High-frequency induction heating of shrink-fitting parts of turbogenerators

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Abstract. The advantages and disadvantages of induction heating by high-frequency currents during large-sized parts mounting and dismounting are studied. The deviations of the temperature field and the deformation field of the part from the axial symmetry with the horizontal position of the shaft are analyzed. Recommendations were developed on how to take into account these deviations in the technology of mounting and dismounting of the retaining rings of turbogenerators.

1. Introduction
High reliability, durability and full axial symmetry of shrink-fitting assembled parts cause wide use of this connection method in different branches of mechanical engineering. During parts and assemblies operation large-sized shaft-mounted parts experience considerable centrifugal forces, so, during designing the interference fit is calculated based on mechanical loads (nominal and allowed overspeed), mechanical properties of parts’ materials and operating thermal modes. There are different technologies of shrink fit mounting – pressing with intense axial force for mounting and dismounting, dismounting with the pressurized oil supplied to the contact zone of parts, mounted part heating and/or shaft cooling. Thermal treating is the most universal technology.

At the present day for retaining rings of powerful turbogenerators titanium alloys are used due to their mechanical and anticorrosive properties combined with relatively low density [3]. The main problem to their wider usage is impossibility of traditional heating methods applying to them – heating of retaining rings with open flame is forbidden [4], and 50 Hz induction heating [5, 6, 7, 8] or higher frequencies (up to 10 kHz [9]) traditionally used for austenitic steels retaining rings cannot be applied for titanium alloys retaining rings – they are transparent for the electromagnetic field at these frequencies, that leads to field penetration to the under-bandage area during heating for dismounting, subsequent heating of teeth zone, damping half-rings and coil ends, also it creates a risk of disruption following with the electrosparking erosion of contact surfaces under the retaining ring and defecting of expensive parts.

The induction heating method using high-frequency currents, proposed in [10, 11] solves this problem, and also has following advantages compared to supply frequency heating [12, 13, 14]:
• completely eliminates high-frequency electromagnetic field penetration to the contact zone of shaft and mounted part for all range of metals – magnetic and non-magnetic steels, aluminum and titanium alloys;
• shaft heating through the mounted part with high-frequency currents is impossible;
• electro-sparking erosion of contact surfaces do not occur;
• currently the method is the only one that guarantees the dismounting of turbogenerators titanium retaining rings;
• since no water-cooling of inductor is used, the risk of severe accidents caused by water entering the rotor windings is eliminated;
• mounted part overheating is prevented, because the thermocouple can measure the maximal surface temperature under the inductor;
• levels of voltage and external magnetic field are safe for human;
• heating can be done directly at the place of mounting or dismounting, even during handling operations;
• high efficiency;
• low current in inductor and insignificant electrodynamic forces;
• simple and universal inductor design;
• high-frequency heating installations are compact and mobile.

On the other hand, during surface high-frequency induction heating expansion of mounted part is smaller compared to more uniform supply frequency heating due to temperature gradient along the thickness and internal stresses. This feature should be taken into account when developing mounting and dismounting technology for each part and is not an obstacle for solving practical problems.

During induction heating besides significant temperature gradient along thickness and length of parts the temperature field along the perimeter can be ununiformed too, that leads to deviations from the axial symmetry in geometry of mounting parts and have influence on the process of contact surfaces disconnection during dismounting.

The main cause of non-uniformity of temperature field along the perimeter is the positioning of parts during mounting and dismounting – vertical or horizontal [13, 14].

Vertical positioning, which is common for mounting and dismounting of steam turbines impellers, has low axial symmetry deviations.

Mounting and dismounting of retaining rings and other turbogenerators mounted parts (coupling flanges, fans) executed only in horizontal position of the rotor and perimeter nonuniformity in this case is practically inevitable.

Main temperature distribution non-uniformity causes during induction heating with horizontal position are inductor sagging (gap between part and inductor in the top half is less than in lower) and convective air-flow that cools lower part intensively. This problem is significant for high-frequency heating, while inductors used for supply frequency heating are more massive and rigid, have water cooling, i.e. do not change shape during heating, do not sag and on top of that their structural elements block airflow.

2. Research

To heat magnetic parts for shrink fitting using high frequency induction heating it is advisable to use multi-wind inductors made from flexible wire in heat-resistant insulation, without water cooling. Such inductor design is universal, i.e. it allows to heat parts with different diameters by the same inductor, which is wound directly on the heated part surface. Length of wire inductor is chosen so that with full adherence along the length of wire to the heated part inductor is optimally matched with the power source without any matching transformer [13, 14].

Wire inductor is not used to heat non-magnetic metals [15] (stainless steels, aluminum and titanium alloys), because it will need many turns and thus will have very high voltage, that can lead to high-frequency discharge. In this case wide single-turn inductors from copper strip are used [12, 13, 14],
which are tightly pressed to the heated surface with thin electrical insulation (without thermal insulation). The thickness of such inductor is approximately equal to the skin depth on the working frequency. The band inductor requires matching transformer to match power source nominal resistance.

Band inductor [12] have a tension unit for sagging reducing, it heaves band elongation and eliminates sagging during heating. Wire inductor inevitably sags during heating, because such mechanism can’t be applied to it.

Inductor sagging when part axis is in horizontal position leads to higher power density level on part’s top. Also, free convective cooling for such shaft position leads to more intensive convective cooling in lower part [16]. Both causes – inductor sagging and convection conditions – lead to maximum temperature occurrence at the top of the part. Below contribution of each of them is evaluated.

To study axial symmetry deviation caused by inductor sagging the model of induction heating by high-frequency current using wide single-turn band inductor of hollow non-magnetic cylinder was set up; the inductor has constant 2 mm gap at the top half and variable 2 to 10 mm or 2 to 4 mm gap in lower part. For both cases cooling conditions are uniform along the perimeter, so only sagging influence on heating process is evaluated. Figure 1 shows results of these simulations – power density and temperature distribution along the perimeter after 1 hour of heating; variable gap is also shown.

![Figure 1](image)

**Figure 1.** Inductor sagging influence on surface temperature distribution after one hour heating by high-frequency band inductor (without convective cooling). Solid lines for gap 2-10 mm, dashed for gap 2-4 mm.

8 mm band inductor sagging in maximum gap zone leads to power density lowering by 24%, that results in 20% temperature difference between highest and lowest part points after 1-hour heating. With 2 mm band sagging power density difference is only 6% temperature difference – 5%. So sagging reducing measures (e.g. tension unit [12]) lead to much more uniform heating along the perimeter and shorten heating time required for parts disconnection.
High-frequency induction heating of magnetic steel parts comes with extensive wire inductor windings sagging and, thus, with considerable heating power density lowering at the lower point, but high level of magnetic steels thermal conductivity dampens heating inequality along the mounted part perimeter, making this method acceptable for practical use.

Unsymmetrical cooling by free convection was studied experimentally, results are shown on Figure 2.

As expected, temperature maximum occurred at the top point of the part, side minimum determined by forced air cooling of current input leads.
Two numerical simulations were set up to estimate influence of ununiformed temperature distribution along the cylindrical part perimeter on part’s shape changing and shaft release conditions: one of them has uniform power density along the perimeter without any losses, the other have free convective cooling boundary conditions for horizontally placed cylinder, which is studied in details and well described in [17]. To make results comparable power density in second case is higher to compensate convective losses. Also, the system “part-shaft” has free fall acceleration applied, so gap forms in gravitational field. Simulation results are represented on Figures 3 and 4.

![Figure 3](image.png)

**Figure 3.** Gap forming for case of uniform heating power density without heat losses (a) and for case with free convective cooling for infinite horizontal cylinder [17] applied (b). Numbers are for control points: 1 – top outer surface of mounted part, 2 – bottom outer surface of mounted part, 3 – top inner surface of mounted part, 4 – bottom inner surface of mounted part, 5 – top shaft surface, 6 – bottom shaft surface.
As one can see from Figures 3 and 4, uniformly heated part keeps cylindrical shape during expansion, so gap forms in the lower part due to gravity. Taking into account closer to real convective cooling conditions the situation changes – contact surfaces disconnection begins at the top, where temperature of mounted part is higher and only some time after this initial contact loss the part slips down the shaft.

3. Conclusions
Analyzed in study axial symmetry deviations during high-frequency induction heating of large-sized mounted parts with horizontal shaft positioning are important for the mounting and dismounting technology development – obvious that the inductor should be fastened properly with ability to pull and tighten during heating to minimize sagging. Actual free convection cooling conditions and current input leads forced blowing create temperature difference along the perimeter with maximum temperature occurrence at the top, so it should be controlled there. Finally, gap development starts at the top part too, so it should be controlled there to catch moment of shaft and part contact surfaces disconnection, that is necessary to start dismounting rigging works.

Despite noted features of large-sized mounted parts high-frequency induction heating, the 2-dimensional axi-symmetric environment can be used to simulate such processes due to relatively small deviations of such objects from the axial symmetry even with horizontal shaft position, thus time of calculation can be reduced significantly as well as machine resources requirements.

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