Splits of Windage Losses in Integrated Transient Rotor and Stator Thermal Analysis of a High-Speed Alternator during Multiple Discharges

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Abstract— For a high speed electrical alternator, the rotor outer banding and stator inner liner are typically made of high strength graphite epoxy composites due to their high strength and stiffness. Machine structural integrity at high rotating speeds degrades significantly as the composite resins lose their strength at high temperatures. The magnitude of the frictional windage losses generated in the air gaps and the splits of the windage losses between the rotor and stator become crucial to the machine design since these windage losses greatly influence the rotor outer and stator inner surface temperatures.

Splits of windage losses generated by an enclosed high speed composite rotor in low air pressure environments were investigated by The University of Texas at Austin Center for Electromechanics and described in a companion paper. The windage splits are dictated by the air temperature gradients at the rotor outer and stator inner surfaces. Unique heating, cooling, and component material properties of a typical high-speed alternator during repetitive-discharge events make its transient air-gap windage splits very much different from those of the test setup.

This paper describes transient windage splits in integrated rotor and stator thermal analyses of a high-speed alternator designed for multiple discharges. The transient windage splits in the air-gap airflow were obtained through multiple iterations on windage losses, air-gap air temperatures, and rotor and stator surface temperatures.

Keywords: *Splits of windage losses, high-speed alternator, multiple discharges*

I. INTRODUCTION

Cooling of a mobile high speed rotating electrical machine is extremely challenging due to the fact that the machine is usually designed for high energy storage and high power density applications. A continuous or multiple-discharge operation demands a significant amount of heat losses generated in the rotor, stator, and air gaps be effectively removed without overheating the insulation and composite material used in the machine. Thermal management of such a machine requires accurate calculations of electrical losses and frictional losses associated with fluids caused by relative

motion, reliable predictions of how these losses are distributed and dissipated, and a compact cooling system design. In the past, little research has been done in integrated machine thermal analysis and cooling design for continuous high speed and high power rotating electrical machine operations.

For electrical machines rotated at relatively low speeds, such as rotor tip velocities less than 250 m/s, air-gap windage losses are generally not very significant, and these frictional losses can be removed by active air-gap cooling if needed. However, atmospheric windage friction is too excessive to be tolerated as the rotor velocity becomes very high. A high speed rotor is typically designed to be operated in a partial vacuum environment to reduce windage drag. Depending on the capabilities of the rotating seals and vacuum pumps, the air-gap windage losses might be significant enough to degrade the rotor and stator surfaces in a partial vacuum system. In an electrical machine with non-ventilated air gaps, the air-gap windage loss needs to be removed by the rotor and stator cooling systems. Since the windage splits between the boundary surfaces largely depend on the rotor and stator surface temperatures, an integrated transient rotor and stator thermal analysis with air-gap windage included in the thermal modeling becomes important to predict the machine's thermal behavior. The individual heating, cooling, material properties of both rotor and stator are all essential to the windage splits in the air gaps since they determine the rotor and stator surface temperatures.

The University of Texas at Austin Center for Electromechanics (UT-CEM) has designed and conducted a series of composite rotor spin tests to measure the windage losses and temperature distributions of a test setup at high rotor speeds and low air pressures [1-4]. The windage tests were designed to validate the windage loss predictions and investigate the air-gap windage loss distributions between the test rotor and stator under the test conditions. Investigation of windage splits in an enclosed test fixture having a high speed composite rotor in low air pressure environments has been reported in [4]. This paper describes a detailed thermal simulation in which transient windage splits in a high-speed alternator, designed for multiple discharges, are analyzed and predicted.

II. AIR-GAP WINDAGE SPLIT ANALYSIS METHODOLOGY

For a continuum laminar Couette flow, which is a shear flow between parallel plates or concentric rotating cylinders, having constant fluid properties, the gap fluid temperature distribution can be analytically predicted as follows [4, 5]:

$$\frac{T_s - T}{T_s - T_r} = \frac{y}{L} \left[1 - \frac{\mu U^2}{2k(T_s - T_r)} \left(1 - \frac{y}{L} \right) \right] \quad (1)$$

where T_s and T_r are the solid boundary surface temperatures, T is the gap fluid temperature which is a function of radial location in the gap, y is the radial coordinate in the gap, L is the gap dimension, μ is the fluid dynamic viscosity, U is the rotor surface velocity, and k is the fluid thermal conductivity. Depending on the magnitudes of the air pressure, air temperature, air gap dimension, and rotor speed, the flow regimes associated with a wall-driven air-gap air flow are typically categorized as continuum flow, slip flow, and free-molecule flow. The application of equation (1) is restricted to continuum laminar Couette flows having constant fluid properties.

Windage tests [1-4] have successfully measured the total windage losses and temperature distributions for a high speed composite rotor spinning in a stator assembly. The data collected are used as benchmark data for development of models to predict windage losses and operating temperatures for high-speed alternators. Equation (1) was used to analyze two windage tests [4], where continuum laminar flows or near continuum laminar flows were observed [6]. It was found that the transient rotor and stator temperature distributions generated by the predicted windage splits closely matched to what have been measured in the tests. This validation provides us a basis of using this equation to analyze the transient windage splits in an alternator design, in which the radial air-gap air flow at the designed rotor peak velocity is a continuum laminar flow at an air pressure of 1 torr.

In order to perform an integrated transient thermal analysis for a high speed alternator power supply, where air-gap windage heating must be coupled to the electrical heating and active cooling in the rotor and stator, provision of rotor surface temperatures, stator surface temperatures, and air thermal and fluid properties is required. These air-gap air and boundary temperatures are typically unknown if the windage split is unavailable in the first place. Alternatively, we have carried out this integrated thermal analysis by performing sequential iterations outlined as follows:

- Assume a transient windage split first (typically a constant even windage split)
- Perform transient rotor and stator thermal finite element analyses (FEA) based on predicted windage losses, assumed windage splits, calculated electrical losses, and designed active cooling boundary conditions
- Use the averaged rotor and stator surface temperatures obtained from the FEA results and find air thermal and

fluid properties based on a guessed initial average air-gap air temperature

- Use equation (1) to perform iterations until the calculated average air-gap air temperature equal to the guessed air-gap air temperature for a given rotor and stator surface temperature combination
- Calculate the air temperatures and air temperature gradients at the solid surface boundaries for all transient rotor and stator surface temperature combinations to determine a new transient windage split curve
- Use the new transient windage split curve to perform transient rotor and stator FEA again
- Iterate, based on the above procedures, until the FEA-predicted transient rotor and stator temperatures converge

The described sequential iteration procedures have been utilized to perform integrated transient rotor and stator thermal analyses, in which electrical thermal loads and windage losses were all included, for a multiple-discharge event with active rotor and stator cooling included and a laboratory test without providing active cooling.

III. INTEGRATED THERMAL ANALYSIS INCLUDING ACTIVE COOLING

A need of removing significant amount of electrical losses in the rotor field coils and stator armature coils of a repetitively discharged alternator requires both of these coils have their own active cooling systems. Alternator operating and cooling boundary conditions assumed in the stator and rotor thermal analyses are listed as follows:

- Transient heat losses
 - One-hour windage preheating, followed by multiple discharges
 - windage loss calculated at 1 torr and 15,000 rpm during the entire event (radial air-gap windage loss calculated at an average air temperature of 100°C)
- Water and water-glycol mixture used for coolants
- Coolant inlet temperature = 25°C
- Cooling boundary conditions included in Table I.

Five rotor and stator FEA iterations have been carried out and the transient average alternator temperatures and windage splits are plotted in Figs. 1 to 4. As shown in Fig. 4, after iteration #5, the average rotor outer-diameter (OD) and stator inner-diameter (ID) surface temperatures converged within 2°C. At the end of the last discharge, the rotor-stator windage split ratio is approximately 24-76%. The transient stator ID temperatures, rotor OD temperatures, air-gap air temperatures, and windage splits are plotted in Fig. 5. The rotor and stator temperatures shown in Figs. 1 to 4 are the average surface temperatures, which are the arithmetic averages between the hottest and coldest surface temperatures, and the actual maximum rotor and stator temperatures are higher than those average temperatures.

TABLE I. FEA COOLING BOUNDARY CONDITIONS (A MULTIPLE-DISCHARGE EVENT)

	Coolant Temp. (Preheating Period) (°C)	Coolant Temp. (Discharge Period) (°C)	Heat Transfer Coef. (Preheating Period) (W/M ² /K)	Heat Transfer Temp. Coef. (Discharge Period) (W/M ² /K)
Stator	26.3	44.5	1,201	15,870
Rotor	25.0	25.0	20,000	20,000

Figure 3. Transient average alternator temperatures and windage splits (iteration #4, multiple-discharge event)

Figure 1. Transient average alternator temperatures and windage splits (Iteration #2, multiple-discharge event)

Figure 4. Transient average alternator temperatures and windage splits (iteration #4, multiple-discharge event)

Figure 2. Transient average alternator temperatures and windage splits (iteration #3, multiple-discharge event)

Figure 5. Temperatures and windage splits after iteration #5 (multiple-discharge event)

For this integrated multiple-discharge thermal analysis, major analysis conditions and observations can be summarized as follows:

- A constant radial air-gap air temperature of 100°C was assumed in the windage loss calculation, which was conservative in the one-hour windage preheating and less conservative in the multiple-discharge period.
- For a continuum laminar Couette flow, a closed-form equation, equation (1), was used to predict transient windage splits based on known transient rotor and stator surface temperatures through iterations.
- A near even windage splits between rotor and stator occurred during the initial one-hour windage preheating and more windage losses went to stator as the rotor surface temperatures became higher than the stator surface temperatures during discharges.

IV. INTEGRATED THERMAL ANALYSIS WITHOUT ACTIVE COOLING

In a separate integrated thermal analysis for a laboratory test with reduced number of discharges, the stator current was allowed to flow in the copper coolant tubes so that the stator armature coil loss could be reduced. Also, the stator coil and coolant tube eddy-current losses, which were not considered in the previous multiple-discharge thermal analysis, were taken into account in the thermal analysis for the laboratory test. Major rotor and stator thermal considerations are listed as follows:

- A given laboratory motoring profile with a maximum speed of 15,000 rpm
- A constant radial air-gap air pressure of 1 torr
- Discharge dependent and temperature dependent current conduction losses in stator coils and stator cooling tubes
- Discharge dependent and temperature dependent eddy current losses in stator coils and stator cooling tubes
- Rotor speed dependent radial air gap sizes and air-gap air temperatures for windage loss calculations
- No active cooling

Fig. 6 shows the transient average air-gap air temperatures used in the windage loss calculations. Fig. 7 shows the laboratory motoring profile and the predicted transient radial air-gap windage losses. Rotor and stator thermal analysis iterations were performed until the thermal results converged after the fourth iteration. Figs. 8 to 11 show the transient average rotor OD and stator ID surface temperatures and the windage splits predicted in four thermal analysis iterations. Fig. 12 shows the average surface temperatures of the rotor, average surface temperatures of the stator, average radial air-gap air temperatures, maximum air-gap air temperatures, and windage splits after the fourth iteration. Fig. 13 shows the transient rotor speeds and windage splits in the Iteration #4. Referring to Figs. 12 and 13, after the time of 1,600 s where the rotor speeds drop below 4,300 rpm, 100% of the windage losses go to rotor as results of high stator ID surface temperatures, low rotor OD

surface temperatures, and low windage viscous dissipation at low rotor speeds. As shown in Fig. 7, the radial air-gap windage losses generated at rotor speeds lower than 4,300 rpm are insignificant as compared to that generated at the peak speed of 15,000 rpm.

For this integrated laboratory test thermal analysis, major analysis conditions and observations can be summarized as follows:

- Iterated time-dependent radial air-gap air temperatures were used to calculate windage losses.
- A near even windage splits between rotor and stator occurred during the initial rotor acceleration and more windage losses went to rotor as the stator surface temperatures became higher than the rotor surface temperatures during discharges and rotor deceleration.
- After 1,600 s, rotor speeds dropped below 4,300 rpm and 100% windage losses went to rotor as results of high stator surface temperatures, low rotor surface temperatures, and low windage viscous dissipation at low rotor speeds. However, the radial air-gap windage losses generated at rotor speeds lower than 4,300 rpm were insignificant.

Figure 6. Average radial air-gap air temperatures for windage calculation (laboratory test)

Figure 7. Rotor speeds and radial air-gap windage losses (laboratory test)

Figure 8. Transient average alternator temperatures and windage splits (iteration #1, laboratory test)

Figure 11. Transient average alternator temperatures and windage splits (iteration #4, laboratory test)

Figure 9. Transient average alternator temperatures and windage splits (iteration #2, laboratory test)

Figure 12. Temperatures and windage splits after iteration #4 (laboratory test)

Figure 10. Transient average alternator temperatures and windage splits (iteration #3, laboratory test)

Figure 13. Rotor speeds and windage splits in iteration #4 (laboratory test)

V. CONCLUSION

This paper describes how to analyze transient windage splits in the radial air gap of a high-speed alternator during multiple discharges. Windage distribution is largely dependent on the flow regime and fluid temperature distribution in the air gap. The air-gap fluid temperature distribution is determined by the magnitude of the windage loss and boundary surface temperatures. Without knowing the transient temperatures of the air-gap air and boundary surfaces at the beginning, transient windage splits could be obtained through multiple iterations on windage losses, air-gap air temperatures, and rotor and stator surface temperatures. For a particular rotating electrical machine design, the electrical losses and cooling systems associated with the rotor and stator provide a unique transient air gap boundary temperature variation. Air-gap windage splits can become quite uneven if the boundary temperatures differ significantly.

The air-gap fluid temperature distribution equation described in this paper is restricted to continuum and laminar flows which have constant fluid properties. More researches are required to analyze windage splits in non-continuum and non-laminar flow regimes to cover a broad spectrum of air-gap flows in rotating electrical machines under various operating pressures and speeds.

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VII. REFERENCES

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