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IMPROVEMENT OF THE RELIABILITY OF EMERGENCY GENERATORS

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Abstract

The paper shows how the operational parameters and stability of independently operating generators (island mode of operation) could be influenced and improved, respectively, even during the design process by the approximative method of calculation. It presents the main types of generators in island operation and their characteristics, which may be helpful in selection of the emergency generator.

The publication discusses the peculiarities of the special operation and load, respectively, giving advice to the investigation of the effects of saturation, asymmetric mode of operation and overload. It directs the attention to the advantageous properties of the less known and investigated asynchronous-synchronous generators.

Keywords: emergency generator, stability, excitation.

Introduction

The emergency generators are such generators of more or less constant speed the driving motors of which are internal combustion engines, air vanes, water turbines, etc. with a stabilized speed . They are applied in agriculture, building industry, in geological research and in specific fields of industry as emergency current sources in 'island' mode of operation.

Even in the phase of design we have to give thoughts to the improvement of the operational safety of the emergency generators. The majority of them is not properly and sometimes for a very long time stored and transported, but their quick implementation and reliable operation are expected in spite of the unfavourable conditions. Because of this, sliding contacts as well as parts which could become damaged easily are avoided, and constructions are selected which can be manufactured simply.

The following three types of generators meet these requirements the best:

- synchronous generators with permanent magnets,
- asynchronous generators operating as independent units,
- asynchronous-synchronous generators operating as independent units.

This paper is investigating some points of view of the design of these types of generators which are improving the safety of operation taking the usual approximation and the saturation of the magnetic circuit into consideration.

Synchronous Generators with Permanent Magnet

In certain small-sized synchronous generators the magnetic field has been developed already for years by permanent magnets (such types are the bicycle generators, the flywheel generators, etc.). It is evident to try to produce the flux of the independently operating generators with permanent magnets. The usual advantage of this is that there are no excitation coil, excitation losses, sliding contacts, etc. With an optimum design at load conditions, there is a promise for a better stability of the terminal voltage, too. The build-up and the operation of the generator is rather similar to a salient pole synchronous generator having conventional excitation. But some properties of it are deviating from the expected ones. Especially these special properties allow its advantageous application as emergency generator.

Possible Permanent Magnets to be Applied

In synchronous generators cast anisotropic magnets are applied mostly. Though in principle oxide based and rare earth metal magnets could be applied as well, in emergency generators they are not or hardly applied, the afore mentioned ones because of their small remanent induction and air gap flux, while the latter ones due to their high price. Development in manufacturing NdFeB magnets may result in their wide-range application.

Investigation of Stability

It is well known that the relative permeability of the permanent magnets is small ($\mu_r = 1-5$). In the case of the cast magnets, which are recommended for application $\mu_2 \sim 3$, because of the small relative permeability, the value of the direct axis synchronous reactance X_d will decrease and can be even smaller than the quadrature axis synchronous reactance X_q, which can be increased by design and by having a smaller air gap. This could be applied for the development of a special generator the terminal voltage of which is more or less constant independently from its load. For the justification of

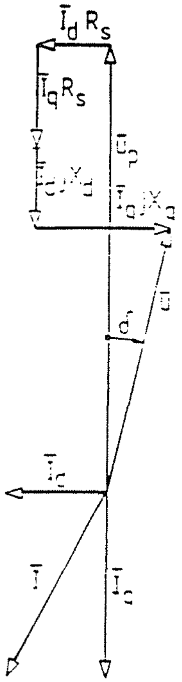

Fig. 1.

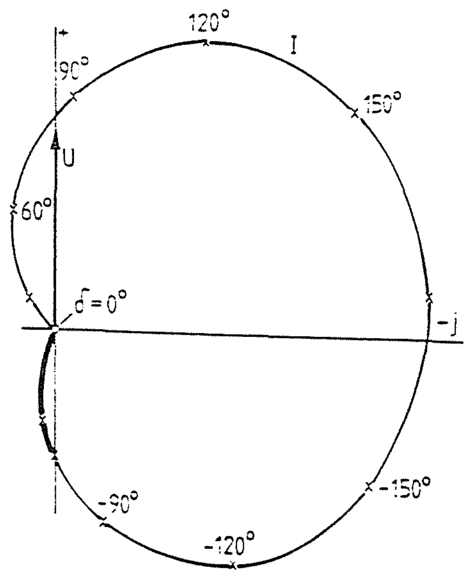

Fig. 2.

this statement, for constant terminal voltage the current operation diagram is established.

In order to do this from the phasor diagram of *Fig. 1* the voltage equation in $\underline{d}$ and in $\underline{q}$ directions are as follows:

$$\begin{bmatrix} U\cos\delta e^{j\delta} - U_p e^{j\delta} \\ U\sin\delta e^{-j(\frac{\pi}{2}-\delta)} \end{bmatrix} = \begin{bmatrix} jX_d & R_s \\ R_s & jX_q \end{bmatrix} \cdot \begin{bmatrix} \overline{I}_d \\ \overline{I}_q \end{bmatrix}, \tag{1}$$

where

$X_d = X_s + X_{ad}$	is the direct axis synchronous reactance
$X_q = X_s + X_{aq}$	is the quadrature axis synchronous reactance
δ	the torque angle
U_p	the field-induced voltage

From here $\overline{I}_d$ and $\overline{I}_q$ can be determined, from which the current

$$\overline{I} = \overline{I}_d + \overline{I}_q \tag{2}$$

can be obtained.

Now the resultant current will be expressed with the machine parameters. After rearrangement, introducing the $\varepsilon = U_p/U$ notation:

$$\overline{I} = \frac{\overline{U}}{(R_s^2 + X_d + X_q)} \left[R_s - j\frac{X_d + X_q}{2} + \right.$$
$$\left. + \varepsilon(-R_s + jX_q)e^{j\delta} + j\frac{X_d - X_q}{2}e^{j2\delta} \right] . \tag{3}$$

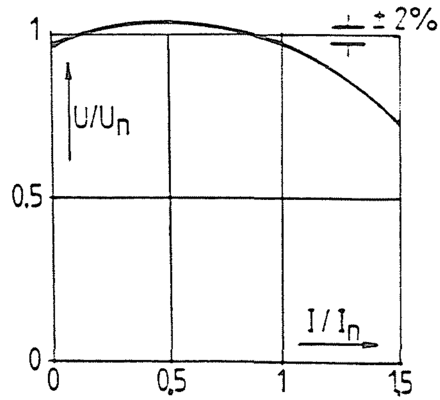

Fig. 3.

Eq. (3) is the equation of a Pascal limacon, the peak point of which is falling to the opposite side — towards the origo — into which the current work diagram for conventional salient pole synchronous generators shows, because $X_q > X_d$. Though this current work diagram is valid for constant terminal voltage, it gives good orientation for the voltage drop of the 'isle' mode of operation as well. If the current work diagram, the reactance and the flux of the synchronous generator is chosen in such a way that the origo is close to that working point of the Pascal limacon which has the $\delta = 0$ parameter (see *Fig. 2*), then as the effect of the load, at $\cos\varphi = 1$ the terminal voltage first will increase, then it will drop (*Fig. 3*). The demagnetizing effect of the load current is negligible because of the small relative permeability of the permanent magnet. ($\mu_r = 1 - 3$ and $X_d < 100$ % , respectively).

Independently Operating Asynchronous Generators

An interesting and recently frequently applied type of the emergency generators is the independently operating asynchronous generator the reactive power of which is produced by a properly selected condenser unit.

Though the generator mode of operation of the asynchronous machines is well known, the operation of the asynchronous generators operating independently shows many special features. Because of this, it is necessary and useful to investigate the stability of these machines. The following points cause difficulties in carrying out the analysis

- the saturations have to be taken into account,
- in the machine there is usually an elliptic field (this is the case at changing load at single phase machines, and at asymmetric load at polyphase generators)
- the frequency is decreasing with the load even at constant generator speed this causes further decrease in voltage).

This paper gives the analysis of the excitation, load and stability problems of the asynchronous generators having elliptic field. The aim is to find out:

- which methods of design will lead to the stabilization of the terminal voltage;
- how the loadability could be determined in the case of inductive consumers;
- which is that speed range within which the generator braking of small asynchronous generators can be realized.

Along the analysis constant generator frequency is presumed, thus such a special driving machine is 'ordered' to the generator the speed of which increases with load. As in this work the potentialities of design are presented, the problems of voltage stabilization will be discussed first of all. In connection with this the case of inductive load must be detailed as well. For the analysis of the asynchronous generator mode of operation it is indispensable to determine the speed range of the self-excitation. This range will obviously give at the same time the range of the generator braking.

Self-excitation of the Asynchronous Generator Having Elliptic Field

The self-excitation of the asynchronous generator having an elliptic field will be investigated for the machine the circuit diagram of which is shown in *Fig. 4*.

The build-up voltage — like the self-excitation of the direct current machines — will realize only then if the rotor possesses a remanent mag-

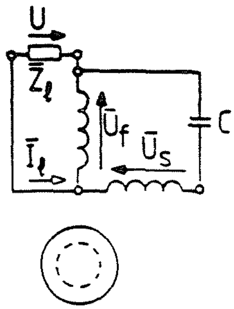

Fig. 4.

netism which will have the effect that a rotating magnetic field corresponding to the number of poles will be generated.

For the actual realization of the self-excitation the generator has to be rotated with a speed higher than the synchronous one ($n > n_0$) and reactive power of the generator should be covered by a capacitor. The real power taken by the shaft under no load conditions is the no load loss of the generator (mechanical-, iron-, and no load copper losses).

Under no-load conditions after rearranging the from *Fig. 4* derived nodal equation, it can be written with the symmetrical components of the phase currents at $I_l = 0$

$$\overline{I}_{po}(k_1 + j) = -\overline{I}_{no}(k_1 - j) , \tag{4}$$

where k_1 is the ratio of the effective number of turns for the fundamental harmonic.

No-load voltage of the generator is

$$\overline{U}_o = \overline{U}_{ao} = \overline{I}_{po}\overline{Z}_{po} + \overline{I}_{no}\overline{Z}_{no} . \tag{5}$$

By the help of equation (4), equation (5) can be rearranged

$$\overline{U}_o = \overline{I}_{po}\left[\overline{Z}_{po} - \overline{Z}_{no}\frac{(k_1 + j)^2}{k_1^2 + 1}\right] . \tag{6}$$

From equation (6) it can be seen, though the accurate value of the no-load voltage is given by the sum of the voltage of positive and negative order, the voltage component of negative order has only a limited correction function.

Under no-load conditions for the circuit shown in *Fig. 4* it can be written

$$\overline{U}_{ao} + \overline{U}_{bo} - \overline{I}_{bo} jX_c = 0 . \tag{7}$$

With symmetric components after rearrangement

$$\overline{I}_{po}\left[\overline{Z}_{po}(1-jk_1)-\frac{X_c}{k_1}\right]=-\overline{I}_{no}\left[\overline{Z}_{no}(1+jk_1)+\frac{X_c}{k_1}\right] . \tag{8}$$

After rearrangement, *Eq.* (8) is divided by *Eq.* (4)

$$\overline{Z}_{po}+\overline{Z}_{no}=j\frac{2X_c}{1+k_1^2} . \tag{9}$$

From Eq. (9) we get with good approximation

$$X_c=\left[2X_s+X_m+\frac{X_m\cdot X_r}{X_m+X_r}\right]\frac{k_1^2+1}{2} . \tag{10}$$

The process of voltage build-up can be easily followed from *Fig. 5.*

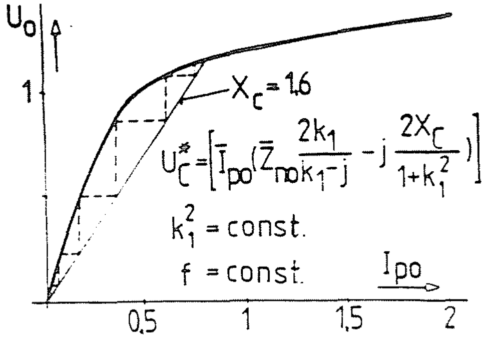

Fig. 5.

The magnitude of the voltage can be changed (at f = const) with the steepness of the line of the U_c^* capacitor voltage. Decreasing the C capacitance value, the capacitor's voltage tangent direction is increasing, the working point A is moving towards the origo. Increasing the capacitance, the tangent direction of the line of the voltage of the capacitor is decreasing, working point A is moving towards the points having larger U_0 voltage, thus, U_0 is increasing. When frequency decreases, the value of X_c increases, thus, the steepness of the line of the voltage U_0, the U_0 cutting point of the induced voltage decreases, thus, the terminal voltage of the generator will decrease because of both of these effects.

From *Fig. 5* it can be seen that

- the magnetic circuit of the asynchronous motor is always saturated;
- application of up-to-date lamination material (heat treated siliconless) is advantageous;
- this is right if the whole magnetic circuit becomes saturated at the same instant;
- the method of the investigation of the self-excitation and that of the stability of the machine having an elliptic field is in its method identical with the analysis with the machine having a symmetrical rotating magnetic field, but the capacitor has to compensate even the demagnetizing effect of the counter rotating component.

The frequency of the self-excitation and the speed range can be determined fast if for the equivalent circuit of *Eq.* (9), (*Fig. 6.a*), a frequency and an angular frequency working diagram is drawn (*Fig. 6.b*). If the frequency diagram is cutting the real axis, then a speed and a frequency range, respectively, can be determined — section g-h in *Fig. 6.b*- within which the generator mode of operation and the self-excitation, respectively, will be realized.

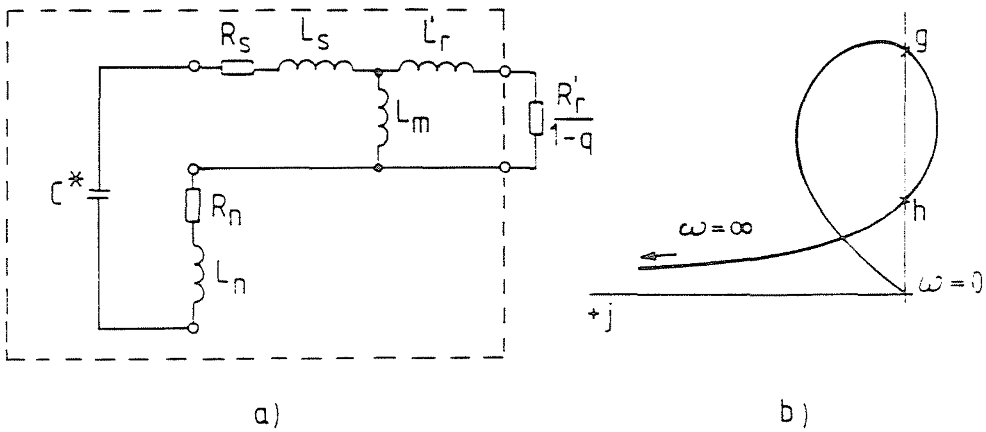

Fig. 6.

The Determination of the Working Point

The working point of the asynchronous generator — point *A* in *Fig. 5* which is the cutting point of the straight line of U_c^* of the capacitor and that of the magnetizing curve — will be selected in such a way that even having a 40 – 50 % overload demagnetization should not occur, the capacitor power should be at minimum rate and the voltage increase of the generator running under no-load conditions should be, at unchanged capacitor value of minimum magnitude. From the nodal equation written for *Fig. 4* and after rearrangement the load current is determined:

$$\overline{I}_l = \overline{U}\frac{2X_c + j(k_1^2+1)(\overline{Z}_p + \overline{Z}_n)}{X_c(\overline{Z}_p + \overline{Z}_n) + 2jk_1^2\overline{Z}_p\overline{Z}_n} . \tag{11}$$

Based upon Eq. (11), having $\overline{U}$ = const. and f = const., the speed range can be determined within which the generator mode of operation can be realized (*Fig. 7.a*). When load is increased at constant generator speed and at $\cos\varphi_t$, the terminal voltage of the generator will decrease (*Fig. 7.b*). As it can be seen from *Fig. 7.a*, the magnetizing current is decreasing, the slip of the generator is increasing and, as a consequence, the frequency is decreasing, this is what causes the drop in the terminal voltage.

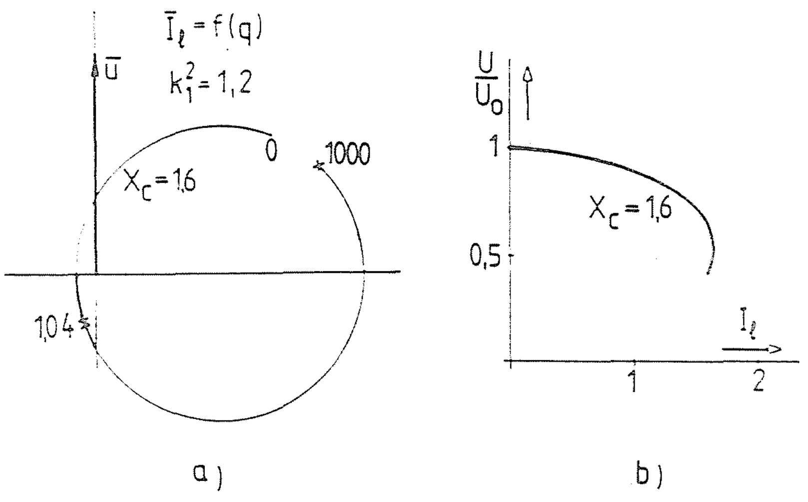

Fig. 7.

Though based upon the curves of *Fig. 7* the magnitude of the load current belonging to the demagnetization and the measure of the increase of the voltage of the generator running under no-load conditions can be determined, there is no basic point for the design of the generator which belongs to a minimum capacitor power.

Based on physical consideration it can be seen that power of the capacitor is considerably influenced by the main field inductance. To a

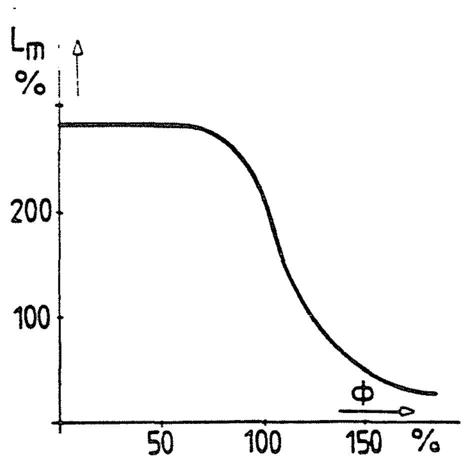

Fig. 8.

small main field inductance and a large saturation, respectively, a large excitation current and a large capacitor power belong, however, at the same time, the unsaturated generator is unfit for operation.

In *Fig. 8* the curve of $L_m = f(\phi)$ is shown. In order to decrease the measure of the change of the terminal voltage, the measure of the change of the flux has to be decreased. This condition is satisfied if:

$$L'_{m\,\min} = \frac{\partial L_m}{\partial \phi} \quad \text{or} \quad L'_{m\,\max} = \left|\frac{\partial L_m}{\partial \phi}\right| . \tag{12}$$

Thus, the measure of the voltage drop is the smallest if the working point is on the steepest section of the curve. Namely, in this case a small change in flux can be achieved. Obviously, for operation and load, respectively, it has to be taken into consideration that also the reactive power demand of the consumer must be covered by the generator, because of this the loadability decreases considerably. This decrease could be avoided partly or even fully if the reactive power demand of the consumers is satisfied by a separate capacitor unit.

Asynchronous — Synchronous Generators

These are such independently operating small generators (*Fig. 9*) the stator of which is identical with that of the asynchronous generators, its rotor is similar to the synchronous machines having salient pole rotor.

On the rotor there are two excitation coils perpendicular to each other in space, by the help of which the realization of excitations in d and q

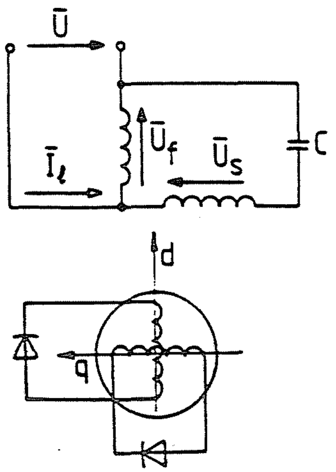

Fig. 9.

directions becomes possible. These coils are through diodes separately short circuited. Because of the diodes the induced voltage will drive a unidirectional current and as a consequence the mmf in the direct axis direction will support the previous main flux and the mmf in the quadrature axis direction will compensate the armature mmf. In this way — though having a squirrel cage rotor this will have a more complicated construction — the terminal voltage will be constant or at load it can even increase.

The Recovery of the Excitation of the Generator

The recovery of the excitation of the generator takes place in the same way as it was discussed in Point 2 in connection with the independently operating asynchronous generators, but the saturation of the generator and the power of the capacitor can be here considerably smaller. During the time of the recovery of the excitation the generator is working under no-load conditions. It is advisable under no-load conditions to seek after a symmetric rotating magnetic field. Then the rotor currents are developed by the space harmonics and the asymmetries.

The Effect of the Load

When loading the generator an elliptic field will develop, and as an effect of this the direct axis and the quadrature axis mmf will increase. Qualitative analysis shows that a twofold compensation will be realized: the direct axis mmf is increased and, as a consequence, the flux in direction $\underline{d}$ and the pole voltage, respectively, as well, furthermore, the quadrature axis flux increases and, thus, the armature mmf is directly compensated.

There are no special conditions set for the diodes built into the rotor, but along the design and manufacturing procedure care has to be taken of their positioning and fastening, furthermore, that the warming up of the rotor and the technology of impregnation should not cause any damage to them.

Summary

Three characteristic types of the simple and reliable generators working in 'isle' mode of operation have been shown. Attention has been drawn to some characteristic features of operation in design as well. It has been shown that the quality and the reliability of the machines are definitely substantially influenced by the design and manufacturing process.

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