

Turbogenerator Electromagnetic Analysis with Changing Reactive Load

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Abstract. Comparative numerical analysis of electromagnetic processes in the end zone of powerful turbogenerators has been carried out at changes in reactive load from rated duty to underexcitation, as well as performance parameters of static overload that determine the stability of synchronous operation of turbogenerators in the power system.

It was demonstrated that the representation of magnetic field sources and calculation results in the form of rotating waves allows simplifying and speeding up the solution of three-dimensional electromagnetic problems in the turbogenerator end zone.

Using a previously developed calculation method, the electromagnetic fields and processes in over- and underexcitation modes, in particular, peculiarities of shielding in turbogenerators are studied.

It was established that the added losses and electrodynamic forces in underexcitation modes acting on the outermost core packages, pressure plate, and stator shield increased by 1.5–3.0 times, resulting in accelerated aging of the turbogenerator end zone. An appropriate margin shall be provided in the cooling system and the structural design of the turbogenerator end zone.

Static overload capacity in nominal conditions is determined by the ratio of maximum power to rated power. An analytical functional relationship between static overload capacity and load conditions was established.

It was demonstrated that when switching to the underexcitation mode while maintaining the active load due to a decrease in the excitation current and maximum power, the static overload factor decreases to unity, that there is virtually no static stability margin of the turbogenerator in this mode.

Calculations were made for turbogenerators with a capacity of 200–1111 MVA.

It is recommended to limit the operation of turbogenerators in underexcitation modes and to use specialized compensators more extensively.

Key words. Turbogenerator, electromagnetic analysis, end zone, underexcitation, static overload.

Introduction

In electrical networks with renewable energy sources, conventional generating equipment is periodically switched to reactive power compensation or underexcitation modes to ensure stable operation of the power system.

The underexcitation modes are permissible in accordance with the typical P-Q capability diagram of IEC 60034-3 [1] (section C in Fig. 1) and are limited by end zone heating, or by static stability conditions, or by both criteria simultaneously. Technical documentation for generators usually specify the parameters of these generators at rated load. Special aspects of operation in the underexcitation modes are not specified as a rule.

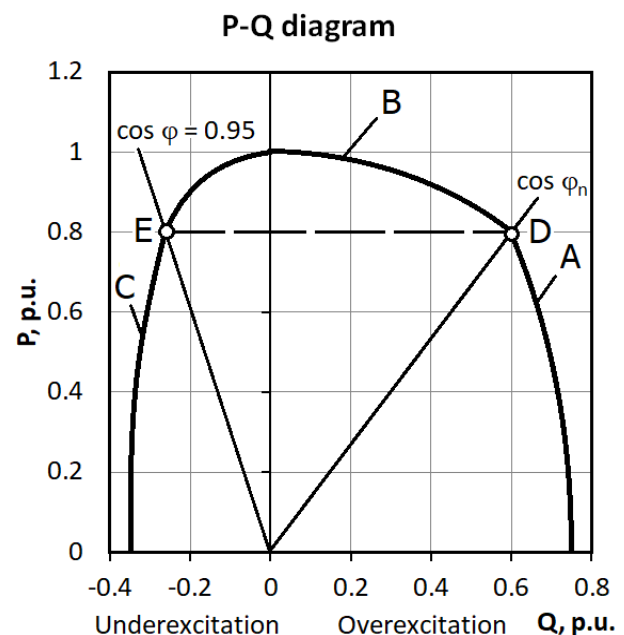


Fig.1. Turbogenerator P-Q diagram in overexcitation and underexcitation modes

The purpose of this article is to conduct a comparative analysis of the electromagnetic state of a high power turbogenerator and especially its end zone, including comparative analysis of the turbogenerator overload capacity when varying operating modes from rated conditions to underexcitation mode in accordance with the requirements and recommendations of IEC 60034-3. For this purpose, to determine the effect of reactive power, the active load is assumed to be unchanged (line DE in Fig. 1).

The mathematical framework and software products developed taking into account the peculiarities of rotating magnetic fields and the properties of turbogenerator designs were used.

1. Electromagnetic analysis

A. Magnetic field in the turbogenerator end zone

When calculating the end-zone field, the rotating magnetic field method was used [2]. Analytical representation of rotating waves of field sources with homogeneous or periodic electromagnetic characteristics of the machine design allowed obtaining the results of field calculation also in the form of a superposition of rotating waves:

$$X(r, \varphi, z, t) = X_m(r, z) \cdot \exp[j(\omega \cdot t - \nu \cdot \varphi + \phi_x)], \quad (1)$$

where $X_m(r, z)$ – complex amplitude, ν – harmonic number, ϕ_x – initial phase.

For rotating fields, the three-dimensional magnetic scalar potential, taking into account the results of differentiation with respect to direction of rotation " φ ", is expressed in terms of two-dimensional operators in plane (r, z) :

$$\text{div}_2 \mu \cdot \text{grad}_2 U_m - (\nu^2 / r^2) \cdot \mu \cdot U_m = \text{div}_2 \mu \cdot H_{0m}, \quad (2)$$

where H_{0m} is the amplitude of the vector-valued function of the current, μ is the magnetic permeability of the medium.

In the region of eddy currents, to reduce the calculation error, not secondary sources are used, but Maxwell's differential equations for field vectors are directly

integrated. In this case, differential equations are also expressed in terms of two-dimensional operators.

The classical boundary conditions are used, as well as those of the impedance type on the outer ferromagnetic boundaries.

The calculation model takes into account the phase ratios of currents, the geometry and spatial layout of the windings, the magnetization characteristics of the materials of the stator and rotor cores, the geometry and electromagnetic parameters of structural materials.

Numerical calculations derived the distribution of electromagnetic fields, eddy currents, additional losses and electromagnetic forces in the structural components of the end zone of a high power turbogenerator, including the stator winding, end packages of the stator core, pressure plates, electromagnetic shields, ventilation screens, and the generator housing.

Numerical analysis was made for air-cooled turbogenerators with a capacity of 200 MVA and for water-cooled turbogenerators with a capacity of 1111 MVA.

B. End zone in underexcitation mode

Based on the results of numerical calculations, the effect of a change reactive load on electromagnetic processes in the turbogenerator end zone was analyzed at a unchanged active load, confirming and developing the previously performed qualitative analysis [3].

In the underexcitation mode, a significant increase in losses and electromagnetic forces was obtained in the end core packages, the pressure plate and the shield of the turbogenerator end zone, associated with an increase in the axial component of the resulting magnetic field in this mode (Fig. 2–4).

At the same time, when the magnetic flux is drawn into the stator core end, there is a slight decrease in losses in the ventilation screen of the turbogenerator.

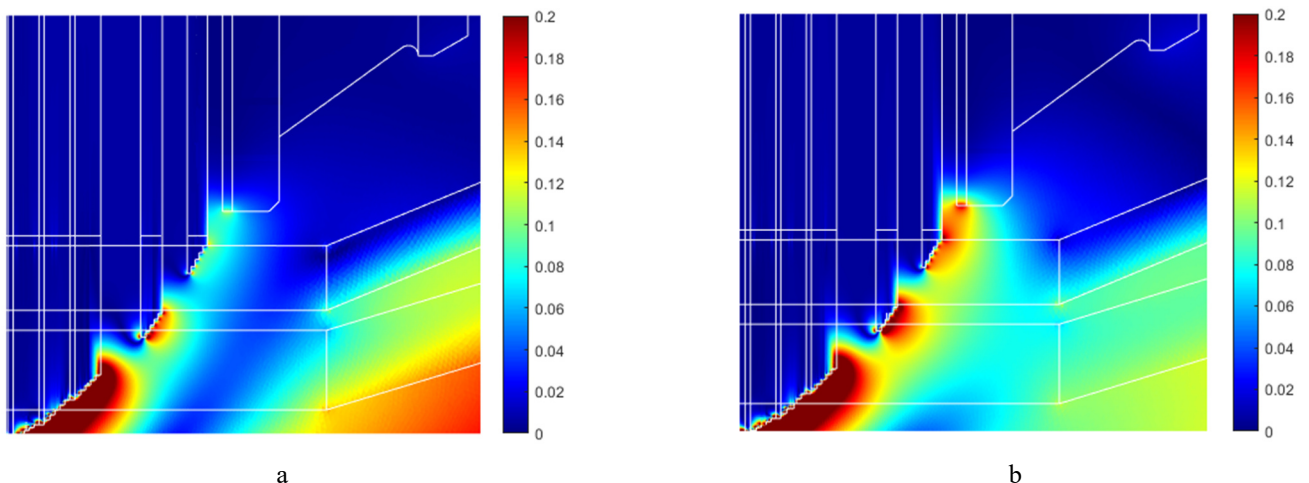


Fig. 2. Axial magnetic field component in the turbogenerator end zone at rated load (a) and at underexcitation (b)

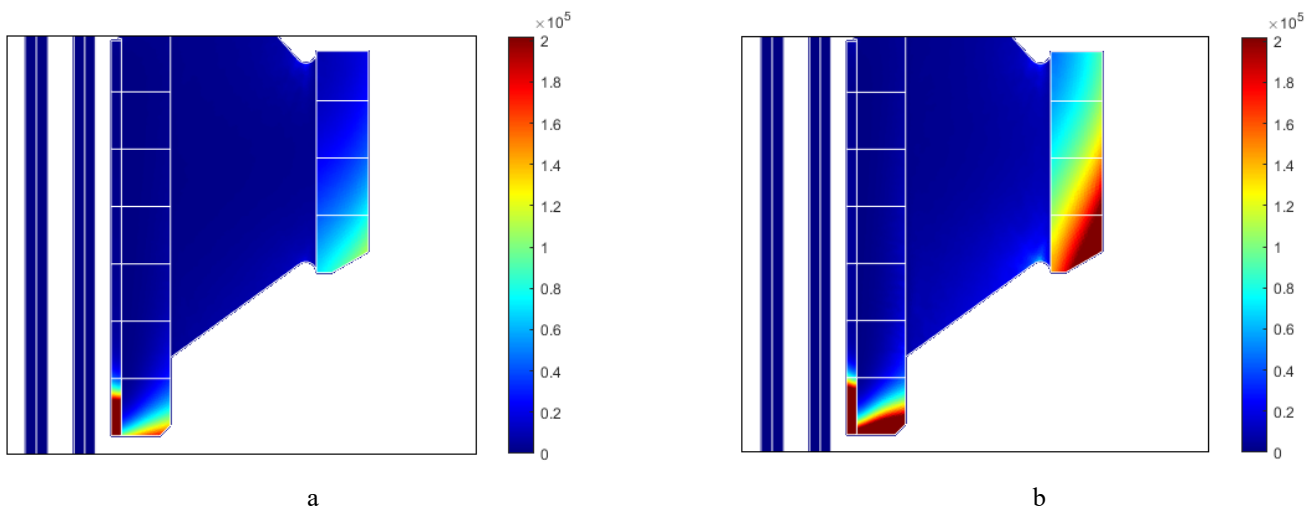


Fig. 3. Distribution of losses in the section of the pressure plate and the shield of the turbogenerator end zone at rated load (a) and underexcitation (b)

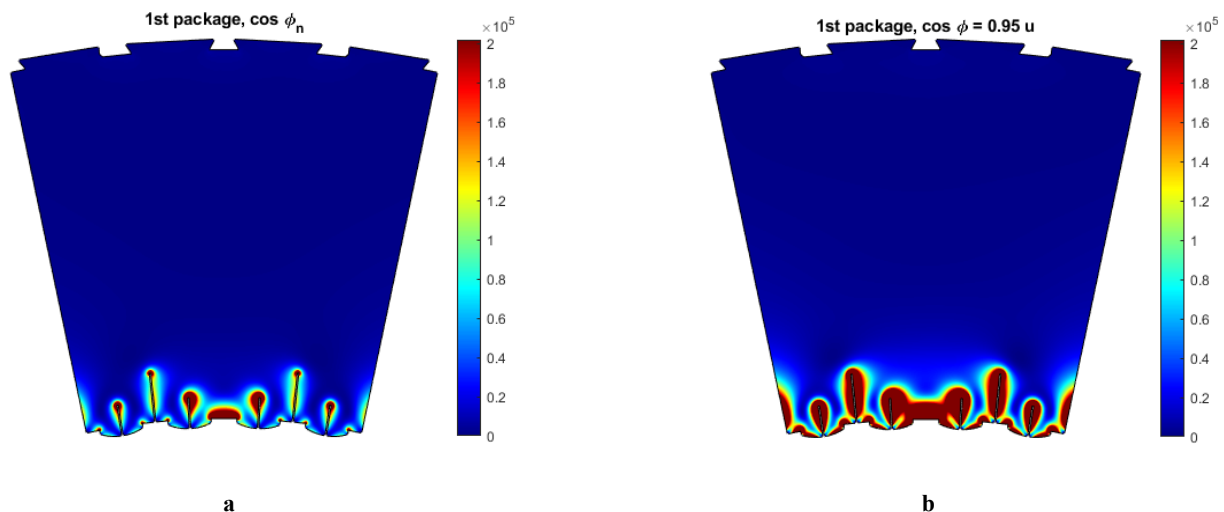


Fig.4. Distribution of losses in the stator core end package of the turbogenerator at rated load (a) and underexcitation (b)

Eddy currents in the electromagnetic shield and pressure plate protect the stator core from axial magnetic field component. Additional losses depend on the operating mode (Fig. 3, 5).

It was demonstrated the greatest losses are allocated at the lower edge of the pressure plate and the electromagnetic shield and increase in the underexcitation mode (power factors with "u" index in Fig. 5) by 1.5–3 times compared to the rated load conditions.

The edge effect in this area reduces the shielding efficiency due to the phase shift of the eddy currents in the lower edge of shield relative to the resulting magnetic field.

Increased losses and heating are common to the by shield uncovered teeth and slot bottoms of the stator end packages. An appropriate margin shall be provided by the cooling system and the design arrangement of the

turbogenerator end zone, including a stepped bevel and slotting of the teeth and the slots bottom of the stator end packages (Fig. 4), also by reducing the thickness of these packages.

Interaction of eddy currents with the magnetic field creates electromagnetic forces and end zone vibrations transmitted to the stator winding, including connecting and output busbars. They supplement the forces and vibrations formed by direct interaction with the magnetic field of the winding's and busbars own currents.

An increase in the electromagnetic forces acting on the stator core end packages in the underexcitation mode results in increased vibrations of the teeth of electrical steel segments and their accelerated wear. To increase the performance reliability of the stator end zone, the segments of the core end packages are glued together.

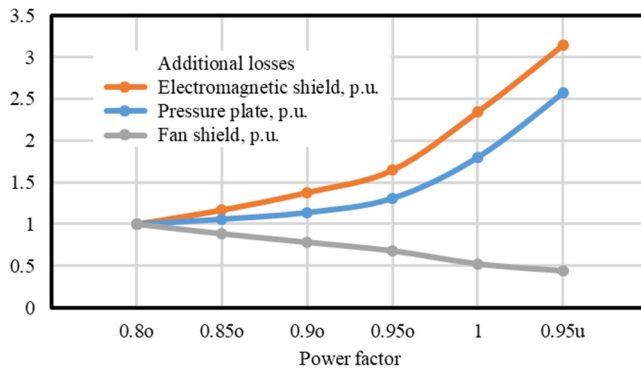


Fig. 5. Total additional losses in the turbogenerator end zone structural elements, as function of changing reactive load

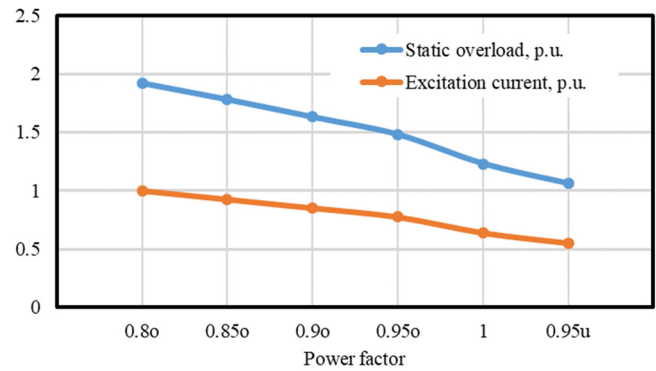


Fig. 6. Excitation current and static overload, as function of changing reactive load

C. Static overload

Let us consider the dependence of the turbine generator static overload capacity on the reactive load (or power factor at unchanging active power), which affects the stability of operation in the power grid during short-term overloads and short circuits. In rated conditions, the static overload capacity s_n is determined by the ratio of the maximum P_{mn} and rated P_n active powers and is expressed in terms of the load angle Θ_n between the rated excitation electromotive force vector E_{fn} and the voltage of the m -phase machine U_n .

$$s_n = P_{mn} / P_n = 1 / \sin \Theta_n, \quad (3)$$

$$P_n = m \cdot E_{fn} \cdot U_n \cdot \sin \Theta_n / x_d, \quad P_{mn} = m \cdot E_{fn} \cdot U_n / x_d, \quad (4)$$

where x_d —synchronous reactance at rated load.

When changing the reactive load and maintaining the active power according to the DE line in the P-Q diagram in Fig. 1, we go from the rated conditions to underexcitation mode. Thus reduces the excitation current (Fig. 6), the corresponding excitation electromotive force E_f and the maximum power P_m for this mode.

Static overload capacity with changing reactive power and maintaining active power, rated voltage and frequency changes proportionally to the excitation current and is related to static overload capacity for rated conditions (3) by formula (5):

$$s = (i_f / i_{fn}) \cdot (\cos \varphi / \cos \varphi_n) s_n = 1 / \sin \Theta, \quad (5)$$

where (i_f / i_{fn}) , $(\cos \varphi / \cos \varphi_n)$ is the ratio of excitation currents and power factors in this mode and at rated load, Θ is the load angle in this mode.

When deriving formula (5) on the basis of (3), (4), the direct proportionality of the electromotive force to the excitation current, and the inverse proportionality of the synchronous reactance to the power factor, were taken into account.

In the underexcitation mode, the static overload factor decreases to values close to unity (Fig. 6), and the load angle approaches 90 degrees, that is, this mode lacks stability margin for synchronous operation.

The peculiarity of operation of turbine generators in the underexcitation mode shall be taken into account when ensuring the reliability of the power system.

3. Conclusion

Analysis showed that the operation of powerful turbogenerators in underexcitation mode results in increased electromagnetic, thermal, and mechanical loads of structural elements of the end zone of turbogenerators, increasing by 1.5–3 times compared with the rated load mode and resulting in the reduction of the operating life of turbine generators.

On the other hand, the lack of static overload margin of turbogenerators in this mode reduces the reliability of the power system.

In this regard, it is advisable to limit the operation of conventional turbogenerators in reactive power consumption modes.

To consume reactive power in the network, it is reasonable to use static or electromechanical compensators, for example of asynchronized type [4].

References

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