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Electromagnetic Forces and Mechanical Stresses in the Outer Segments of Turbine Generator Stator

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Abstract. In light of design features, electromagnetic loads and operating modes of turbine generators, a traveling wave of electromagnetic force density acting on the outer segments of the stator end stacks was determined. Concentration of force action on the edges of the teeth of loose segments is introduced in the analytical solutions for the ripple bending electromagnetic moments acting on the radial and tangential fixings (restraints) of the segments. Solutions for bending moments are obtained using the equivalent concentrated force in terms of generalized functions. It has been established that, for the ratios of the width of the teeth and the pole arcs used in turbine generators, bending moments are substantially unchanged across the width of the teeth, regardless of the location of the restraints.
Stresses in the segment restraints were determined and failure criteria (if exceeded) were defined. It has been shown that the most dangerous bending stresses are those at the edges of tangential restraints, as it appears from inspections of turbine generators at power plants. Recommendations are given for preventing failure of outer segments in the end areas of turbine generators.

Key words. Turbine generator, end stacks, electromagnetic forces, mechanical stresses.

1. Introduction

During the operation of high-power turbine generators, the segments of the outer stator stacks may be gradually damaged [1]. Break-off particles of electrical steel, when exposed to a magnetic field, can damage the insulation of the turbine generator stator winding. To prevent damage, timely overhaul and replacement of the stator outer stacks is required [2]. As design solutions, along with improving the quality of the stator core compaction, beveled and baked outer core stacks are used. Speaking from operating experience, the technical solutions used extend the time between overhauls, but do not radically erase the problem. Further electromechanical analysis is required.
The purpose of this paper is to determine electromagnetic forces, bending moments and mechanical stresses in the segments of the outer core stacks of the stator core, to establish criteria for fatigue failure of the stator core segments.

2. Electromagnetic Forces Density

Based on the distribution of the axial component of magnetic field induction on the surface of the segment, the density of the electromagnetic force wave (Maxwell force) acting on the segment is determined, changing in time and space according to the harmonic law of a traveling wave. The force wave density is proportional to the square of the magnetic induction component normal (orthogonal) to the surface and has a frequency twice that of the induction wave and a spatial period halved. The force waves act in opposite directions on the outer and inner surfaces of the segment, creating a resulting force wave. According to the results of numerical computation, the force wave density is concentrated at the edges of the teeth, as verified by simulation and other works [3, 4]. This enabled the use of an equivalent concentrated force in computation. The equivalent force increases as the segment detaches from the stator stack.

3. Moments in Radial Restraint

An analytical solution is obtained for the bending moment from the action of a distributed traveling Maxwell force on a cantilever-mounted plate of the stator core segment tooth (with radial restraint). The total bending moment of the electromagnetic force acting on the plate relative to the radial restraint line is determined by integrating the moment density wave over the surface of the delaminated segment.
Integrating the force wave over the width of the segment tooth transformed the traveling wave into a pulsating wave proportional to the width of the tooth. When integrating along the length of the tooth to the restraint line, the concentration of the square of axial induction at the edge of the segment was considered and the Saint-Venant's principle was applied. A solution is obtained in terms of generalized functions, which corresponds to replacing the distribution of the electromagnetic force density with an equivalent force concentrated at the edge of the segment.
The bending moment relative to the radial restraint is similar to the moment of a cantilevered beam and is proportional to the equivalent force at the edge of the

tooth and the arm of this force from its application up to the restraint line.

4. Moments in Tangential Restraint

A solution was also obtained for the bending moment due to the action of a distributed Maxwell force on a cantilever-mounted tooth of a stator core segment with a tangential restraint (tooth support or vent finger). The total bending moment of the electromagnetic force relative to the tangential restraint line, as before, is determined by integrating the moment density over the surface of the delaminated segment with the transformation of the traveling force wave into a pulsating one. The pulsating wave of moment with tangential restraint is phase-shifted relative to the moment with radial restraint by an angle depending on the position of the tangential restraint.

It was shown above that the change in the force wave across the width of the stator tooth is insignificant, due to the small ratio of the tooth width to the length of the pole arc. This is especially true for the unfixed section of the tooth from the lateral edge up to the tangential restraint.

It should be noted that here there is a direct impact of the force density on the restraint. In this case, the total force on the radial section of the edge of the segment is of significance, that is, the integral over this section of the force density, which, under conditions of concentration of the force density on the edge of the segment, also leads to the problem statement in terms of generalized functions.

The bending moment in a tangentially restrained plate is similar to that of a cantilever beam located along the edge of the plate, with an equivalent force uniformly distributed along the length from the lateral edge up to the restraint.

The bending moment is equal to the product of the equivalent force concentrated on the radial edge of the tooth in the center between the tangential edge of the segment and the restraint, and the arm of this force up to the restraint line.

5. Comparison of Stresses

A comparison of mechanical stresses with radial and tangential restraint (Fig. 1, 2) shows that the fatigue strength limit is exceeded when the radial restraint is removed an order of magnitude further from the radial edge of the segment tooth than the tangential restraint is removed from the lateral edge of the tooth. The difference between the moments of resistance is that the tangential restraint is not subject to an impact averaged over the width of the tooth, but to a direct impact of the maximum values of the force wave. Therefore, one can expect the onset of segment failure from a rupture along the tangential restraint line from the edge of the tooth, which corresponds to the results of turbine generators inspections at power plants during operation [1].

As can be seen from Fig. 2, with an axial induction exceeding 1 T and delamination from the tangential restraint by 10 mm or more, the bending stresses in the restraint exceed the fatigue strength limit, and a fracture of the delaminated segment from the radial edge along the tangential restraint is possible.

From Fig. 1 it is evident that with an axial induction exceeding 1 T and delamination from the radial restraint by 100 mm or more, the bending stresses exceed the fatigue strength limit, and a fracture along the radial restraint is possible. Thus, delaminations with tangential restraint are more dangerous.

Design solutions must be adopted to prevent such failures, especially in the case of delamination with tangential restraint. Periodic monitoring of the condition of the outer stacks is required to prevent delamination and failure of the outer segments

6. Conclusion

6.1. Bending stresses are proportional to the square of the equivalent axial induction. In low and medium power turbine generators up to 300 MVA with end area axial induction of less than 1 T, bending stresses, as a rule, do not exceed permissible values.

6.2. In turbine generators with a capacity of over 300 MVA, electromagnetic loads, including axial induction, increase in the end area, and special design solutions are required to prevent delamination of the outer segments and limit bending stresses.

6.3. A widely used technical solution for limiting the impact of axial stator winding leakage fields on the main core stacks is the use of outer stepped beveled stacks in the form of magnetic shunts.

6.4. To improve the mechanical strength of the outer segments, it is recommended to make them from isotropic electrical steel.

6.5. Delamination of segments with tangential restraint leads to dangerous stresses at distances an order of magnitude smaller than for radial restraint of the segment. If admissible stresses are exceeded, the initial rupture of the segments may occur along the tangential restraint in the radial direction.

6.6. It is recommended to place the tangential restraint (tooth support or vent finger) at a distance of less than 10 mm from the lateral edge of the segment and to structurally secure the segment edges to prevent delamination.

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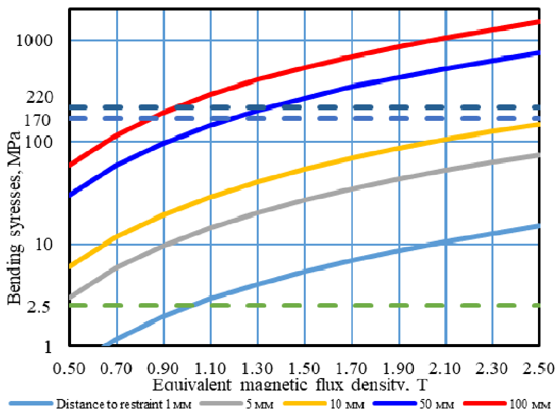

Fig. 1. Bending stresses in radial restraint.

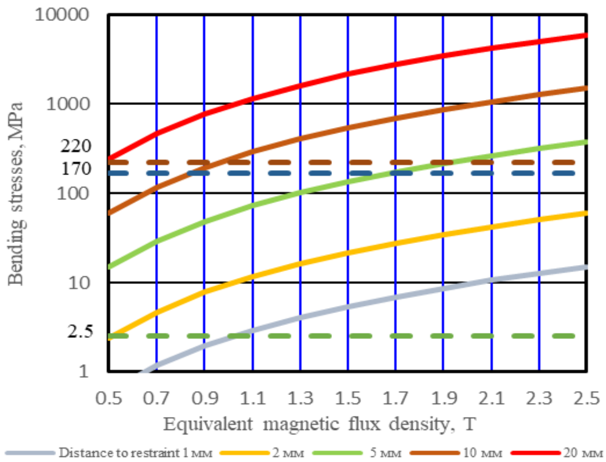

Fig. 2 Bending stresses in tangential restraint