Multiphysical-Domain Integration Design of Oil-Cooled Permanent Magnet ISG Motor

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Received 1 July 2019; Revised 19 December 2019; Accepted 2 January 2020; Published 29 February 2020

1. Introduction

Integrated-starter-generator (ISG) motors as a key part of new-energy vehicle dynamic systems. To more efficiently design higher-performance permanent magnet ISG motors, we proposed a multiphysical-domain integrated design method by designing the electromagnetism and thermal performance of motors and the mechanical structure strength of rotors together. A 48-slot and 8-pole oil-cooled permanent magnet ISG motor was designed by using this method and simulated via the finite element method. Also, a motor-testing platform was built to experimentally validate this method. The simulation results were consistent with the test results, which confirmed that the new method was accurate and effective and can be referred to during the practical design and development of high-density permanent magnet motors.

The key problems of permanent magnet motors have been extensively studied. For instance, a 42 kW water-cooled vehicular permanent magnet synchronous motor was analyzed via multiphysic coupling thermal performance simulation based on a circuit, electromagnetic field, and temperature field intercoupling analytical method [5]. The magnetic-thermal coupling of a 4 kW axial magnetic flux permanent magnet motor was analyzed [6]. The thermal-magnetic coupling of a double-salient-pole and double-rotor permanent magnet motor was analyzed by integrating thermal networks and the finite element method (FEM) [7]. The thermal network method and 3D fluid analysis were combined when the thermal effects of a hanging structure on surface-mounted permanent magnet motors were
considered [8]. An 8 kW permanent magnet synchronous motor was simulated and experimentally validated on the basis of an electromagnetic-thermal fluid analytical method, and the effectiveness of the coupling simulation model was confirmed [9]. A three-dimensional model of an axial radial magnetic flux permanent magnet synchronous motor was established, the steady-state thermal performance was analyzed, and the motor winding was designed as the temperature field distributions of high-temperature superconducting wires and copper wires [10]. A 30 kW 60000 r/min high-speed cylindrical permanent magnet motor equipped with magnetic bearing was designed, a magnetic field analytic model was built, and the magnetic force resolution was deduced [11]. A novel permanent-magnet motor with surface-mounted outer rotor transversal magnetic flux was designed, and an improved stator design method was proposed, which can partially convert leakage flux into main flux [12]. The torque, torque pulsation, efficiency, and opposing electromotive force of IPM motors for electric vehicles with 5 types of rotor structures were compared, and the rotor containing the permanent magnet with the smallest volume performed the best [13]. Also, a novel linear reluctance permanent-magnet motor meeting the requirements of high dynamic and low power consumption was presented [14, 15]. A design method of air gap harmonic direction of a V-shape flux-modulated permanent-magnet motor was proposed, which integrated air gap harmonics into motor design and considered three key factors, including permanent magnet source, modulator, and winding [16]. The systematic optimization design and control of a less-rare earth hybrid permanent-magnet motor was proposed, which comprehensively considered the design level and control level of the motor [17]. Moreover, a double-rotor flux-switching permanent-magnet machine and a multiobjective optimization method were proposed. According to the design requirements of various driving modes, the response surface method and the sequential nonlinear programming algorithm were used to effectively achieve the compromise among the design objectives [18]. The mechanical structure strength of a high-speed large-torque built-in permanent magnet wheel-wheel generator rotor was studied and compared with the equivalent method and FEM, and the precision application conditions for the equivalent method were proposed [19]. In addition, the strength of a high-speed permanent magnet motor equipped with a solid cylindrical permanent magnet rotor was analyzed, and the rotor stress conditions were simplified into a planar stress problem, and thereby, the resolution equation of rotor mechanical structure strength was put forward [20]. The magnetic pole subsection axial magnetic flux permanent magnet motor rotor suitable for high-speed operation was structurally studied, and the resolution calculation model for rotor strength was built. Moreover, the effects of the arc factor, rotor flange breadth, and number of rotor magnetic pole sections on the rotor mechanical strength were studied using an analytical method and FEM [21].

The above studies indicate there are many methods feasible for designing the electromagnetism, thermal performance, and mechanical structure of permanent magnet motors, but there is rare research on the multiphysical-domain integrated design (MPDID) methods for vehicular permanent magnet motors, especially oil-cooled PMIMs. In this study, based on the rationale of motor electromagnetic design, thermal design, and mechanical structure design, we proposed an MPDID theoretical method that simultaneously designed electromagnetism and thermal and mechanical structure. A 48-slot and 8-pole oil-cooled PMIM was designed, and its effectiveness and advantages were validated by FEM and experiments.

2. Equations for MPDID of PMIM

The PMIM to be designed should have the smallest motor size, the highest efficiency, the largest torque, and the stator winding temperature below its limit temperature in the design process. At the same time, the rotor should have sufficient mechanical structure strength to ensure the long-term stable operation of the motor. The following three aspects are theoretical analysis of the main dimension design, stator winding temperature rise design, and mechanical structure strength of the rotor.

2.1. Major Dimensions of the PMIM. The electromagnetic torque of the motor can be calculated as follows [22]:

\[ T_{em} = \pi K_i K_{NM} K_{dp} D_s^2 l_{ed} A B_\delta \frac{K_{em}}{2} \]

where \( K_i \) is the motor phase current waveform coefficient, \( K_{NM} \) is the magnetic field waveform coefficient, \( K_{dp} \) is the winding factor, \( D_s \) is the motor stator inner diameter, \( l_{ed} \) is the effective stator core length, \( A \) is the linear load, and \( B_\delta \) is the peak value of air gap magnetic density.

When the electromagnetic load, effective core length, armature-phase voltage, phase current waveform coefficient, magnetic field waveform coefficient, and winding factor are all constant, the electromagnetic torque of the motor is decided by the inner diameter of the motor stator, which also critically decides the motor performance. Then, the dimensions of the motor inner diameter were deduced.

The stator inner diameter and stator tooth width of motor are computed as follows [22]:

\[ D_{is} = f(D_{os}) = \frac{B_{is}^{os} \pm \sqrt{B_{is}^{os^2} - A_{is}^{os^2} C_{is}^{os^2}}}{A_{is}^{os^2}} \]

where

\[ A_{is}^{os^2} = \frac{\pi^2 a_k^2 k_{is}^2}{4 p^2 k_{Fes}^2 k_{ls}^2} + \frac{\pi^2 k_{is}^2 k_{ls}^2}{p^2 k_{Fes}^2 k_{ls}^2} \frac{2 a_p k_{is}^2}{k_{Fes} k_{ls}^2} - 1 \]

\[ B_{is}^{os^2} = \left( k_{is} + \frac{\pi k_{is}}{2p} \right) \frac{a_p k_{is}}{K_{Fes} k_{ls}^2} - \frac{2 A}{f_s l_{sf}} \]

\[ C_{is}^{os^2} = D_{es}^{os^2} \]

\[ b_{is} = \frac{\pi a_p k_{is} D_{is}}{Z_{is} k_{Fes} k_{ls}} \]

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where \( b_{th} \) is the stator tooth width, \( D_{os} \) is the stator outer diameter, \( \alpha \) is the computation arc coefficient, \( k_{m} \) is the ratio of peak magnetic density in air gap to the magnetic density at stator yoke; \( k_{s} \) is the ratio of the magnetic density in air gap to the magnetic density in the stator tooth; \( k_{b} \) is the iron core length coefficient and usually is approximated to 1; \( K_{Fe} \) is the core stacking coefficient; \( p \) is the number of pole pairs, \( f_{s} \) is the stator winding current density, and \( S_{f} \) is the slot full rate.

2.2. Temperature Rise in the Stator Slot of the PMIM. By introducing the unit temperature difference and the heat per unit slot heat transfer area, we can determine the equivalent thermal conductivity at the slot winding \( \lambda_{sl} = 1/R_{sl} \) [23] as follows:

\[
R_{sl} = \frac{\delta_{s} + \frac{1}{4} \left[ \frac{b_{cs} \left( 1 - \sqrt{S_{f}} \right) k_{l}}{\lambda_{l}} + \frac{b_{cs} \left( 1 - \sqrt{S_{f}} \right) \left( 1 - k_{l} \right)}{\lambda_{n}} \right] \frac{b_{cs} \left( d - d_{w} \right) \sqrt{S_{f}} \lambda_{sl}}{\lambda_{sl}}}{\frac{b_{cs} \left( d - d_{w} \right) \sqrt{S_{f}} \lambda_{sl}}{\lambda_{sl}}},
\]

where \( \delta_{s} \) is the slot insulation thickness, \( b_{cs} \) is the equivalent slot width, \( \lambda_{i} \) is the slot insulation thermal conductivity, \( \lambda_{l} \) is the thermal conductivity of the impregnating varnish, \( \lambda_{n} \) is the thermal conductivity of air, \( \lambda_{sl} \) is the thermal conductivity of wire coating film, \( k_{l} \) is the paint filling coefficient, and \( d \) and \( d_{w} \) are the outer diameter of the varnished wire and the diameter of bare wire, respectively. Thus, the temperature rise inside each slot can be calculated as follows [23]:

\[
\Delta \theta_{w} = \frac{P_{cu}}{Z_{cu} R_{sw}} \times \frac{R_{sl} \lambda_{sl}}{Z_{b_{cs} h_{ef}}},
\]

where \( P_{cu} \) is the copper loss and can be empirically calculated according to the motor efficiency requirements and engineering design, \( \Delta \theta_{w} \) is the temperature rise inside each slot, and \( R_{sw} \) is the equivalent thermal resistance in slot. Clearly, under the same copper loss, when the slot full rate and the thermal conductivity coefficients of slot insulation, impregnating varnish and varnish films, and the varnish filling coefficient are all constant, the temperature rise of the stator slot is inversely proportional to the equivalent slot breadth \( b_{cs} \) and the stator core length \( l_{ef} \). Empirically, at the ambient temperature \( T_{a} \) > 40°C, the permitted temperature rise of motor winding should meet the following condition [22]:

\[
\Delta \theta_{w} \leq 0.9 \left( T_{h} - T_{a} \right),
\]

where \( T_{h} \) is the highest temperature and can be assigned with different empirical values according to the grade of insulation (e.g., A, B, F, and H).

2.3. Design of PMIM Rotor Mechanical Structure Strength. During the normal working of a motor, the rotor is affected by the centrifugal force, electromagnetic force, and thermal stress. Since the effect of the centrifugal force is reportedly far larger than other forces, here we only considered the centrifugal force when studying the mechanical structure strength of the rotor. There were also three hypotheses: (1) the forces of the rotor support were considered only when the motor was under the stable status and was thereby simplified (which shortened the computation time), and the forces imposed on the steady-state motor maximized when the rotating speed was the largest; (2) the effect of temperature rise on the rotor was ignored; (3) the effect of motor vibration was ignored.

As for high-speed motors with built-in magnetic circuit, due to the very narrow magnetic bridge, the centrifugal force undertaken by the permanent magnet is fully imposed on the magnetic bridge. Thus, during the PMIM design, the forces of the magnetic bridge should be critically analyzed so as to ensure the safe operation of the motors. With the built-in V-shaped rotor structure as example (Figure 1), \( b_{1}, b_{2}, \) and \( b_{3} \) are the widths of 3 sections of the magnetic bridge, where \( b_{1} = b_{3} \) and the rotor is symmetrical around y-axis.

According to the principle of equivalent ring, the permanent magnet and core were equivalently placed onto the equivalent ring, and the equivalent density was calculated as follows [24, 25]:

\[
\rho_{eq} = \frac{\rho_{m} S_{m} + \rho_{Fe} S_{Fe}}{S_{eq}},
\]

where \( \rho_{m} \) and \( S_{m} \) are the core density and area, respectively; \( \rho_{Fe} \) is the density and area of the permanent magnet, respectively; and \( \rho_{eq} \) and \( S_{eq} \) are the density and area of the equivalent ring, respectively. With the consideration of the
margin effect of the rotor slots, when the rotating speed is $n_{\text{max}}$, the maximum mechanical stress $\sigma_{\text{max}}$ is located at the margin of the equivalent ring. The maximum tensile stress of the core material should be smaller than the yield strength $R_p$ of the core material, and thus, the inner largest allowable stress of the core should meet the following equation:

$$
\sigma_{\text{max}} = 2 \left[ \frac{(r_{\text{ro}} + r_{\text{ri}}) n_{\text{max}} }{60} \right]^2, \quad \rho_{\text{eq}} < \frac{R_p}{S},
$$

where $r_{\text{ro}}$ and $r_{\text{ri}}$ are the outer diameter and inner diameter of the equivalent ring, respectively, and $S$ is the safety factor.
The mechanical structure stress of the rotor is reflected in the calculation formula of the outer diameter and inner diameter of the rotor, and the maximum outer diameter of the rotor meets the following requirement:

\[ D_{or\max} = r_{ro} = \frac{\sigma_{\max}/2\rho_{eq}}{(\pi n_{\max} - r_n)}. \tag{10} \]

Then, the winding temperature rise is reflected in the calculation formula of the inner diameter and tooth width of the stator of PMIM. The main dimensions of PMIM are calculated as follows:

\[ b_{ts} = \frac{\pi l_{ct}Z_sD_{oa} - 2\pi l_{ct}Z_sh_{ts} - P_{cu}R_{sl}}{\Delta\theta_{w}l_{ct}Z_s}. \tag{11} \]

Therefore, when designing the major dimensional parameters of PMIM, the temperature rise of the stator winding and the strength of the mechanical structure of the rotor can be considered comprehensively through equations (10) and (11).

In sum, the major dimensional parameters of the PMIM not only relate to its electromagnetic performance but also critically affect the winding temperature rise and rotor mechanical structure strength.

### 3. Key Technical Flowchart of PMIM Based on MPDID

The key techniques of the PMIM mainly include electromagnetic design, temperature rise design, and mechanical structural strength design. The principle for MPDID of PMIM was proposed: the main dimension parameters and winding temperature rise of the motor and the mechanical structure strength of the rotor were associated below. Firstly, the stator outer diameter and inner diameter, the pole-slot combination, stator tooth breadth, and rotor outer diameter were determined according to the theories of motors. Then, according to the resolution relations of the three, the stator winding temperature rise and rotor mechanical structure strength were determined, and it was judged whether or not the winding temperature rise condition and rotor mechanical structure condition were met. If not, the above dimensional parameters were fine-tuned and the two parameters were reestimated until the conditions were met. Finally, the concrete electromagnetic scheme was worked out, which must simultaneously meet the requirements of electromagnetism and thermal and mechanical structure strength. This in process, the electromagnetism, thermal and rotor mechanical structure strength were designed simultaneously.

Figure 2 shows the key technical flowchart of PMIM based on MPDID. First, according to the design requirements, the appropriate pole-slot combination was selected, and the outer diameter and core length of the PMIM stator were determined. The magnetic density was estimated according to the preset rotating speed, and the stator inner diameter and tooth width were computed from equations (2) and (4). After the refined adjustment, the shape of the stator slot was determined. Second, the PMIM winding temperature rise was calculated and judged according to equations (6) and (7). If the requirements of stator temperature rise were unsatisfied, the PMIM inner diameter \( D_{so} \), tooth width \( b_{ts} \), and tooth height \( h_{ts} \) should be adjusted according to equation (11) until equation (7) was met. The maximum mechanical stress was calculated according to equation (9). According to equations (9) and (10), it was judged whether the requirements of rotor mechanical structure strength were met. If not, the magnetic isolation bridges \( b_1, b_2, \) and \( b_3 \) should be adjusted until equation (9) was met. Finally, a complete PMIM model was established for computation via FEM. The electromagnetic torque, efficiency, temperature rise, rotor mechanical structure strength, and other performance indices of PMIM were evaluated. If the design requirements were unsatisfied, the PMIM dimensions and structure should be adjusted or refined until the design requirements were met.

### 4. FEM Simulation of PMIM Based on MPDID

According to the dimensional relation in Section 2.1, we set the outer diameter = 210 mm, pole-slot combination = 48-slot and 8-pole, waveform coefficient \( K_i = 1.414 \), electromagnetic power waveform coefficient \( K_{p} = 0.5 \), axial length \( l_{rt} = 90 \text{ mm} \), and rated rotating speed \( n = 4775 \text{ rpm} \) and thereby approximately estimated the electromagnetic density. The stator inner diameter \( D_{so} \) can be preliminarily estimated from equation (2). At the core stacking coefficient \( K_{Fe} = 0.97 \) and \( B_{g} = 0.6 \text{ T} \), we calculated the stator tooth width from equation (4).

Based on the above preliminary design, the V-shaped structure rotor was designed, the insulation grade of the prototype winding was \( H \), and the ambient temperature was \( 90^\circ \text{C} \). Thereby, the winding temperature rise was estimated according to equations (6), (7), and (11). Then, according to equations (9) and (10), the rotor mechanical structure strength was calculated. Then, the dimensional parameters were further refined. Finally, the FEM calculation was carried out, and the electromagnetism, thermal simulation, and mechanical structure stress were simulated by ANSYS-Maxwell, Motor-CAD, and JMAG respectively. The prototype performance and main dimensions as determined are listed in Table 1, which met the performance requirements of

| Parameters Value | Table 1: Performance and main dimensions of prototype machine. |
|------------------|-------------------------------------------------------------|
| Rated power (kW) | 50                                                          |
| Rated speed (rpm)| 4775                                                        |
| Maximum power (kW)| 70                                                            |
| Maximum speed (rpm)| 7000                                                        |
| Stator outer diameter \( D_{oa} \) (mm) | 210                                                          |
| Rotor inner diameter (mm) | 67                                                            |
| Pole/slot | 8/48                                                        |
| Core length (mm) | 90                                                          |
| Stator slot height \( h_t \) (mm) | 20                                                            |
| Tooth width \( b_{ts} \) (mm) | 6.54                                                         |
| Air gap length (mm) | 0.8                                                          |
| Winding insulation level | H                                                             |

**Note:** The table lists the performance and main dimensions of the prototype machine designed using MPDID.
Figure 3: No-load back-EMF at 7000 r/min.

Figure 4: Simulation efficiency MAP diagram of PMIM in generator model.

Figure 5: Temperature distributions of the PMIM. (a) 4000 r/min@ 115 N·m. (b) 7000 r/min@90.2 N·m.
torque, efficiency, temperature rise, and mechanical structure strength. Next, the simulation results were analyzed.

The no-load back-EMF simulation waveform of the PMIM at 7000 r/min is shown in Figure 3, and the virtual value was 204.6 V. The simulation efficiency MAP diagram of PMIM in generator model is shown in Figure 4, and clearly, the largest efficiency was 95%.

Motor-CAD is a computer-aided software package for the thermal design of electric machine and is very suitable for engineering practice. Motor-CAD was applied to thermal

| Speed (r/min) | Act torque (N·m) | Power (kW) | Simulation values (°C) | Experimental values (°C) |
|--------------|-----------------|------------|------------------------|-------------------------|
| 1000         | 114.22          | 12         | 122.3                  | 127                     |
| 2000         | 114.59          | 24         | 124.5                  | 130                     |
| 3000         | 114.98          | 36         | 136.1                  | 140                     |
| 4000         | 114.98          | 48         | 144.9                  | 147                     |
| 5000         | 114.22          | 60         | 145.1                  | 148                     |
| 6000         | 102.2           | 64         | 141.0                  | 145                     |
| 7000         | 90.18           | 66         | 132.6                  | 135                     |

Table 2: Maximum temperature in winding of the prototype machine.

| Material name | Young's modulus (MPa) | Poisson ratio | Density (g/cm³) | Tensile strength (MPa) | Yield strength (MPa) |
|---------------|-----------------------|---------------|-----------------|------------------------|----------------------|
| DW310-35      | 207,000               | 0.30          | 7.85            | 530                    | 395                  |
| N48UH         | 15,000                | 0.28          | 7.6             | 80                     | —                    |
| New epoxy     | 11,000                | 0.38          | 1.84            | 60                     | —                    |

Table 3: Material properties.

Figure 6: Mechanical stress simulation analysis of rotor structure at 7000 r/min and 10,000 r/min without epoxy. (a) Distribution of deformation at 7000 r/min. (b) Centrifugal stress distribution at 7000 r/min. (c) Distribution of deformation at 10,000 r/min. (d) Centrifugal stress distribution at 10,000 r/min.
design simulation of the PMIM. The temperature distributions of the oil-cooled PMIM simulated under two working conditions of 4000 r/min@115 N·m and 7000 r/min@90.2 N·m are shown in Figure 5. Using the same simulation method, the temperature distribution under other working conditions can be obtained, and the simulated temperatures at key parts are listed in Table 2. Clearly, the temperatures of the winding did not exceed its temperature tolerance.

The rotor mechanical structure strength stress of the PMIM when the interface between the permanent magnet and rotor was not added with epoxy-resin is shown in Figure 6. The epoxy-resin analytical method was stated above. The material properties and stress analysis results are listed in Tables 3 and 4 respectively. Clearly, the centrifugal force maximized at section $b_2$ of the magnetic bridge. The maximum deformation and the maximum centrifugal force on the rotor surface at the highest rotating speed were smaller than the tensile strength of the silicon steels. Under the 1.4-fold highest rotating speed and without addition of epoxy-resin, the rotor mechanical strength still met the requirements, which ensured the long life time of the motor.

5. Prototype Experimental Validations

The schematic diagram of prototype structure is shown in Figure 7, and the test platform of the prototype is shown in Figure 8. This system adopted two motors at the rated power of 50 KW and in the towing mode. The tested motor and the assisting motor were controlled by torque and the rotating speed, respectively. The system was equipped with an oil-cooled subsystem, and a thermistor was placed inside the terminal winding to detect the winding temperatures. The cooled oil inlet was set at 90°C, and the flow speed was 5 L/min.

The measured waveform of line back-EMF on no-load at 7000 r/min is shown in Figure 9, with the virtual value of 214 V. Clearly, the experimental data were very consistent with the simulation results in terms of line waveform amplitude and shape.

The measured motor efficiency MAP under the generation model is shown in Figure 10, with the largest efficiency at 95.395%, which was very close to the simulated result.

| Speed(r/min)         | Maximum deformation (mm) | Maximum centrifugal stress (MPa) |
|----------------------|--------------------------|---------------------------------|
| No epoxy @ 7000 r/min| 0.0128                   | 40.5                            |
| No epoxy @ 10,000 r/min| 0.0264                  | 82.6                            |
| Epoxy @ 7000 r/min  | 0.001                    | 17.3                            |
| Epoxy @ 10,000 r/min| 0.0021                   | 35.3                            |

Figure 7: Schematic diagram of prototype structure. (a) Stator. (b) Rotor.

Figure 8: Test platform for prototype machine.
The prototype machine stator winding temperatures measured at different speeds are listed in Table 2, which were very close to the simulated results.

Finally, the motor at the 1.4-fold largest rotating speed (or namely 9800 r/min) was tested, and no failure of the rotor was found, which confirmed that the mechanical structure strength of the newly-designed rotor can be met.

In all, the electromagnetic simulation results and thermal simulation results were very close to the experimentally measured results, and the rotor mechanical strength was also met, indicating that the oil-cooled PMIM MPDID method proposed here was accurate and effective.

6. Conclusions

An efficient oil-cooled PMIM MPDID method that integrated electromagnetism design, temperature rise design, and rotor mechanical structure design was proposed. Compared with the traditional single performance design, the design efficiency of the motor and the performance of the motor are further improved. According to the main size parameters of the PMIM, the electromagnetic design of the motor was carried out, the temperature rise of the winding was calculated according to the equivalent thermal conductivity in the slot of the PMIM, and based on the precise equivalent ring principle, the rotor mechanical structure strength of the PMIM was designed and analyzed. Finally, a 48-slot and 8-pole PMIM with the rated power 50 KW was built for electromagnetic-thermal-mechanical structural rotor integrated design. The experimental data were consistent with the simulated data, which confirmed the effectiveness and accuracy of the MPDID method and offered an efficient design method for practical engineering applications.

Data Availability

The nature of the data is the motor size parameters, and the data can be accessed from Electrical Machinery Laboratory of Shanghai University. The complete data belong to the joint ownership of the Electrical Machinery Laboratory of Shanghai University and the enterprise.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the Anhui Provincial Quality Engineering Project under Grant no. 2018jyxm0974 and the Open Project of Jiangsu Key Laboratory of Transportation and Safety Assurance under Grant no. TTS2018-07.

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