Electromagnetic Design of PMa-SynRM Double V and Inverter Delta

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This paper will present detail design of PMa-SynRM double V and Inverter Delta in sinusoidal step skewing rotors. Electromagnetic performances of double 2V layer- inverter delta VI layer permanent magnet assistance synchronous machines (PMa-SynRMs) have been implemented for high constant torque in wide range speed in electric vehicle applications. The torque density, torque ripple, and output power are studied with FEA-finite-element analysis in different topologies. Electromagnetic designs of two-layered rotor structure with double 2V and VI are good choices because it is simple structure and easy to manufacture in mass production. With higher torque density and efficiency, the two-layered 2V or VI magnet can adjust sinusoidal step skewing to minimize harmonics torque ripple and back EMF. Finally, the proposal design PMa-SynRM with 2V and V-I layered magnets rotor is implemented to verify their torque and output power in comparison with commercial IPM motor of WOLONG EVs.

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

1. INTRODUCTION

The performance of PMA-SynRM machines is significantly affected by the magnet rotor topologies because they have several key designs of magnet shapes, flux barrier and multi-layer arrangements. Many multi-layered magnet layers rotor topologies have been reported in the literature for EV application [1-3]. The multi-layered IPM machine with double V and V-I shapes is proposed for EV applications [4]. A multi-layered IPM machine with 2V and VI shapes is proposed for EV applications [5]. Five rotor design topologies for an interior permanent-magnet machine for a hybrid electric vehicle have been analyzed in [7] but the double V and VI flat are potential candidates, and they are suitable design for punching mud when manufacturer will carry out mass production. The interior permanent-magnet motor (IPM) is selected for EVs because they have torque and power densities in very high speed. However, there is a high magnitude of back emf due to the strong permanent magnets and high speed which is higher the DC link voltage. It is difficult to keep constant torque in overall speed. Therefore, the winding configuration and magnet design is important to get the desired characteristics. Different 2V and V-I type of magnet configuration used in this proposed machine are V-I layer -interior permanent magnet assistance. In this paper, the back EMF, torque, power and efficiency performances are verified and compared by sinusoidal step skewing rotor. Finally, an PMA-SynRM machine with two-layered V-I magnet rotor is implemented to verify the requirements of commercial products.

2. ELECTROMAGTIC DESIGN PMA-SYNRM ROTOR 2V AND VI TOPOLOGIES.

The proposal IPM is designed based on an existing IPM with 70 kW peak power at 4000 rpm, as shown in Fig. 1. with 4poles, 24 slots, and PM in delta arrangement. However, the target PMa-SynRM was designed with 2V and

VI magnet design to be able to change torque ripple, reluctance torque and back EMF. The main specifications of the original IPM is shown in Table 1.

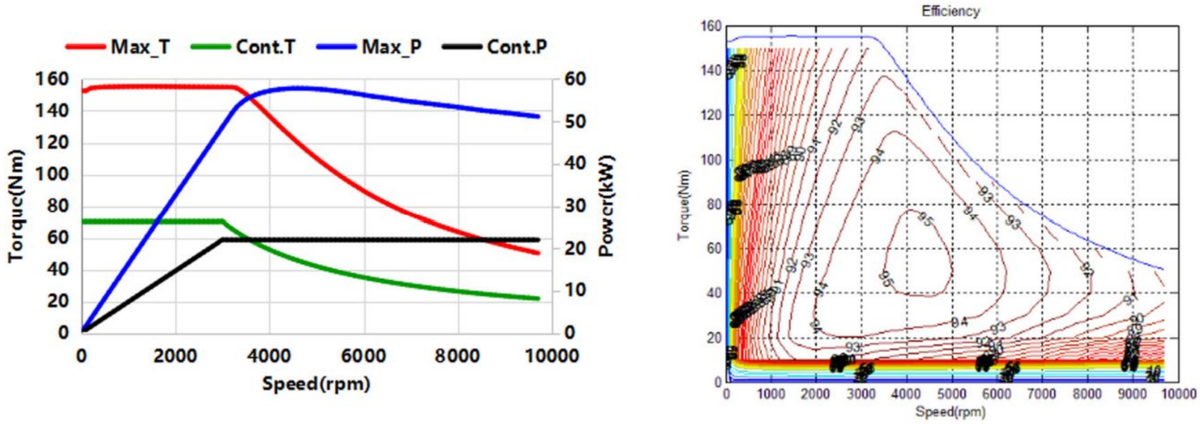
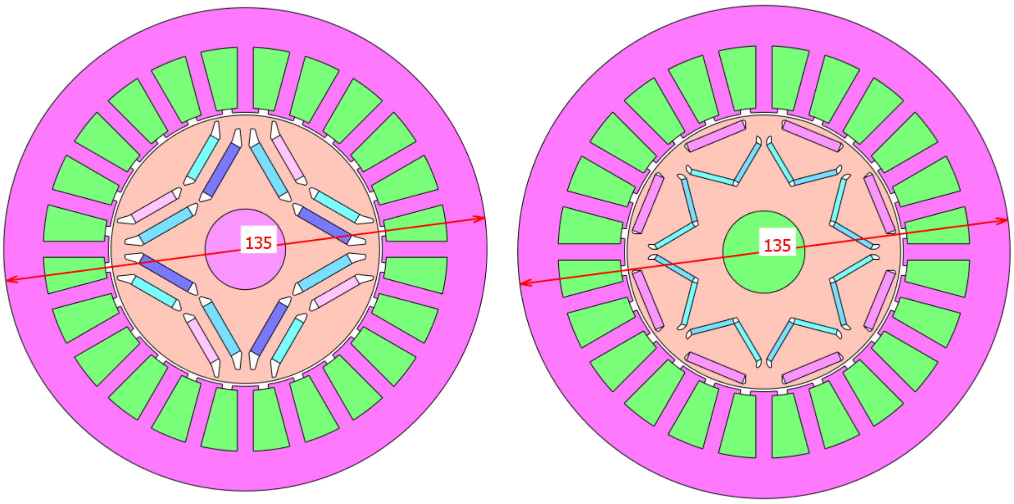


Figure 1. Torque and Power requirement

Motor Type	PMSM	No.	TZ180XS015
Connection	Y	Cooling	Liquid
Rated voltage (VDC)	292	Back EMF (V peak)	540V@10000rpm
Rated power (kW)	22	Peak power (kW)	50
Rated torque (Nm)	70	Peak torque (Nm)	150
Rated speed (rmp)	2850	Peak speed (rpm)	9700
Insulation	H	Ingress Protection	IP67
Size (mm)	φ 217*L277	Max current (Arms)	230A
Mass (KG)	34	Duty	S9

The numbers of slot and poles, stack length, the diameter of stator and rotor, the air-gap length listed in table 1 is designed for the power inverter of 400VDC/250 A, the continuous rated power of IPM machine is 100 kW, and the maximum speed of the machines is 10000 rpm.



(a) 2V (b) IV

Figure 2. 2V and IV Magnet design

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 listed below:

Table 1. Dimensions of PMA-SynRM

Parameters	**Values**	**Unit**
Slot Number	24	
Stator Lam Dia	135	mm
Stator Bore	112	mm
Tooth Width	4.15	mm
Slot Depth	21.1	mm
Motor Length	120	mm
Stator Lam Length	120	mm
Magnet Length	150	mm
Rotor Lam Length	150	mm
Pole Number	4	mm
Airgap	0.75	mm

Table 1 shows the design parameters of the two models such as number of permanent magnet segment, pole, slot, and stack length. The total weight of magnet segment and copper winding are almost the same. Detail parameters and material weight is summarized in table 2.

Table 2. Detail parameters and weight materials

Total Weight, kg	24.16
Total Volume, mm^3	2.951e+06
Coil - Mass, kg	8.337
Coil - Volume, mm^3	9.304e+05
Stator Core - Mass, kg	11.41
Stator Core - Volume, mm^3	1.453e+06
Part Weight(stator_02)	19.75
Rotor Magnet2 - Mass, kg	0.2133
Rotor Magnet2 - Volume, mm^3	2.844e+04
Rotor Magnet - Mass, kg	0.2133
Rotor Magnet - Volume, mm^3	2.844e+04
Rotor Core - Mass, kg	3.673
Rotor Core - Volume, mm^3	4.678e+05
Rotor Magnet3 - Mass, kg	0.1526
Rotor Magnet3 - Volume, mm^3	2.146e+04
Rotor Magnet4 - Mass, kg	0.1609
Rotor Magnet4 - Volume, mm^3	2.146e+04
Part Weight(rip_014)	4.413
Rotor Magnet2, kg m^2	1.192e-04
Rotor Magnet, kg m^2	1.192e-04
Rotor Core, kg m^2	2.874e-03
Rotor Magnet3, kg m^2	1.233e-04
Rotor Magnet4, kg m^2	1.3e-04
Total, kg m^2	3.366e-03

Outer Diameter, mm	150
Gap Length, mm	0.75
Stack Height, mm	150
Number of Slots	24
Outside Diameter, mm	150
Outside Diameter of Coil, mm	112.9
Inside Diameter of Coil, mm	78.86
Inside Diameter, mm	76.5
Width of Teeth, mm	4.45
Slot Opening, mm	2.729
Number of Poles	4
Outside Diameter, mm	75
Shaft Diameter, mm	22.5
Magnet Width1, mm	15.8
Magnet Thickness1, mm	3
Position of Magnet D1, mm	19.8
Position of Magnet W1, mm	3
V angle1, deg	150
Excess Slit Length1, mm	0.75
Excess Slit Length2, mm	0.75
Outer Slit Length1, mm	4.73
Outer Slit Length2, mm	3.19
Angle of Outer Slit1, deg	144.17
Angle of Outer Slit2, deg	165.95
Excess Slit Length3, mm	0.75
Excess Slit Length4, mm	0.75
Inner Slit Length1, mm	2.85

From the total weight of IPM is 24 kg less than 34 kg from requirement. The arrangement of the PM is regarded as requisite for efficient operation in double V and inverter triangle shapes. There are several shape of prototype model however they are much complicated to locate PM inside and it is hard to compare the effectiveness of the PM position and combination as well with all different size of PM. The double V and inverter triangle shapes coordinates of the rotor have been drawn as a condition until the mechanical constraint moment of machine is reached. The ribs have a fixed value due to inherent manufacturing limitations. A MATLAB program coupling to CAD is automatically calculated to electromagnetic with current limited and voltage limit.

With current-limited maximum torque, phase angle γ between V_m and E, the electromagnet torque can be calculated as:

$$T_e = mp[\Psi_{1Md} I \cos\gamma - I^2 \sin\gamma \cos\gamma \, (L_d - L_q)]. \quad (1)$$

With constant current I, to maximize torque. The phase angle γ is calculated

$$\gamma_{Tmax} = \sin^{-1} \frac{1}{4}\left[-\frac{\Psi_{1Md}}{\Delta\Psi} + \sqrt{\left(\frac{\Psi_{1Md}}{\Delta\Psi}\right)^2 + 8} \right] \quad (2)$$

where $\Psi = (Ld - Lq)I$, Tmax is not a fixed, but depends on the current. Moreover, Ld and Lq both vary as a result of saturation, and this further complicates the problem of finding the optimum value of γ

Voltage-limited maximum torque — With constant voltage V_m but variable phase angle δ between V_m and E, the torque can be calculated by X_d and X_q.

$$T_e = \frac{mp}{\omega}\left[\frac{EV_m}{X_d} \sin\delta + \frac{V_m^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right) \sin 2\delta \right]. \quad (3)$$

To find the phase angle δ which maximises the torque. After some simplification the result is:

$$\delta_{Tmax} = \cos^{-1}\left[\left(-\zeta \pm \sqrt{\zeta^2 + 8}\right)/4\right] \quad (4)$$

Where

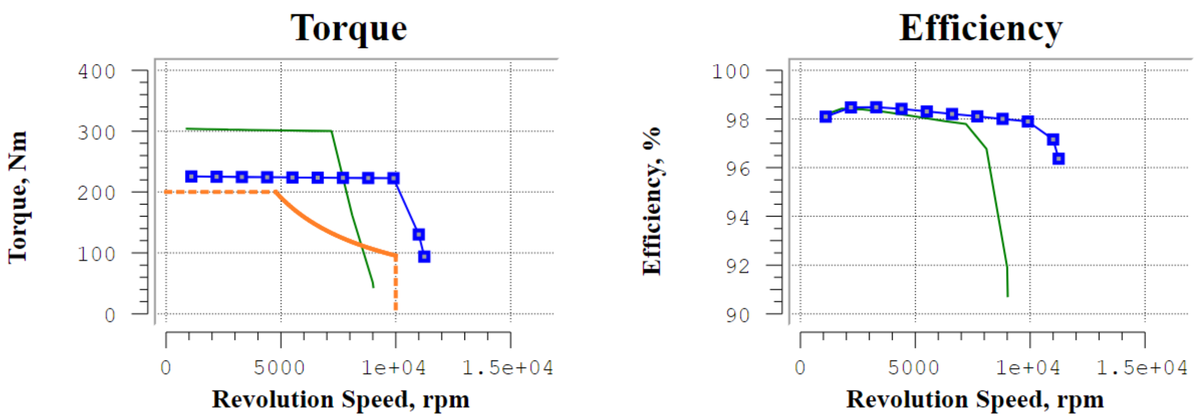
$$\zeta = \frac{E/V_m}{1 - X_d/X_q}. \quad (5)$$

Two proposed PMA-SynRM machines are designed and compared table 3.

Table 3. Efficiency comparison of Model 2V and VI

Parameter	**2V**	**VI**	**Unit**
Average torque	161.63	171.09	Nm
Torque Ripple	17.734	13.19	Nm
Torque Ripple [%]	10.949	7.6935	%
Cogging Torque Ripple (Ce)	2.4068	5.6558	Nm
Input Power	1.72E+05	1.81E+05	Watts
Total Losses (on load)	5767.1	6284.8	Watts
System Efficiency	96.639	96.837	%
Shaft Torque	158.33	167.3	Nm
Armature DC Copper Loss (on load)	1951	1951	Watts
Magnet Loss (on load)	14.53	6.006	Watts
Stator iron Loss [total] (on load)	3521	3935	Watts
Rotor iron Loss [total] (on load)	265.6	248.2	Watts
Total Losses (on load)	5767	5685	Watts

Detail torque, power, loss and efficiency performances of both model designs in above table is obtained by FEA method at base speed of 3000 rpm. In order to verify torque and power vs speed curves, an power inverter of 450VDC/300A was supplied to PMa-SynRM, maximum spees is about 98%.



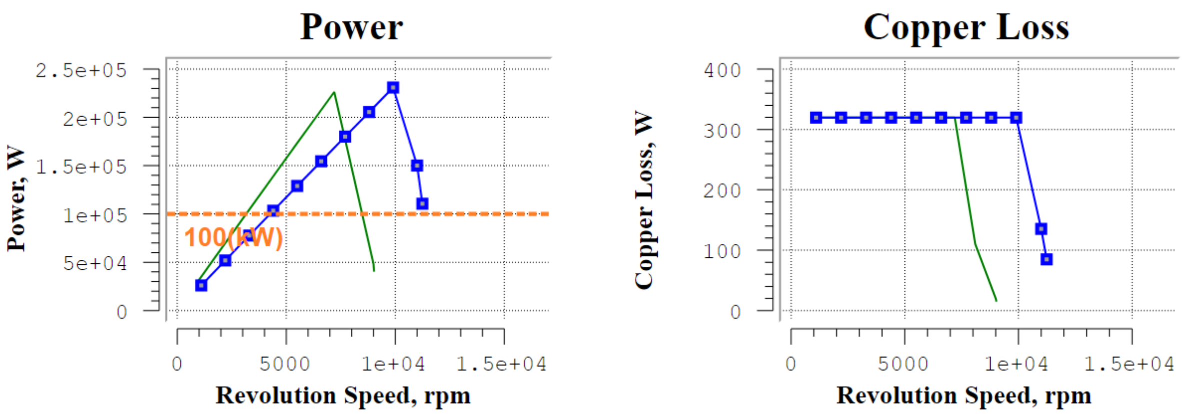
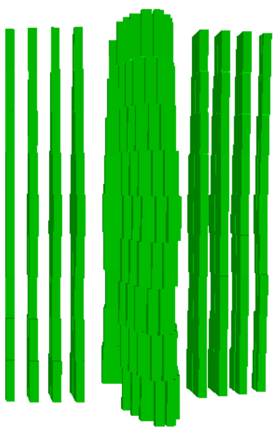


Figure 3. Torque, Power, and efficiency comparison of 2V and VI

Figure 5 shows the peak torque and power versus speed characteristics of 2V and VI shapes up to 10000 rpm. With the increase of phase current density up to 14 A/mm2, the peak torque and power are 245 Nm and 240 kW.

3. STEP SINUSOIDIAL SKEWING PMA-SYNRM

To verify the electromagnetic performances of a 28/4p proposed PMa-SynRM, the back-EMFs and torque of designed PMa-SynRM with VI shape by FEM is calculated and analyzed below. The result indicates that the step skewing magnet has lower torque ripple and harmonics of back EMF are eliminated.



Slice	Proportional	Angle
		Mech Deg
Slice 1	1	-3
Slice 2	1	-1.5
Slice 3	1	0
Slice 4	1	1.5
Slice 5	1	3
Slice 6	1	1.5
Slice 7	1	0
Slice 8	1	1.5
Slice 9	1	3

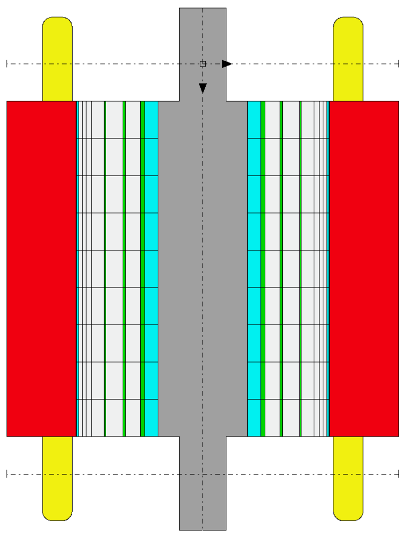
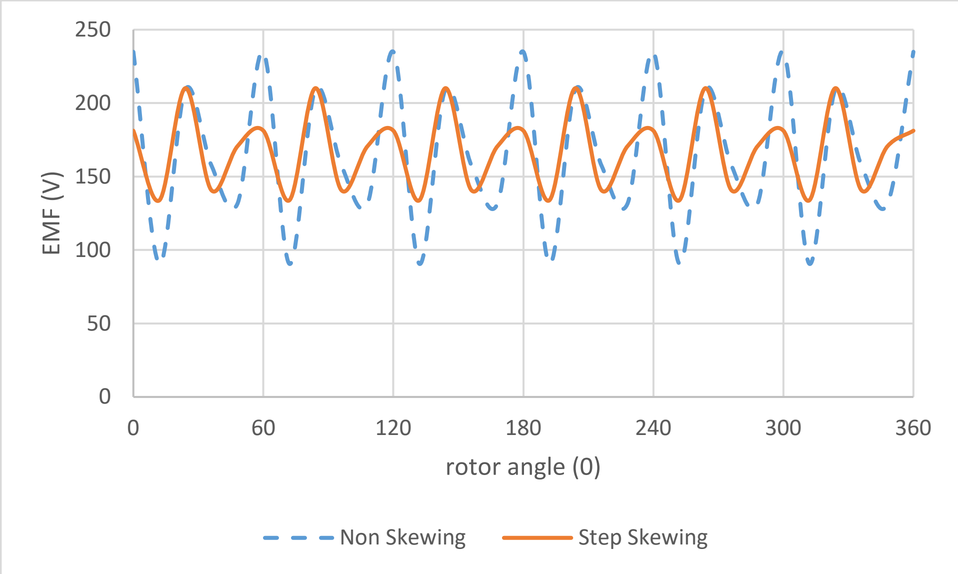
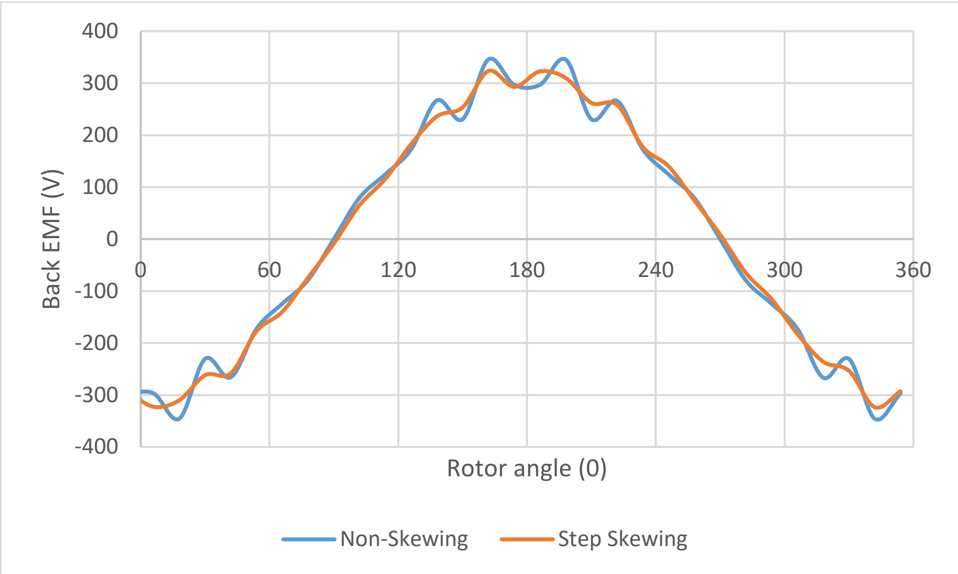


Figure 4. Step Skewing Magnet Design



a. Torque waveforms



b. Back EMF wavefroms

Figure 5. Torque and back EMF comparison Non and Step Skewing Magnet Design

From the torque and back EMF results non skewed and skewed results, the step skewing design is able to adjust torque ripple and sinusoidal waveform of back EMF.

4. CONCLUSIONS

This paper has analyzed and compared the electromagnetic performance of two multi-layered PMa-SynRM machines for EV applications. The two-layered rotor structure with VI shape has better performances. The model V-I design has the lower torque ripple and core loss because the harmonics of air-gap density are reduced by combination of I simple and optimal V angle to adjust their performances. To verify the proposed design, an detail design of a 3-phase 24-slot and 4-pole hybrid rotor PM machine is implemented to evaluate torque, power and efficiency. The back EMF and torque has been analyzed by step skewing rotor slots.

REFERENCES

[1] B. Ozpineci, “Oak Ridge National Laboratory annual progress report for the electric drive technologies program,” Oak Ridge Nat. Lab., Oak Ridge, TN, USA, Tech. Rep. ORNL/SR-2016/640, Oct. 2016.

[2] M. Taniguchi et al., “Development of new hybrid transaxle for compactclass vehicles,” SAE Tech. Paper 2016-01-1163, 2016, doi: 10.4271/2016-01-1163.

[3] T. Huynh and M.-F. Hsieh, “Comparative study of PM-assisted SynRM and IPMSM on constant power speed range for EV applications,” IEEE Trans. Magn., vol. 53, no. 11, Nov. 2017, Art. no. 8211006.

[4] X. Chen, J. Wang, B. Sen, P. Lazari, and T. Sun, “A high-fidelity and computationally efficient model for interior permanent-magnet machines considering the magnetic saturation, spatial harmonics, and iron loss effect,” IEEE Trans. Ind. Electron., vol. 62, no. 7, pp. 4044–4055, Jul. 2015

[5] Shushu Zhu , Weifang Chen, Mingqiu Xie, Chuang Liu, and Kai Wang,” Electromagnetic Performance Comparison of Multi-Layered Interior Permanent Magnet Machines for EV Traction Applications. IEEE TRANSACTIONS ON MAGNETICS (2020),

[6] Y. Nie, I. P. Brown, and D. C. Ludois, “Deadbeat-direct torque and flux control for wound field synchronous machines,” IEEE Trans. Ind. Electron., vol. 65, no. 3, pp. 2069-2079, Mar. 2018.

[7] A. Wang, Y. Jia, and W. L. Soong, “Comparison of five topologies for an interior permanent-magnet machine for a hybrid electric vehicle,” IEEE Trans. Magn., vol. 47, no 10, pp. 3606-3609, Oct. 2011.