in the nominal synchronous operation. The load in asychronous operation is generally not limited by the heating of the rotor, but by that of the stator. The active power to be delivered continuously is important, being 50—70% of the rated active power in synchronous operation. It is true, that also the reactive power at the same time necessary in the asynchronous operation is quite great, generally somewhat higher than the reactive power delivered in the nominal synchronous operation; in most of the power stations, however, this might be covered. Consequently, as against the notion current previously, the asynchronous operation is in most cases permissible without having any deleterious effect on the machine, or the network. The possibility of the asynchronous operation permits the machine to remain connected to the network with an absence of excitation taking place at a field fault and to furnish as an asynchronous generator a high, active power, or if this should not be possible, even a relatively short asynchronous operation facilitates passing over to an emergency excitation, or the distribution of loading over the other generators. Thereby the number of service disturbances may be reduced, as well as an increase of the power supply service safety may be realized.

The scope of this paper is not to detail the problem in a theoretical, practical, or historical relation, therefore, regarding the details, reference is made to the literature at the end of the article and below the facts relating to the subject are described in short.

In the course of elucidating the turbogenerator's asynchronous operation conditions, the fact became known that due to the rotor asymmetry, in asynchronous operation a fluctuation ensues within a slip period in the time course of both the stator current and reactive power and of the slip, while the active power remains practically constant. The values mentioned are pulsating with a double slip-frequency. According to experiences, the measure of pulsations is very important especially in case of a short-circuited field coil: the deviation with respect to the mean value is 20—25% with respect to the stator current, and 25—30% in respect to the reactive power in case of heavier generator loads. The pulsation means no danger to the machine, it is, however, unfavourable from the system point of view, especially if we consider that at the same time, on account of the reason necessitating adoption of the asynchronous operation, the network may otherwise be in a critical state, too. Therefore, literature suggests an insertion into the field a de-excitation resistance belonging to the quick-excitation equipment, during asynchronous operation. The value of the de-excitation resistance is generally 5—10-times the field resistance. Inserting this resistance into the field, pulsations become more moderate: fluctuation in the stator current is reduced to 12—16%, that of the reactive power to 15—20%. This degree of the pulsations is as a rule supportable, but is still relatively great. From the viewpoint of pulsations some authors consider the open state of the field as the most favourable, this way of operation is not, however, suggested, as in case of the possible transients (e.g. short-circuits) overvoltages may arise in the open field, endangering its insulation. In the literature no more profound tests, or better suggestions for solving the pulsations problem can be met with. In view of the fact, how great attention is paid by the different authors, dealing with this subject, to the other problems relating to the asynchronous operation, settling the problem of fluctuations by using the de-excitation resistance may hardly be considered to be more than an involuntary acknowledgement of the pulsations fact.

Starting from these considerations, present paper set the aim to present methods easy to realize in the practice and suitable for the efficient reduction of the pulsations in asynchronous operation.

Possibilities of reducing the pulsations in asynchronous operation

As already mentioned, in asynchronous operation pulsation of the characteristic quantities is a consequence of the rotor asymmetry. The measure of pulsations depends on the degree of asymmetry. Asymmetry is caused by the field coil mounted on the rotor. For improving the rotor symmetry, only the possibility of intervening into the field is available in the practice. In the following the formation of the pulsations measure will be examined with different ways of field closing.

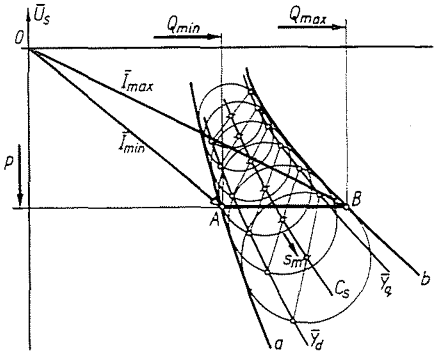

Fig. 1. Graphical determination of the characteristic quantities in the asynchronous operation of turbogenerators

In the examinations the graphical calculating method elaborated by Csáki will be adopted. The method may be found in detail in the literature [3—II, 8, 9, 10]. So, here, merely the particulars important for the subsequent understanding are summarized.

Determination of the characteristic quantities follows according to Fig. 1. As a starting point the direct- and quadrature-axis admittance diagram ($\bar{Y}_d$ and $\bar{Y}_q$) of the machine must be known, within the range of the small slips to be considered. The points of the admittance diagrams belonging to the same slip are connected by straight lines and circles and drawn to the straights, as to circle diameters. Marking the slip values belonging to the individual circles at the centres of the curve (C_s) connecting the circle centres, we make a slip scale. Finally the envelope curves (*a* and *b*) of the family of curves are plotted. In asynchronous operation the end point of the stator current vector, in case of a given $P = constant$ capacity, moves on the section falling between the envelope curves of the straight line parallel with the horizontal (imaginary) axis (Section $\overline{AB}$). Consequently, the extreme values of the stator current and of the reactive power ($I_{\min}$, $I_{\max}$ and $Q_{\min}$, $Q_{\max}$) may be read off at an arbitrary power in the way illustrated on the figure. At the intersection of the straight $\overline{AB}$ with curve C_s the value of the mean slip (s_m) belonging to the respective power may be read off, too.

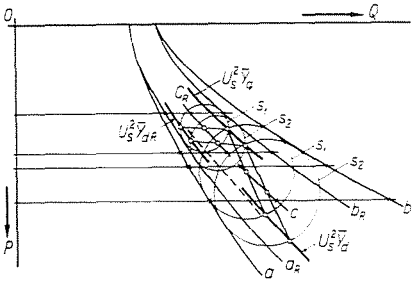

Fig. 2. Graphical determination of admittance diagrams from measurement data obtained in asynchronous operation

The admittance diagrams necessary for applying the above procedure may be determined by two sets of measurements in asynchronous operation. Accordingly, in asynchronous operation the maximum and minimum values of the reactive power are to be measured, at several different powers, as well as the value of the medium slip. The measurements are to be effected for two cases: once with a short-circuited field coil, thereafter by inserting a resistance *R* into the field. On the basis of the above values measured in the two cases, determination of the admittance diagrams follows as per Fig. 2: in the co-ordination system *P*—*Q* to the power values *P* having been determined in the course of the measurements, the maximum values $Q_{\min}$, $Q_{\max}$ of the relative power are plotted, for both cases of measurements. (As an example, some points denoted by x in the figure.) Connecting the points in this way illustrated by a full line, four curves (*a* and *b*, and a_R and b_R, respectively) are obtained. In compliance with the above clause, these are by pairs the envelope curves valid for the two cases. Fitting tangential circles also to the curves *a*—*b* and a_R—b_R, the loci *C* and C_R of the centre of the tangential set of curves may be fixed. On the basis of the slip values measured, a slipscale is made on the latter two curves. Thereafter, plotting a tangential circle for each of any arbitrary slip, the — generally right-side — point of intersection of the two circles provides the point of the quadrature-axis admittance, belonging to the respective slip. Plotting a diameter from this point in both circles, the farther end-points of the diameters give the point of the direct-axis diagrams belonging to the respective slip. When plotting is realized for many slip-values, the direct- and quadrature-axis admittance diagrams ($U_s^2\overline{Y}_d$ and $U_s^2\overline{Y}_q$) being valid for a short-circuited field coil, as well as the direct-axis diagram for the case of a field resistance R ($U_s^2\overline{Y}_{dR}$) are obtained, in the slip-range of asynchronous operation. For the sake of a better perspicuity, plotting is given in the figure for two — s_1 and s_2 — slips only.Based on the measurements, in knowledge of the admittance diagrams determined according to the foregoing, diagrams being valid for other, arbitrary field resistances may be plotted, too; a simple method serving this purpose is given in the Appendix.

The investigations of asynchronous operation to be discussed below were carried out for a turbogenerator with cross-coiled rotor of Hungarian (GANZ) manufacture. To determine the admittance diagrams needed, measurements were carried out on one of the turbogenerators of this type at the Borsod power station. Data of the machine are as follows:

Cross-coiled, steel-wedge rotor, 3000 rpm, type OG 930.3500/2,
44 MVA, 10.5 kV, 3 phase, 50 cycles, 2.42 kA, $\cos \varphi = 0.7$ capacitive.
Resistance of the field coil at 75° C 0.15 ohm.
De-excitation resistance 1.25 ohm, 800 A.

I wish to take the opportunity here to express my thanks to the Institute for Electrical Power Research (VILLENKI) and to the Borsod Thermal Power Station for organizing and realizing the measurements.

In the following, first of all the results obtained with a short-circuited field coil and in case of a field coil closed through a de-excitation resistance will be given. These two asynchronous ways of operation — having been till now in general use in the practice — will serve as a basis of comparison for judging the methods of operation to be discussed later. The numerical results are given in relative units referred to the machine nominal data. The relative power values refer to the rated *apparent* power.

1. Short-circuited field coil

This operational method may be regarded as the basic case of asynchronous operation. As the field coil is practically short-circuited through the exciter armature, the excitation falling out, the following case arises. In quadrature-axis, the short-circuited field coil is not effective at all, while in direct-axis it is considerably felt. Consequently, with this operational method we may count on small slips, but great pulsations.

For this case the results which interest us are available directly from the measurements data. The curves denoted by I of Figs. 3, 4 and 5 show the run of the characteristic values in function of the active power. In the figures P means the active power delivered, s_m the mean slip in the *time*, further

$$\varepsilon_I = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

the value characterizing the pulsation of the stator current and

$$\varepsilon_Q = \frac{Q_{\max} - Q_{\min}}{Q_{\max} + Q_{\min}}$$

that of the reactive power.

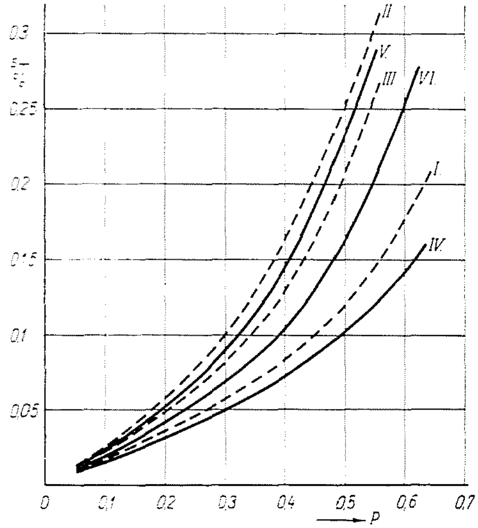

Fig. 3. Course of the average slip in function of the load, in the asynchronous operation of a 44 MVA, cross-coiled rotor turbogenerator, with different closings of the field
I — short-circuited field; II — field closed through de-excitation resistance; III — field closed through optimum resistance; IV — field short-circuited in two-phases; V — field closed in two phases through a de-excitation resistance; VI — field closed in two-phases through optimum resistance

At a sustained load permissible from the viewpoint of stator heating, the arithmetical mean of the stator current (I_m) may be about 10% higher than the rated value. Namely, the course of the current in time is characterized by a proportion of about 1 : 1.1 between the mean-square value and the arithmetical mean [3, 4, 11, 19]. The characteristic quantities, determined by the per unit current $I_m = 1.1$, meaning the limit of loading, are summarized in line I of Table 1.

On basis of the figures and table, respectively, the following may be stated. The power to be delivered in asynchronous operation is a round 70%

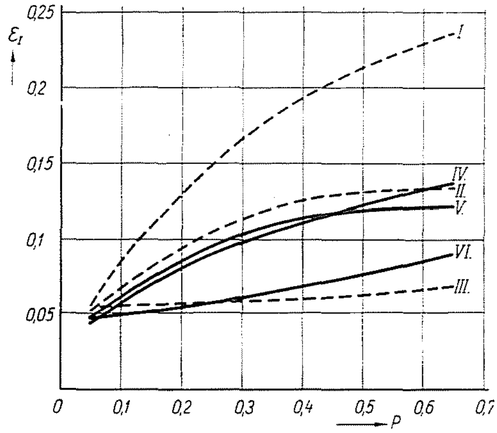

Fig. 4. Course of irregularity characteristic of the stator current fluctuation in function of the load, in the asynchronous operation of a 44 MVA, cross-coiled rotor turbogenerator, with different closings of the field

I — short-circuited field: II — field closed through de-excitation resistance; III — field closed through optimum resistance; IV — field short-circuited in two-phases; V — field closed in two-phases through de-excitation resistance; VI — field closed in two-phases through optimum resistance

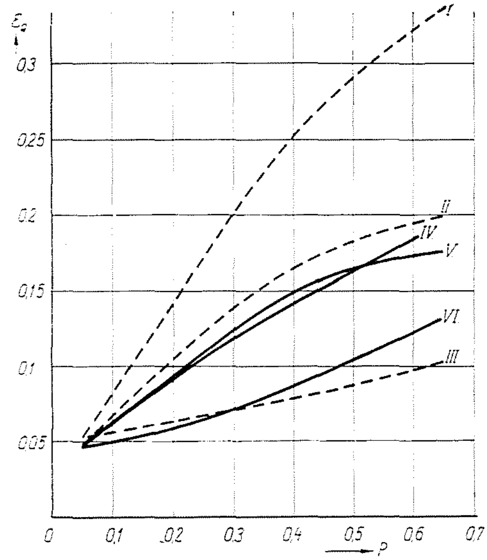

Fig. 5. Run of irregularity characteristic of the reactive power fluctuation in function of loading, in the asynchronous operation of a 44 MVA, cross-coiled rotor turbogenerator, with different closings of the field

I — short-circuited field; II — field closed through de-excitation resistance; III — field closed through optimum resistance; IV — field short-circuited in two-phases; V — field closed in two-phases through de-excitation resistance; VI — field closed in two-phases through optimum resistance as a maximum, of the rated active power of synchronous operation, consequently it is of importance. At the same time the average reactive power taken as (Q_m) is about 20% higher than the rated reactive power delivered in synchronous operation, accordingly, during asynchronous operation more than a two-fold outage of reactive power may be counted on. The average slip is very small, the section of the examined torque-slip characteristic is steep. At the limit of loading the average loss arising in the rotor is $0.00113 \cdot 0.487 \cdot 44 \cdot 10^3 \approx 24$ kW, this being only a fraction of the about 120 kW excitation loss permissible in normal asynchronous operation, so from the rotor heating point of view there is no cause for anxiety. It is, however, most unfavourable from the viewpoint of pulsations primarily of interest to us. The fluctuation of the stator current and of the reactive power exceeding 21% and 28%, respectively, is barely tolerable. Therefore, instead of this way of operation the following is suggested by literature for adoption in practice.

Table 1

$I_m = 1.1$ p. u.

Operation	P	Q_m	s_m (%)	ε_I	ε_Q
I.	0.487	0.85	0.113	0.213	0.285
II.	0.523	0.84	0.27	0.13	0.185
III.	0.535	0.84	0.242	0.063	0.09
IV.	0.505	0.855	0.103	0.122	0.163
V.	0.523	0.84	0.255	0.12	0.166
VI.	0.517	0.845	0.173	0.079	0.106

2. Field coil closed through a de-excitation resistance

The effect of the field coil resulting in rotor-asymmetry and so in pulsations may be moderated the most simply in an electrical way, inserting an ohmic resistance into the field. For this purpose adoption of the de-excitation resistance, available with all machines, seems to be practicable; the insertion of this may be realized through de-excitation automatics by simply pushing a button.

The de-excitation resistance of the machine tested is 8.34-times the field resistance. As for the service conditions appearing by inserting this relatively high resistance into the field, we have measurement data, too. The course of the quantities which interest us is illustrated by curves II of Figs. 3, 4 and 5, while the values appearing at the limit of loading are shown in line

II of Table 1. Comparing these data with those obtained by the short-circuited field coil, the following may be stated.

The power to be delivered is somewhat higher — while in the reactive power there is practically no variation. As was to be expected, the torque-slip had risen considerably. Thus, the average rotor loss is now 62 kW, this still being a tolerable small value, all the more, because about $^1/_5$th of this arises in the inserted, external resistance, so not heating the rotor. Formation of the pulsations degree is favourable; with respect to the case of the short-circuited field coil the fluctuations in both the current and the reactive power were reduced roundly to a $^2/_3$rds value. This pulsation level can be tolerated, though not satisfactory.

3. Field coil closed through a resistance of optimum value

In literature according to widespread opinion when further increasing the field resistance, the pulsations of asynchronous operation are further decreasing. This conception is based on the symmetry of the solid rotor body assumed to be quite good. According to this, in the limit case $R = R_{\mathrm{opt}} = \infty$, with an open field, from the viewpoint of pulsations, optimum conditions determined by the assumed symmetry of the solid rotor would be formed. As shown below, this idea is generally not acceptable.

In the case of the tested machine, it will be proved that by increasing the resistance value inserted into the field beyond the value of the de-excitation resistance, the rotor symmetry does not improve, on the contrary, it becomes worse. Further, it is demonstrated that the field resistance has at its fixed, finite value, being smaller than the de-excitation resistance, a practically excellent optimum from the pulsations point of view. This notion permits to find a simple way for reducing the pulsations of asynchronous operation to a minimum.

For demonstrating the afore-said, let us examine the run of the admittance diagrams shown in Fig. 2, keeping in view that the measure of rotor-asymmetry, together with that of the pulsation are determined by the difference of the direct- and quadrature-axis admittances. This circumstance is expressed in a graphical presentation by the length of the diameters of tangential circles. Inserting a resistance into the field merely changes the formation of the direct-axis diagram, this manifesting itself above all in the circumstance that the distribution of the points belonging to the individual slips gets changed along the curve, in a way the section of the admittance diagram referring to a given slip-range becomes contracted. (This is a consequence of increasing the rotor ohmic resistance, well-known, however, from the asynchronous motors theory.) So e.g. in Fig. 2 the point of the direct-axis diagram belonging to the slip s_1 wanders in the direction of the dotted arrow, when inserting a resistance R.

One can clearly recognize from the figure that increasing the field resistance starting out from the short-circuited condition, the diameter of the tangential circle belonging to a given slip is decreasing for a certain time, thereafter again increasing. Therefore, in the latter range the distance between the envelope curves, and consequently, the degree of pulsations, is growing. The situation is also the same in the case of turbogenerator tested by us. When examining the admittance diagrams determined on the basis of measurements it turned out, that inserting the de-excitation resistance (R_{DE}), we get to the range where the rotor asymmetry shows a rising tendency, when increasing the resistance. Consequently, it is evident that the field resistance of optimum value assuring the best symmetry must be looked for between the values $R = 0$ and $R = R_{DE}$. Determination of the optimum resistance value is based on the condition, that the distance measured between the points of the direct-axis admittance belonging to this and the points of the quadrature-axis diagram relative to the same slips — that is, the rotor asymmetry — should be the smallest. This state is regarded, from the pulsations point of view, as the most favourable one.

In regard the tested machine, the optimum resistance value was determined by the method described in the Appendix with the result $R_{\text{opt}} = 1.85$ R_r, in the range of greater loads. Consequently, in the case of the machine given, the practical minimum of the pulsations is realized, when 1.85-times the field-coil resistance is inserted into the field. Similarly to the method given in the Appendix, the direct-axis admittance diagram belonging to the above was also determined. Knowing the admittance diagrams, to determine the characteristic quantities, the graphic procedure as per Fig. 1 was adopted. The results obtained are shown in curves III of Figs. 3, 4 and 5, and by the data of line III of Table 1, respectively.

According to data obtained there is practically no difference in the powers with respect to the former case. The slip and thereby the average rotor loss is 10% smaller than when using a de-excitation resistance. The pulsations considerably decreased. As compared with the operation with de-excitation resistances, having universally been accepted in the practice up till now, the degree of pulsations was reduced to the half. The fluctuation in the current and reactive power of 6 and 9%, respectively, seems even continuously already to be tolerable. At the same time, the conditions are somewhat more favourable also from the rotor heating point of view than in case of a de-excitation resistance.

4. Two-phase short-circuited field coil

The method for reducing the pulsations described below has reached the aim set by reducing the effect of the field coil exerted in the rotor direct axis through an ohmic resistance inserted into the field, that is, by harmonizing this effect most favourably with the quadrature-axis conditions. The problem arises, if there is a possibility to influence the quadrature-axis conditions seemingly unchangeable and if so, what results may be achieved? One recognizes in the following, that with the machines with cross-coiled rotor of Hungarian manufacture, the effect of the field coil may be extended to a certain degree also in quadrature-axis, giving us a new possibility of reducing to a minimum the pulsations of asynchronous operation in case of these machines.

Location of the field coil on the cross-coiled rotor is shown schematically in the outline of Fig. 6. The whole field coil is divided into two equal half-coils, the heads of which are intercrossing at the frontal sides. The two half-coils fall to one third of the rotor periphery each, so that their magnetic axes include a 120° axis with each other, due to the geometrical layout. The picture would show a symmetrical, three-phase winding, if a third phase-coil, similar to the half-coil were not missing. Imagining this as being placed on the third part of the rotor not wound, we see a three-phase winding with a tapped neutral. Namely, the junction of the two half-coils is, because of manufacturing reasons, in metal connection with the rotor iron body. So this point is quite easy to access, permitting to short-circuit separately the two half-coils according to Fig. 7. Due to their geometrical layout, the short-circuited half-coils will also be effective in quadrature-axis, and thereby the rotor symmetry is increased.

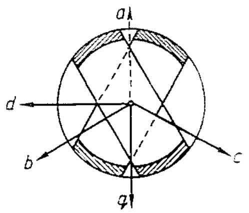

Fig. 6. Scheme of the field coil layout in a cross-coiled rotor

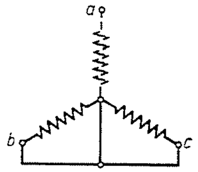

Fig. 7. Two-phase short-circuiting of the field coil in a cross-coiled rotor

The connection was tried out in the course of the measurements. The results that interest us are shown by the curves IV of Fig. 3, 4 and 5 and in line IV of Table 1. Based on these, it can be proved that from the pulsations point of view practically the same conditions are present, as in case of a field coil closed through a de-excitation resistance. There is an important difference, however, in the slip value as compared with the operation with de-excitation resistance, this being merely one third of the value to be found there. This means that the same degree of pulsations experienced with a de-excitation resistance may also be achieved by a two-phase short-circuiting, but in the latter case the thermal load is reduced to a third of its value. The connection tested proves to be advantageous first of all as regards the favourable formation of the rotor heating and that of the rate-of-rise of the torque-slip characteristic. The slip was reduced as compared with the normal short-circuiting, too.

For realizing the most favourable conditions from the viewpoint of the pulsations attainable by a two-phase connection, the necessity of inserting an ohmic resistance arises here, too.

5. Field coil closed in two phases through a de-excitation resistance

In case of the connection discussed, insertion of the ohmic resistance as per Fig. 8 is realized by connecting in series with the two half-coils one-one resistance of equal value. First let us see the case when the available de-excitation resistance with all machines is applied, making on it a mid-tap for this aim. Then $R = R_{DE}/2$.

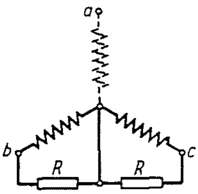

Fig. 8. Two-phase closing of the field coil through resistance, in a cross-coiled rotor

For the calculation of the admittance diagrams valid in the connection tested this was determined as $R = R_{DE}/2$. In knowledge of the diagrams the graphical calculating method shown in Fig. 1 has been employed, the results of which are given in curves V of Figs. 3, 4 and 5 and by line V of Table 1. The data prove that using the de-excitation resistance only that unfavourable result was arrived at that the slip was considerably increasing with respect to the former case; otherwise practically the same results have been obtained in all respects. Consequently, it is to be stated that adoption of the de-excitation resistance is not practicable in the scheme tested here, either.

6. Field coil closed in two phases through an optimum resistance

Testing the run of the admittance diagrams valid for the cases of two-phase connection, detailed in the foregoing, based on the train of thoughts it may also be demonstrated here that between the cases of short-circuiting the field coil and the closing through a de-excitation resistance, there must be an optimum position from the pulsations point of view. The result of the extreme-value calculation was actually that with $R = 1.035\ R_r$, where there is a minimum of rotor asymmetry in the range of small slips in asynchronous operation. Consequently, with the machine tested, in case of two-phase connection the most favourable conditions are realized, from the pulsations point of view by connecting in series with the half coils a resistance of a value approximately equalling the total field coil. With the optimum resistance values calculated, the admittance diagrams were determined, and afterwards the graphical calculating method was applied. The results are illustrated in curves VI of Figs. 3, 4 and 5, as well as in line VI of Table 1.

The data show that practically the same conditions appear, as in case of a field coil simply closed through an optimum resistance, with the difference that the slip is roundly a two-third part of that found in the former case. Accordingly, a minimum pulsation may be achieved in a two-phase connection by a considerably smaller heating of the rotor than in single-phase connection. It may again be stated that the two-phase connection is favourable from the rotor heating and the rate-of-rise of the torque-slip characteristic point of view.

Thus, the cross-coil type rotor of Hungarian manufacture has a favourable feature from the viewpoint of asynchronous operation, but for making use of this, provision must be made for a connection with the centre of the field coil. In view of the fact that this point is connected to the rotor iron body, junction may be realized by a brush assembly. The brush assembly needed is most simple, because, on the one hand, there are no insulation problems and, on the other hand, the current flowing through the brushes even in case of great loads is merely a third of the normal field current of synchronous operation, so it is relatively small. With the machine tested, a brush assembly was provisionally mounted between the field-side shield and the main exciter, having brushes bearing directly against the rotor axis. Nevertheless, from a practical point of view it must be admitted that whatever simple brush assembly could be considered, necessity of this would rise great difficulties as regards the connection discussed. Below it is demonstrated that a brush assembly becomes absolutely unnecessary, if the field coil is of a so-called "sandwich" arrangement.

For illustrating this, in Figs. 9 and 10 the two possible layouts of the field coil on a cross-coiled rotor have been schematically drawn. For the sake of simplicity, in the figures merely two slots were shown by half-coil sides. In case of the arrangement as per Fig. 9, the two half-coils are of opposite turn direction. The twins placed in the slots of each half-coil are connected parallelly by slots. The two half-coils consisting of parallelly connected slop coils are in series connected at the points which are in metal connection with the rotor iron body. The normal field current of synchronous operation establishes the direct-axis excitation with the current directions shown in picture *a* of the figure. Short-circuiting the field coil at the sliding rings, in case of asynchronous operation a direct-axis excitation may be formed, too. For establishing excitation also in quadrature-axis, the current directions shown in picture *b* of the figure must follow. As is well illustrated in the figure, this is possible only by making provision for a connection — marked in the figure by a dotted line — between the sliding rings and the rotor iron body in a way already mentioned before. The feature of this common coil arrangement, disadvantageous from the asynchronous operation point of view, is eliminated by the "sandwich" winding, shown schematically in Fig. 10. The sandwich arrangement means that the slots being wound in an opposite direction, alternately follow each other within both half-coils (hence the denomination). The slot-coils of identical turn directions are parallelly connected according to Fig. 10, while the two coils so formed become series connected at the points that are metal connected with the rotor iron body.

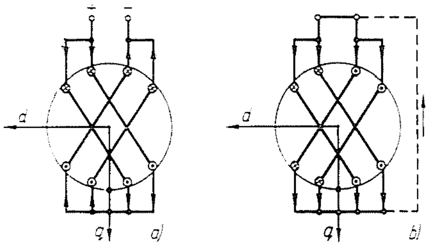

Fig. 9. Connection of the field coil on a cross-coiled rotor

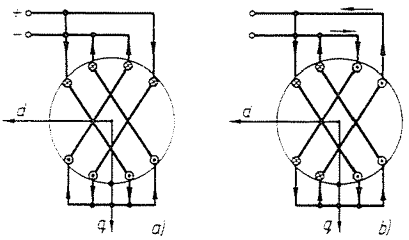

Fig. 10. Connection of the field coil on a cross-coiled rotor, in a sandwich arrangement

In part *a* of the figure the position corresponding to the normal synchronous operation is shown. On the basis of image *b* it becomes clear that with this winding arrangement a quadrature-axis excitation may be formed without establishing a conducting connection between the field coil terminals and the rotor iron body, moreover, without short-circuiting the field coil terminals. The sandwich winding assures in itself — through its internal tie — the quadrature-axis efficiency of the field coil. At the same time the ohmic resistance inserted between the sliding rings merely affects the direct-axis conditions, consequently — concluding from the course of the admittance diagrams — the value of the resistance being the most favourable from the pulsations point of view, and so the slip too, may be even smaller, than before. So after all, adoption of the above-mentioned auxiliary brush assembly is eliminated by the field coil sandwich arrangement, at the same time favourably influencing the slip appearing in the optimum case.

The sandwich arrangement is of common use only with the parallel-slot machines, type *OF* of the Ganz Factory. The original purpose of the sandwich arrangement was to assure the symmetry of the half-coils at the field coil body contact, otherwise the magnetic asymmetry may lead to the intense vibration of the rotor. The Fig. 11 shows the sandwich arrangement for 5 slots by half-coil sides. This is also the slot number with the examined turbogenerator type OG, 44 MVA. One recognizes from the figure that in this case the sandwich layout is not fully equivalent to the two-phase short-circuiting: the rotor impedance shows itself to be somewhat greater with respect to the latter case, but the deviation is not more than some per cents, so it may be neglected. If the field coil of the examined machine were of sandwich arrangement (the coil data being otherwise unchanged) then the most favourable conditions from the pulsations point of view could be realized — similarly to case III — by a single resistance, inserted between the sliding rings, the optimum value of which is, as per the Appendix, 0.475 R_r in this case. Then the slip would be 0.13% at the limit of loading, this being by about 25% smaller than in case VI and roundly by 50% smaller than in case III (Table 1). In the same proportion the loss power would decrease heating the rotor, too. At the same time no auxiliary brush assembly is needed. Accordingly, from the asynchronous operation point of view, the sandwich arrangement of the field coil may be recommended in all cases. As a consequence of the afore-said, a minimum of pulsations may be achieved in the same simple way, but with about half of the slip value and rotor heating, respectively, as compared with case III.

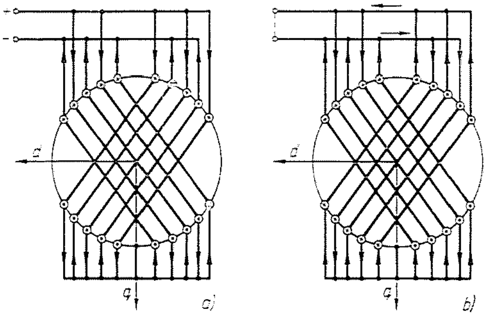

Fig. 11. Connection of a field coil with sandwich arrangement, with uneven slot numbers by half coil sides

7. Test of a 26.5 MVA machine

In the tests carried out in the foregoing those results are to be regarded as the most valuable that at a fixed, finite value of the ohmic resistance inserted into the field, optimum conditions follow from the asynchronous operation pulsations point of view. This contradicts the assumption that the most favourable conditions would appear in case of an open field. If the former, or latter case is valid for a certain machine, this evidently depends on the rotor construction, as the constructional layout influences the rotor asymmetry. The fact that from the pulsations point of view practically well tolerable asynchronous working conditions may be realized without maintaining the machine field in an open state, is absolutely advantageous from the machine point of view. Nevertheless, the individual machine types are not uniform as regards the rotor construction, moreover, some differences may occur even within a certain type. Consequently, the question arises, this being important from the viewpoint of the profitable application of the good results obtained in the foregoing, to what extent could these results be generalized and if the formation of this kind of the work conditions is not merely a casual, individual feature of the machine tested. This question can be answered only by comparing the results of the tests effected on other machines.

For this purpose assessable asynchronous operation measurement data are available in the literature for the 26.5 MVA machine of the cross-coil type OG 930.2200/2, with steel- and bronze-slot wedges. [L. 3-II, 6, 7]. The measurements were carried out with both machines for two cases, that is, with a short-circuited field and also a field closed through a de-excitation resistance, in the usual, single-phase connection. (The resistance of the field coil with both machines is 0.0817 ohm, while the de-excitation resistance is 0.3 ohm, 600 A.) On the basis of the measurement data, according to the method of Fig. 2, we have determined the admittance diagrams of the two machines for the measured cases. It could also be stated from these that the most advantageous conditions cannot be reached with an open field for these machines, either. Determining the optimum value of the field resistance by the method given in the Appendix, the value $R_{\text{opt}} = 1.24\ R_r$ was obtained with the machines of steel-wedge rotor, while $R_{\text{opt}} = 1.55\ R_r$ with that having a bronze-wedge rotor. Plotting the admittance diagrams belonging to the above-mentioned with the aid of the graphical procedure as in Fig. 1, we have determined the value of the characteristic quantities which are the most interesting at the limit of loading. The result is shown in the last line of Table 2. As a comparison, in the first two lines of the table also the values belonging to the case of short-circuited and through a de-excitation resistance closed field coil are indicated.

The data of the table for both the tested machines show the same picture, as obtained for the 44 MVA machine in the foregoing, under clauses 1—3. Though for the case of the two-phase connections no measurement data are available for the 26.5 MVA machines, the good accordance, presenting itself in the single-phase cases, as well as the theoretical considerations made in clauses 4—6 permit to conclude, that conditions similar to those obtained with the 44 MVA machine will ensue in the two-phase connection and with the sandwich arrangement of the field coil, respectively, in case of the 26.5 MVA machines, too. Consequently, it may be declared that our statements regarding the most favourable conditions from the pulsations point of view, as well as for the optimum values of the field resistance may be generalized for the Hungarian (GANZ), OG type turbogenerators with cross-coiled rotor.

Table 2

$I_m = 1.1$ p. u.

Field resistance	Steel-wedge		Bronze-wedge	
	rotor			
	s_m (%)	ε_Q	s_m (%)	ε_Q
$R = 0$	0.126	0.263	0.082	0.277
$R = R_{DE}$	0.2	0.15	0.146	0.166
$R = R_{\text{opt}}$	0.176	0.089	0.121	0.085

In addition to this, Table 2 shows that the slip of the machine with a bronze wedge is considerably smaller — roundly two-third part — of that of the machines with steel-wedge, due to the presence of the bronze rods. This permits to conclude that the bronze-slot wedges from the asynchronous operation point of view are more favourable than the steel-slot wedges.

Conclusions

In the foregoing the possibilities, easy to realize in the practice, of reducing pulsations due to the rotor asymmetry in the asynchronous operation of turbogenerators have been examined. The detailed test was carried out on an OG type, 44 MVA turbogenerator of GANZ manufacture, while our main statements were checked on a 26.5 MVA machine of the same type. On the basis of the results obtained — being valid for the OG type, cross-coiled rotor machines of Hungarian manufacture — the following statements may be made:

1. the active power to be delivered in asynchronous operation is 70—75% of that in rated synchronous operation,

2. the mean value of the reactive power obtained at the same time is roundly 120% of that delivered in rated synchronous operation,

3. the loading in asynchronous operation is not limited by the rotor heating, but by that of the stator. From the viewpoint of rotor heating, the bronze-wedge blocking of the rotor slots is much more favourable than the steel-wedge slot termination,

4. in the case which is the most favourable from the pulsations point of view, the fluctuation in the stator current may be reduced to 6—8%, while

that of the reactive power to 9—11%. These values are half of those obtained with the de-excitation resistance which had been general up till now,

5. the minimum of pulsations may be realized in the practice with a very simple method, that is, by inserting an ohmic resistance of suitable value into the field; the resistance needed may simply be determined on the basis of the asynchronous operation measurement data, by the method given in the Appendix. For applying the optimum field resistance with machines of cross-coil rotor, many possibilities present themselves:

a) The resistance is inserted into the field in the normal (single-phase) way. The optimum resistance value at this time, with the 44 MVA, steel-wedge rotor machine is 1.85-times the field resistance, with the 26.5 MVA machine, in case of steel-wedge rotor 1.24-times, with bronze-wedge rotor 1.55-times the field resistance.

b) The field is closed in a two-phase way. The optimum value of the great resistances connected in series with the half-coils are in this case, with a 44 MVA, steel-wedge rotor machine, individually equal to the resistance of the total field. The advantage of the connection with respect to case *a* is that the rotor heating is about 30% smaller, its disadvantage is the need of a separate auxiliary brush assembly.

c) If the field coil is of sandwich arrangement, the above-mentioned brush assembly is superfluous, the two-phase connection is simplified to the one in case *a*. The optimum value of the resistance to be inserted into the field is in this case, with a 44 MVA steel-wedge rotor machine, roundly half of the field resistance. The sandwich-arrangement of the field coil reduces the rotor heating by about 50%.

On the basis of the afore-said, for the asynchronous operation of the turbogenerators of the type tested, adoption of the optimum field resistances indicated above may be suggested. The necessary resistance values are quite easy to realize by e.g. a suitable branch made on the de-excitation resistance. From the asynchronous operation point of view both the sandwich arrangement of the field coil and the bronze-wedge termination of the rotor slots may, in general, be recommended.

APPENDIX

Below the procedure will be discussed permitting to determine the admittance diagrams and optimum field resistances serving as a basis for the above examinations. The method starts from the admittance diagrams plotted with the aid of the two series of measurements in asynchronous operation, mentioned in Fig. 2.

A.1 Determination of admittance diagrams belonging to an arbitrary field resistance

In the case of the tested machines, we started out from the admittance diagrams plotted from the data of the series of measurements effected with a field coil, short-circuited in the usual way, and with one closed through a de-excitation resistance. The ohmic resistance inserted into the field merely influences the direct-axis admittance ($\overline{Y}_d$), while the quadrature-axis admittance ($\overline{Y}_q$) remains unchanged. In Fig. 12 the equivalent circuit of the machine is illustrated, valid in direct-axis, with an external resistance R in the field. The resistances and reactances of the rotor circuits are, due to the skin effect, arising in the rotor body, values changing with the slip. The question is, that if at a given slip the direct-axis admittances ($\overline{Y}_{d1}$ and $\overline{Y}_{d2}$) belonging to two values of R ($R = 0$ and $R = R_{DE}$) are known, how can the value $\overline{Y}_d$ be determined in case of an arbitrary R for the same slip. If the slip is constant, all impedances of the equivalent circuit are constant and if merely changing the resistance R inserted into the field, then — as is well known — the terminal of the resultant admittance vector draws a circle on the complex plane. Consequently, with a constant slip, having a variable R, the expression of the admittance is

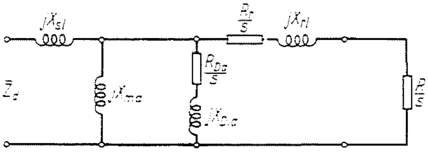

Fig. 12. Equivalent circuit of the direct-axis impedance

$$\overline{Y}_d = \frac{\bar{A} + \bar{B}R}{\bar{C} + R} \tag{1}$$

where the complex numbers $\bar{A}$, $\bar{B}$ and $\bar{C}$ are constants to be determined in knowledge of the three points of the circle. Two points of the circle are known from the measurement data:

$$R = 0, \quad \overline{Y}_d = \overline{Y}_{d1} \tag{2a}$$

$$R = R_{DE}, \quad \overline{Y}_d = \overline{Y}_{d2} \tag{2b}$$

As third point of the circle let us take the admittance belonging to resistance $R = -R_r$. Denoting this by $\overline{Y}'_d$, the third point of the circle yields

$$R = -R_r, \quad \overline{Y}_d = \overline{Y}'_d \tag{2c}$$

On the basis of the three points, at a given slip s the circle, as well as the parameter scale R belonging to the circle may be plotted. Thereby the value

$\overline{Y}_d$, corresponding to an arbitrary resistance R, or inversely, the value R belonging to any circle point $\overline{Y}_d$ may easily be determined. Plotting the circle diagram for a sufficient number of slip values, the complete admittance diagram, belonging to resistance R may be plotted.

Examining the values of the admittance $\overline{Y}'_d$ more closely, one recognizes that in the field of the small slips interesting us, the task may be simplified. Namely, in case of $R = -R_r$ at $s = 0$, $\overline{Y}_d = 1/jX'_d$, while at $s = \infty$, $\overline{Y}_d = 1/jX''_d$, consequently $\overline{Y}'_d$ — depending on the slip — is a value varying between the transient and subtransient admittance (see the equivalent circuit of Fig. 12). Restricting ourselves to small slips, the transient admittance may be counted with. This is about five times the nominal admittance of the machine, so approximately $\overline{Y}'_d \approx -j5$. For judging the numerical conditions, let us examine Fig. 13, illustrating the diagrams of a 26.5 MVA, steel-wedge rotor machine in per unit values, power scales. If we assume $\overline{Y}'_d$ as a value illustrated in the figure, we may immediately understand that we have circles of such long diameter, the arc of which falling between the diagrams $\overline{Y}_{d1}$ and $\overline{Y}_{d2}$ may practically be replaced — in the slip range to be considered in asynchronous operation — by a chord. The chord may be expressed as follows:

$$\overline{Y}_d = \frac{\bar{A} + \bar{B}R}{R_r + R} \tag{3}$$

Determining the constant $\bar{A}$ and $\bar{B}$ on the basis of (2a)—(2b):

$$\bar{A} = R_r \overline{Y}_{d1} \tag{4a}$$

$$\bar{B} = \frac{R_r}{R_{DE}} (\overline{Y}_{d2} - \overline{Y}_{d1}) + \overline{Y}_{d2} \tag{4b}$$

Substituting these into (3), after ordinating

$$\overline{Y}_d = \frac{R_{DE} R_r \overline{Y}_{d1} + [R_r (\overline{Y}_{d2} - \overline{Y}_{d1}) + R_{DE} \overline{Y}_{d2}] R}{R_{DE}(R_r + R)} \tag{5}$$

Consequently, the end point of the admittance vector $\overline{Y}_d$ moves, in case of a constant slip, with a changing R, taken by a very good approximation, along the straight line determined by relation (5) — connecting the points of $\overline{Y}_{d1}$ and $\overline{Y}_{d2}$ belonging to the same slip — while the resistance R is changing between the limits $0 \leq R \leq R_{DE}$. For simply tracing on the straight line a vector terminal belonging to some of the resistances R, we calculate the distance between the point in question and the point $\overline{Y}_{d1}$. On the basis of (5) we obtain for this

$$|\overline{Y}_d - \overline{Y}_{d1}| = |\overline{Y}_{d2} - \overline{Y}_{d1}| \frac{(R_r + R_{DE}) R}{R_{DE}(R_r + R)} \tag{6}$$

Denoting by λ the relation of distance $|\overline{Y}_d - \overline{Y}_{d1}|$ with respect to $|\overline{Y}_{d2} - \overline{Y}_{d1}|$, (6) yields

$$\boxed{\lambda = \frac{(1 + r_{DE})\, r}{r_{DE}(1 + r)}} \tag{7}$$

where the symbols

$$r = \frac{R}{R_r} \text{ and } r_{DE} = \frac{R_{DE}}{R_r} \tag{8}$$

have been introduced. In knowledge of $\overline{Y}_{d1}$ and $\overline{Y}_{d2}$, determination of the admittance diagram belonging to any intermediate resistance R thereafter follows as discussed below (see Fig. 13):

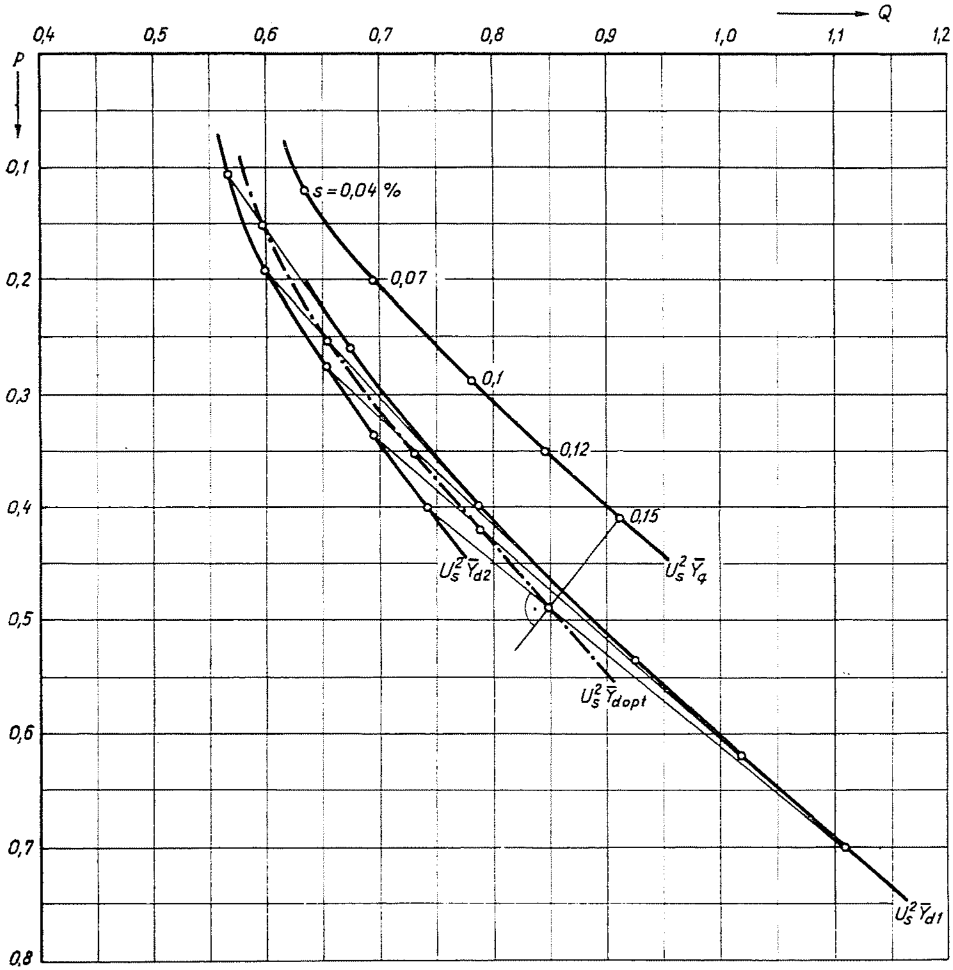

Fig. 13. Graphical determination of the field resistance, optimum from the pulsations point of view and of the admittance diagram belonging to it

the points of the admittance diagram $\overline{Y}_{d1}$ and $\overline{Y}_{d2}$ belonging to the same slip are interconnected by a straight line, and then the length $|\overline{Y}_{d2}-\overline{Y}_{d1}|$ of the straight is measured. According to (7), the λ relation belonging to the value R and r, respectively, is determined. finally the λ-times of the distance $|\overline{Y}_{d2}-\overline{Y}_{d1}|$ is sized up along the straight, starting from point $\overline{Y}_{d1}$. The so obtained point is the point of the admittance diagram sought for, belonging to the respective slip. Plotting the straight line connecting the points of identical slip of $\overline{Y}_{d1}$, $\overline{Y}_{d2}$ for a number of slips and sizing up λ-times the own value of all straights according to the above-said, we obtain the admittance diagram in question within the range of the small slips interesting us. (As an example, on Fig. 13 with this procedure we have plotted the diagram $\overline{Y}_{dopt}$ belonging to the optimum resistance). Inversely, if we are looking for the value R belonging to an arbitrary point $\overline{Y}_d$ given on one of the straights, then determining the relation λ of the above-mentioned distance, the field resistance in question may be calculated from (7):

$$\boxed{r = \frac{r_{DE}\lambda}{1+r_{DE}(1-\lambda)}} \tag{9}$$

A.2 Determination of the optimum field resistance

Based on the foregoing, the field resistance from the pulsations point of view being optimum it may easily be determined. The respective plotting may be seen in Fig. 13, too. Now our task is to mark out the point of the straight connecting the points of identical slip of $\overline{Y}_{d1}$ and $\overline{Y}_{d2}$ these being the closest to the point belonging to the same slip of the quadrature-axis diagram $\overline{Y}_q$. According to clause 3, this point will be the point belonging to the respective slip of the direct-axis admittance diagram which is valid in the most favourable case. For denoting this point, as per the simple rule of elementary geometry we may drop a normal straight from point $\overline{Y}_q$ to the straight line $\overline{Y_{d_1} Y_{d_2}}$. The intersection of the two straights furnishes just the point demanded at the given slip. Sizing up the distance between the point so obtained and the point $\overline{Y}_{d1}$, the ratio λ, and finally, as per (9), the value of the optimum resistance, may be determined. (Making the simple plot for many slips, we find, that the value r_{opt} does not depend but slightly on the slip; it is practicable to determine the optimum resistance at a slip belonging to a greater load.)

Applying the admittance diagrams having been determined from the measurement data available in case of the machines tested by us, the optimum resistance values given, as well as the admittance diagrams belonging to these were obtained by the method described above. The optimum resistance value necessary in case of the sandwich-arrangement assumed in clause 6 was determined in the same way with the 44 MVA machine. Namely, the method is also valid at a time when the quadrature-axis admittance diagram is not influenced by the field resistance with a sandwich arrangement, either. (Naturally with a sandwich arrangement, the quadrature-axis diagram is different from that obtained without a sandwich-layout of the field coil; the quadrature-axis diagram needed was available from the data of the measurements effected on the 44 MVA machine for case IV.)

If the field coil has no sandwich arrangement and the two-phase connection as per Fig. 8 is employed, a calculating method somewhat different from the above procedure is to be adopted. Namely, the resistances connected in series with the half coils influence simultaneously the direct- and quadrature-axis admittance. Further, as a consequence of the connection, zero-sequence quantities also appear. For elaborating the calculation, first of all the equivalent circuit diagrams valid in case of the connection as per Fig. 8 must be established, as well as the zero-sequence elements figuring in the former ones. On the basis of the equivalent circuit diagrams, for determining the admittance diagrams, a simple graphical method similar to the former one may be deduced.

Determination of the optimum resistances is, however, due to the simultaneous variation in $\overline{Y}_d$ and $\overline{Y}_q$ is somewhat more complicated than in the above case. Elaboration of the calculating method to be applied with two-phase connections encounters no difficulties of principle, but as is perceptible from the afore-said, requires a lengthy deduction. In view of the fact that this connection can by no means be used in the practice because of the above-mentioned reason, the exposition of the calculating method needing a circuitous deduction will be disregarded.

Summary

In the paper methods are given for the efficient reduction of the pulsations arising in the asynchronous operation of turbogenerators, caused by rotor asymmetry. It is established that as against the current idea, the conditions the most favourable from the viewpoint of pulsations in asynchronous operation. do not occur with an open field, but at a fixed. finite value of the field resistance in case of the cross-coiled rotor machines of Hungarian (GANZ) manufacture. Finally a calculating method is given for determining the field resistance which is optimum from the pulsations point of view.

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