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Some aspects of comparing the operational properties of synchronous machines with a conventional and two mutually shifted excitation windings

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Abstract. A comparative analysis of the operational properties of traditional and two-valve synchronous machines with a rotor, having a reciprocating axis, excited from independent regulated DC sources, is generalized. On the basis of research, it has been shown that the use of a control quadrature excitation winding significantly improves the performance of synchronous machines at low costs for its manufacture. The authors have shown a significant improvement in the performance of machines with different operating modes based on the results of theoretical and experimental studies carried out on synchronous machines with a rotating axis of magnetic saturation, attached to various designs of quadrature excitation winding. It has been recognized that neglecting magnetic saturation in performance calculations for synchronous machines leads to significant estimation errors properties of the studied machine. In addition, the advantages of synchronous machines with sine-cosine field winding are shown. With an insignificant complication of the manufacturing technology, it opens the way to solving the problem of creating energy-saving turbine generators, which have a property that is very important for the practice of operation, i.e. an almost unchanged (sinusoidal) shape of the resulting magnetic field in the air gap of the machine within the allowable range of load variation under steady-state symmetric modes.

1 Introduction

Automatic excitation controls (AEC), used to increase the stability of synchronous machines with conventional excitation in some operating modes, cannot meet the requirements imposed by them. Therefore, the search for new means of increasing stability led to the creation of synchronous machines having two windings on the rotor with mutually shifted axes on 90; 60; 120° [1-3].

By their property, they are synchronous machines with a rotating magnetization axis. When the excitation windings are powered from independent regulated DC sources, they are called synchronous longitudinal-transverse excitation machines (further SM d-q) [4,5],

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and when powered from regulated alternating current sources of frequency $f_2 = sf_1$ - asynchronous synchronous machines (ASM) [6]. In both types of synchronous machines (SM), the improvement of operational characteristics is achieved due to the manifestation of a new (valuable) property of the machine due to the placement of two windings with mutually shifted axes on the rotor, in which the resulting magnetic flux created MDF of the excitation windings can vary not only in magnitude, but also in phase relative to the pole axis. When evaluating the properties of SM, it is necessary to pay attention to the following qualities: maneuverability, reliability (high stability under various operating modes) and energy efficiency in operation; cost (lower costs in the manufacture or modernization of machines) or a short payback period for the costs invested in the manufacture. Comparison of the operational properties of the SM must be carried out under the same working conditions.

2 Methods

In this article presents a comparative analysis of the operational properties of a SM with a conventional and two mutually shifted excitation windings powered by independent regulated DC sources. The numbers indicated below by the index "d" indicate under what conditions and operating modes CM with a conventional excitation winding cannot meet the requirements of operation (in power engineering and special installations) or do not perform the functions assigned to them qualitatively. The efficiency of using synchronous generators (SG) and compensators (SC) with two mutually shifted field windings is given under the same numbers, but with the index "d- q".

3 Results and discussion

1(d). The main field of an ordinary SM is stationary relative to the rotor of the machine, i.e. it is rigidly connected to the rotor and it can change its position in space only when the angular position of the rotor changes relative to the stator field.At constant values: voltage U, excitation current I_f and in inductive resistance along the longitudinal axis X_d, The angle θ between the EDF vector E_{fq}, and the voltage vector of the generator (U_r) is the load angle, is the angle of the load, that is, the angle of stability SM.

l(d-q). Due to the additional transverse magnetization, the SM acquires a new property, that is, depending on the polarity of the current in the transverse excitation winding, the axis of the resulting excitation field can be rotated by rotation of the rotor or in the opposite direction relative to the longitudinal axis of the machine, as a result of which it has greater maneuverability, which is a very valuable property for improving the operational characteristics of the SM. For CM d-q, the angle $\theta=\Delta\pm\alpha$ is not a load angle (the angle of the device), because it depends not only on the load angle (indicated by the letter "Δ"), but also from the angle of shift α = arctg (E_{fd}/E_{fq}) of the vector of the resulting excitation EDF $E_f = \sqrt{E_{\mathrm{fd}}^2 + E_{\mathrm{fq}}^2}$ and the transverse axis q. In SM d-q, the angle θ determines the angle of displacement of the rotor (Fig.1).

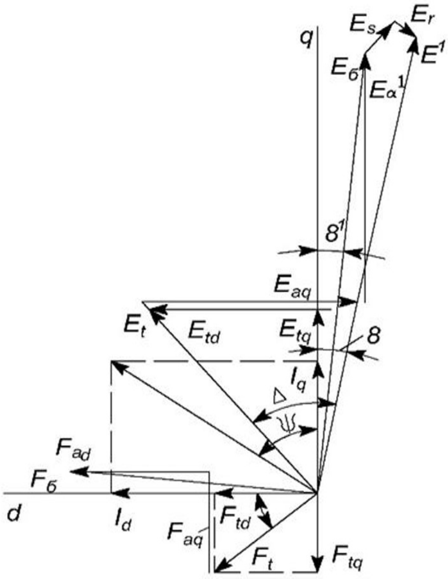

Fig. 1. Vector diagram of the generator mode under excitation

2(d). In traditional CM, an increase in stability during deep voltage landings as a result of three-phase short circuits in the network or with significant load changes is usually provided by maximum forcing of the excitation current, however, the reactive power changes significantly, therefore, not all requirements of a regime nature can be provided simultaneously. The post-accident transient process fades very slowly.

2(d-q).With the ability to control the phase of the resulting vector EMF when additional regulation of excitation in the transverse axis of the synchronous turbine generator (STG), due to the asynchronous torque values are significantly reduced power fluctuations, due to the significant changes in the load, and provides other requirements of a sensitive nature, then eats maximum stability; minimal loss of energy in the car and on the network; suppression of vibrations of the rotor; maintaining voltage, which leads to increased reliability STG d-q [4,7, 8]. The post-accident transient process attenuates approximately an order of magnitude faster than when forcing the excitation current only in the longitudinal axis.

3(d). Conventional two-pole STGs, due to the presence of a large tooth on the rotor, have some magnetic non-symmetry, which under certain conditions can be a source of fluctuations in current, voltage and power of the machine, as well as additional mechanical vibrations.

3(d-q). With a symmetrical distribution of the grooves of the excitation windings around the circumference of the rotor barrel, the above-mentioned tendency of the machine to fluctuations in the operating parameters and additional mechanical vibrations of the double frequency of the network are almost absent.

4(d). In conventional SG and SC, it is impossible to ensure a stable operating mode when the reactive power consumption is of sufficient magnitude [4, 9, 10].

4(d-q). As shown by theoretical and experimental studies [4, 10-14], the regulation of excitation in the transverse axis by the constancy of the angle θ=0 allows increasing the reactive power consumed from the network to a value that is limited by a short-term permissible overload, and if necessary, a long-term mode-by the nominal value of the armature current, while maintaining stable operation in the mode with negative excitation (Figure 2).

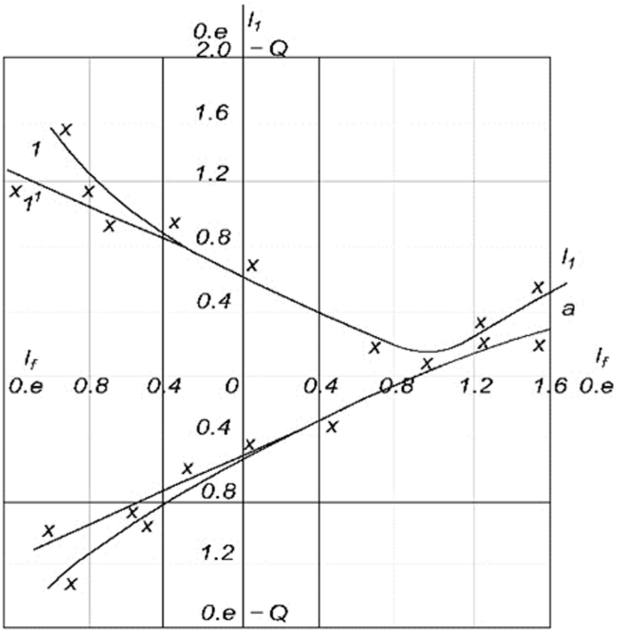

Fig. 2. U-shaped (1;1) and $Q = f(If)$ [2;2'] characteristics of the synchronous compensator of longitudinal-transverse excitation in the mode of reactive power consumption: 1-without compensation of the transverse armature reaction; 1-with compensation of the transverse armature reaction by meansof the MDF of the transverse excitation winding; xxx-experimental points.

5(d). At small angles of displacement of the rotor of the usual SM, characteristic of the occurrence of self-oscillation, regulation in the longitudinal axis is not able to affect the movement of the rotor. Synchronous self-excitation due to the parametric moment of the single-pole SM can be suppressed by the ARC in the longitudinal axis, and asynchronous self-excitation of the SM due to the dynamic parametric moment of the such regulation does not apply (4).

$$M_{d.p.} = (U^2/2\omega_1).(1/X_q - 1/X'_d) \qquad (1)$$

5(d-q).At small angles of displacement of the rotor SM, the most effective means of eliminating electromechanical instability (self - leveling) is the ARC in the transverse axis of the machine. At the same time, a current with the frequency of the rotor swing should flow in the transverse excitation winding, and the phase of this current should be ahead of the rotor oscillations by 90° el. An effective means of eliminating electromagnetic instability (both forms of self-excitation) of SG and SC is also the regulation of excitation in the transverse axis, in which energy losses in the active resistance of the stator circuit and the electromagnetic moment caused by it are compensated [4, 15].

6(d). In conventional SG, when they work with a heavy load due to the armature reaction, the resulting field in the air gap is significantly deformed, which leads to an increase in the amplitude of the higher harmonics of the magnetic field, and this in turn leads to both an increase in losses in the stator teeth and a decrease in the stability of the machine.

6(d-q). When performing the excitation windings of non-polar SG in the form of a sine-cosine structure [16, 17], in all steady-state symmetric modes (within permissible loads), the shape of the magnetic field in the air gap of the machine remains almost sinusoidal.

Consequently, there are no higher harmonic fields arising from the armature reaction and the losses caused by them. With the sinusoidal shape of the magnetic field, the stability of the machine and energy indicators also increase.

7(d). When the excitation system fails, the synchronous operation of a conventional STG is impossible, and it switches to asynchronous mode. At the same time, "according to the "Rules of technical operation", the active power should be reduced to 50%, and the duration of operation is limited to 15 minutes.

7(d-q). In case of complete failure of one of the two excitation systems, the STG with symmetrical excitation windings can continue to operate in synchronous mode as a conventional STG, which is another advantage of the STG with two excitation windings compared to traditional ones. But, due to the symmetrical arrangement of the excitation windings on the MDF rotor, each of the windings is 2 times smaller than in conventional STG, so its load must be reduced by 20% [18].

8(d). In a conventional SG, the EDF increment of the armature ΔE due to the regulation of the excitation current ($I_{fd} = I_{fd0} + \Delta I_{fd}$) is always directed along the transverse axis of the rotor and causes deviations of both the active powerΔP and the reactive power ΔQ of the machine [18].

8 (d-q). By changing the ratio of currents in the excitation windings SM d-q, the phase and the magnitude of the ΔE - vector of the armature EDF increment can be adjusted: if it is perpendicular to the armature voltage vector U, then, as noted in [1,18], only the active power can be adjusted, and if the EMF increment is directed along the vector U, then the reactive power. This differentiation of regulatory functions between.

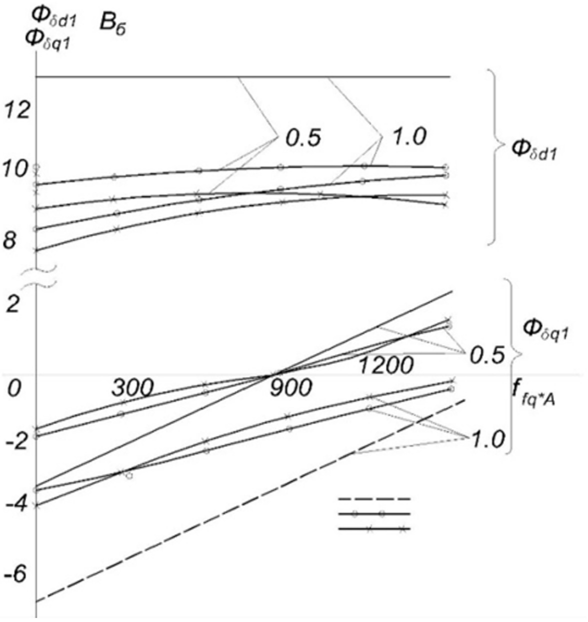

Fig. 3. Magnetic characteristics of $\Phi_{\delta d1}$, $\Phi_{\delta q1} = ƒ(F_{fd})$by Ψ = O, F_{fd} = 1240 A = const and MDF armature Fα = 0,5; 1 and 2 - without and taking into account saturation, respectively.

This distinction regulatory functions between the windings and excitation is of great practical importance, however, studies show magnetic characteristics SM d-q (Fig. 3), even at θ≈0, we cannot exclude the phenomenon of mutual influence of magnetic fields in the longitudinal and transverse axes high voltage SM (shear excitation windings 60°. The mutual influence of MDF them even stronger), resulting in regulation (especially with boost) excitation current in one axis leads to changes in the magnetic flux in the other axis [19-21].

In [22], to assess the stability of the STG with a transverse control winding on the rotor, the coefficients of cross-regulation are used in the characteristic equation of the regulated machine, "additives" due to the mutual influence of the ARC on different axes. Such an artificial accounting technique is approximate, and correct accounting of the mutual influence of the longitudinal and transverse contours is possible only on the basis of calculating the magnetic field in the SM d-q air gap according to the real distribution of the MDF of the excitation windings and the armature winding [19].

Thus, separate regulation without taking into account the mutual influence of longitudinal and transverse fields leads to errors that depend on the nature of the regulation of the machine, for example, with "strong" regulation of excitation, errors can be significant.

9(d). In conventional SG, the provision of dynamic stability is limited by forcing the current in the longitudinal excitation winding, whose MDF in normal mode is $F_{fd} = I_{fd}.W_{fd}$. At the same time, synchronous mode is provided, but with large fluctuations in some operating parameters.

9(d-q). In SM d-q, the resulting MDF of the excitation windings is equal to $F_{f(d-q)} = \sqrt{F_{fd}^2 + F_{fq}^2}$.Let's compare the EDF in the stator windings of the implicitly polar SG caused by the MDF of machines with one excitation winding F_{fd} and the resulting MDS of the excitation windings SM d-q corresponding to the same values of the MDF of the excitation windings $F_{f(d\cdot q)}$,, the value of which is $F_{f(d\cdot q)} = F_{fd}$. At the same time, the EDF induced in the stator winding of the MDF of each of the excitation windings is almost $\sqrt{2}$ times less than in a machine with one excitation winding.Despite this, due to the ability to control the phase of the longitudinal-transverse MDF excitation, the limit of dynamic stability in a SG with two excitation windings mutually shifted axes is 25-30% higher than in a machine with one excitation winding [18, 21].

10(d). Previously, when testing STG at the manufacturer's stands, the active load was provided by the phase difference between the EMF of two conventional SM coupled on a common shaft. At the same time, the phase shift was carried out by mechanical rotation of the rotor, which led to an abrupt change in the load and, in addition, the test process was time-consuming work [22].

10(d-q). The use of SG with biaxial excitation of sufficient power in return operation circuits (and mutual loading, as their special case) when testing STG and other large synchronous machines makes it possible to ensure a smooth change in the active load in a purely electrical way and, in addition, the testing process becomes easier.

11(d). In the experimental study, methods of physical modeling aimed at developing variants of new designs are of particular importance. To study (test) a conventional synchronous machine under load, an adjustable load device is required.

11 (d-q). In SG d-q, due to the possibility of creating a transverse field of excitation, it is possible to simulate the active load of SG in autonomous operation, which is another feature of such machines compared to conventional SM.

12(d). In the practice of electrophysical research, pulses with a flat top of a short duration, measured in milliseconds, are obtained by forcing excitation in conventional shock generators. In some cases, it is desirable to have a large steepness of the leading edge, which is impossible to implement on conventional shock generators [23].

12(d-q). If a shock SG d-q is used to increase the rate of current rise in the load and a current is applied to the transverse excitation winding in such a direction that the magnetic field of the rotor turns in the direction of rotation of the rotor, then the rotation speed of the field is greater, the greater the voltage applied to the transverse winding and the smaller its time constant, therefore, the transverse winding is connected to a pre-charged capacitor bank [23].

4 Conclusions

1) The main technical and economic advantages of synchronous machines with two mutually shifted excitation windings are obtained during their operation by increasing reliability and maneuverability in operation, reducing losses in power transmission lines or in power supply nodes, reducing the cost of installing reactors, etc.

2) Synchronous machines with a transverse control winding on the rotor in most cases meet the requirements of operation with low costs for the manufacture of an additional winding when upgrading them in order to improve the basic properties and extend the service life specified in the standards.

3) When regulating in two SM axes (especially when forcing excitation), the mutual influence of longitudinal and transverse contours can make significant changes to the results of regulation. Correct accounting of this phenomenon is possible only on the basis of determining the magnetic field in the air gap of the machine, taking into account magnetic saturation.

4) The use of a sine-cosine excitation winding with a slight complication of the manufacturing technology opens the way to solving the problem of creating energy-saving turbo generators that have a very important property for the practice of operation, that is, an almost unchanged (sinusoidal) shape of the resulting magnetic field in the air gap of the machine within the permissible limits of load variation under steady-state symmetrical modes.

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