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IMPROVEMENT IN CONSTANT TORQUE OF INTERIOR PERMANENT MAGNET MOTORS FOR RANGE OF SPEED FOR ELECTRIC VEHICLES

CẢI THIỆN KHẢ NĂNG DUY TRÌ MÔ MEN TRÊN TOÀN DẢI TỐC ĐỘ CHO ĐỘNG CƠ ĐỒNG BỘ NAM CHÂM VĨNH CỬU GẮN CHÌM CHO XE ĐIỆN

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Abstract:

This paper presents a multi permanent magnet layers for ▿ -V-U shape rotor designs of interior permanent magnet synchronous motor and permanent magnet assisted synchronous reluctance motor to maximize the torque and power for wide range capability for electric vehicle applications. Six models of the ▿ -V-U layer shapes of the interior permanent magnet synchronous motor and permanent magnet assisted synchronous reluctance motor are evaluated in the constant torque for wide range speed by analytical torque-current-speed methods. The average, ripple and cogging torque, and the output power are proposed with different rotor magnet designs via an analytical torque model. The rotor topologies are then checked by the analytical method and finite element method for their constant power for wide range performances. It is shown that the ▿ 2U rotor structure with double U layer -permanent magnet assistance has the higher average torque and efficiency for wide range speed up to 20000 rpm.

Keywords:

Interior Permanent Magnet Synchronous Motor, permanent magnet assisted synchronous reluctance motor, analytic method, finite element method.

Tóm tắt:

Bài báo này nghiên cứu về các lớp nam châm vĩnh cửu rôto xếp dạng chữ ▿ -V-U của động cơ đồng bộ nam châm vĩnh cửu gắn chìm và động cơ từ trở đồng bộ có nam châm vĩnh cửu nhằm tối đa hóa mô men và công suất với dải tốc độ cao ứng dụng trong xe điện. Sáu mô hình của hình dạng lớp ▿ -V-U nam châm vĩnh cửu gắn chìm được đánh giá khảo sát theo khả năng giữ mô-men không đổi trên toàn dải tốc độ dựa trên phương pháp tối đa hóa mô-men với dòng điện đặt. Mô-men xoắn trung bình, gợn sóng và và công suất đầu ra được tính toán với các hình dạng nam châm khác nhau. Các cấu trúc thiết kế rôto sau đó được kiểm tra bằng phương pháp phân tích và phương pháp phần tử hữu hạn theo chỉ tiêu giữ công suất không đổi trong toàn dải tốc độ. Kết quả cho thấy, cấu trúc rôto ▿ 2U có nam châm vĩnh cửu lớp U kép cho mô-men trung bình và hiệu suất lớn nhất trong phạm vi tốc độ lớn lên đến 20000 vòng/phút.

Từ khóa:

Động cơ đồng bộ nam châm vĩnh cửu gắn chìm, động cơ từ trở đồng bộ có nam châm vĩnh cửu, phương pháp giải tích, phương pháp phần tử hữu hạn.

1. INTRODUCTION

The electromagnetic torque and efficiency performances of interior permanent magnet (IPMSM) and permanent-magnet-assisted synchronous reluctance machines (PMa-SynRM) are significantly affected by the magnet rotor topologies. Many multi-layered magnet rotor topologies have been presented in the literature for electric vehicle (EV) applications [1]-[3]. The multi-layered IPM machine with "2V" shape is proposed for the EV applications [5]. The obtained results have been indicated that the proposed models are computationally efficient and numerically robust. A multi-layered IPM machine with "∇" shape has been also proposed for EV applications [5]. The IPM and PMa-SynRM are the most suitable for EVs, because the output torque and power can be kept as a constant at the high speed EVs. Especially, the PMA-SynRM with less permanent magnets (PMs), and the back electromotive force (EMF) reduction can obtain a constant torque in wide range speed. Therefore, several different delta-D or V types of the magnet arrangement used in this proposed machine have been implemented for the IPM and PMa-synRM with three or four layered permanent magnet designs. In this paper, the electromagnetic performance of multi-layered IPM and PMa-SynRM are investigated for the EV applications. Firstly, the back EMF waveform of rotor is checked to validate the development. The torque harmonics have been compared with different topologies. Finally, an IPM with three-layered magnet rotor is manufactured to verify the results obtained from the finite-element method (FEM). Six models covering the two types of machines are designed with different ∇-V-U layer of PM and reluctance torques [7].

2. IPM ROTOR TOPOLOGIES

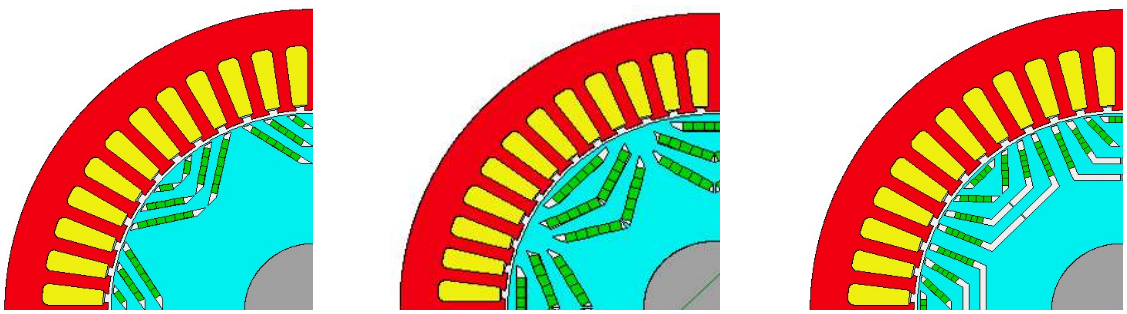
Six magnet configurations is shown in Figure 1, where the different models are respectively in (a), (b), (c) and (d). The delta and two U-∇2U with inner and outer PM structures are designed in Figure 1. Many magnet segments with standard sizes are easy to change the rating of magnet per slot or barrier width, the total volumes of the permanent magnets (NdFeB) and original material cost are the same or changing less 5%.

In orde to maximize the reluctance torque, amount of PM is limited, the arrangement of the PM is regarded as requisite for efficient operation in D, U and V shape. There are several shapes of the 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 the PM. The 4U and 4V shape 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 redrawn with regard to the change of factor (K_w) of equation (1) and the number of flux barriers is indicated in Figure 2.

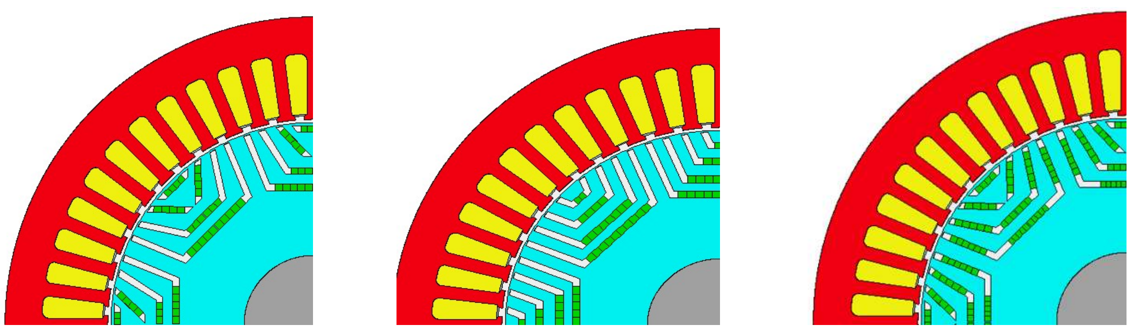
$$K_w = \frac{\sum W_{air}}{\sum W_{iron}}, \qquad (1)$$

where $\sum W_{air}$ is the total flux barrier width and $\sum W_{iron}$ is the total rotor sheet width ???

Motor parameters used for computing are given in Table 1. The magnet volumes in these models are identical. The number of slot/poles is 48/8, the stack length is 51 mm, the diameter of stator and rotor is 260 and 152 mm, the air-gap length is 0.7 mm, the thickness of electrical steel sheet is 0.2 mm, the continuous phase current amplitude is 400 A, the continuous rated power is 150 kW and the maximum speed of the machines is 12000 rpm. The no-load air-gap density of the model I is lower than other models due to the magnets located at the radial. The magnets buried deeply is similar to a PMa-SynRM.



a) Model 1-3V shape b) Model 2-I2V shape c) Model 3-∇2U outter



d) Model 4-∇2U inner e) Model 5-4U half f) Model 6-∇2U Half

Fig. 1. PM shape topologies

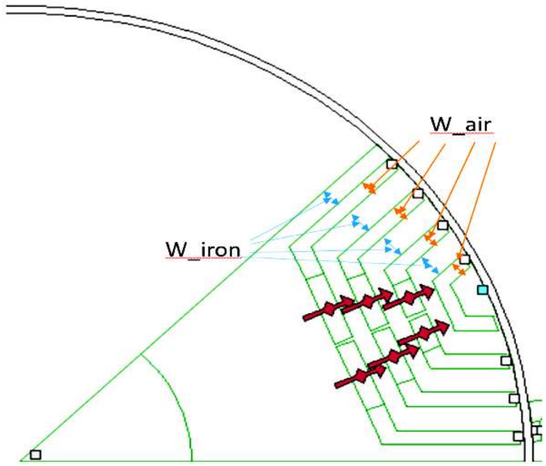


Figure 2. Flux barrier topologies

Table 1. Motor parameters

Stator Dimension	Value (mm)	Rotor Dimension	Value (mm)
Slot Number	48	Pole Number	8
Stator Lamination Diameter	260	Notch Depth	1
Stator Bore	185	Notch Arc Outer [ED]	20
Slot Width (Bottom)	10	Notch Arc Inner [ED]	0
Slot Width (Top)	7,5	Magnet Layers	4
Slot Depth	21	L1 Diameter	152
Slot Corner Radius	1	L2 Diameter	168
Tooth Tip Depth	0,5	Banding Thickness	0
Slot Opening	5	Shaft Dia	60
Tooth Tip Angle	40	Shaft Hole Diameter	0
Sleeve Thickness	0	Rotor Duct Layers	1
Airgap	0,5	L1 RDuct Inner Dia	80

Based on the analytical method, some geometry parameters of stator and rotor can be calculated as follow chart in Figure 3.

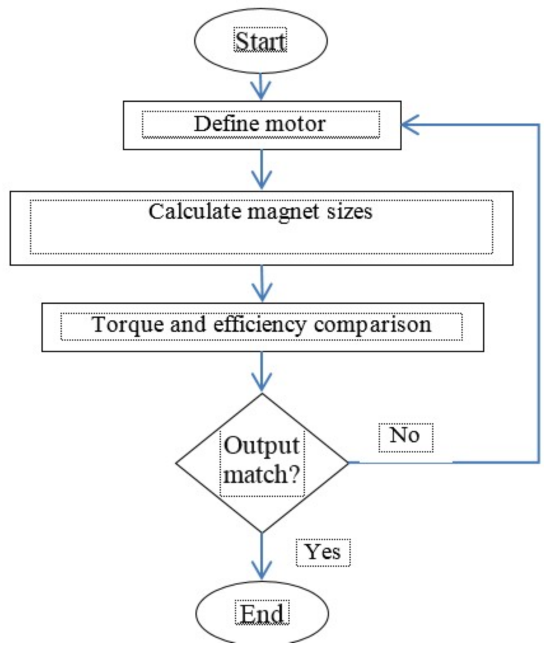


Figure 3. Calculation process

The analytical model has been proposed to define basic parameters. Based on the volume torque density (TVR), from 65 to 80 kNm/m3 [5]-[8], it is assumed that the rotor diameter is equal to the rotor length. The rotor diameter (D) and length (L) of IPM are defined as follow:

$$T = \frac{\pi}{4}.D^2.L_s.TRV, \qquad (2)$$

where T is the electromagnetic torque (N.m), L_S is the length of core (m).

In general, the design process of IPM is like that of the induction motor. The main parameters (such as outer diameter, rotor diameter, motor length, stator slot, airgap length) are defined by taking into account some practical factors with desired input requirements. The main part of the process is to design the rotor configuration which is embedded in the PM. The PM configuration needs to create sufficiently the magnetic voltage for the magnetic circuit. In fact, there are some possible configurations sorted by the shape and position of the PM inside rotor as listed Table 2.

Table 2. Motor weight comparison parameters

Component	**Material**	**Model 1 (3V)**	**Model 2 I2V**	**Model 3 ∇2U inner**	**Model 4 ∇2U Outer**	**Model 5 4V Half**	**Model 6 ∇2U hafl**
Stator Back	M350-50A	8.26	8.26	8.26	8.26	8.26	8.26
Stator Tooth (mm)	M350-50A	5.245	5.245	5.245	5.245	5.245	5.245
Stator Core		13.5	13.5	13.5	13.5	13.5	13.5
Armature Winding	Copper (Pure)	4.138	4.138	4.138	4.138	4.138	4.138
Armature Front	Copper (Pure)	1.027	1.027	1.027	1.027	1.027	1.027
Armature Rear	Copper (Pure)	1.027	1.027	1.027	1.027	1.027	1.027
Total Winding		6.193	6.193	6.193	6.193	6.193	6.193
IPM Magnet Pole	M350-50A	4.403	4.403	4.403	4.33	4.403	4.241
Total Rotor		10.38	10.38	10.38	10.3	10.38	9.935
Magnet	***N30UH***	***1.872***	***1.872***	***1.872***	***1.253***	***1.26***	***1.201***
Total		34.22	34.22	34.22	33.53	33.61	33.11

3. FEM-CAD-DESIGN PROGRAM

The program is divided into three main parts (Figure 4): analytical calculation, exporting drawing and magnetic simulation. There are also some supporting parts including material library which also associate with the FEM library.

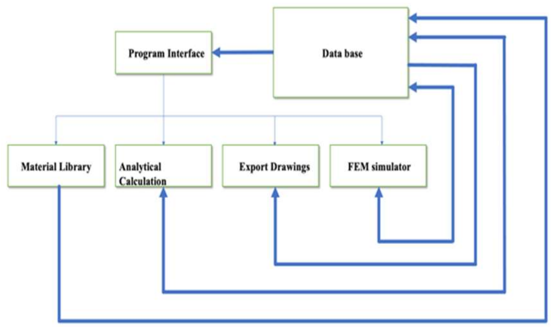


Figure 4. Program Structure

The program interface is a well defined set of the Matlab function to parse, manage and present data. The interface is written by the Matlab GUIDE. The calculation progress cannot be activated without parameters, i.e, power, torque, pole numbers. However, there are default materials for each part of the motor. All the dimensions of motor are saved in database in matrix form. The motor - cad software has integrated the function of automatically exporting DWG files to AutoCad software accurately and easily to help designers save time and workload. The Motor – Cad software will export 3 drawings: motor, rotor and stator separately. These drawings can be used in several simulation program and design and manufacturing progress.

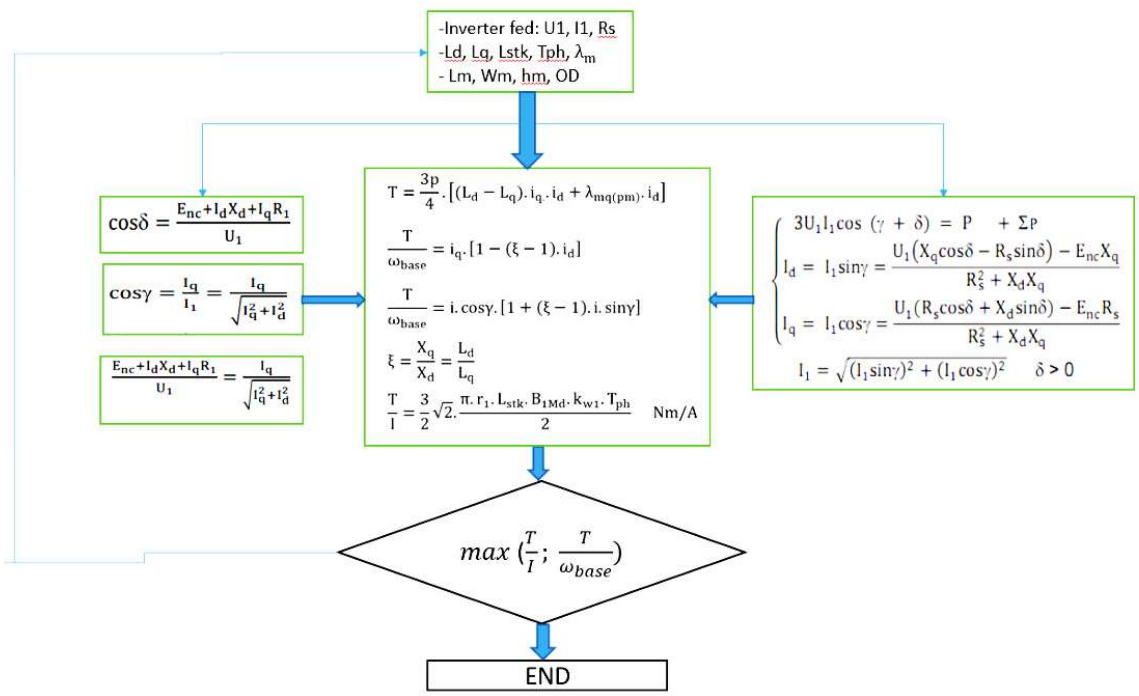


Figure 5. Calculation process of stator and rotor performances

DWG files to AutoCad software accurately and easily to help designers save time and workload. The Motor - Cad software will export 3 drawings: motor, rotor and stator separately. These drawings can be used in several simulation program and design and manufacturing progress.

As mentioned, all calculated dimensions and material information are stored in library, the program will export the drawing to the FEM. The calculation process of stator and rotor performances is presented in Figure 5. To exchange the data, the programming language will be used for this task. With the well-defined function, the drawing can be created with a simpler algorithm. The electromagnetic torque will be expressed in following equation [7]-[9]:

$$T_e = mp\frac{\Psi_{pk}.i_{pk}}{2}\cos\left(\frac{\pi}{2}-\beta\right) = mp\frac{\Psi_{pk}.i_{pk}}{2}\sin\beta = \frac{mp}{2}i_{pk}.\Psi_Q = \Psi_{pk}.i_{pk}.\frac{2mp}{\pi} \quad (3)$$

$$\frac{T}{I} = \frac{3}{2}\sqrt{2}.\frac{\pi.r_1.L_{stk}.B_{1Md}.k_{w1}.T_{ph}}{2} = 4\sqrt{\frac{3}{2}}.r_1.B_{Mg}.L_{stk}.T_{ph} \quad (4)$$

The electromagnetic torque algorithm has been calculated and added some contraints to maximize torque per current and torque per speed characteristics in equations (5) and (6)

One of the advantages of system is that in the FEM, the winding can be easily adjusted. The winding type plays an important role in all motor structures to decide the flux distribution and cost. It requires programs to define in each stator slot coil its corresponding winding depending on type of winding. Boundary problems is also similar. When a rotating machine is sectioned, there are usually several segments that must be joined up. Arc segments, connecting the nearly-coincident mid-gap points, are drew. The arc length spanned by these segments should be rotated angle.

3. ELECTROMAGNETIC COMPUTATION

The program can be easily applied for several designs to investigate the torque, torque ripple and efficiency. The program can also be linked to some optimize functions to choose the best solution for specific objective. The comprehensive performances have been analyzed in Table 3.

Table 3 IPM amd PMA-SynRM performance results

Parapeters	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Unit
Average torque	154.98	152.86	140.77	177.79	176.14	187.14	Nm
Torque Ripple	15.695	22.591	33.146	38.682	12.701	21.793	Nm
Torque Ripple [%]	***10.034***	***14.644***	***23.263***	***21.549***	***7.1457***	***11.539***	***%***
Cogging Torque Ripple	4.5174	4.1239	3.6719	10.526	4.1458	9.2029	Nm
Cogging Torque	4.1508	2.8972	3.6748	9.5345	2.7713	7.9613	Nm

Parapeters	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Unit
Ripple							
Electromagnetic Power	1.64E+05	1.62E+05	1.49E+05	1.88E+05	1.86E+05	1.98E+05	Watts
Input Power	1.66E+05	1.63E+05	1.51E+05	1.90E+05	1.88E+05	2.00E+05	Watts
Output Power	1.60E+05	1.57E+05	1.45E+05	1.84E+05	1.82E+05	1.94E+05	Watts
Total Losses	6252.1	6183.1	6428.4	5958.1	6495.1	6188.5	Watts
System Efficiency	***96.228***	***96.218***	***95.747***	***96.863***	***96.547***	***96.902***	***%***
Shaft Torque	152.32	150.22	138.2	175.68	173.41	184.82	Nm
Armature DC Copper Loss	1951	1951	1951	1951	1951	1951	Watts
Magnet Loss	1.658	1.86	0.7654	1.662	0.4815	1.39	Watts
Stator iron Loss	3870	3878	4013	3.61E+03	4099	3796	Watts
Rotor iron Loss	414.3	337.3	448.5	380.7	429.6	425.1	Watts
Total Losses	6252	6183	6428	5.96E+03	6495	6188	Watts
Speed limit for constant torque	***4556.9***	***4563***	***4603.5***	***4559***	***5332.9***	***5886.2***	***rpm***
Speed limit for zero torque	***27537***	***20252***	***19816***	***15524***	***44788***	***60933***	***rpm***

From the torque performence and efficiecny results of six model designs, the efficiency and average torque of model 6 has highest values and the torque ripple is only 11.5% higher than model 5 (7.1%) but this performance can improve by adjusting flux barriers and width of magnet layers. In order to make clear torque ripples, the torque waveforms of six models have been plotted in Figure 6. Finally, the maximum speed limit for the constant torque and zero torque for model 6 is presented in Table 3. In order to define this value, the ratio of torque per current (T/I) and the torque per base speed (T/ω_base) have been calculated by many step to get maximum values.

The torque ripple of Model 5 with PMa-SynRM- 4U shape is the lowest value because the total barrier width and silence ratio of L_d/L_q are suitable values.

The cogging torque of six models are also shown in Figure 6.

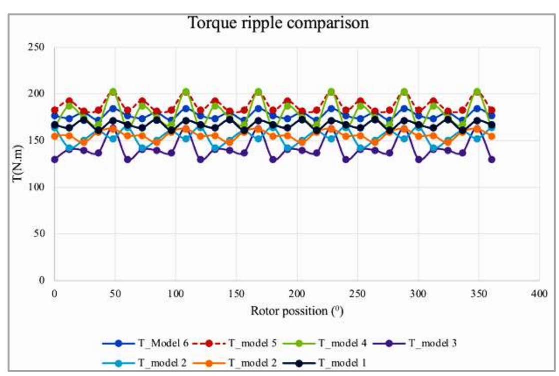


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Figure 6. Torque ripple waveforms of six models

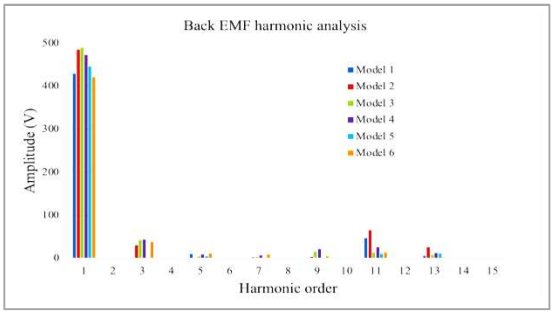

Figure 7. Back EMF harmonic order analysis of six mode

The cogging torque of model 2 has the lowest value because the magnets are quite close to airgap. The flux variation dΦ/dt is small, thus the cogging torque in this case is the best performance.

$$T_{cogging} = F_c.\frac{d\Phi}{dt}, \quad (5)$$

where F_c is the changing flux area and dΦ/dt is the flux variation in airgap.

The back EMF harmonic of six models has been analyzed by the fourrier transform from the electromagnetic force waveform from 1st order to 15th order. The back EMF amplitude versus is implemented by the Matlab function to obtain the results pointed out in Figure 7. From the back EMF harmonic result, the total harmonic distortions (TDH) of Model 5 is the smallest value of 4.2%. The TDH of Model 6 is a little higher than the Model 5. This means that it is acceptable.

Based on the torque and efficiency performance comparison, the proposal design of Model 6 "PMa-SynRM D2U" is selected. The base speed is calculated to be 5000 rpm and the maximum speed of 15000 rpm with the average torque 100N.m is shown in Figure 8. The efficiency map of the PMa-SynRM (Model 6-∇2U) is depicted in Figure 10, with the speed of 15000 rpm and maximum torque of 300 N.m. The efficiency loops are between 96% and 97% accounting almost operation areas. The Efficiency map of ∇2U PMa-SynRM is shown in Figure 9.

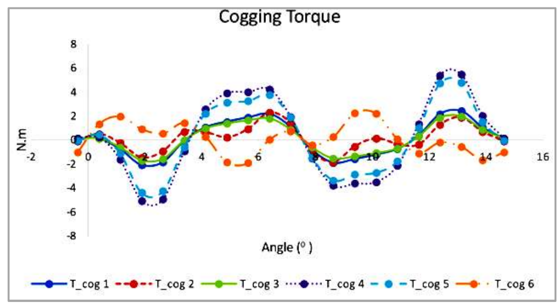

Figure 8. Cogging torque waveforms of six models

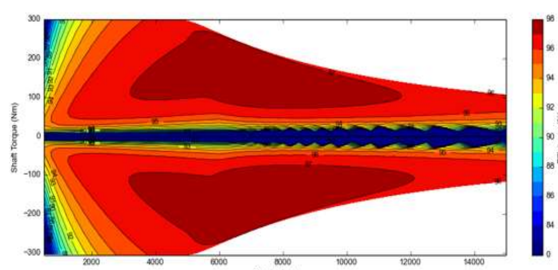

Figure 9. Efficiency map of ∇2U PMa-SynRM

4. CONCLUSION

This paper has investigated and compared the performances of IPM and PMa-SynRM on the constant torque in the wide range speed for EV applications. The investigation has been also indicated that the best design to achieve high CPSR is Model 6 which has four magnet layers in Δ and 2U shapes. The amount of PM for PMaSynRM is changed from 1.24 kg to 1,8kg. The best design has the medium weight of PM. Six prototypes of IPMSM and PMa-SynRM have been investigated from Model 1 to Model 6. The prototype of ∇2U magnet shape of PMa-SynRM shown distribution of the flux density with the sinusoidal waveform in the air gap, because the TDH of back EMF waveform is smallest. This paper has been given out the torque calculation modelling for a maximum torque per current. The speed limit for constant torque is also calculated for all models and analyzed results.

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