Detail Design of Interior Permanent Magnet Motor for Electric Vehicle

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Abstract

Electromagnetic torque of I-V-U-2U interior permanent magnet (IPM) motor has been implemented for electric vehicle applications. Average torque and output power are implemented by FEA-finite-element analysis. It is show that the rotor structure with double U layer -interior permanent magnet has the higher power and efficiency. The two-layered permanent magnet assistance 2U has the highest Lq/Ld rate because of flux barrier width and length. Finally, the IPM machine with 2U layered magnets rotor is verified with commercial motors.

Keywords : Interior Permanent Magnet Motor-IPM Motor, Fenite Element Analysis-FEA.

1. Introduction

The performance of IPM machines is significantly affected by the magnet rotor topologies. Many multi-layered magnet layers rotor topologies have been reported in the literature for EV application [1-3]. The multi-layered IPM machine with "2V" shape is proposed for EV applications [4], and the results indicate that the proposed models are computationally efficient and numerically robust. A multi-layered IPM machine with "∇" shape is proposed for EV applications [5], and the results indicate that the core loss is significantly reduced by optimize the rotor barriers. The interior permanent-magnet motor (IPM) is the most suitable electric motor for EVs because the torque and power densities are applied to be very high speed EVs. However, there is a high magnitude of back emf due to the strong permanent magnets which deteriorated the voltage characteristics of the motor in wide range speed. Therefore, the winding configuration and magnet design is important to get the desired characteristics. In this paper, Different I-U-D-2U type of magnet configurations are designed to verify the electromagnetic performances for EV applications. First, the average and efficiency are verified and compared with constant of material of silicon steel, copper, and magnet weight. The rate of Lq/Lq is compared to evaluate flux barrier effective. Finally, average torque and power of proposal design is verified with commercial IPM motors.

2. Detail Model Design

There are several simple types of rotors magnet designs which can have lower manufacturing and material such as I-U-D-2U structures. In this study, an IPM 48 slot/ 8poles, stack length of 100 mm, the diameter of stator and rotor is 242 and 140 mm, the air-gap length is 0.5 mm, the thickness of electrical steel sheet is 0.35 mm, the continuous phase current amplitude is 200 A, the continuous rated power/peak power is 30kW/70kW, and the maximum speed of the machines is 10000 r/min. Detail design parameters are inferred form requirement in table 1.

Table 1. Electric motor requirements

Motor Type	PMSM	No.	TZ200XS020
Connection	Y	Cooling	Liquid
Rated voltage (VDC)	336	BackEMF (V peak)	585@9000rpm
Rated power (kW)	30	Peak power (kW)	75
Rated torque (Nm)	102	Peak torque (Nm)	200
Rated speed (rmp)	3000	Peak speed (rpm)	9000
Insulation	H	Ingress Protection	IP67
Size (mm)	φ 242X280	Max current (Arms)	280A
Mass (KG)	47	Duty	S9

For electric motor in industrial applications, copper and iron loss is required for high motor efficiency. In order to reduce the iron loss of electrical steel sheets, lower iron loss density is important and copper losses is affected by cooling methods by liquid or oil spray systems.

Based on the electrical drive system requirements, detail geometry parameters of stator and rotor can be calculated as follow chart in table 2. An analytical model was undergone many calculation steps to define basic parameters. Based on torque volume density TVR from 35 to 80 kNm/m^3 [5], if we assume rotor diameter equal to rotor length, the rotor diameter D and length L sizes of IPM is determined as follow:

$$T = \frac{\pi}{4}. D^2. L_s. TRV$$

With :

T : Electromagnetic torque (N.m).

D : Out diameter (m).

L_S : Length of core (m).

TVR : Torque and volume ratio (kWm/m^3).

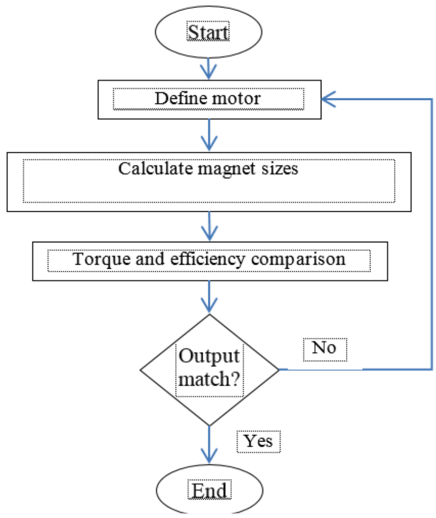


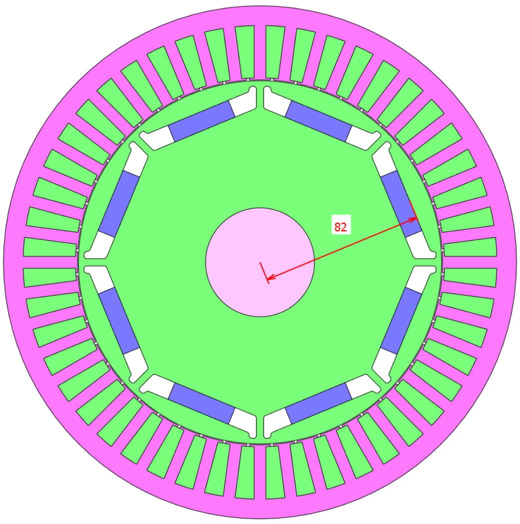
Fig.1 Calculation process

Table 2. Motor parameters

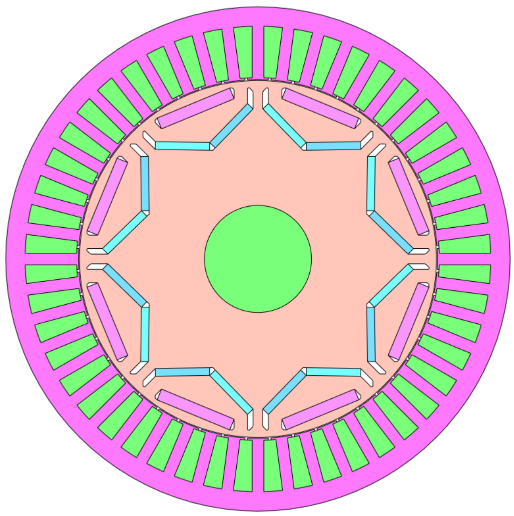
Stator Dimensions	**Value**
Slot Number	48

Stator Lam Dia	260
Stator Bore	185
Rated power	100
Rate speed	3500
Maximum speed	10000
Maximum current	400
Supply Voltage	600
Maximum Diameter	200
Maximum Length	150
Poles	8
Airgap	0,5

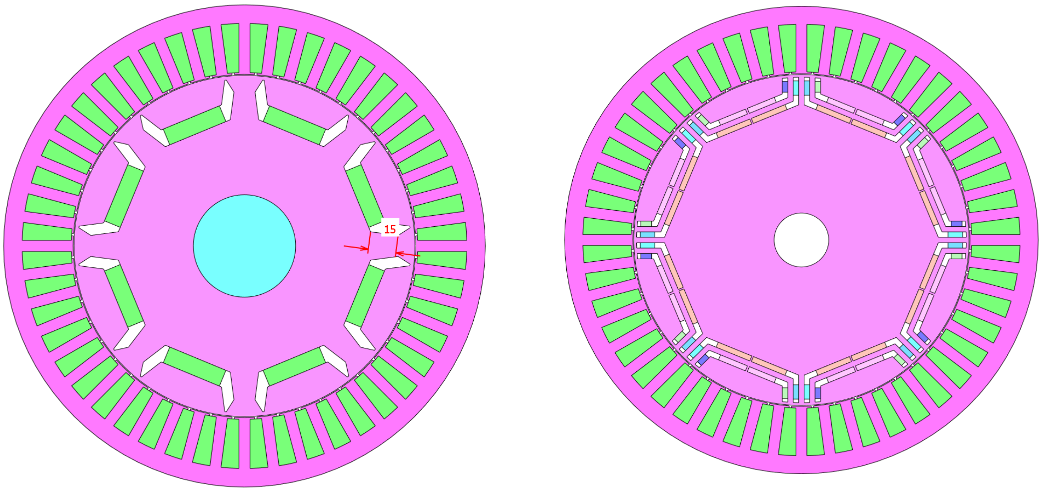
The main parameters such as outer diameter, rotor diameter, motor length, stator slot, airgap length is defined by electromagnetic material and working conditions to meet desired input requirements. It is also considered some practical factors such as overload capacity and manufacturing technologies. The main part of the process is to design the rotor configuration which is embedded permanent magnet. The PM configuration needs to create sufficiently magnetic voltage for magnetic circuit. In fact, there are some possible configurations sorted by the shape and position of PM inside rotor as drawn below:



a.I-Shape



b. Inverter Delta-D Shape



c. U-Shape

d. Double U-Shape

Fig.2 Permanent magnet rotor shapes

Detail design parameter of stator, rotor and winding are shown in Table 2. Total weight of IPM motor has been also calculated in below table.

Table 2. Dimension and mass property

Dimension		
All	Outer Diameter, mm	260
	Gap Length, mm	0.5
	Stack Height, mm	200
stator : stator_02	Number of Slots	48
	Outside Diameter, mm	260
	Outside Diameter of Coil, mm	240
	Inside Diameter of Coil, mm	187
	Inside Diameter, mm	185
	Width of Teeth, mm	6
	Slot Opening, mm	1.3
ipm_rotor : rip_009	Number of Poles	8
	Outside Diameter, mm	184
	Shaft Diameter, mm	30
	First Outside Magnet Width, mm	8
	Firtst Inside Magnet Width, mm	20
	First Outside Magnet Tickness, mm	3
	First Inside Magnet Thickness, mm	3
	Position of Inside Magnet1, mm	70
	Clearance between Outside Magnets1, mm	3
	Clearance between Inside Magnets1, mm	0.9
	Outside Slit Width1, mm	2
	Outside Slit Depth1, mm	1.5
	Second Outside Magnet Width, mm	6
	Second Intside Magnet Width, mm	16
	Second Outside Magnet Thickness, mm	3
	Second Inside Magnet Thickness, mm	3
	Position of Inside Magnet2, mm	3
	Clearance between outside Magnet2, mm	3
	Clearance between Inside Magnet2, mm	1.13
	Outside Slit Width2, mm	2
	Outside Slit Depth2, mm	1.5

Mass Property		
Total	Total Weight, kg	96.54
	Total Volume, mm^3	1.181e+07
Stator	Coil - Mass, kg	32.59
	Coil - Volume, mm^3	3.637e+06
	Stator Core - Mass, kg	25.13
	Stator Core - Volume, mm^3	3.202e+06
	Part Weight(stator_02)	57.72
Rotor	Rotor Magnet - Mass, kg	1.44
	Rotor Magnet - Volume, mm^3	1.92e+05
	Rotor Core - Mass, kg	35.22
	Rotor Core - Volume, mm^3	4.486e+06
	Rotor Magnet2 - Mass, kg	0.288
	Rotor Magnet2 - Volume, mm^3	3.84e+04
	Rotor Magnet3 - Mass, kg	0.288
	Rotor Magnet3 - Volume, mm^3	3.84e+04
	Rotor Magnet4 - Mass, kg	1.152
	Rotor Magnet4 - Volume, mm^3	1.536e+05
	Rotor Magnet5 - Mass, kg	0.216
	Rotor Magnet5 - Volume, mm^3	2.88e+04
	Rotor Magnet6 - Mass, kg	0.216
	Rotor Magnet6 - Volume, mm^3	2.88e+04
	Part Weight(rip_009)	38.82
Inertia	Rotor Magnet, kg m^2	7.568e-03
	Rotor Core, kg m^2	0.143
	Rotor Magnet2, kg m^2	2.06e-03
	Rotor Magnet3, kg m^2	2.06e-03
	Rotor Magnet4, kg m^2	7.029e-03
	Rotor Magnet5, kg m^2	1.586e-03
	Rotor Magnet6, kg m^2	1.586e-03
	Total, kg m^2	0.1649

Different I- U- D-2U shapes are applied in this study and material weight all design model are kept the same especially permanent magnet weight. After four models were calculated, the copper and iron losses are determined. Other results of inductance, current density and torque per amp factor have been also obtained in table 3.

Table 3. Inductance, loss, and power calculation

Machine Constant		
Revolution Speed	N, rpm	1000
Inductance	Ld, H	2.914e-04
	Lq, H	8.955e-04
	Self Inductance, H	3.956e-04
	Mutual Inductance, H	-1.978e-04
Torque Constant	Kt, Nm/A	1.048
Voltage Constant	Ke, V s/rad	1.21
Magnetic Circuit	Average Teeth Flux Density, T	1.247
	Average Back Yoke Flux Density, T	1.411
	Average Gap Flux Density, T	0.5632
Electric Part	Phase Current(RMS), A	212.1
	Wire Current Density, A/m^2	4.242e+06
Power	Torque, Nm	299.7
	Efficiency, %	97.85
	Power, W	3.137e+04
	Power Factor	0.8272
Loss	Copper Loss, W	234.8
	Iron Loss, W	443.6
Electric Circuit	Phase Voltage(RMS), V	60.9
	Line Voltage(RMS), V	105.5

The analytical calculation used and stored by Matlab programming language; program interface was developed by Matlab GUI. After calculation, the system can present on screen as well as export drawings in dxf type. All drawings can be integrated or coupling to FEMM simulation. The program has to find the best choice for special parameters to find out output torque or the air gap flux density. The output torque is taken by a block integral of the shaft and the air gap flux density similarly can be collected by function. All result will be stored in database and used for further comparison. In addition, results which belonged to calculation progress and resulted in simulation progress are saved separately in 2 file.

3. FEA Model Results

The program is divided into three main parts : analytical calculation, exporting drawing and magnetic simulation. There are also some supporting parts including material library which also associate with FEMM library.

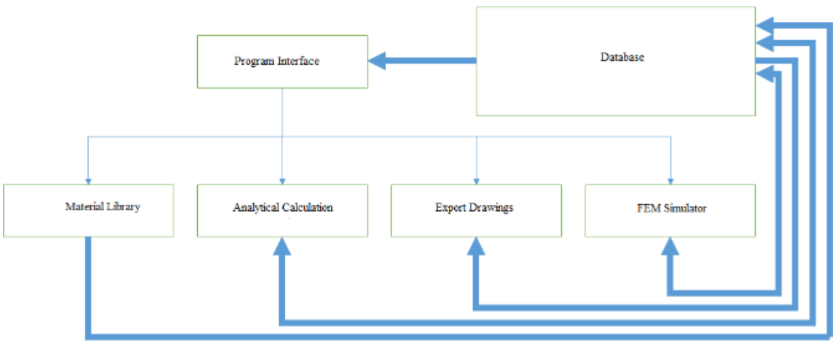
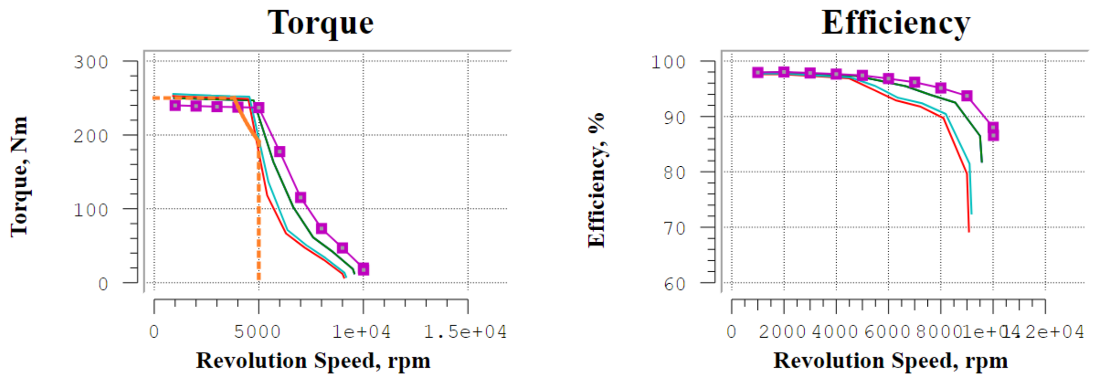
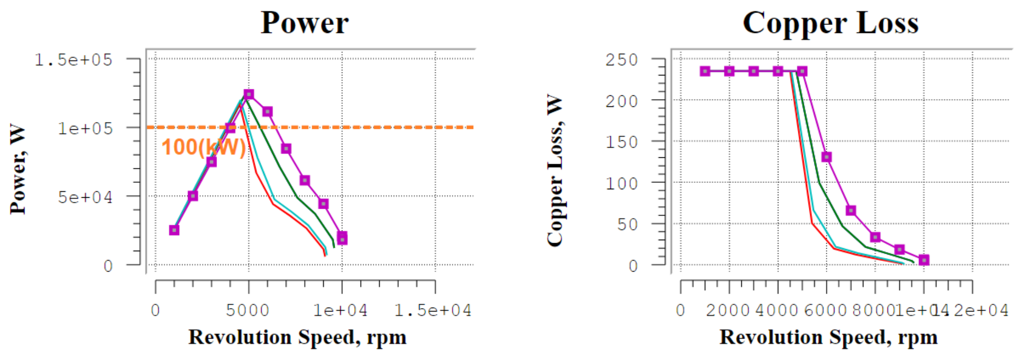


Fig.3 Program Structure

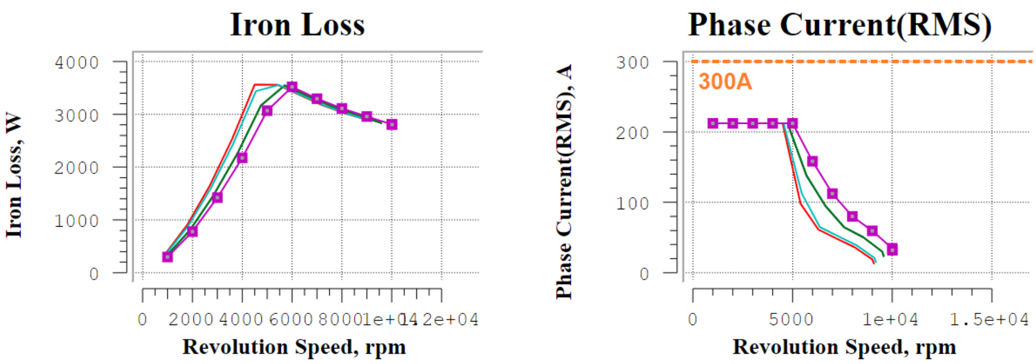
The program interface is a well-defined set of Matlab function to manage and exchange design results. The interface links to database, material library as well as calculation results. When the system receives main parameters for motors, calculations will be executed. The results will be stored in database in mat format. Library consists of wire, permanent magnet, electrical steel library. In the library, material will be defined by specific parameters. The wire library includes the diameter, electrical conductivity. Not similar to other material which is chosen by user, wire diameter will be calculated to choose the suitable one. Its parameter will have influence in both analyzing and simulating. The permanent magnet will require relative permeability, coercivity and electrical conductivity. The library support neodymium (NdFeB) magnets with various types, samarium cobalt (SmCo) magnets and ferrite ones. Electrical steel parameters consist of B-H curve and electrical conductivity.



a. Torque and efficiency comparison



b. Power and copper loss comparison



c. Iron loss and phase comparison

Fig.4 Comparative results of four model design

Electromagnetic results of four models have been evaluated in above figure and torque, power, efficiency and loss curved with marker are good performances. One of important results is efficiency which is compared in table 5.

Table 4. Efficiency comparison

Speed	Model 1 (I shape)	Model 2 (D shape)	Model 3 (U shape	Model 4 (double U)
950	97.8601	97.6027	97.7036	97.9268
1900	97.9404	97.6383	97.7539	98.0161

2850	97.7522	97.4047	97.5375	97.8342
3800	97.5381	97.1375	97.2893	97.6351
4750	97.3028	96.8614	97.0292	97.4057
5700	96.3948	94.8708	95.5569	96.83
6650	95.4597	92.8517	93.3561	96.1763
7600	93.8919	91.809	92.3813	95.1294
8550	92.5019	89.6989	90.4392	93.7112
9500	86.4816	79.6632	81.4555	88.0262
10000	81.8358	69.2412	72.4623	86.567

The program can be easily converted to the one that can generate several designs in small time which can help the user can choose the best design. The program can also be linked to some optimize function to choose the best solution for specific objective. For electric vehicle application, some key parameters of Ld,Lq and torque per ampe are determined in table 5. The 2U design has highest Lq/Ld rate because it has longer flux barriers.

Table 5. Inductance rate

Phase Current(RMS), A	Ld, H	Lq, H	Kt, Nm/A	Ke, V s/rad	Lq/Ld
2.12E+02	4.52E-04	1.55E-03	8.73E-01	1.01E+00	3.43E+00
2.12E+02	3.95E-04	1.24E-03	8.82E-01	1.02E+00	3.14E+00
2.12E+02	4.19E-04	1.32E-03	8.92E-01	1.03E+00	3.16E+00
2.12E+02	4.46E-04	1.69E-03	8.37E-01	9.67E-01	3.78E+00

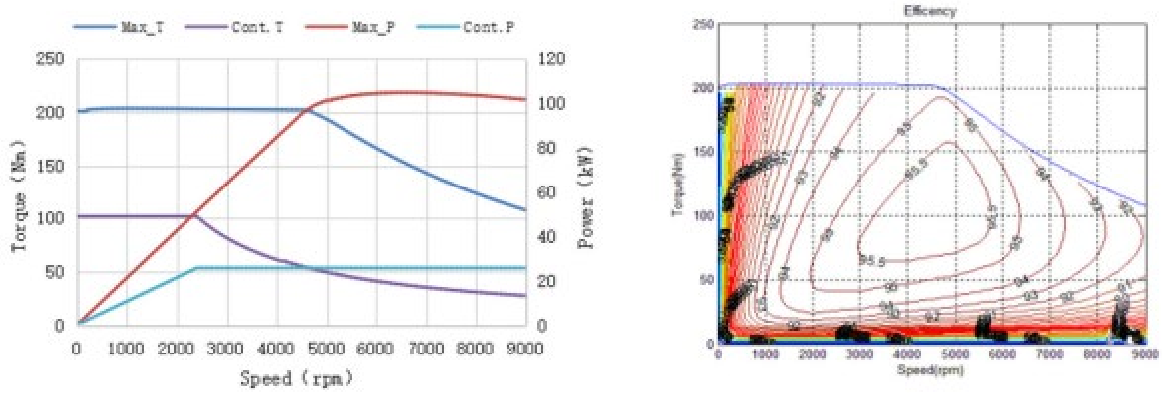


Fig.5 IPM torque and power requirement from commercial products

The torque and power curves in figure 4 (a) and (b) are compared with power and torque requirement of WOLONG EV IPM motor which is manufacturing for several electric cars. The maximum torque and power of proposal design are 250 Nm and 130kW over than those requirements.

4. Conclusions

In this paper, several types of magnet configurations are implemented to evaluate the electromagnetic performances for EV applications. Firstly, the average and efficiency are verified and compared with constant of material of silicon steel, copper, and magnet weight. The rate of Lq/Lq is compared to evaluate flux barrier effective. Finally, average torque and power of proposal design is verified with commercial IPM motors. The final design has better performances than the commercial EVs motors.

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