SOME REMARKS CONCERNING THE QUICK-RESPONSE OVEREXCITATION OF SYNCHRONOUS GENERATORS

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In case of the procedure called quick-response overexcitation, the excitation of the synchronous generator is raised suddenly well over the working value. This is necessary in short-circuits, or switching operations accompanied by great reactive power consumption (e. g. selfsynchronization). The sudden increase of excitation is generally realized by short-circuiting the exciter field rheostat (Fig. 1). The aim of quick-response overexcitation is to re-establish the network voltage by raising the generator excitation, to facilitate the acceleration of asynchronous motors, slown down to the working speed, and so to produce from the point of view of network stability a favourable effect.

Author in the Institute of Electrical Power Research mapped out a quick-response overexciting equipment. Description of the equipment and its operation is not dealt with here, as this may be found in other places [1, 2, 3]. The present article discusses only some questions concerning quick-response overexcitation and especially examines the conditions of quick-response overexcitation, in which the synchronous generator is in no case exposed to inadmissible load.

1. Questions of overheating. Time of quick-response overexcitation

From the point of view of overheating of the rotor and stator the quick-response overexcitation has not a great importance. This — as will be shown below — is mainly due to the fact that the quick-response overexcitation lasts relatively for a short time.

1.1. *Overheating of the rotor*

The overheating per second, neglecting the heat transfer (in case of copper wire) may be computed by formula

$$\frac{1}{160}\,i^2 \qquad \text{or} \qquad \frac{1}{140}\,i^2$$

where i is the current density. The first formula refers to a smaller (about 50° C), the second to a greater (about 130...140° C) initial temperature.

At rated operation of the generator (in case of rated stator voltage), stator current and at the worst power factor prescribed the current density in the exciting coil of the rotor may be taken exaggeratedly 6 A/mm². If the relation of overexcitation is 2, the maximal current density is $i_{max} = 12$ A/mm², i. e., the overheating is about 1° C/sec. If the duration of the quick-response overexcitation is limited to 15 sec, the temperature of the rotor increases only with 15° C. But in most cases quick-response overexcitation will end in a considerably shorter time, after some seconds, so the thermal load of the rotor will become much smaller. (By changing to exciters with unsaturated poles and raising the relation of overexcitation e. g. to 2,5 we can count on a temperature rise of 1,6° C/sec. Limiting the maximum duration of overexcitation to 9—12 sec, the overheating of the rotor would furthermore not exceed the value of 15—20° C.)

1.2. *Overheating of the stator*

Standards prescribe that every rotating machine must withstand without damage the $1^1/_2$-times of the rated current, starting from a warm state. On the basis of the identical overloss (corresponding approximately to an identical overheating) the following equation may be written for the stator currents [4] :

$$(1{,}5^2 - 1)\ 120\ [\text{sec}] = \left(\frac{I^2}{I_n^2} - 1\right) t\,[\text{sec}]$$

from which

$$t\,[\text{sec}] = \frac{150\ [\text{sec}]}{\dfrac{I^2}{I_n^2} - 1}.$$

On the basis of the formula above we obtain for some of the overcurrent values the times included in Table 1.

The short-circuit ratio of turbogenerators is between 0,5—0,8, the field current at rated load is 3...2-times of that at no-load, so the steady-state current of a three-phase terminal short-circuit is $0{,}5 \cdot 3I_n = 1{,}5I_n$, resp. $0{,}8 \cdot 2I_n = 1{,}6I_n$. If the ratio of overexcitation is 1,8-times, a steady-state three-phase short-circuit current of $1{,}8 \cdot 1{,}6I_n = 2{,}88I_n$ (if 2,5-times, then $2{,}5 \cdot 1{,}6I_n = 4I_n$) is produced.

So according to Table 1, resp. to the above formula, neglecting the subtransient, transient, as well as the d. c. short-circuit current components, but at the same time calculating with the maximum steady-state short-circuit current, the duration of the quick-response overexcitation may be about

Table 1

Time of overload in function of the overcurrent

I/I_n	1,5	2	2,5	3	4
t [sec]	120	50	28,5	18,7	10

20 sec (resp. 10 sec). In view of the fact, that the value of the two-phase steady-state short-circuit current is about 1,6-times that of the three-phase one, considering a two-phase short circuit, from the point of view of the stator a duration of 8 sec (resp. 4 sec) would be permissible for the overexcitation.

The above calculations are informative. For a given machine with full knowledge of the permissible overheatings, maximum duration of the quick-response overexcitation can and must be determined exactly.

2. Experimental determination of the factors figuring in the quick-response overexcitation

Before realizing the quick-response overexcitation at a certain synchronous generator unit, the ceiling voltage of the exciter, the maximum field current of the synchronous generator must be predetermined as well as how quickly the values mentioned are established after the start of quick-response overexcitation. It is the most advisable to clear the above questions experimentally.

Measurement may be effected as follows [4]: All the three terminals of the de-energized generator must be short-circuited, afterwards excitation must be increased until an approx. rated current appears in the stator circuit. Short-circuiting all resistances in the field circuit of the exciter (Fig. 1), development of stator current, rotor current and rotor voltage is recorded by oscillograph (Figs. 4 and 5).

In the meantime we would like to mention that at the set-up test of the quick-response overexciting equipment a similar measurement may be effected and at this time also the self-time of the quick-exciting equipment (the time elapsing from the breakdown of the stator voltage up to the closing of the contacts of the quick-response overexciting contactor) can be determined.

It is advisable to control by calculation the development of the quantities tested, too.

2.1. *Simplified calculating method for determination of the quantities figuring in the quick-response overexcitation*

Some remarks are made concerning the course of the oscillograms. The physical explanation of the occurring processes is complicated by the presence of magnetic saturation, remanence and eddy currents. In first approximation we neglect their effect. If we also neglect the small stator resistance of the generator, the phenomena taking place in the "direct axis" of the machine are independent of those occurring in the "quadrature axis" [5]. With the presumed neglections, the equivalent circuit for the direct axis

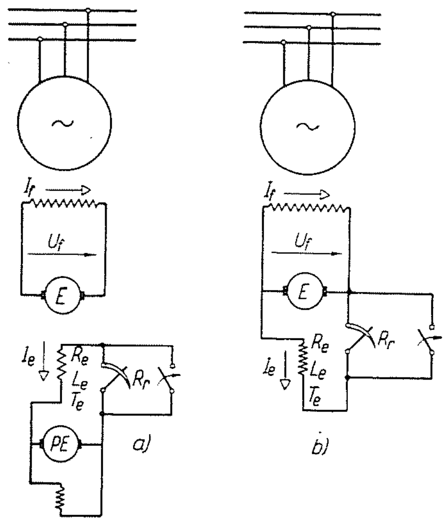

Fig. 1. Schematic circuit diagram of the quick-response overexcitation. *a)* Exciter with separate excitation; *b)* exciter with shunt excitation

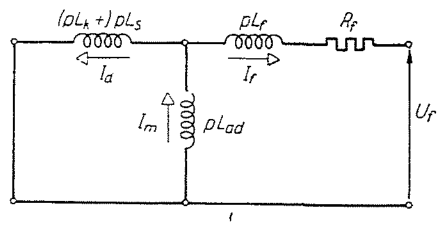

Fig. 2. Direct-axis circuit diagram of the generator with short-circuited stator

of the machine, with short-circuited stator, may be seen on Fig. 2; the mutual inductance between the rotor and stator circuits is L_{ad}, the leakage inductance of the stator coil is L_s, that of the field coil is L_f, its resistance is R_f, latter quantities are, similarly to the transformers, related to the stator. I_d is the direct-axis component of the stator current (being absolutely reactive by neglecting the stator resistance),* I_f is the current in the field circuit of the

* The current I_d determines only the envelope-curve of the stator current. The phase-currents themselves are [7]:

$$I_a = I_d \cos(\omega_0 t + \Theta_0) - I_q \sin(\omega_0 t + \Theta_0) = I_d \cos(\omega_0 t + \Theta_0)$$

$$I_b = I_d \cos\left(\omega_0 t + \Theta_0 - \frac{2\pi}{3}\right) - I_q \sin\left(\omega_0 t + \Theta_0 - \frac{2\pi}{3}\right) = $$
$$= I_d \cos\left(\omega_0 t + \Theta - \frac{2\pi}{3}\right)$$

$$I_c = I_d \cos\left(\omega_0 t + \Theta_0 + \frac{2\pi}{3}\right) - I_q \sin\left(\omega_0 t + \Theta_0 + \frac{2\pi}{3}\right)$$
$$= I_d \cos\left(\omega_0 t + \Theta_0 + \frac{2\pi}{3}\right)$$

Here in the right-side figures, the relation $I_q = 0$ was already taken into consideration.

generator, U_f is the field voltage, latter two quantities are also related to the stator.

The change in the field current occurring under the effect of the change in the field voltage ΔU_f:

$$I_f = \frac{\Delta U_f}{R_f + pL_f + \dfrac{pL_{ad}\, pL_s}{pL_{ad} + pL_s}} . \tag{1}$$

Let us introduce the following time constants:

$$T'_{do} = \frac{1}{R_f} (L_f + L_{ad}) \tag{2}$$

the transient no-load time constant, and

$$T'_d = \frac{1}{R_f} \left(L_f + \frac{L_{ad} L_s}{L_{ad} + L_s} \right) \tag{3}$$

the transient short-circuit time constant. Evidently,

$$\frac{T'_d}{T'_{do}} = \frac{\dfrac{L_{ad} L_s + L_{ad} L_f + L_s L_f}{L_{ad} + L_s}}{L_{ad} + L_f} = \frac{\dfrac{L_{ad} L_s + L_{ad} L_f + L_s L_f}{L_{ad} + L_f}}{L_{ad} + L_s} = \frac{X'_d}{X_d} , \tag{4}$$

where

$$X_d = \omega_0 (L_{ad} + L_s) \tag{5}$$

is the synchronous reactance and

$$X'_d = \omega_0 \left(L_s + \frac{L_{ad} L_f}{L_{ad} L_f} \right) \tag{6}$$

the transient reactance.

Considering these, we get from (1):

$$\Delta I_f = \frac{1}{pT'_d + 1} \cdot \frac{\Delta U_f}{R_f} . \tag{7}$$

The change in the direct-axis component of the stator current according to Fig. 2:

$$\Delta I_d = - \frac{L_{ad}}{L_{ad} + L_s} \Delta I_f . \tag{8}$$

On the basis of (7) and (8)

$$\Delta I_d = \frac{1}{pT'_d + 1} \cdot \frac{X_{ad}}{X_d} \cdot \frac{\Delta U_f}{R_f}, \tag{9}$$

where $X_{ad} = \omega_0 L_{ad}$.

Supposing the terminal voltage of the pilot exciter to be constant, the quick-response overexcitation, i. e. short-circuiting the exciter field rheostat (in Fig. 1a R_f) has an effect as if we connected to the field coil of the main exciter a voltage equal to the voltage ΔU_{e0}, which existed between the terminals of the rheostat before the short circuit. Consequently, a change of current takes place:

$$\Delta I_e = \frac{\Delta U_{e0}}{R_e + pL_e} = \frac{1}{pT_e + 1} \cdot \frac{\Delta U_{e0}}{R_e}, \tag{10}$$

where L_e is the full inductivity of the field-circuit of the main exciter, R_e is its resistance and $T_e = L_e/R_e$ is the time constant of the excitation system. The change of internal voltage* (with an approximation: of its terminal voltage) may be expressed as follows:

$$\Delta U_f = k\Delta I_e = \frac{\Delta U_{f\infty}}{pT_e + 1}, \tag{11}$$

where $\Delta U_{f\infty}$ is the change of voltage occurring in the main exciter effected by the steady-state current change in the field circuit: $\Delta U_{f\infty} = k\Delta U_{e0}/R_e$. The change in the field current of the generator on the basis of (7) and (11) is

$$\Delta I_f = \frac{1}{pT_e + 1} \frac{1}{pT'_d + 1} \cdot \frac{\Delta U_{f\infty}}{R_f}, \tag{12}$$

while the change in the envelope-curve of the stator current from expressions (9) and (11) is:

$$\Delta I_d = \frac{1}{pT_e + 1} \frac{1}{pT'_d + 1} \frac{X_{ad}}{X_d} \frac{\Delta U_{f\infty}}{R_f}. \tag{13}$$

The time functions with the expansion theorem [5] are: the change in the field voltage from relation (11):

$$\Delta U_f = (1 - e^{-t/T_e})\, \Delta U_{f\infty}, \tag{14}$$

* Internal voltage is equal in magnitude to the e. m. f., but opposite in sign.

the change in the field current from expression (12):

$$\Delta I_f = F(t)\,\frac{\Delta U_{f\infty}}{R_f} = F(t)\,\Delta I_{f\infty}\,, \tag{15}$$

the change in the envelope-curve of the stator current from relation (13):

$$\Delta I_d = -\,F(t)\,\frac{X_{ad}}{X_d}\,\frac{\Delta U_{f\infty}}{R_f} = \frac{X_{ad}}{X_d}\,\Delta I_f, \tag{16}$$

where

$$F(t) = 1 - \frac{T'_d\,e^{-t/T'_d} - T_e\,e^{-t/T_e}}{T'_d - T_e}\,. \tag{17}$$

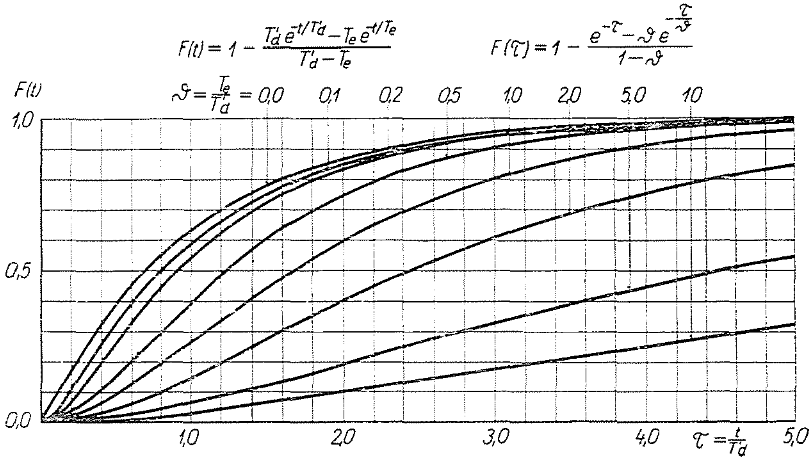

Fig. 3. The function $F(\tau) = F(t/T'_d)$ in case of different parameters $\vartheta = T_e/T'_d$

Consequently, the field voltage alters according to one, the rotor and stator current according to two time constants.

On Fig. 3 the function $F(t)$ determining the process of current changes is shown for different time-constant ratios of $\vartheta = T_e/T'_d$. It is noted that by introducing the relative time $\tau = t/T'_d$, the function $F(t)$ may be expressed in the following general form:

$$F(\tau) = 1 - \frac{e^{-\tau} - \vartheta\,e^{-\tau/\vartheta}}{1 - \vartheta}\,. \tag{18}$$

As can also be seen from Fig. 3, the time constant T_e of the field circuit of the exciter has primarily an effect on the initial section of the curve $F(t)$. On the basis of the set of curves it can be stated that if the time constant T_e is a fracture of T'_d ($\vartheta = 1/3\ldots1/5$), an important gain cannot be realized by reducing the time constant T_e. Consequently, the efficiency of the quick-response overexcitation is only slightly influenced by the time constant T_e of the excitation system. This is even more supported by the fact that in case of asymmetrical, or distant symmetrical short circuits, the value of time constant T'_d becomes greater :

$$T'_d = \frac{X'_d + X_k}{X_d + X_k} T'_{do} \quad \text{instead of} \quad T'_d = \frac{X'_d}{X_d} T'_{do},$$

where X_k is the reactance being characteristic of the asymmetrical, or the distant symmetrical short circuit.

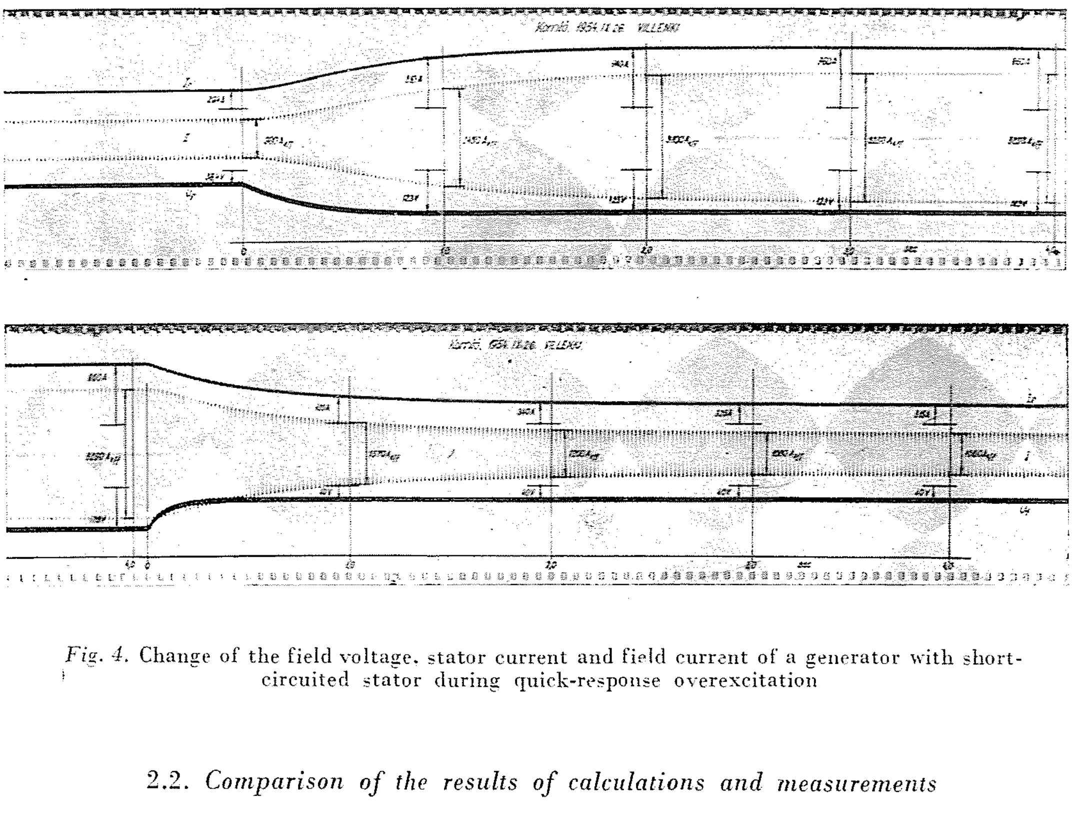

Fig. 4. Change of the field voltage, stator current and field current of a generator with short-circuited stator during quick-response overexcitation

2.2. *Comparison of the results of calculations and measurements*

Checking of the formula deduced was made by the oscillograms of Figs. 4 and 5, on which the stator current, field current and field voltage can be seen [6].

Fig. 4*a* shows the overexciting, Fig. 4*b* the de-exciting process, Fig. 5 the overexciting and de-exciting process for some cases. Table 2 informs about the values measured at different times on the basis of the oscillograms.

Records refer to a two-pole, Ganz OF 760 × 1900/2 type, 10 MVA rated output, 5750 V rated voltage, 1000 A rated current (power factor 0,7), star-connected turbogenerator. For information data of the main exciter are: type EGS 390/220, 120 V, 650 A, 3000 r. p. m., 6 poles; data of the

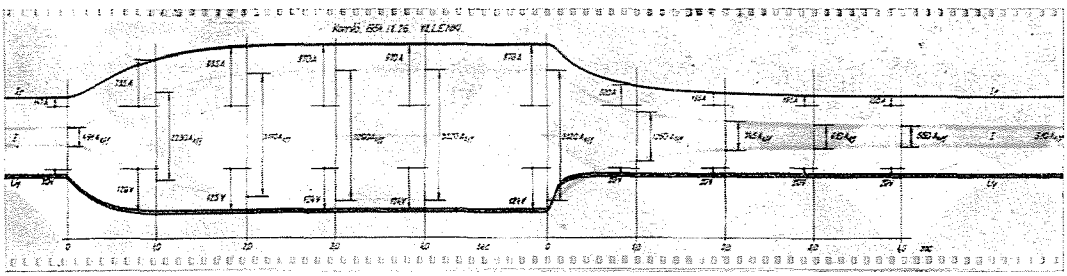

Fig. 5. Change in the field voltage, stator current and field current of the generator with short-circuited stator during quick-response overexcitation

pilot exciter are as follows: EG 180/60, 120 V, 12 A, 3000 r. p. m., 4 poles. On the no-load characteristic of the generator a field current $I_f = 168$ A belongs to the $U_n = 5750$ rated phase-to-phase voltage of the stator. On the short-circuit characteristic of the generator a field current of about $I_f = 294$ A belongs to the $I_n = 1000$ A rated stator current.

Calculations were made using the expressions (14), (15), (16) and (17). Though equations (14) and (15) refer strictly to the quantities related to

Table 2

Summary of the quick-response overexcitation measurements

		Fig. 4.			Fig. 5.		
	t sec	I_f A	I A	U_f V	I_f A	I A	U_f V
Overexcitation	0	294	980	38,4	147	491	20
	1	810	2480	123	735	2230	126
	2	940	3100	123	935	3110	125
	3	960	3250	123	970	3290	124
	4	960	3250	123	970	3320	124
De-excitation	0	960	3250	123	970	3320	124
	1	425	1570	40	320	1250	20
	2	340	1200	40	195	745	20
	3	325	1080	40	161	610	20
	4	315	1060	40	150	550	20

the stator, they can also be used for determining the real change in the field voltage and field current.

Tests showed that the ceiling voltage of the main exciter was 123...124 V. So in the first case $\Delta U_{f\infty} = 123$ V — 38,4 V = 84,6 V, and in the second one $\Delta U_{f\infty} = 124$ V — 20 V = 104 V.

The resistance of the field coil is 0,112 Ω at a temperature of 31° C. If temperature of the rotor is assumed to be about 65° C during the tests, the resistance of the field coil is about 0,127...0,125 Ω. Consequently, the steady-state change in the field current effected by the steady-state change in the field voltage is $\Delta I_{f\infty} = \Delta U_{f\infty} : R_f = 84{,}6$ V : 0,127 Ω = 666 A, and $\Delta I_{f\infty} = \Delta U_{f\infty} : R_f = 104$ V : 0,125 Ω = 832 A, resp.

As in the case of a short-circuited generator a stator current of 1000 A belongs to a field current of 294 A, in the first case a change in stator current of $\Delta I_{d\infty} = 2270$ A belongs to a change of field current of $\Delta I_{f\infty} = 666$, and in the second case a change in stator current of $\Delta I_{d\infty} = 2830$ A corresponds to a change in the field current $\Delta I_{f\infty} = 832$ A.

With the above data, using $T_e = 0{,}25$ sec and $T_d' = 0{,}5$ sec, on the basis of the formulas (14), (15), (16), and (17) we computed the value of ΔU_f, ΔI_f and ΔI_d in function of time. To compare the calculations and measurements Figs. 6 and 7 were drawn for the first, and the second case, resp. On both figures the dashed lines show the results of calculations, while the continuous curves were drawn on the basis of the oscillogram records of Figs. 4 and 5. Coincidence may by regarded to be good in spite of the neglections made during the calculation. So the simplified calculating method discussed above may be well used for the preliminary estimation of the quantities, important from the point of view of quick-response overexcitation.

2.3. *Remarks regarding the process of the quantities tested*

On the basis of the discussed calculations, some comments may be made in connection with the process of the quantities recorded by oscillograph. It can be observed that the voltage U_f reaches its steady-state value in case of overexcitation in a longer time than at de-excitation. This is due to the fact that in case of overexcitation the value of the time constant T_e is

$$T_e = \frac{L_e}{R_e},$$

but in case of de-excitation it is smaller :

$$T_e' = \frac{L_e}{R_e + R_r}.$$

In case of de-excitation, according to the time constant T_e' the current ΔI_f — and also the envelope-curve of the stator current ΔI_d — is nearer to a purely exponential curve, depending only on one time constant T_d'.

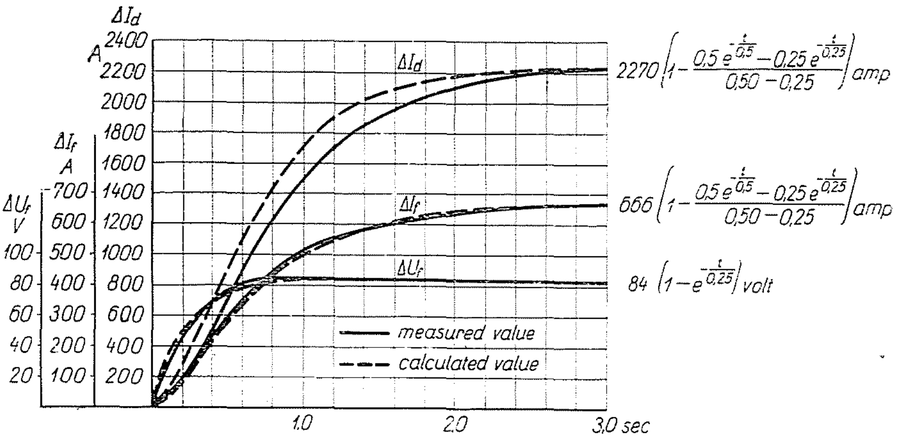

Fig. 6. Comparison of the results of calculations and measurements

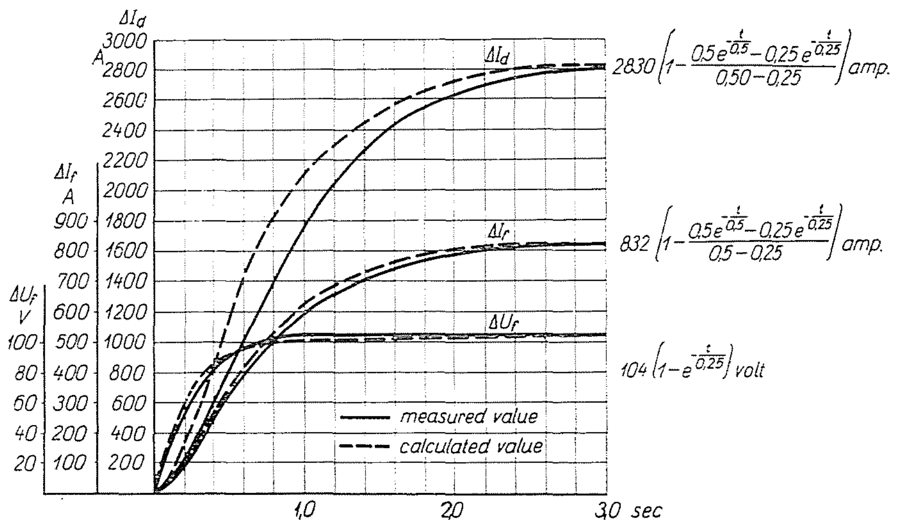

Fig. 7. Comparison of the results of calculations and measurements

It can be also observed that during de-excitation all quantities recorded tend to a somewhat greater value than the initial one. This is due to the residual magnetism.

3. The electrical processes of the generator if its circuit breaker works during quick-response overexcitation

We have also to answer the question, whether it is not dangerous from the point of view of the generator if its circuit breaker works in an overexcited state.

3.1. *If quick-response overexcitation is maintained*

Investigation is only carried out for simplified cases. Let us assume that the generator was short-circuited merely through an external X_k reactance (so that resistances of the stator circuit are neglected, consequently, the equi-(valent circuit of the direct axis can be further on used for our calculations (Fig. 2) — if the neglections made in paragraph 2,1. are henceforward accepted) and so only the operational inductance pL_k, according to the external reactance X_k, must be connected in series with the operational inductance pL_s. In addition, let us suppose the quick-response overexciting equipment had worked, and the steady-state condition took place, consequently, in the field circuit a $\Delta I_{f\infty}$ current flows.

Now the steady-state direct-axis component of the stator current's envelope-curve is

$$I_{d\infty} = -\frac{L_{ad}}{L_k + L_s + L_{ad}} I_{f\infty}, \tag{19}$$

the current of the quadrature-axis is zero :

$$I_q = 0 . \tag{20}$$

Now assuming, for example, that under the effect of the protective devices the circuit breaker of the generator operates, but the automatic de-energizing equipment does not and the quick-response overexcitation also maintains itself : constantly $U_{f\infty}$ = const. Breaking the stator current is equivalent with the operation of a current generator in the short-circuiting branch, giving a current of $-I_{d\infty}$. On the basis of the superposition theorem, current will be zero in the stator circuit :

$$I_d = I_{d\infty} - I_{d\infty} = 0 \tag{21}$$

while (considering Fig. 2), in the magnetizing branch a current of

$$I_{md} = -\frac{R_f + pL_f}{R_f + p\,(L_{ad} + L_f)} I_{d\infty} \tag{22}$$

flows, as the branch of the exciting circuit must be short-circuited ($U_{f\infty} = 0$), when calculating the superpositional current. Taking into consideration (19) :

$$I_{md} = \frac{L_{ad}}{L_k + L_s + L_{ad}} \cdot \frac{R_f + pL_f}{R_f + p\,(L_{ad} + L_f)} I_{f\infty} \tag{23}$$

and, using the expansion theorem [5], from expression (23) the time function is :

$$I_{md} = \frac{L_{ad}}{L_k + L_s + L_{ad}} \left(1 - \frac{L_{ad}}{L_{ad} + L_f} e^{-t/T'_{do}}\right) I_{f\infty} . \tag{24}$$

To the superpositional current I_{md} must be added the initial current

$$I_{mo} = I_{d\infty} + I_{f\infty} \tag{25}$$

originally established in the magnetizing branch. Considering (19),

$$I_{mo} = \frac{L_k + L_s}{L_k + L_s + L_{ad}} I_{f\infty} \tag{26}$$

while the total current appearing in the magnetizing branch, from relations (24) and (26) :

$$I_m = I_{mo} + I_{md} = \left(1 - \frac{L_{ad}}{L_k + L_s + L_{ad}} \cdot \frac{L_{ad}}{L_{ad} + L_f} e^{-t/T'_{do}}\right) I_{f\infty} . \tag{27}$$

Considering expressions (5) and (6), after some algebraic transformation :

$$I_m = \left(1 - \frac{X_d - X'_d}{X_d + X_k} e^{-t/T'_{do}}\right) I_{f\infty} \tag{28}$$

The direct-axis component of the resulting flux linkage of the stator (according to Fig. 2) :

$$\psi_d = (L_s + L_{ad})\, I_d + L_{ad}\, I_f = L_s\, I_d + L_{ad}\, I_m , \tag{29}$$

and now the quadrature-axis component ψ_q is zero :

$$\psi_q = L_{aq}\, I_q = 0 \tag{30}$$

as $I_q = 0$. Considering expressions (21) and (28), from (29) we get

$$\psi_d = \left(1 - \frac{X_d - X'_d}{X_d + X_k} e^{-t/T'_{do}}\right) L_{ad}\, I_{f\infty} . \tag{31}$$

The fundamental equations of the synchronous machine are [7] :

$$\begin{aligned} U_d &= p\,\psi_d - \omega_0\,\psi_q + R\,I_d \\ U_q &= \omega_0\,\psi_d + p\,\psi_q + R\,I_q\,. \end{aligned} \tag{32}$$

Considering expressions (20), (21), (30) :

$$\begin{aligned} U_d &= p\,\psi_d \\ U_q &= \omega_0\,\psi_d\,. \end{aligned} \tag{33}$$

Differentiating the expression (31) of the flux-linkage ψ_d, respectively, multiplying it by ω_0, we may be convinced that (even at the initial time) the voltage-component U_d is by an order of magnitude smaller, than the voltage component U_q, therefore it is neglected. Introducing on the basis of expression

$$\omega_0\,L_{ad}\,I_{f\infty} = U_{0\infty}\,, \tag{34}$$

the maximum voltage $U_{0\infty}$ obtainable by quick-response over excitation on the generator at no-load, on the basis of expressions (31), (33) and (34) finally we get*

$$U_q = \left(1 - \frac{X_d - X'_d}{X_d + X_k}\,e^{-t\,/T'_{do}}\right) U_{0\infty}\,. \tag{35}$$

In the steady-state condition

$$U_{q(t=\infty)} = U_{0\infty}\,, \tag{36}$$

at the initial time

$$U_{q(t=0)} = \frac{X'_d + X_k}{X_d + X_k}\,U_{0\infty} = U'. \tag{37}$$

(It is to be noted that having also considered the effect of the damping coil, or that of the solid iron, we would have got another expression instead of (35) — and instead of (37) the following relation would be valid :

$$U_{q\,(t=0)} = \frac{X''_d + X_k}{X_d + X_k}\,U_{0\infty} = U''.). \tag{38}$$

For comparison, let us compute also the terminal voltage having been established before the interruption of the short-circuit current. Let us substitute

* U_q gives only the envelope-curve of the stator voltage, the stator voltage itself is : $U_a = - U_q \sin(\omega_0 t + \Theta_0)$, etc.

into expression (29) of the flux linkage ψ_d the expressions (19) of $I_d = I_{d\infty}$ and $I_f = I_{f\infty}$:

$$\psi_d = \left(1 - \frac{L_s + L_{ad}}{L_k + L_s + L_{ad}}\right) L_{ad} I_{f\infty}. \tag{39}$$

Considering expressions (33), (34) and (39), finally :

$$U_{q0} = \frac{X_k}{X_d + X_k} U_{0\infty}. \tag{40}$$

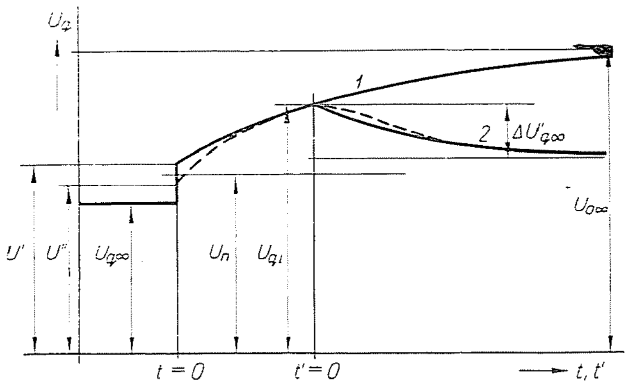

Fig. 8. Change of the envelope-curve of the stator voltage in case of operation of the circuit breaker during short circuit and quick-response overexcitation

Curve 1. Quick-response overexcitation maintains itself unchanged ; *Curve 2.* Quick-response overexciting equipment works and stops quick-response overexcitation

On the basis of the above it may be stated that in maintenance of the quick-response overexcitation, the terminal voltage grows at the initial time after the interruption of the short circuit from the value U_{q0} given by (40) to a value U'' given by expression (38), being the so-called voltage behind the subtransient reactance, and after some cycles it corresponds to a voltage U' given by (37), being the so-called voltage behind the transient reactance. Later the voltage grows according to the transient no-load time constant T'_{do} and finally reaches the maximum voltage $U_{0\infty}$ (see Fig. 8).

In the foregoing we only gave a qualitative picture of the processes, having neglected the saturation. As by quick-response overexcitation an about 4...5-times greater field-current, than that at no-load can be obtained, without saturation the no-load voltage would also grow in the same proportion. But on the basis of the no-load characteristic of the generators it may be stated that on account of the saturation the terminal voltage would reach only 1,5...1,6-times of the rated stator voltage (Fig. 8 was drawn in this consideration). As this value may be dangerous from the point of view of insulation, it must be assured in all cases that at the work of the circuit breaker the process of quick-response overexcitation should stop. Fortunately, there is a time for intervention, as in the first cycles the voltage U' behind the transient reactance is competent (which, even in the worst case is not much greater than the rated voltage), while the terminal voltage would reach the too high $U_{0\infty}$ voltage after a longer time (after some seconds).

3.2. *If the quick-response overexciting equipment operates automatically*

In the following the processes will be examined occurring in case of operation of the quick-response overexciting equipment too, when the circuit breaker interrupts the short-circuit current. According to the operating value and the holding ratio of the equipment, when reaching a certain voltage, the contacts of the voltage-dip relay separate and break the circuit of the quick-response overexciting contactor. According to the release time of the contactor, the R_r' field rheostat is again inserted after a certain delay (Fig. 1a), where $R_r' \neq R_r$, as during the quick-response overexcitation the value of the rheostat could have changed (e. g. because the automatic voltage regulator sets another value). Let us assume the terminal voltage of the generator to be U_{qi} at this initial time. The flux linkage is then $\psi_{di} = U_{qi}/\omega_0$, while the magnetizing current

$$I_{mi} = \frac{\psi_{di}}{L_{ad}} = \frac{U_{qi}}{X_{ad}} . \tag{41}$$

Insertion of R_r' has such an effect as if we connected a $-\Delta U_{e0}'$ voltage — equal in magnitude to the voltage arising at the terminals of the field rheostat just after the insertion — to the field coil of the main exciter. Consequently, a change of current of

$$\Delta I_e' = - \frac{\Delta U_{e0}'}{R_e' + pL_e} = - \frac{1}{pT_e' + 1} \frac{\Delta U_{e0}'}{R_e'} \tag{42}$$

takes place, where $R_e' = R_e + R_r'$ and $T_e' = L_e/R_e'$.

The change in voltage of the main exciter is

$$\Delta U_f' = k \Delta I_e' = - \frac{\Delta U_{f\infty}'}{pT_e' + 1} , \tag{43}$$

where $\Delta U_{f\infty}' = k \Delta U_{e0}'/R_e$.

Change of the field current is :

$$\Delta I_f' = \frac{\Delta U_f}{R_f + p(L_{ad} + L_f)} \tag{44}$$

and considering (43):

$$\Delta I'_f = -\frac{1}{pT'_e + 1} \cdot \frac{1}{pT'_{do} + 1} \frac{\Delta U'_{f\infty}}{R_f} . \tag{45}$$

The time function by aid of the expansion theorem [5]:

$$\Delta I'_f = -F'(t') \frac{\Delta U'_{f\infty}}{R_f} = F'(t') \Delta I'_{f\infty} , \tag{46}$$

where

$$F'(t') = 1 - \frac{T'_{do} e^{-t'/T'_{do}} - T'_e e^{-t'/T'_e}}{T'_{do} - T'_e} . \tag{47}$$

The full magnetizing current with addition of expressions (41) and (46):

$$I_m = I_{mi} + \Delta I'_f = I_{mi} - F'(t') \Delta I'_{f\infty} \tag{48}$$

while the quadrature-axis stator voltage:

$$U_q = \omega_0 L_{ad} I_m = U_{qi} - F'(t') \Delta U'_{q\infty} \tag{49}$$

where $\Delta U'_{q\infty} = \omega_0 L_{ad} I'_{f\infty}$.

In the steady-state, on the basis of (49) and (47):

$$U_{q(t'=\infty)} = U_{qi} - \Delta U'_{q\infty} . \tag{50}$$

From the foregoing it may be stated that the quick-response over-exciting equipment, stopping the process of overexcitation, reduces the terminal voltage of the generator from the maximum U_{qi} value (where $U' < U_{qi} \leqslant U_{0\infty}$, though U_{qi} is perhaps somewhat greater, than the rated voltage of the generator) to a non-dangerous value determined by (50) (Fig. 8). It must be noted that the time constant T'_{do} is by an order of magnitude greater, than the time constant T'_d, therefore the process of stator voltage with a good approximation instead of (49) may be expressed by

$$U_q = U_{qi} - (1 - e^{-t/T'_{do}}) \Delta U'_{q\infty} . \tag{51}$$

3.3. *If the automatic de-energizing equipment is in operation*

Finally, we would mention that during the quick-response overexcitation the automatic de-energizing equipment can work, too. Assuming the field current to be $I_{f\infty}$ and the de-exciting resistance R_l to be parallelly inserted into the exciting circuit of the generator, while the exciter providing the exciting voltage is disconnected. As the exciting circuit of the generator has an inductivity, in the first instant the field current remains unchanged and produces a voltage $I_{f\infty}R_l$ on the resistance R_l. It must be controlled, if this voltage is not dangerous from the point of view of the rotor-insulation of the generator.

Naturally, after the operation of the automatic de-exciting equipment the field current decreases to zero, therefore the terminal voltage of the no-loaded generator, as well as the stator current of the short-circuited generator, decreases to zero.

4. Conclusions

On the basis of the aforesaid, as to the development of the quick-response overexciting equipment, the following conclusions may be drawn.

1. Under normal conditions quick-response overexcitation establishes no dangerous thermal loads from the point of view of the rotor nor that of the stator of the generator. Nevertheless, it is advisable to limit the maximum duration of quick-response overexcitation, to avoid exaggerated heating even in extraordinary cases (continuous breakdown, fault of protection).

2. The effect of quick-response overexcitation prevails completely only after a certain delay and after the termination of a certain process. Therefore, in case of a sudden short-circuit, quick-response overexcitation does not at all influence the initial subtransient current governing the dynamical forces, and scarcely the transient current; it only increases the steady-state short-circuit current.

3. If the quick-response overexcitation is maintained, even after the operation of the circuit-breaker of the generator, dangerous overvoltages may rise in the generator. Therefore, when the circuit-breaker works, care must be taken to stop quick-response overexcitation. If at these times quick-response overexciting equipment stops the overexcitation, the increase in voltage will not become dangerous.

4. The de-energizing resistance must be checked from the view-point, if an exaggerate voltage did not rise in the field circuit of the generator, when during quick-response overexcitation the automatic de-energizing equipment had worked.

Summary

The article examines the conditions prescribed for the quick-response overexcitation, assuring, that the synchronous generator is in no case exposed to an exaggerate stress on account of quick-response overexcitation. The questions of overheating, the electrical processes of the generator due to quick-response overexcitation: the process of currents and voltages, are discussed in details.

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