Electromagnetic and Thermal Design/Analysis of an Induction Motor for Electric Vehicles

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Abstract—The most commonly used electrical machine is the induction machine since it is durable, easy to manufacture and control. Additionally, it requires less maintenance, and responses different loads. In this study, the design of 115kW (continuous 85kW) squirrel cage induction motor is presented for electric vehicle applications. Main design constraints and performance criteria of the motor are determined and depending on these values, computer aided design is performed. In the design procedure, initially, an analytical design of the electric vehicle motor is performed depending on specified design criteria. Then, the analytical design is verified by using finite element analysis. Depending on the obtained results in electromagnetic analyses, the squirrel cage induction motor is modified in order to improve the obtained performance further. The electromagnetic and thermal analyses of the designed motor are performed by using Maxwell® and ANSYS software programs, respectively. Designed motor will stand maximum allowable temperature based on temperature rise of the used insulation class. The analyses results show that the designed motor satisfies the design criteria.

***Index Terms*—Induction motor, electric vehicle, thermal analysis, electromagnetic analysis**

I. Introduction

Popularity of the electric vehicles (EVs) has continuous to increase worldwide depending on the decreasing petrol sources and increasing emissions. Considering this, vehicle manufacturers placed on the market several commercial electric vehicles such as Toyota RAV4 EV, Chevrolet Volt, Tesla Model S and Renault Twizy [1, 2].

Electric powered vehicles mainly consist of four subsystems: battery, traction motor, motor drive and control unit. Battery supplies the required power to the both traction system and electrical equipment of the vehicle. It is the duty of the battery management system to check the battery level and the temperature so that it does not exceed any critical level. In the traction system, an electric motor is used which is generally a brushless permanent magnet motor [3, 4], squirrel cage induction motor [5, 6] or switch reluctance motor [7, 8]. Motor driver is used for variable speed/torque control of the motor as well as regenerative breaking. The control unit collects all available data from the other subsystems/components, and perform high level control of the vehicle.

Asynchronous motors are widely used in the industry for their low cost and robustness. Industrial asynchronous motors are generally used without driver and usually do not operate at extreme working cycles. These motors are designed with respect to constant voltage and constant frequency values depending on the grid voltage and frequency values. In literature, there are many analytical and experimental data and tables for the design of these types of asynchronous motors. These results help the designer to choose design parameters such as pole number, slot type, airgap value, current and flux density values in the design process. On the other hand, motors with driver operate at variable frequency, voltage and power values as it is in the electric vehicle applications. Therefore, the most of the data and tables (such as stator-rotor slot combination) used in the design procedure of industrial asynchronous motors are not valid anymore for the design of variable frequency asynchronous motors. In the case of electric vehicle applications, an electric motor must fit the driving pattern by satisfying the different speed and torque characteristics. This necessity leads to special considerations in the motor design for electrical vehicles.

In Fig. 1, the torque and power characteristics of an electric motor with driver are given [9]. The operating region under the base frequency is named as the constant torque region. In this region, the maximum torque value which is needed for acceleration of the electric vehicle can be provided constantly for different speeds by controlling voltage and frequency. The region between the base and maximum frequencies is named as the constant power region. Since the maximum voltage value obtained from the driver is limited depending on the capacity of the battery pack, the power of the motor become constant after the base frequency. Therefore, the torque obtained from the motor decreases in the constant power region when the motor speed increases.

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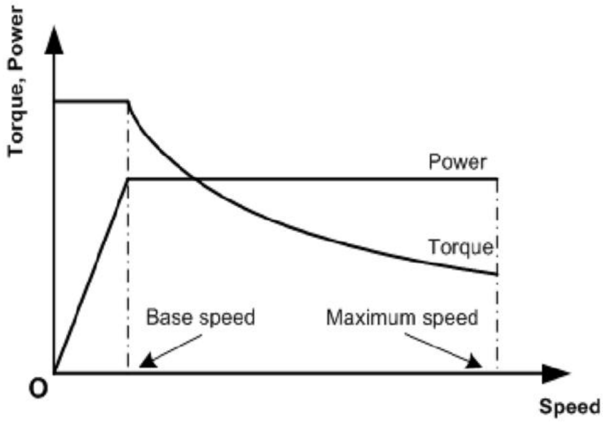

Figure 1. Power and torque characteristics of electric motor.

In this study, 115kW (continuous 85kW) squirrel cage induction motor is designed and the results of electromagnetic/thermal analyses are given.

II. Induction Motor Design

A. Factors that Affect Electrical Machine Design

In the electrical machine design, economical factors, limits related to motor materials, requirements related to standards, and other special factors that have an effect on the design are taken into consideration [10].

In industry, the cost of an electrical machine has generally great importance. Technical and economical limits related with materials such as thickness and magnetic saturation value of steel lamination, size and type of conductor material and dielectric material directly influence size and performance of electrical machines by determining the maximum flux density values, losses, efficiency and the weight.

The electrical machine should be designed, tested and manufactured depending on international standards such as IEEE, IEC, NEMA [11-13]. On the other hand, there may be special conditions for the electrical machine. For example, the electrical machine can be used in the environment having extreme temperature conditions. In this case, these requirements must be considered specially in the design process.

B. Design Steps

Before starting the electrical machine design procedure, design criteria such as power, phase number, supply voltage, frequency, desired efficiency, power factor, conductor current density, air gap flux density are specified. Then, the design process is initiated, and systematic revisions are performed by modifying design parameters on the motor model until design criteria are met.

The steps of the electrical machine design can be given as follows [10].

- Electrical design: Depending on given electrical design criteria, stator and rotor dimensions, slot numbers, winding type, coil dimensions and numbers, coil factors, motor connection type, etc., of electrical machine are determined.
- Magnetic design*:* Depending on given design criteria, lamination saturation flux density and airgap flux density are determined. Depending on these values, stator and rotor teeth and yokes are designed.
- Insulation design*:* Depending on the design criteria, motor insulation design is performed to provide electrical safety by considering motor operating temperature and winding voltage.
- Thermal design*:* Since the coil resistance increases when the temperature increase, thermal design has important effect on the motor efficiency. Therefore, thermal design is performed to keep the motor at its desired operation temperature. In the thermal design, cooling type, cooling flow rate, ventilation ducts, etc., are determined.
- Mechanical design: In mechanical design of the electrical machine, shaft design, bearing design, end bracket design and motor frame design are performed by considering critical working speed, noise and vibration of electrical machine, tensile forces acting on shaft, moment of inertia, etc.

C. Special Considerations in the Design of Asynchronous Motors with Driver

In the design procedure of the electric motor for EVs, initially, it is needed to determine the base frequency w_b where the nominal power value is desired to be obtained. In this way, the operating frequency range is determined depending on the desired maximum operating frequency w_{max}. The base operating frequency depends on the determined nominal speed and pole number of the motor. When the pole number is determined, it is important to consider that the maximum operating frequency should not be considerably high. Because, higher maximum frequencies result in higher iron and eddy current losses in the electrical machine. Additionally, the maximum operating speed is directly related with the breakdown torque value of the electrical machine. In order to provide desired maximum operating speed, the breakdown torque value of the motor must be high. Therefore, the leakage inductances in the electrical machine design must be decreased as far as possible.

Second, the voltage range of the battery pack of the EV is considered in the design procedure. The design of the motor can be performed with respect to the minimum voltage value of the battery pack in order the motor to provide desired torque value in even the worst case. On the other hand, increasing motor voltage directly effects the flux densities in the lamination and airgap. Therefore, it should be considered in the design that the flux density values should be under the magnetic saturation value of the lamination material for the case of the maximum voltage value available.

Finally, the maximum power requirement of the EV is an important factor for the electrical and thermal design of the motor. The value and period of the maximum power depend on the current density limit of the motor windings in the design. When the motor is operated above its continuous (nominal) power, the motor current increases. This results in rapid increase at winding temperature. The duration of maximum power operation directly depends on the thermal performance of the motor. Therefore, the designed motor should tolerate the maximum power demand in reasonable duration.

D. Design Constraints and Criteria

Electric motor is one of the subsystems of the EV such as battery pack and main control unit. Therefore, there are several constraints in design procedure depending on the specifications of the other subsystems of EV. The design constraints and criteria of the electric motor to be designed are given in Table I.

TABLE I. DESIGN CRITERIA AND CONSTRAINTS

Motor phase voltage	440VAC
Motor nominal speed	2250 rpm
Motor maximum speed	>6000 rpm
Motor nominal torque	360 Nm (85kW)
Motor maximum torque	476 Nm (115kW)
Efficiency	92%
Motor cooling type	Totally enclosed
Motor operating temperature	135 ℃
Available volume for motor in EV	450x450x400mm

E. Choice of Pole Number/Operating Frequency

Before starting the motor design, pole number/operating frequency of the motor must be determined depending on the values given in Table I. The frequency of a motor is calculated as follows

$$f_1 = \frac{np}{60} \tag{1}$$

where n and p denote speed and single pole number of the motor.

By using (1), nominal and maximum operating frequencies of the motor are calculated as given in Table II with respect to different pole number values.

TABLE II. CHANGE OF MOTOR OPERATING FREQUENCY VALUES WITH RESPECT TO POLE NUMBER

Pole Number ($2p_1$)	Nominal Operating Frequency (Hz)	Maximum Operating Frequency (Hz)
2	37.5	108
4	75	217
6	112.5	325
8	150	433

When operating frequency of the motor increases, losses depending on the motor frequency such as iron and eddy current losses also increase. Considering this point and also desired power requirements, the pole number of the motor is chosen as $2p_1 = 4$.

F. Electrical and Magnetic Design

Before starting the electrical machine design, electrical and magnetic limitations must be determined in addition to performance criteria and constraints given in Table I. The maximum design parameter values are determined as given in Table III.

TABLE III. MAXIMUM DESIGN PARAMETER VALUES

Parameter	Max. Value
Stator current density	8 A/mm2
Rotor bar current density	6 A/mm2
Rotor ring current density	4 A/mm2
Lamination flux density	2.2 T

Considering iron losses, the thickness of lamination material is chosen as 0.35mm. Its magnetic saturation value is 2.3T and its iron loss is 2.5 W/kg (at 1.5 Tesla/50 Hz). Rotor cage is die-cast aluminum. Analytical and magnetic analyses are performed and the motor design is improved with respect to analyses results. Ansoft RMxprt and Maxwell 2D software packages are used in the analytical and magnetic analyses of the motor, respectively.

Main dimensions of the motor are determined depending on the values given in Table I by using output coefficient design method [14]. Stator and rotor design of the motor is performed depending on the specified design values. After systematic analyses, the stator and rotor slot combination is determined as 48/54 to reduce unbalanced rotor forces and harmonics. Additionally, since the breaking torque has to be high enough to enable required maximum speed, leakage inductances are diminished sufficiently.

The lamination geometries of the designed motor and their parameter values are given in Fig. 2 and Table IV, respectively.

TABLE IV. PARAMETER VALUES OF LAMINATION GEOMETRIES

Parameter	Stator	Rotor
Slot number	48	58
Outer diameter	320mm	209
Inner diameter	210mm	60mm
Length	225 mm	

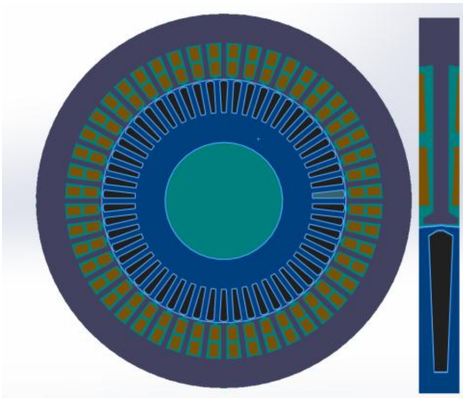

Figure 2. Stator and rotor lamination geometries.

III. THERMAL DESIGN

Thermal considerations of electric motors hold great importance since all of the materials used are sensitive to heat. Resistivity of the copper increases with increasing temperature and this leads to decrease of motor torque which is unfavorable especially in electric vehicle applications.

There are three ways that heat is transferred: conduction, convection and radiation. Conduction occurs between in-touch bodies whereas convection is the transfer of heat by means of a fluid and radiation is the heat transfer between two surfaces where a fluid is not required. Generally, radiation is not taken into consideration in electric motors as its effect is relatively small. Conduction is mostly seen in the rotor, where rotor bars heat the rotor laminations.

For isotropic media, the steady-state heat transfer governing equations and its boundary conditions can be given as below:

$$\nabla(-k\nabla T)=Q \tag{2}$$

$$k\frac{\partial T}{\partial n}\bigg|_S=0 \tag{3}$$

$$k\frac{\partial T}{\partial n}\bigg|_S=-h\left(T-T_f\right) \tag{4}$$

where, k [W/m °K] thermal conductivity, T [°K] temperature, and Q [W/m^3] the heat source, n is the unit normal vector; h is the heat transfer coefficient, W/(m^2 °K); T_f is the fluid temperature (temperature of the cooling agent), °K. The heat sources leading to the temperature rising of the motor come from all losses of the motor. These losses consist of winding loss of the stator and rotor bar losses, iron-core loss, mechanical loss and additional loss.

Convection is the most important transfer type in an electric motor because it helps the motor to cool. In this paper, convection in the air gap is studied and results are used in the heat transfer analysis since the convection in the air gap is quite important. Fluid in the air gap, generally air, removes the heat generated from stator and rotor. Forces occurring from the rotating rotor forces the fluid to tangential movement and therefore toroidal vortices are induced [15]. This movement is known as Taylor vortex flow and described by Taylor number as:

$$Ta_m=\frac{\Omega_a r_m^{0.5}\left(b-a\right)^{1.5}}{v} \tag{5}$$

Low Taylor numbers indicate that heat transfer is closer to the conduction rather than convection. When the number is between 1700 and 10^4 vortices happen with laminar flow and (7) is used for Nusselt number calculation. For Taylor numbers higher than 10^4, flow is turbulent and Nusselt number is modeled as in (8). (6) is critical speed for determination of vortices.

$$\Omega_{cr}=\frac{41.19v}{r_m^{0.5}\left(b-a\right)^{1.5}} \tag{6}$$

$$Nu=0.128{Ta_m}^{0.367} \qquad 1700<Ta_m<10^4 \tag{7}$$

$$Nu=0.409{Ta_m}^{0.241} \qquad 10^4<Ta_m<10^7 \tag{8}$$

$$h=\frac{Nuk}{D_h} \tag{9}$$

where, Ω_a, speed of the motor, v, kinematic viscosity, r_m, rotor radius, b, airgap outer diameter, a, airgap inner diameter, Ta_m, Taylor's number, Nu, Nusselt number, D_h, air gap length.

It is shown that h-convection coefficient obtained from the numerical analysis shows very good agreements to values obtained from analytical [16]. CFD analysis is performed to verify the analytically calculated values of h.

IV. Analyses Results

A. Electromagnetic Analyses

Electrical and magnetic analyses of the designed motor are performed on Maxwell software. The results are shown for the maximum power condition in order to investigate the worst scenario where the motor is at its hardest point.

For maximum power operating mode, calculated winding currents and corresponding flux lines distribution are given in Fig. 3 and Fig. 4, respectively.

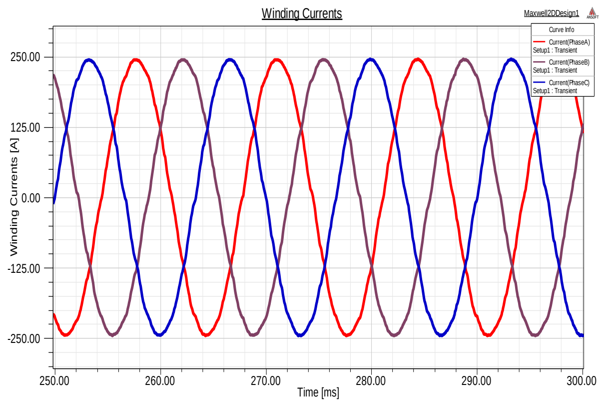

Figure 3. Phase currents in maximum power operating mode.

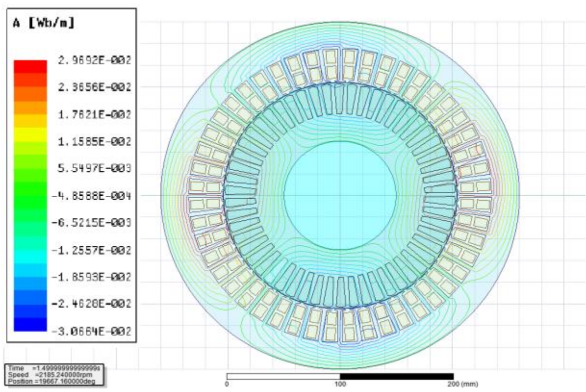

Figure 4. Flux lines distribution.

As it is seen from Fig. 4, flux lines are distributed properly and desired winding poles are obtained. Magnetic flux density distribution of the motor lamination are given in Fig. 5.

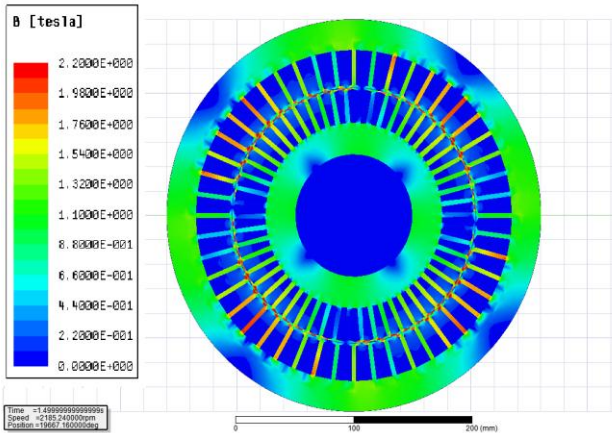

Figure 5. Flux density distribution.

As it is seen from Fig. 5, flux density values are mostly less than 2T. Although there are some narrow regions such as slot openings where flux density values are greater than 2T, the maximum flux density value is less than 2.3T which is the magnetic saturation value of the motor lamination material.

The input-output power and torque computations of the designed motor are given in Fig. 6 and Fig. 7, respectively.

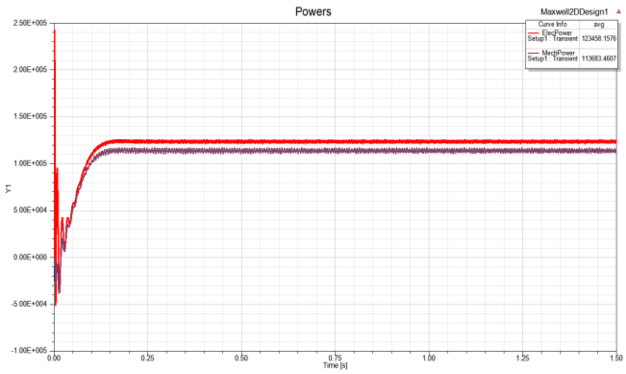

Figure 6. Electrical and mechanical power of the motor.

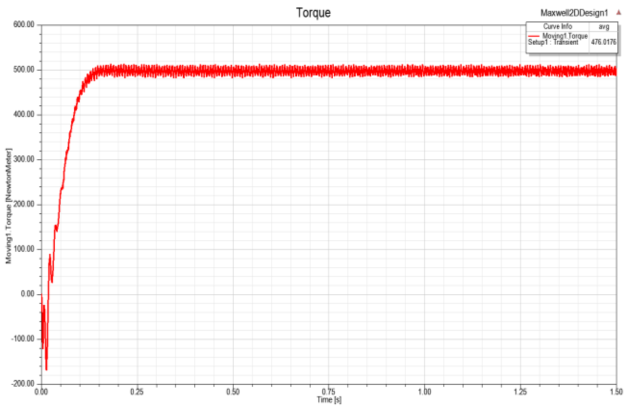

Figure 7. FEA torque computation.

As it is seen from Fig. 6 and Fig. 7, the motor efficiency is approximately 92% and the torque value is 490Nm. Torque ripples are under the acceptable ranges.

Finally, analyses results of the designed motor are given in TABLE V..

TABLE V. ELECTROMAGNETIC ANALYSES RESULTS

Parameter	Value
Mechanical output power	115055 W
Shaft torque	490 Nm
Electrical input power	124169 W
Power factor	0.91
Efficiency	92.66%
Stator current density	7.56 A/mm2
Rotor bar current density	5.40 A/mm2
Rotor ring current density	3.60 A/mm2
Nominal operating frequency	75 Hz
Nominal operating speed	2250 rpm

As it is seen from Table V, desired power, torque and efficiency criteria are satisfied. Additionally, obtained current density values are less than their specified limits given in design criteria. Thus, the designed motor satisfies all electrical and magnetic design criteria.

Motor is controlled by using flux-weakening control method. In this case, output power and torque curves with respect to motor speed are given in Fig. 8 and Fig. 9, respectively, for the cases of nominal-maximum power values.

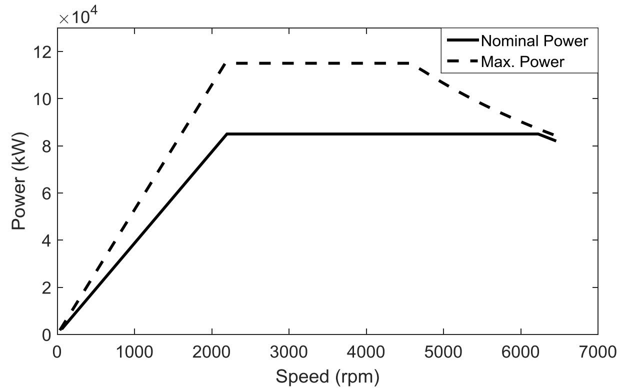

Figure 8. Output power with flux-weakening control.

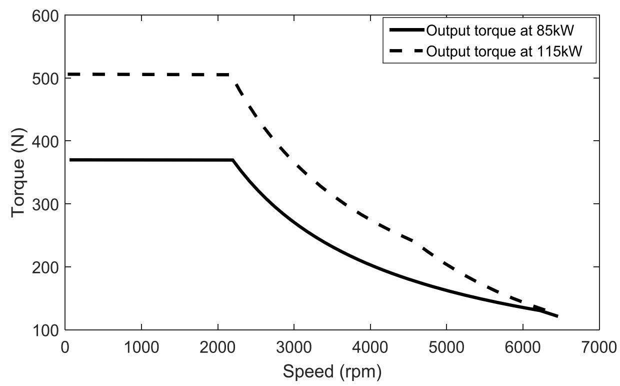

Figure 9. Output Torque with flux-weakening control.

As it is seen from Fig. 8 and Fig. 9, the maximum operating speed of the designed motor in constant power region is approximately 6300 rpm and thus, the design criterion of the maximum operating speed is satisfied.

B. Thermal Analysis

Thermal analysis is done in steady state which means that as if the motor has operated for a certain amount of time until a temperature change does not occur. Temperature distribution of an electric motor gives very valuable information to the designer. High temperature warns the designer to decrease the losses, change the effective cooling type, adjust the fins and frame, propose a new cooling type or optimize the motor. Force convection over the motor will further increase the heat dissipation leading to decrease in temperature. Electromagnetic analysis results show the losses in the machine. These results are used as an input to the thermal analysis software. Core and ohmic losses are behaved as internal heat generation. Convective heat transfer coefficients are calculated by using (5) to (9).

Dimensions of the designed induction motor are given in Table IV. Motor is insulated as H class insulation. By using these dimensional parameter values air gap convection value is found to be 70 W/m^2/K.

The heat sources leading to the temperature rising of the motor come from all losses of the motor. Winding loss of the stator and rotor bar losses, iron-core loss, mechanical loss and additional loss are applied as heat sources. Boundary conditions, given in (3) and (4), are then applied to the boundary, and the temperature field distribution is obtained as shown in Fig. 10 for the designed motor.

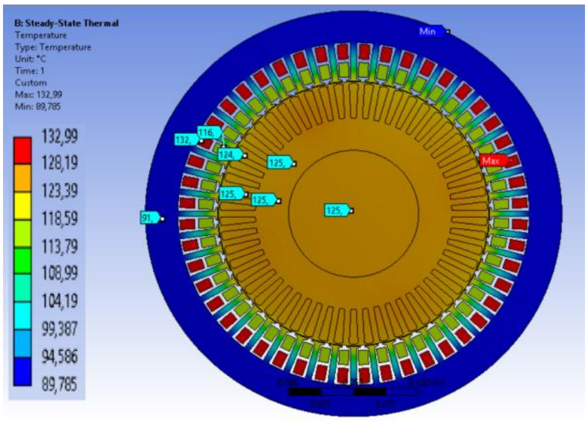

Figure 10. Temperature distribution of the motor at 115 kW.

As shown in Fig. 10, the maximum temperature is found in the rotor and stator winding. The temperature difference between the rotor core and the rotor bar is small, and the highest temperature appears in the stator upper winding. The heat is mainly conducted to the stator through the air-gap, and then taken away. The heat exchange occurs between the stator and the rotor over the air gap. It is also seen that the temperature of the stator upper winding is higher than that of the lower winding in the slot, and the temperature of the stator core yoke is lower. Fan on the shaft to force convection over the motor increases the heat dissipation and decreases in temperature on lower windings sections.

Maximum winding temperature is seen as 133 ℃. It is important that this thermal analysis does not take radiation into account, only natural convection is investigated. If outer frame is as well designed, more heat is going to be extracted from the surface of the stator by convection and what is more, taking radiation into consideration would increase the extraction.

V. Results and Discussion

In this study, an squirrel cage induction motor is designed for electric vehicle traction application. Relevant magnetic and thermal analyses are made and results are presented. Analyses results show that the designed motor satisfies the desired electromagnetic and thermal requirements. In the design of electric motor, Maxwell® and ANSYS software programs are used for magnetic analysis and thermal analysis, respectively.

For the maximum overload condition, it is seen that the temperatures are enough when the operation cycle is considered. The thermal analysis is made for steady state condition in which the maximum overload operation. The motor insulated H class has been designed to withstand maximum allowable temperature. The obtained temperature rise is lower allowable temperature rise of insulation. This means the hot spot temperature will decrease and extends motor life. To obtain full temperature distribution, it is necessary to calculate end winding temperatures. For this, 3D analysis should be realized in the future.

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