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Analysis and Design of Universally Applicable Traction Motor for Heavy-Duty Vehicles

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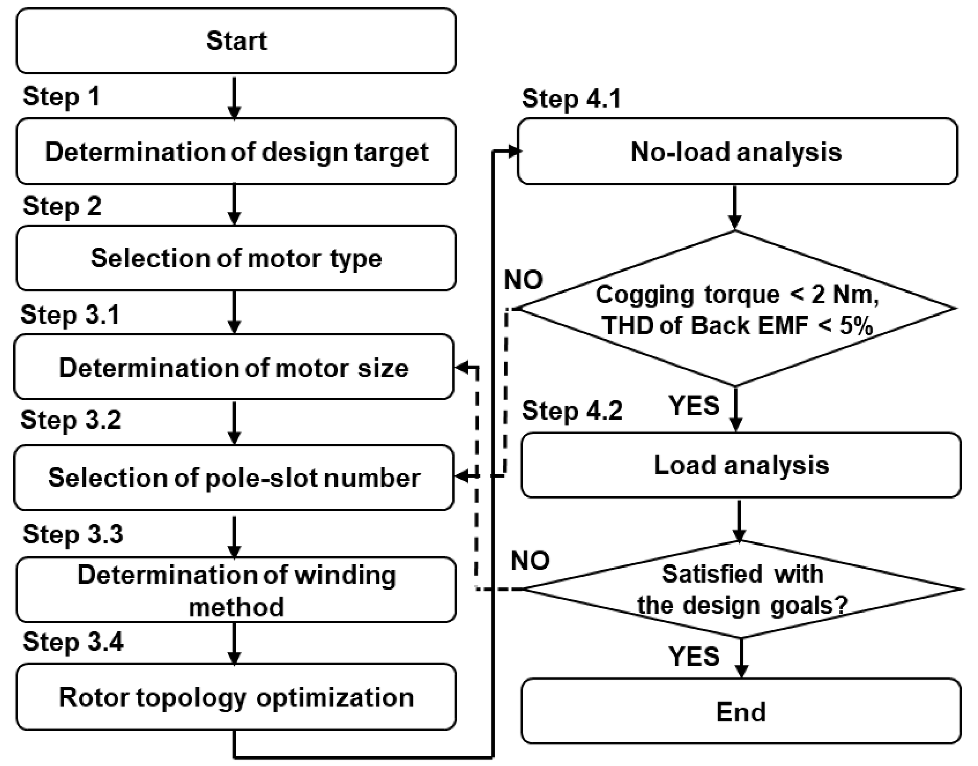
Introduction

- Owing to environmental pollution and the depletion of fossil fuels, interest in EVs is increasing throughout the world.
- Research on high-power density traction motors for commercial vehicles such as buses, trailers, and trucks has received considerable attention.
- The analysis and design of traction motors that can be used universally in heavy-duty vehicles having the greatest effect on environmental pollution were performed.
- The use of universal traction motors compared with those designed for conventional electric buses or trailers can reduce the cost and time required for development.
- . Traction motors for heavy-duty vehicles require a high torque density, high power density, and wide range of speed
- Specifically, an Interior Permanent Magnet Synchronous Motor (IPMSM) with delta-type magnet array is proposed for a high performance.
- In addition, a step skew structure is proposed for the mitigation of vibration and noise via reduction of cogging torque.
- The usefulness of the proposed universal traction motor for heavy-duty vehicles and its analysis and design methods were confirmed through the Finite Element Method (FEM).

Analysis and Design Process



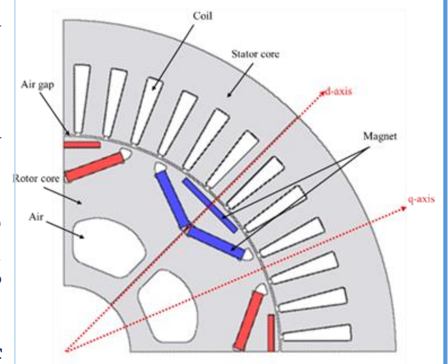
Step 1. Determination of design target

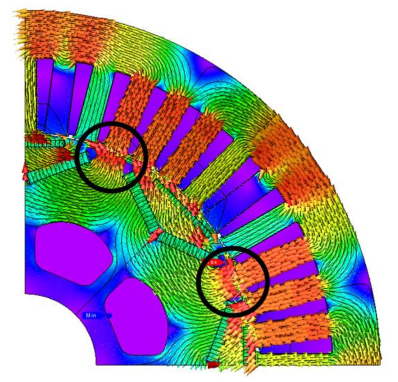
- Traction motors intended to drive heavy-duty vehicles should be capable of achieving higher than the motors for normal passenger cars.
- It is targeted higher torque density, higher power density and wider speed range characteristics than conventional one.
- <u>The goal of this study is to achieve performance with a **maximum torque of 1,200Nm**, **maximum power of 250kW** and **speed range of 6,000rpm** by restricting the motor size of conventional motor.</u>

Analysis and Design Process

Step 2. Selection of motor type

- Traction motors for EVs require high efficiency and high torque.
- Induction motor and IPMSM are generally used as traction motors for EVs.
- However, induction motors have a disadvantage of being less efficient in low-speed urban driving than IPMSM.
- On the other hand, the biggest advantage of IPMSM is that it can obtain high torque by using permanent magnets.
- The delta arrangement of magnets combines bar-type and V-type array. It can increase magnetic torque and reluctance torque.
- Moreover, it facilitates the concentration of magnetic flux to obtain sinusoidal airgap flux density and Back EMF.





$$T = \frac{P}{2}\frac{3}{2}\{\varphi_f i_q + (L_q - L_d) i_d i_q\}$$ (Equation of torque)

P : number of poles, φ_f: flux linkage provided by permanent magnet

i_q, i_d : q-axis and d-axis current, L_q, L_d: q-axis and d-axis inductance

Step 3.1. Determination of motor size

- Proper sizing is a crucial aspect of motor design.
- The goal is to specify a motor that provides the speed, torque, and power.
- In this step, we used JMAG Express which used in the initial design phase allows us to select an approximate size.
- The external diameter of a heavy EV motors are usually less than 400mm. we selected <u>external diameter as 400mm, stack length as 130mm</u>.

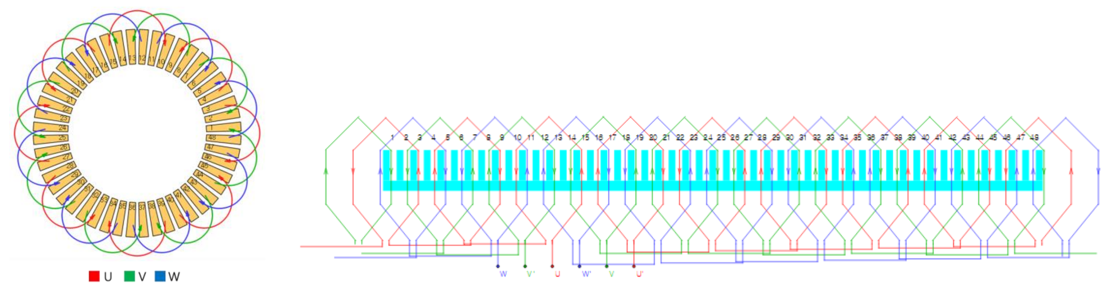
Step 3.2. Selection of pole-slot number

- When choosing the number of poles and slots, conditions such as rotational speed, slot harmonics in the airgap, and leakage inductance should be taken into account.
- For heavy vehicles, it is recommended to select the highest pole number possible for low-speed and high-torque implementations.
- Due to the limitations of the motor's diameter, slot dimension and leakage inductance, <u>**8 poles**</u> are the maximum number of poles allowed.
- To prevent demagnetization caused by heating inside magnets by iron loss and high harmonics, a large <u>slot number per pole per phase (q) is need.</u>
- In case of 24 slots, i.e., q=1, there are high slot harmonics at the 5th and 7th
- Therefore, we decided the slot number of <u>48 slots,</u> i.e., q=2.

Analysis and Design Process

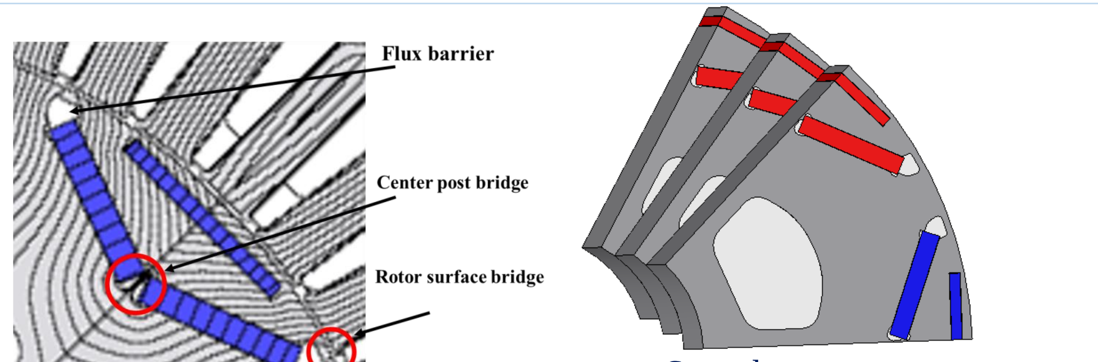
Step 3.3. Determination of winding method

- In general, <u>EV motors are driven by high power and low voltage</u>. Thus, <u>the operational current is large, and serial turn number is low,</u> such that the cross-sectional area of the winding is large and the inductance is significantly small.
- According to the method of coil winding in the slot, the winding can be concentrated or distributed.
- In case of <u>concentrated winding</u>, owing to the concentration of magnetic flux on the stator core, it is difficult to use reluctance torque in the high-speed region, because of the increase in magnetic reluctance caused by magnetic saturation of stator core.
- In contrast, with <u>**a distributed winding**</u>, it is easy to use reluctance torque and make sinusoidal Back EMF wave form.
- Therefore, motor was designed as <u>a single-layer series with distributed winding method.</u>



Step 3.4. Rotor topology optimization

- IPMSM is characterized by the placement of magnets. The <u>delta-type magnetic array</u> allows large area of permanent magnets per poles, which can concentrate the magnetic flux to the center of poles. It increases the maximum value of airgap flux and Back EMF. Additionally, it is possible to increase q-axis inductance and increase the magnetic saliency.
- The <u>**bridge**</u> is designed to be deliberately saturated by the leakage flux for suppressing the leakage of magnetic flux, and the width is determined by considering mechanical stability.
- The <u>**flux barrier**</u> is made of a cavity with large magnetic reluctance around the permanent magnets and is designed to compensate for the harmonics of the torque by intentionally saturating the bridge area.
- Cogging torque is a major factor that influences the torque ripple, control accuracy, vibration, noise, speed ripples and so on.
- <u>**Step skew method**</u> that stacks the rotor by rotating it axially can reduces the cogging torque.
- In this design, <u>the rotor was divided into three parts in the axial direction and rotated at an angle of 7.5 degrees.</u>

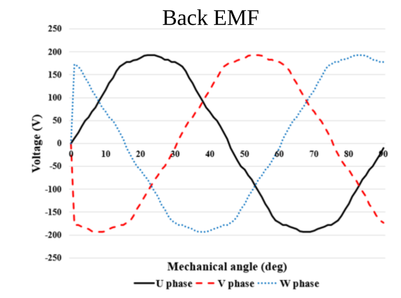


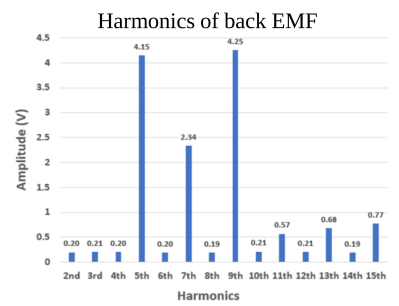
Step skew structure

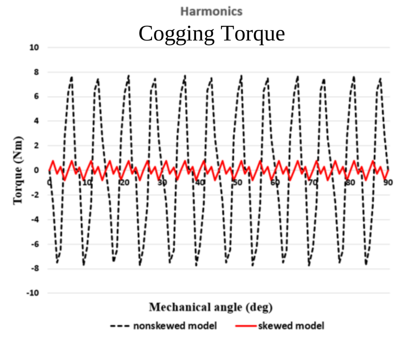
Analysis and Design Process

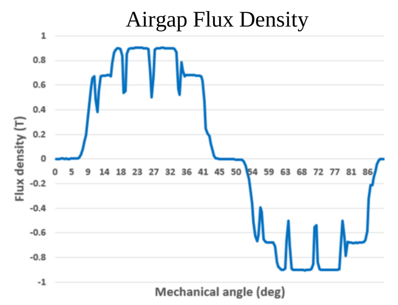
Step 4.1. No-load analysis

- Analysis was conducted at a base speed of 1600rpm.
- Acquiring <u>**sinusoidal waveform of back EMF**</u> is important because non-sinusoidal waveforms contain a lot of high-order harmonics, which can increase the peak current, iron loss, heat, vibration, and noise during operation.
- The Fourier transform of the back EMF allows the high order harmonics to be determined
- The <u>**Total Harmonic Distortion (THD)**</u> was calculated using Equation.
- $$THD = \frac{\sqrt{{V_2}^2 + {V_3}^2 + {V_4}^2 \cdots}}{V_1} \times 100(\%) = 3.91\%$$
- To produce a sinusoidal voltage in a machine, the magnitude of the flux density must vary in a sinusoidal manner along the surface of the **<u>airgap</u>**.
- The <u>**Cogging torque**</u> is reduced to about 20% of the conventional non-skewed model. <u>– **1.4Nm**</u>



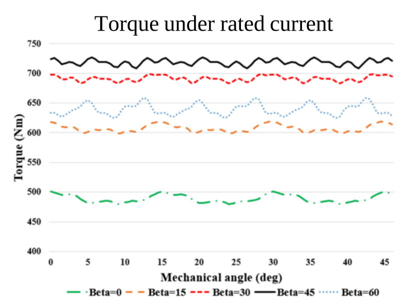






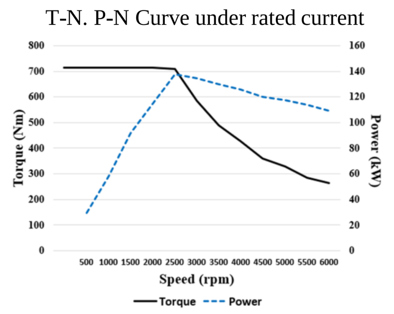
Step 4.2. Load analysis

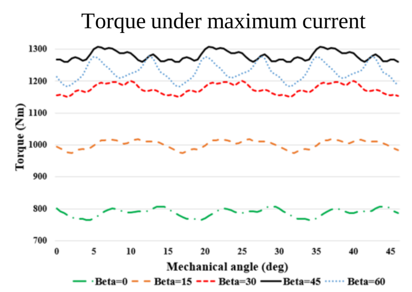
- Analysis was conducted at a base speed 1,600rpm under the load of the rated current (220A) and the maximum current (420A).
- The analysis was conducted by varying the phase angle of the current.
- Under rated current, the highest torque is 718Nm and torque ripple is 2.8%.
- Under maximum current, the highest torque is 1,283Nm, and torque ripple is 4.1%
- In addition, T-N, P-N characteristics were analyzed under rated current and maximum current.
- From the T-N, P-N characteristics curve, it shows that it operates well at the speed range of 6,000rpm.



TORQUE RIPPLE AT RATED CURRENT

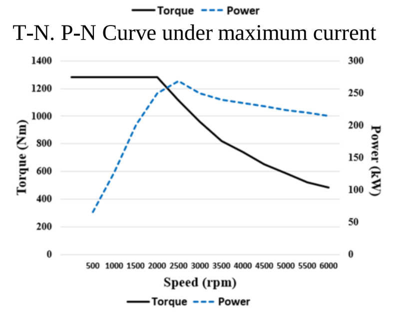
Current Phase (deg)	Torque avg (Nm)	Torque diff (Nm)	Torque ripple (%)
0	490.4	22.9	4.7
15	608.7	22.2	3.6
30	691.2	17.7	2.6
45	718.1	19.9	2.8
60	641.8	37.5	5.8





TORQUE RIPPLE AT MAXIMUM CURRENT

Current Phase (deg)	Torque avg (Nm)	Torque diff (Nm)	Torque ripple (%)
0	786.1	46.5	6
15	996.2	46.5	4.7
30	1174.6	55.8	4.8
45	1283.9	52	4.1
60	1230	106.1	8.6



Analysis and Design Results

- A universal traction motor for heavy-duty vehicles requires a high performance.
- The goal of this design was to achieve maximum torque of 1,200Nm, maximum power of 250kW and speed range of 6,000rpm without increasing the size of the motor compared to the conventional one.
- Analysis results achieved maximum torque of 1,283Nm, and maximum power of 254kW under a speed range of 6,000rpm

SPECIFICATION OF THE DESIGNED TRACTION MOTOR

Components	Parameters	Target
Stator Core	Slot	48
	Outer diameter[mm]	400
	Inner diameter [mm]	262
	Stack length [mm]	130
Winding	Wire diameter [mm]	1.2*25
	Number of turns [Turn]	5
Rotor Core	Pole	8
	Outer diameter [mm]	260
	Inner diameter [mm]	80
	Skew angle [degree]	7.5
Maximum Torque		1,283Nm
Maximum Power		254kW
Speed Range		6000rpm
High voltage supply		490Vdc

CONCLUSIONS

Traction motor for heavy-duty vehicles require a higher torque density, higher power density, and wider speed range characteristics than traction motors for typical EVs.

proposal

Traction motors were designed to satisfy the requirements for the high torque, high power, and wide speed ranges with a limited motor size

Conventional traction motors designed for electric buses or trailers.

proposal

The proposed traction motor can be applied universally through the conversion of gearboxes to heavy duty vehicles.

The advantage of applying this traction motor is that it can significantly reduce the cost and time for developing the traction motors. Significantly, the proposed traction motor can be applied into diverse kinds of heavy-duty vehicles and can have ripple effect in the research of EVs

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