Analysis and Comparison of Interior Permanent Magnet Motors Of Two Different EV

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***Abstract*—This paper presents an analysis and comparison of two electric motors.These machines are permanent magnet machines. The first machine is a DC brushless interior permanent magnet motor. This motor has an output of 225KW and torque 375 Nm. The Second machine is an Interior permanent magnet motor. This motor has an output of 80KW and torque of 280 Nm. The Electromagnetic Analysis, Speed- Torque curves, Efficiency maps and Thermal analysis were determined and compared.The Conclusions of the machine performance were made.**

Keywords*—Permanent Magnets, Interior permanent magnet motor, Electromagnetic analysis, Thermal analysis.

Introduction

Electric Motors are not only the essence of modern living but also the essence of modern industries. Motors are important for every individual no matter where you are, you are directly or indirectly using a motor whether you are in your home, office, or in a factory.

In EV's, electrical energy is converted into mechanical energy by means of electric motors. Electric motors are specially designed for a specific use in electric vehicles.Selection of a particular type of motor for an electric vehicle must be done judiciously as motor characteristics affect the overall performance of a vehicle.

The motors discussed in this paper are used in the Electric Vehicles applications. The first motor is similar to the Tesla S60 rear motor which has an output of 225 kw and 375 Nm torque. The second motor is similar to the Nissan Leaf 2012 model which has a rating of 80 kw and torque of 280 Nm.

Both motor model's are developed and studied in the MotorCAD Ansys software. Some of the parameters of motors are approximated for the analysis purpose. We named motor with rating of 225 kw, 375 Nm as Motor A and other motor as Motor B

I. Electromagnetic Model

A. Geometry of Motor A

The motor A is an interior permanent magnet motor with two layers of magnet and 8 poles,shown in fig 1. The magnet used has the similar characteristics to NdFeB. The material used for stator and rotor lamination is M250-35A. The Armature winding is made up of copper. The B-H curve for M250-25A is shown below in fig 2. and the demagnetization curve for N42UH (used from MotorCAD Material Library) is shown in fig 3.

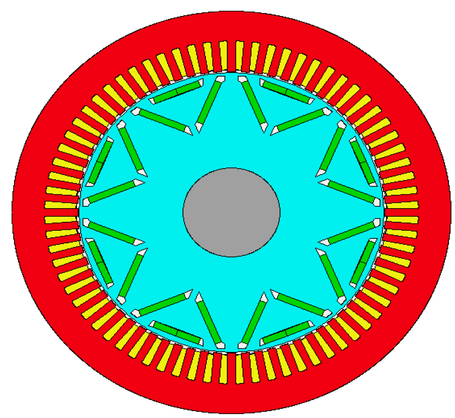

Fig 1: Geometry of Motor A

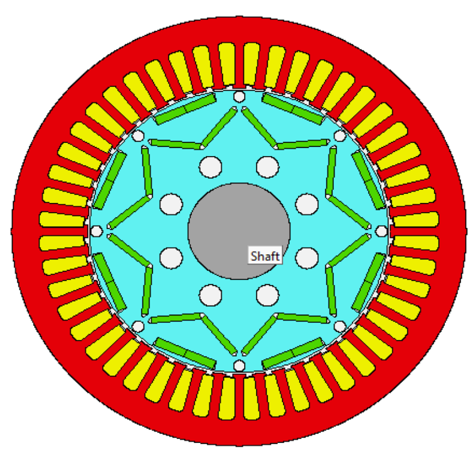

Fig 4: Geometry of Motor B

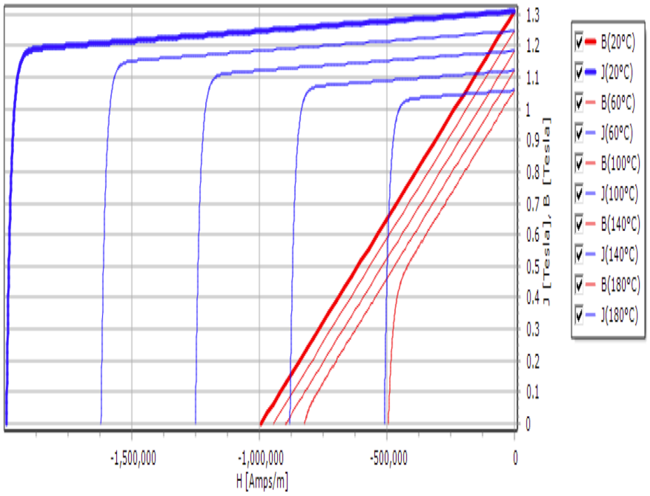

Fig 3: Demagnetization curve of N42UH

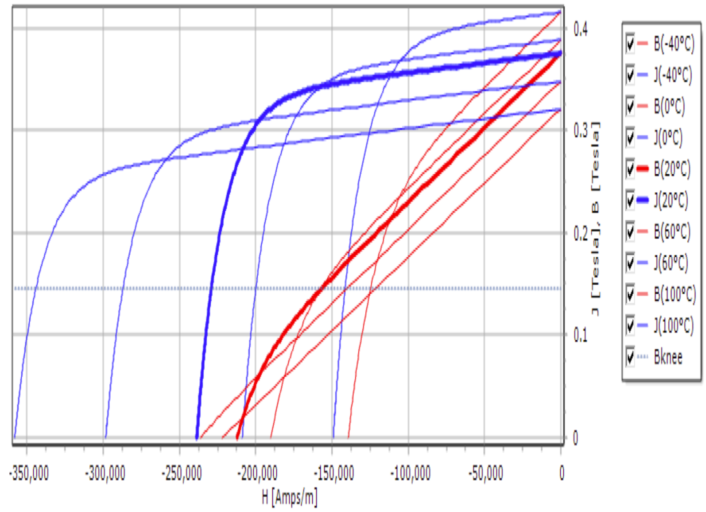

Fig 5: Demagnetization curve of N30UH

Table 1: Specification of Motor A

Parameter	Value
Stator outer Diameter	250 mm
Stator Inner Diameter	175 mm
Number of Slots	72
Slot Depth	20 mm
Tooth width	4.5 m
Slot Opening	3 mm
Air gap	0.8 mm
Shaft Diameter	55 mm
Magnet length	100 mm
Magnet thickness	4 mm
Magnet Width	28 mm
Magnet separation	0.6 mm
Pole V angle	90 mdeg
Pole arc	135 edeg
Magnet Inner Gap	0.2 mm

Table 2: Specification of Motor B

Parameter	Value
Stator outer Diameter	198 mm
Stator Inner Diameter	132 mm
Number of Slots	48
Slot Depth	21.1 mm
Tooth width	4.15 m
Slot Opening	2.814 mm
Air gap	1 mm
Shaft Diameter	45 mm
Magnet length	100 mm
Magnet thickness	2.6 mm
Magnet Width	21.33 mm
Magnet separation	0 mm
Pole V angle	124 mdeg
Pole arc	159 edeg
Magnet Inner Gap	0 mm

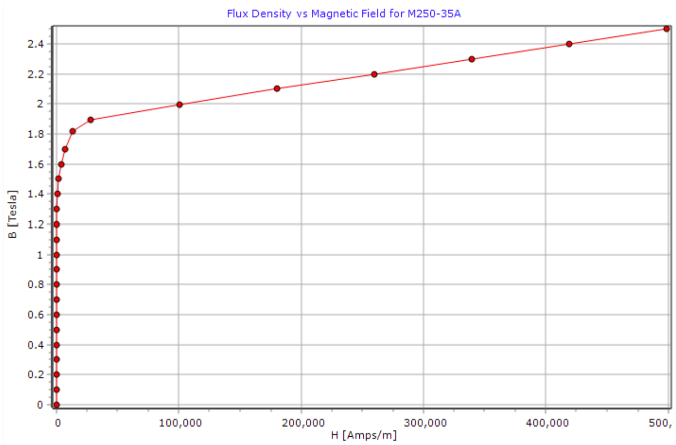

Fig 2: B-H curve of Motor A

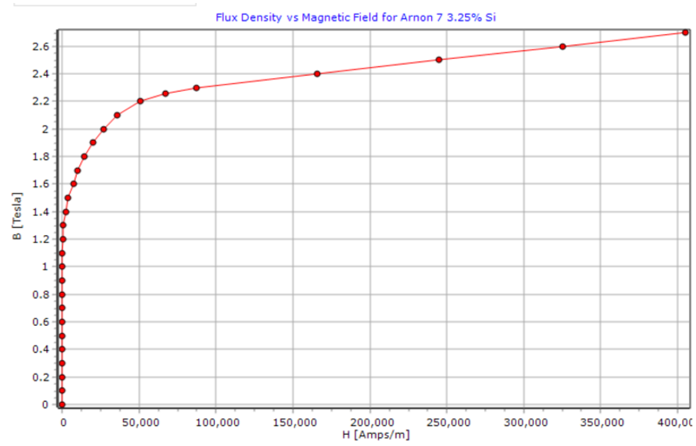

Fig 2: B-H curve of Motor B

B. *Geometry of Motor B*

The Motor B is also an interior permanent magnet motor with two layers of magnet and 8 poles,shown in fig 4. The magnet used has the similar characteristics to NdFeB. The material used for stator and rotor lamination is M250-35A. The Armature winding is made up of copper. The B-H curve for M250-25A is shown below in fig 2. and the demagnetization curve for N30UH (used from MotorCAD Material Library) is shown in fig 5

II. ELECTROMAGNETIC ANALYSIS

A. *Electromagnetic Analysis of motor A*

Most of the characters of the motor can be determined by Electromagnetic analysis for a first principle examination. Besides the torque, voltage, current and loss information, some underlying quantities can be extracted from this type of analysis too. For example, the flux density distribution plot is calculated to make sure that the motor is not saturated during operation.It aims to study the flux distribution at different parts of the motor and to predict safety and efficiency of the motor by increasing torque and current accordingly.

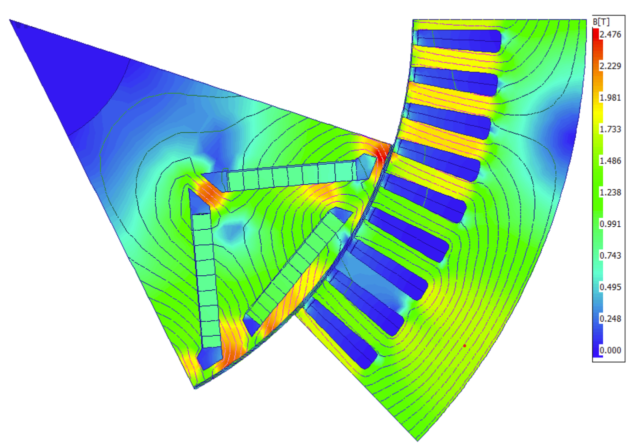

Fig 6: Motor A:Flux Density distribution for operation with maximum power output and maximum torque

The flux density in tooth and back iron was found as 1.74T -1.8T in the analysis for the on load condition to deliver the maximum power output and maximum torque.Here the base speed of 5000 rpm and the material temperature was set to 100 ^{0}C to calculate the flux density at a torque of 375 Nm. During the initial design the tooth width and slot depth can be adjusted to get the desired flux density. Increase in the tooth width reduces the flux density in the tooth whereas increase in the slot depth increases flux density in the stator back iron. The feature of MotorCAD helps to find the phase advance angle and also to eliminate the cogging torque.

B. *Electromagnetic Analysis of Motor B*

During the analysis with MotorCAD application we found the peak flux density in tooth and back iron as 1.8T and 1.68T respectively for the on load condition to deliver the maximum power output and maximum torque. Here the speed used is 3000 rpm and the material temperature was set to 65 ^{0}C. The MotorCAD sensitivity section helps to find the phase advance angle and peak current using which we can get the maximum torque. In this case we achieve a torque of 284 Nm and phase advance angle of 32.87^{0}.

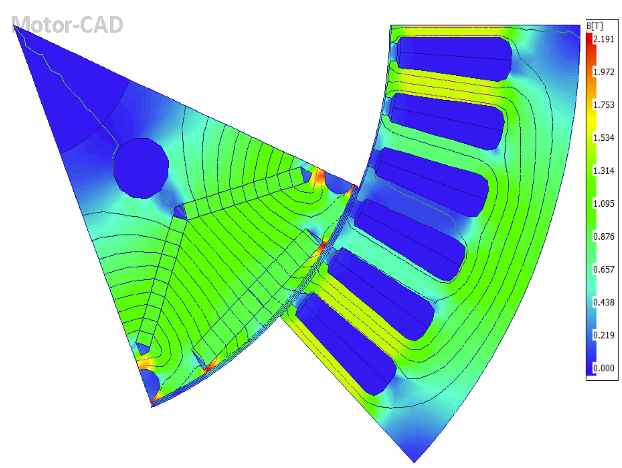

Fig 6: Motor B:Flux Density distribution for operation with maximum power output and maximum torque

Table 3: Output Data achieved in MotorCAD for Motor B

Variable	Value	Units
DC Bus Voltage	375	Volts
Line-Line Supply Voltage (rms)	265.2	Volts
Phase Supply Voltage (rms)	153.1	Volts
Line-Line Terminal Voltage (peak)	269.6	Volts
Line-Line Terminal Voltage (rms)	193.8	Volts
Phase Terminal Voltage (peak)	147.5	Volts
Phase Terminal Voltage (rms)	112.8	Volts
Harmonic Distortion Line-Line Terminal Voltage	8.811	%
Harmonic Distortion Phase Terminal Voltage	15.62	%
Back EMF Line-Line Voltage (peak)	201.8	Volts
Back EMF Line-Line Voltage (peak) (fundamental)	193.8	Volts
Back EMF Phase Voltage (peak)	111.4	Volts
Back EMF Line-Line Voltage (rms)	137.1	Volts
Back EMF Phase Voltage (rms)	79.55	Volts
Harmonic Distortion Back EMF Line-Line Voltage	3.819	%
Harmonic Distortion Back EMF Phase Voltage	10.59	%
Max Line-Line / Phase Voltage Ratio	1.732	

DC Supply Current (mean)	249.2	Amps
Line Current (peak)	480	Amps
Line Current (rms)	339.4	Amps
Phase Current (peak)	480	Amps
Phase Current (rms)	339.4	Amps

Phase Advance	45	EDeg
Drive Offset Angle (Open Circuit)	0	EDeg
Drive Offset Angle (On load)	0	EDeg
Phase Advance to give maximum torque	32.97	EDeg

Phasor Offset Angle	345	EDeg
Phasor Angle (Ph1)	0	EDeg
Phasor Angle (Ph2)	120	EDeg

C. Comparison of Speed- Torque Characteristics

The performance and suitability of an electric motor for a particular application can be decided by its torque-speed characteristics. Torque-speed characteristics are also called mechanical characteristics. When an electric vehicle is used where frequent starting/stopping is required, the motor is operated in constant torque region, while at high speed; it is operated in constant power region.

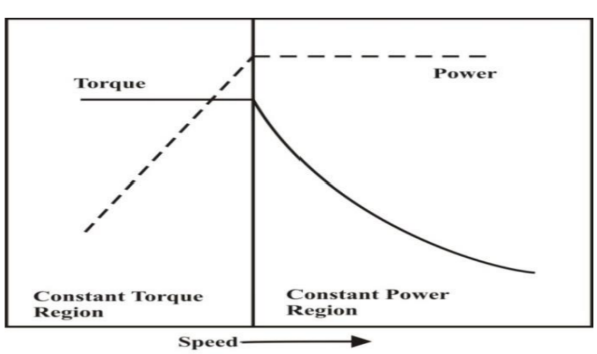

Fig 6: Ideal torque-speed characteristics of Electric motor for EV

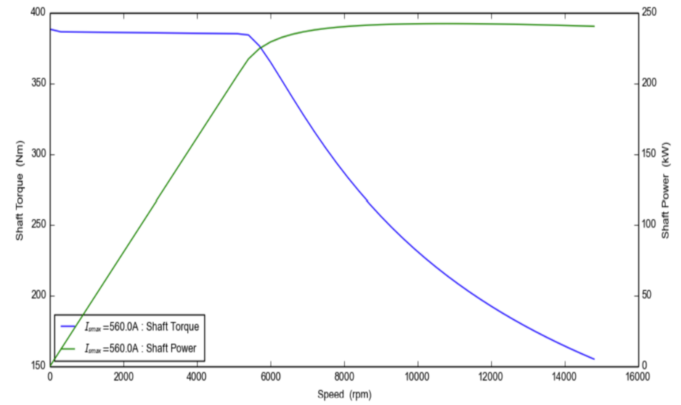

Fig 7: Motor A: Speed-Torque Characteristics

The Fig 6 shows the ideal speed torque characteristics of the electric motor for the electric vehicles. The speed torque characteristics of motor A and motor B achieved through analysis using MotorCAD software is shown in fig 7 and fig 8 respectively.

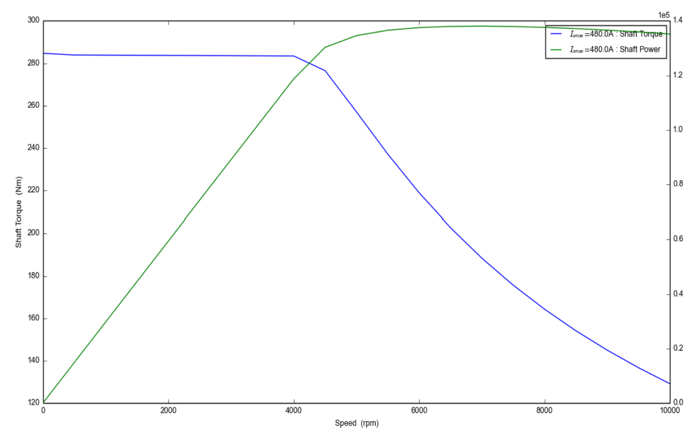

Fig 8: Motor B: Speed-Torque Characteristics

D. Efficiency Map

Motor is an electromechanical device which converts electrical energy into mechanical energy. The entire electrical energy is not converted into mechanical energy but is lost due to various factors. Electrical efficiency of an electric motor gives us the relation between electrical input and useful mechanical output of motor and is generally given by ratio of shaft power output and motor input power. Generally, all electric motors are designed to operate at maximum efficiency at rated output of a motor.

In this case Efficiency of both the motors is calculated in the MotorCAD LAB section. The efficiency of motor A was found to be 95.3%. Fig 9 shows the efficiency map for the motor A. This efficiency map is calculated using the finite element mapping of losses, torque, flux linkage and speed in MotorCAD. The efficiency of motor B achieved in the analysis was 95.17%. Fig 10 shows the efficiency map for the motor B.

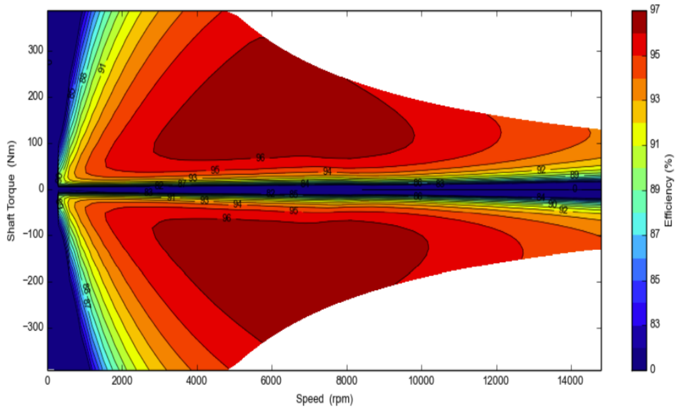

Fig 9: Efficiency map of motor A

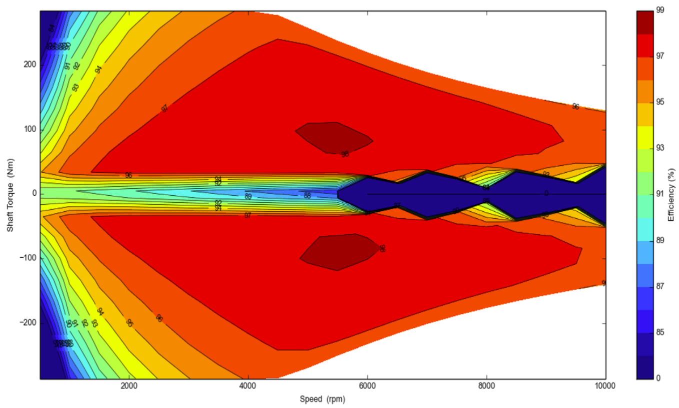

Fig 10: Efficiency map of motor B

III. Thermal Analysis

The thermal analysis of an electric motor is done to study the heat transfer in the slot or winding of the motor. In order to solve rising temperature problems it is important to investigate a magnetic design that reduces the losses themselves because they are a source of heat, but it is also important to study a thermal design that improves heat dissipation and does not let the temperature rise. Copper loss in the coils and iron loss in the core are the dominant heat sources, so this analysis mainly evaluates the effects of this heat. Changes in the magnet's properties due to temperature are large and its heat resistance is low, so it is necessary to design while paying careful attention to rising temperatures during operation.The fig 11 shows the thermal analysis result. The average temperature of 166 ^{0}C is noticed in the winding. The shaft temperature was noticed to be 71.1 ^{0}C whereas magnet temperature was 74.3^{0}C. The temperature rise in the motor A is within the properties limit. Therefore it helps the motor to operate at high efficiency.

Fig 12 shows the FEA thermal analysis view of the rotor of motor A whereas fig 14 shows for motor B. The average temperature of 150 ^{0}C is noticed in the winding. The shaft temperature was noticed to be 145 ^{0}C whereas magnet temperature was 148^{0}C.

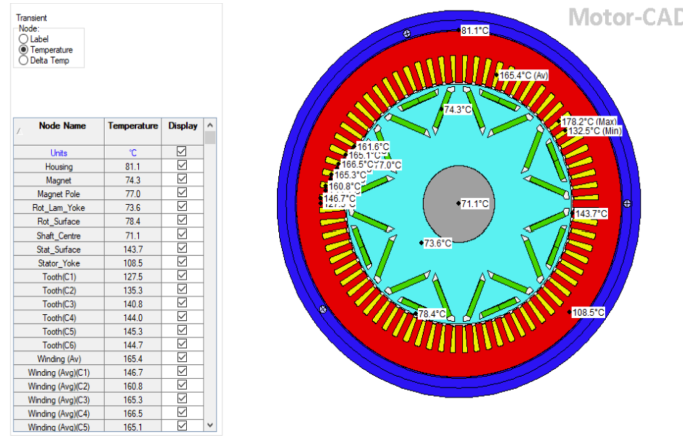

Fig 11: Thermal efficiency of motor A

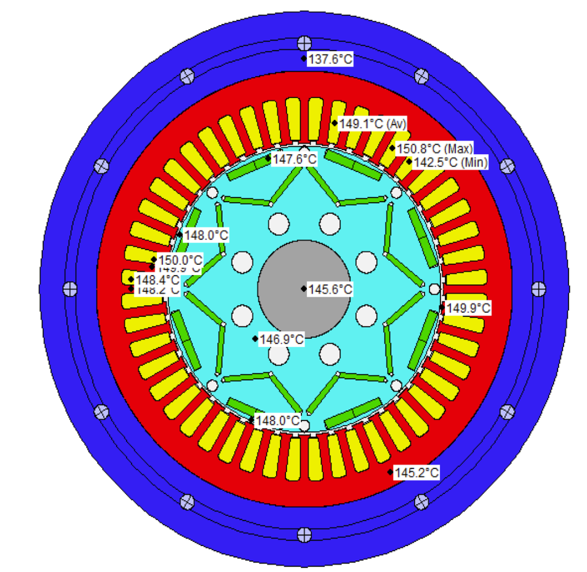

Fig 11: Thermal efficiency of motor B

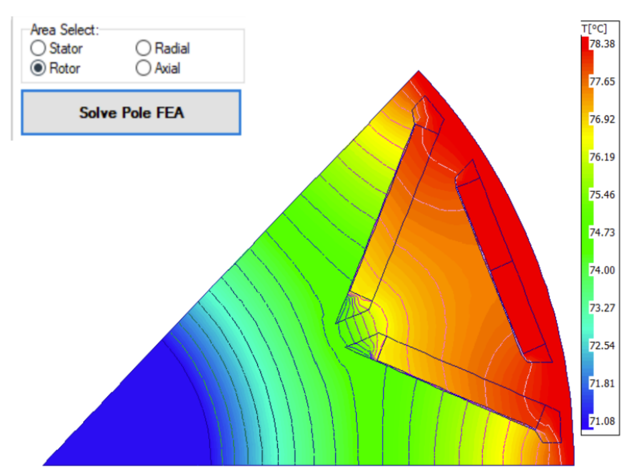

Fig 12: Thermal analysis of rotor of motor A

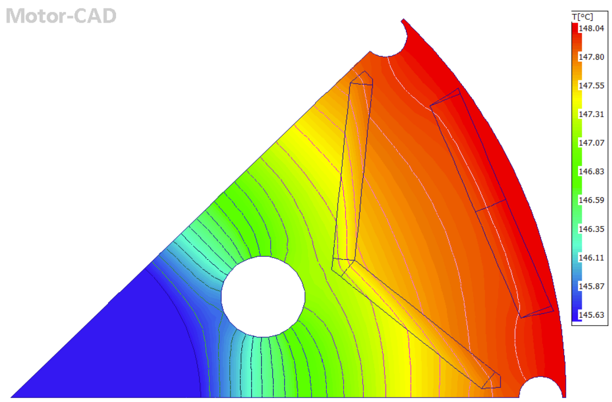

Fig 12: Thermal analysis of rotor of motor B

IV. WINDING ANALYSIS

The **winding factor** is the method of improving the rms generated voltage in a three-phase AC machine so that the torque and the output voltage do not consist of any harmonics which reduces the efficiency of the machine**. Winding Factor** is defined as the product of the Distribution factor (Kd) and the coil span factor (Kc). The distribution factor measures the resultant voltage of the distributed winding regards concentrate winding and the coil span is the measure of the number of armature slots between the two sides of a coil. It is denoted by Kw. The EMF equation is given below:

$$E_p = 4.44 K_w f \varphi T_p$$

The nth order harmonic induced EMF per phase is given by the equation shown below:

$$E_p = 4.44 K_{cn} K_{dn} (nf) \varphi_n T_p$$

Since the strength of the harmonic components of voltage decreases with the increasing frequency, only fifth and seventh harmonics are important. These are known as **Belt Harmonics**.

$$E_{line} = \sqrt{3} \, x \sqrt{E_1^2 + E_5^2 + E_7^2 + E_{11}^2 + \cdots \ldots}$$

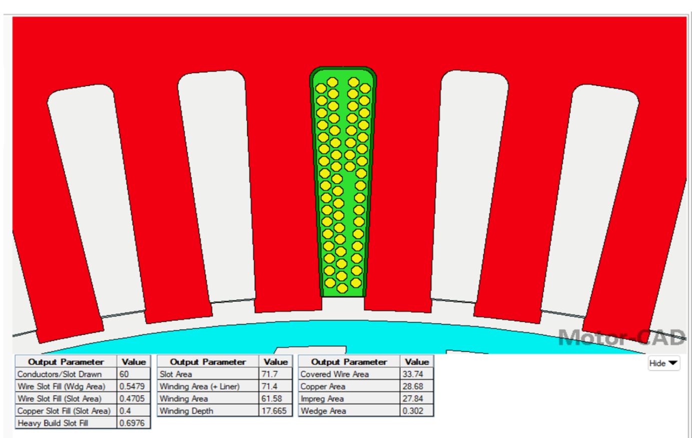

Fig 13: winding structure of Motor A

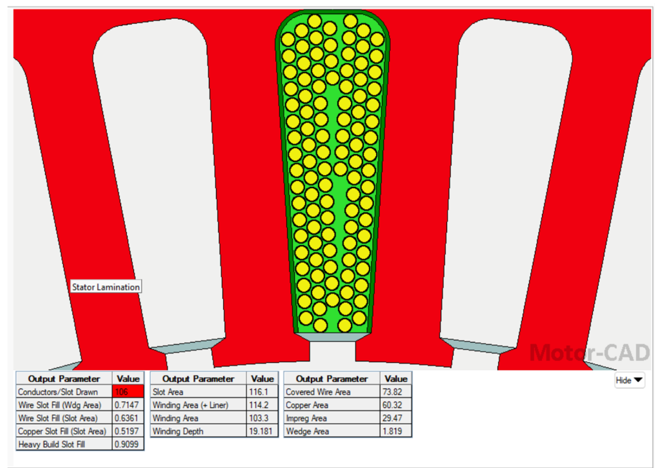

Fig 13: winding structure of Motor B

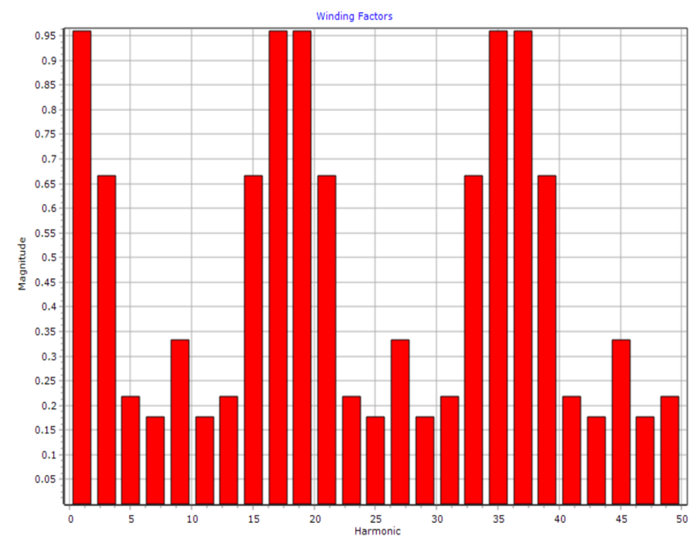

Fig 14: Winding Factors of Motor A

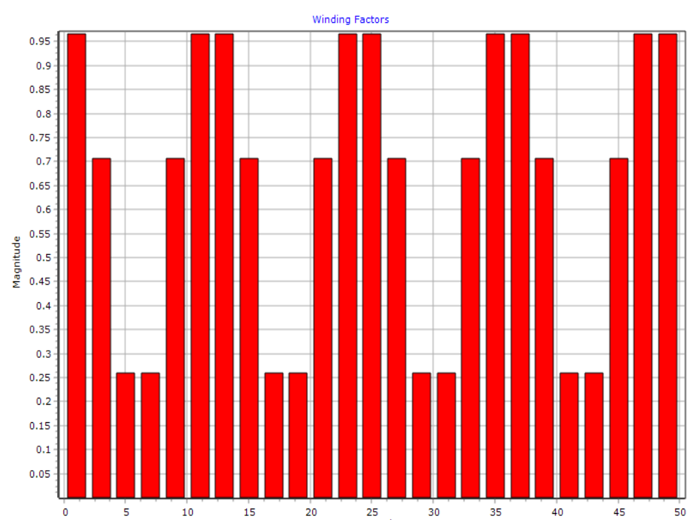

Fig 14: Winding Factors of Motor B

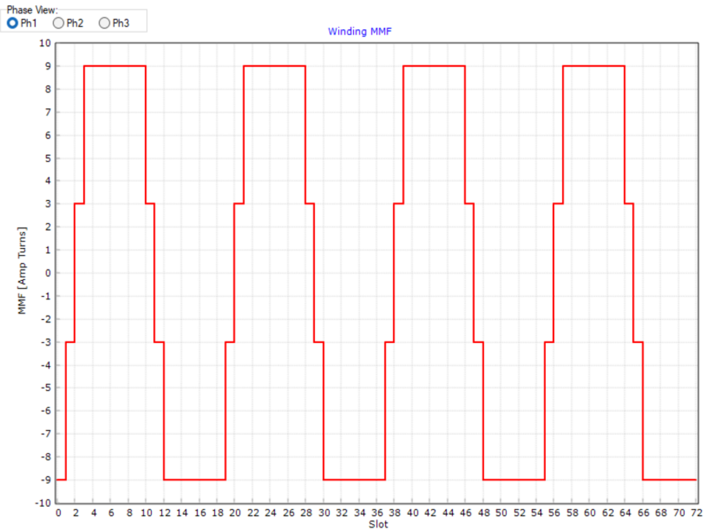

Fig 15: winding MMF of Motor A

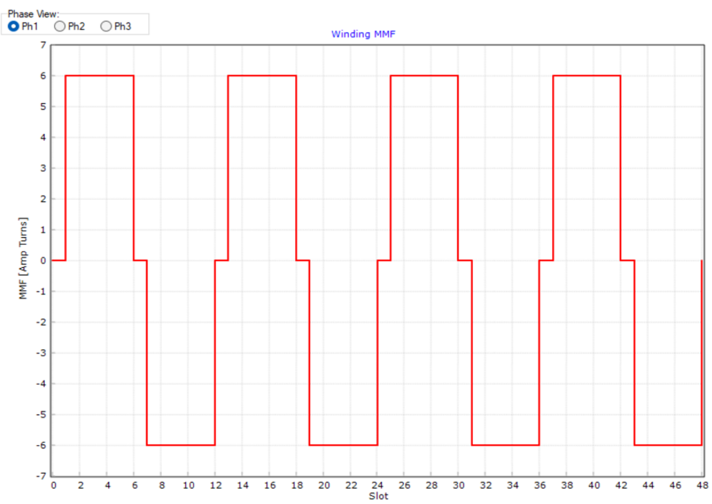

Fig 15: winding MMF of Motor B

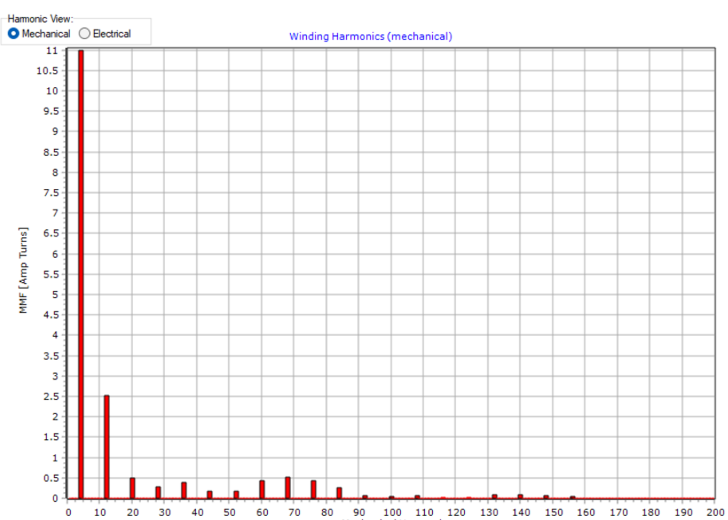

Fig 16: Winding Harmonics (mechanical) of Motor A

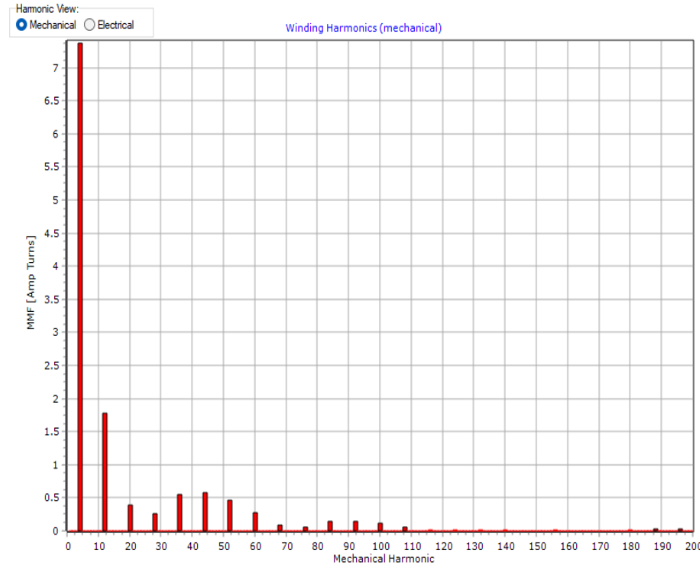

Fig 16: Winding Harmonics (mechanical) of Motor B

V. Conclusion

In this study, we compared the two interior permanent magnet motors for the electric vehicle application on the various parameters like electromagnetic analysis, speed-torque characteristics, efficiency map and thermal analysis. Both the motor specifications are approximated due to lack of exact data. The Tesla S has an induction motor of the same rating as of the motor A but motor A is DC brushless interior permanent magnet. Motor B is similar to Nissan leaf 2012 synchronous interior permanent magnet. Motor A and Motor B are driven at the same voltage as that of Tesla S and Nissan Leaf Motor respectively. Also the output power and torque rating are the same for the motors. Motor A and Motor B are designed and analyzed in MotorCAD and the specifications of the motor are similar to the Tesla Model S and Nissan Leaf 2012 motor respectively.

References

https://www.energy.gov/sites/prod/files/2014/03/f13/ape051_miller_2013_o.pdf

Nissan Leaf teardown (Part 2): main components disassembled - MarkLines Automotive Industry Portal

https://ijtre.com/wp-content/uploads/2021/10/2020080111.pdf

https://www.cadfem.in/fileadmin/PDF_India/Motor_-_CAD/Introduction_to_Motor-CAD_PDF.

Performance-Analysis-of-Electric-Motor-Technologies-for-an-Electric-Vehicle-Powertrain.pdf (motor-design.com)

https://www.cadfem.net/fileadmin/user_upload/05-cadfem-informs/cadfem-newsroom/CASCON-FR/Archives/Archive-Form-CADFEM-Ansys-Motor-CAD-2021.pdf

https://www.cadfem.net/fileadmin/user_upload/05-cadfem-informs/cadfem-newsroom/CASCON-FR/Archives/Archive-Form-CADFEM-Ansys-Motor-CAD-2021.pdf).

(PDF) Performance Analysis of Permanent Magnet Motors for Electric Vehicles (EV) Traction Considering Driving Cycles (researchgate.net)

Tesla Model S (Electric Motor Specifications) | PDF | Tesla Model S | Electric Motor (scribd.com)

Nissan Leaf teardown (Part 2): main components disassembled - MarkLines Automotive Industry Portal.

Benchmarking State-of-the-Art Technologies (energy.gov)

(PDF) Modeling and design analysis of the Tesla Model S induction motor (researchgate.net)

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