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Design Optimization of a Double Stator Cup-Rotor Machine

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Abstract**—**This paper presents the optimum design for a double stator, cup rotor machine; a novel type of BLDC PM Machine. The optimization approach is divided into two stages: the first stage is calculating the machine configuration using Matlab, and the second stage is the optimization of the machine using Finite Element Modeling (FEM). Under the design specifications, the machine model will be selected from three pole numbers, namely, 8, 10 and 12 with an appropriate slot number. A double stator brushless DC permanent magnet machine is designed to achieve low cogging torque; high electromagnetic torque and low ripple torque.

Keywords**—**Permanent magnet machine, low- cogging torque, low- ripple torque, high- electromagnetic torque, design optimization.

I. INTRODUCTION

THERE is an increasing attention focused on wind energy generation applications using permanent magnet machines. Researchers have been motivated to design more efficient, smaller/ lighter machines for this application, and the PMBLDC machine is the only candidate so far to have achieved these goals. Though many efforts have been made to achieve the optimal design such as reducing cogging torque [1]-[3], reducing the ripple torque [4], achieving high electromagnetic torque [5] and choosing the winding type [6]-[8] of conventional PM machines, studies of unconventional PM machines are, so far few in number.

In particular, the design of a machine to provide a high torque with both low cogging torque and torque ripple is a highly desirable aim.

This paper presents the Double Stator Cup-Rotor Machine which has two stators and one rotor. There are many advantages such as more torque can be developed than a conventional machine with only a single stator.

With an electrical connection to both stators' windings by using a Voltage Source Inverter (VSI), the speed, torque and power factor of the DSCR machine can be controlled.

Another aim of this paper is to present an optimization technique for the DSCR machine. The design procedure consists of non-linear equations for calculating slot dimensions, magnet configuration and current density [9]. In order to achieve an optimal design, the integrated machine can be split into two permanent magnet machines (inner and outer part).

II. SPECIFICATION WITH DEPENDENT AND INDEPENDENT VARIABLES

Fig. 1 shows the integrated machine that is divided into two machines. Each machine has physical specifications which are listed in Table I. The variable ranges such as magnet thickness and magnet arc angle can be determined by respective calculations and simulations, respectively. The number of poles was chosen to be 8, 10 and 12. Table II shows the possible pole-slot combinations [10].

TABLE I
SPECIFICATIONS OF BOTH DSCR MACHINE PARTS

Physical Specifications	
Stack length: 59 mm	Inner part inner dia. 44 mm
Magnet material: NdFeB	Inner part outer dia. 150 mm
Air-gap thickness 1 mm	Outer part inner dia. 150 mm
Rated speed 1000 rpm	Outer part outer dia. 204 mm
Rated voltage 200 V	Number of turns 12 turns/coil
Design variables and their ranges	
Magnet thickness (mm): $3 < Mt < 7$	
Magnet arc angle (deg) P_8: $20^o < \alpha < 40^o$, P_{10}: $15^o < \alpha < 30^o$ and P_{12}: $5^o < \alpha < 25^o$.	
Cogging torque limit is $\leq$ 0.08 Nm	

TABLE II
POLE-SLOT COMBINATIONS

Poles	No. of Slots							
8	9	12	18	21	24	27	30	33
10	12	15	24	27	30	33		
12	9	18	27					

The DSCR machine configuration is presented in Fig. 1. The key was to split the integrated machine into inner and outer parts. Each part has been modeled separately as a conventional permanent magnet machine.

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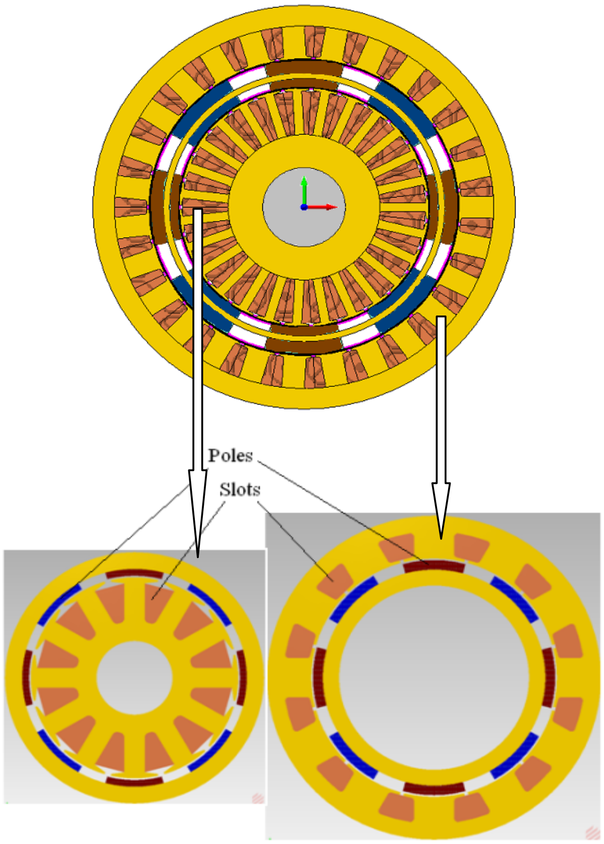

Fig. 1 Integrated machine design

III. DESIGN PROCEDURE

Figs. 2 and 3 show the flowcharts of the machine design procedure. Fig. 2 illustrates the procedure for choosing the minimum cogging torque in each machine part. A low cogging torque considering the limit in Table I, and high electromagnetic torque with low ripple torque are the requirements. In order to investigate the electromagnetic torque of the pole-slot combinations that have minimum cogging torque, the Ampere-turns machine excitation was kept fixed (1080 A-turns) for both the inner and the outer parts as shown in Appendix Table IA and IIA.

The design process starts by selecting the stator slot dimension to avoid stator yoke and tooth saturation with the fixed excitation. Then, to determine the magnet arc angle to achieve a lower cogging torque and high electromagnetic torque for all pole-slot combinations as listed in Table II. Once the magnet arc angle is determined, the Fully Pitched (FP) magnet arc angle and the Gapped Magnet (GM) models were investigated. Finally, any pole-slot combination model producing a cogging torque with less than or equal to 0.08 Nm were examined and further modelled to identify the level of electromagnetic torque.

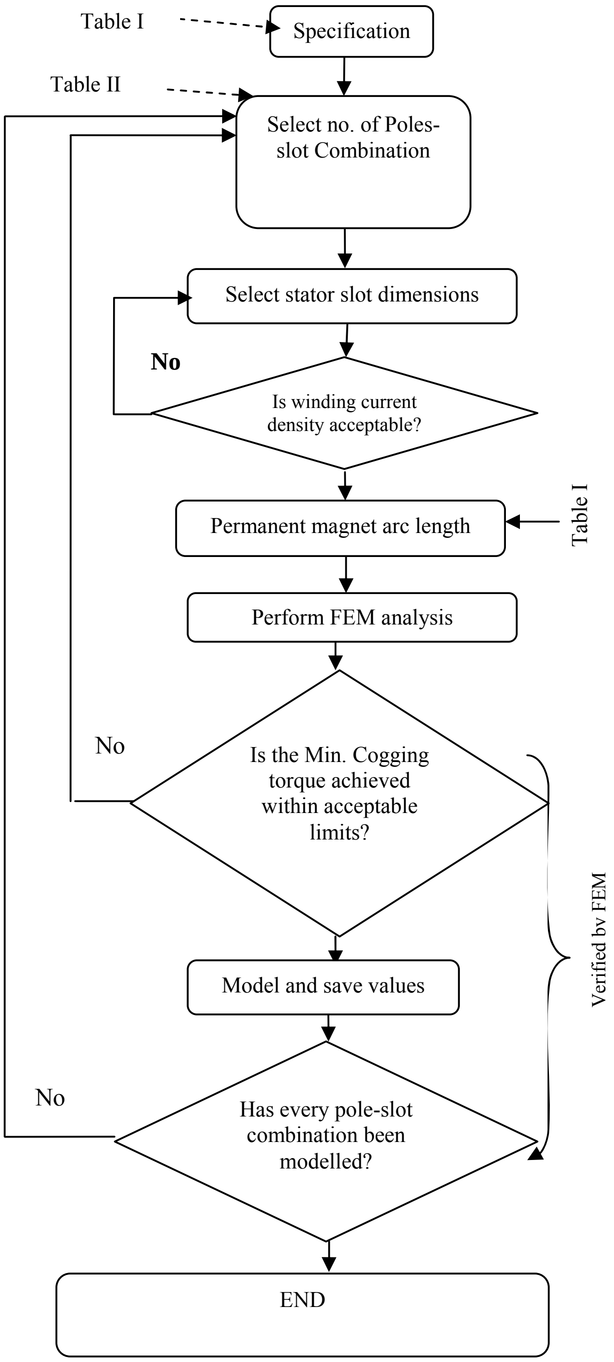

Fig. 2 Logic flowchart applied to each part of the DSCR machine to select the minimum cogging torque

Fig. 3 shows the flow chart of the last stage of the optimization procedure. It consists of two subroutines, one for the inner part and the other for the outer part of the machine. The flow chart shows the program starting with the pole-slot combinations for minimum cogging torque in each machine part, where both algorithms terminate after testing the specified torque and ripple values.

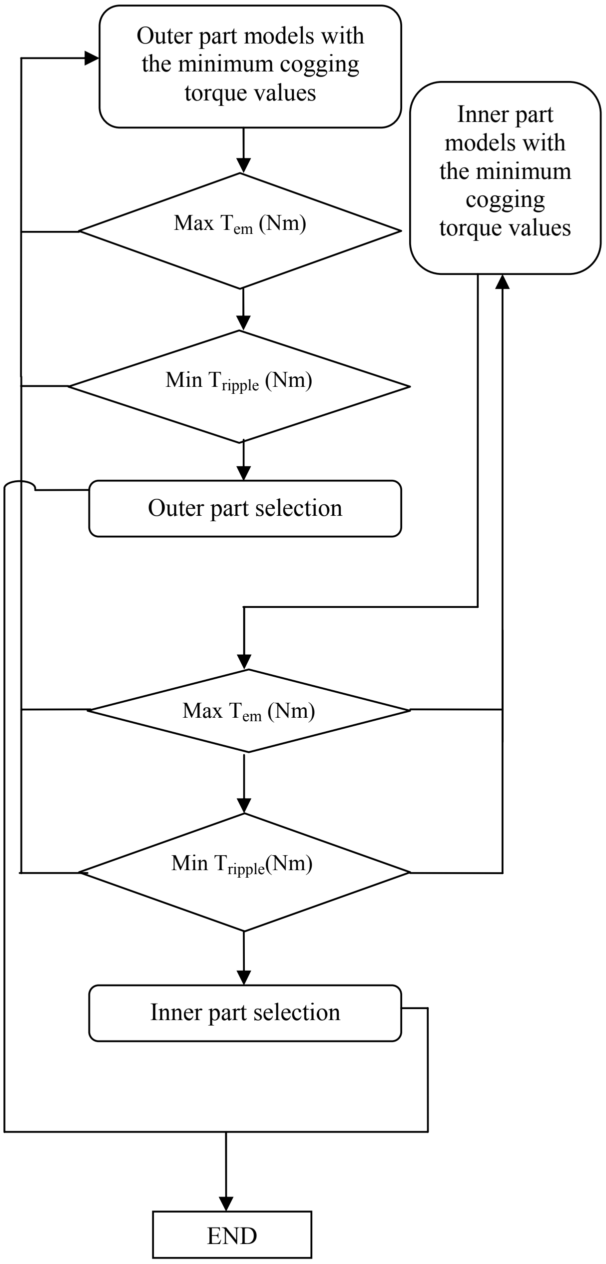

Fig. 3 The flowchart of the design optimization final stage

A. Stator Slot Design

The slot pitch (λ) which is the distance between the stator tooth and slot opening, as shown in Fig. 4, is determined as:

$$\lambda = \frac{D}{S} \tag{1}$$

where, D is the stator bore diameter of the machine.

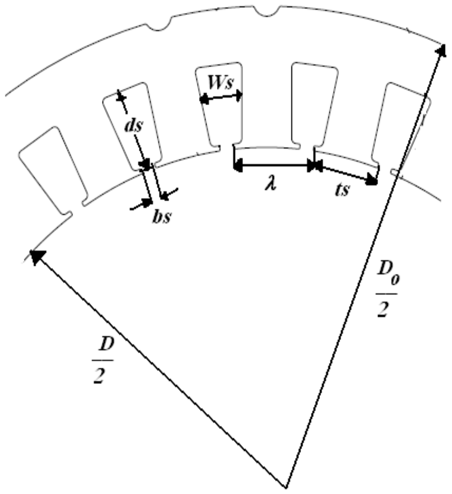

Fig. 4 The stator configuration

Prior to calculating the number of conductors per slot, many variables have to be found such as stator slots per pole per phase (q), distribution factor (k_{ds}) and the pitch factor (k_{ps}). The equations [1A-6A] in the Appendix are used to calculate the winding factor (k_W) from these variables [9], [12]. Equation 2 represents the number of conductors per slot.

$$N_s = \frac{V_{ph}}{P * N_{ph} * f * k_W * \Phi_m} \tag{2}$$

Where, V_{ph} is the phase voltage, N_{ph} is the number of phases, Φ_m is the maximum flux density and f is the frequency. Once the number of conductors per slot is calculated, the slot dimensions can be configured as [12]:

$$0.6\,\lambda \geq W_s \geq 0.5\,\lambda \tag{3}$$

Where, W_s is the slot width and the slot depth (d_s) is chosen between the following ranges:

$$0.8\,\lambda \geq d_s \geq 0.6\,\lambda \tag{4}$$

B. Flux Density Checks

The flux density checks are needed before starting to design the machine. The maximum stator tooth flux density (B_{stm}) and stator core flux density (B_{scm}) can be found by using the following formulae [12]:

$$B_{stm} = (\pi * \Phi_m * P)/(2 * S * t_s * L) \tag{5}$$

$$t_s = \lambda - b_s \tag{6}$$

$$B_{scm} = \frac{\Phi_m}{((D_o - D) - d_s) * L} \tag{7}$$

Where, D and D_o is the inner and outer stator diameter, respectively. The maximum flux that could be produced can be calculated from [9]:

$$\Phi_m = C_1 * 10^5 \sqrt{P_s\left(\frac{60}{f}\right)} \qquad lines \qquad (8)$$

where, Ps is the rated machine power in horsepower (1hp =746 watt). Table III shows the experimental results of the maximum flux density constant per pole, C_1 [9]. There are different values of C_1 according to the pole number of the machine, for example 3.7/pole for 2 poles i.e. the total flux density constant is 7.4 and 2.45/pole for 4 poles that means the total flux density constant is 9.8 and so on.

TABLE III
THE LIMITS OF FLUX DENSITY CONSTANT

NO. OF POLES	C1
2	3.7
4	2.45
6	2.10
8	1.9
10	1.8
12	1.7
14	1.65
16	1.6

C. Choosing Gap Space between Magnets

From the initial pole-slot modelling, the 27 slot- 8 pole combination has been chosen as the preferred model for all simulations. This number of poles and slots has been investigated with changing the magnet arc angle, i.e. the gap between any two magnets. It can be seen from Tables (IV-VI) that the best gap between magnets is chosen according to minimum cogging torque and relatively high electromagnetic torque. It can be concluded that the ratio between the chosen arc angle and the fully pitched arc angle in each analysis is 2/3.

TABLE IV
COGGING AND ELECTROMAGNETIC TORQUES VS POLE ARC ANGLE (8 POLES)

Pole Arc Angle (degrees)	Cogging Torque (N. m)	Electromagnetic Torque (N. m)
40	0.058	14 – 16.5
35	0.055	13.9 – 16.2
30	0.042	15.5-16.2
25	0.045	11.5 – 14
20	0.041	10 – 11.5

TABLE V
COGGING AND ELECTROMAGNETIC TORQUES VS POLE ARC ANGLE (10 POLES)

Pole Arc Angle (degrees)	Cogging Torque (N. m)	Electromagnetic Torque (N. m)
30	0.015	11.2-14
24	0.004	15-16
20	0.017	10-11
15	0.011	7.8-9

TABLE VI
COGGING AND ELECTROMAGNETIC TORQUES VS POLE ARC ANGLE OF (12 POLES)

Pole Arc Angle (degrees)	Cogging Torque (N. m)	Electromagnetic Torque (N. m)
5	0.4	3.1-4
15	0.45	7.8-9.2
20	0.15	8.8-10.2
25	0.38	9-11.8

D. Tooth Gap Width

In order to start comparing pole-slot combinations, the tooth gap width (bs) must be considered and this is shown in Fig. 3. Although, reducing bs leads to a lower cogging torque as shown in Fig. 5, the 2.22 mm can be considered the minimum width.

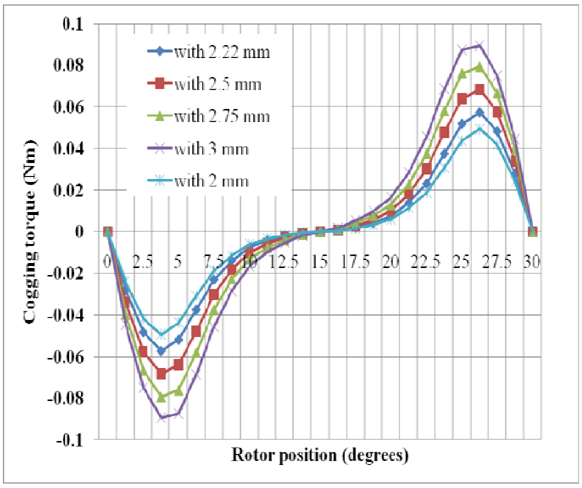

Fig. 5 Tooth gap width Vs cogging torque

E. Choosing the Winding Type

Selecting the winding type is a very important issue in machine design. In order to choose the most suitable winding type, there are many considerations that are important, such as the cogging torque and electromagnetic torque. Using concentrated windings can produce a low torque ripple [7], improve the torque performance, and it can minimize the cogging torque as well [8].

IV. SIMULATION RESULTS

Since the integrated machine was split into two machines and each machine designed and examined with 43 pole-slot combinations in order to find the minimum cogging torque, the electromagnetic torque has been investigated at rated current with both a three phases sine-wave drive and a two phase or six-step drive. The simulation results of the cogging torque, electromagnetic torque and ripple torque are shown in Figs. 6, 7, 8 and 9. The resultant cogging torque is presented in Fig. 10.

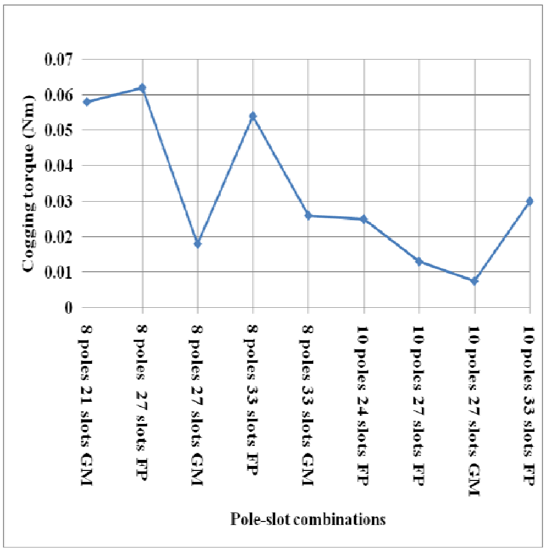

Fig. 6 9 from 34 pole-slot combinations with the lowest cogging torques (inner machine part)

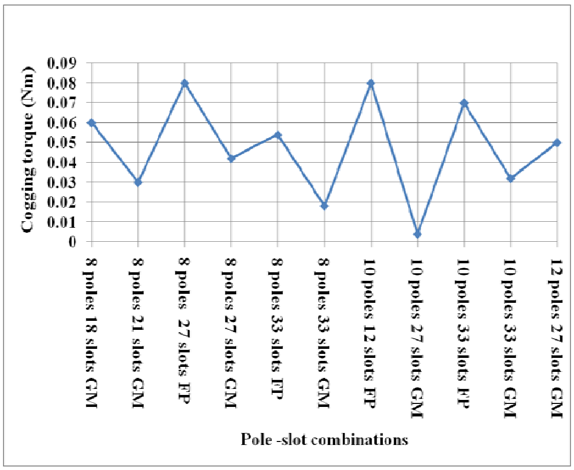

Fig. 7 11 from 34 pole-slot combinations with the lowest cogging torques (outer machine part)

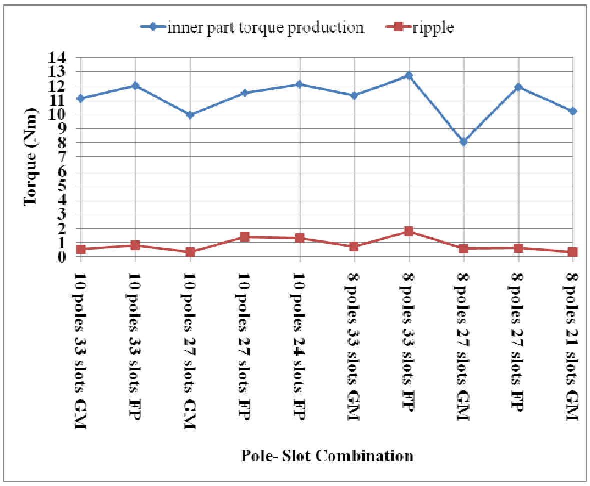

Fig. 8 The electromagnetic torque and the peak to peak ripple torque of the DSCR machine (inner part)

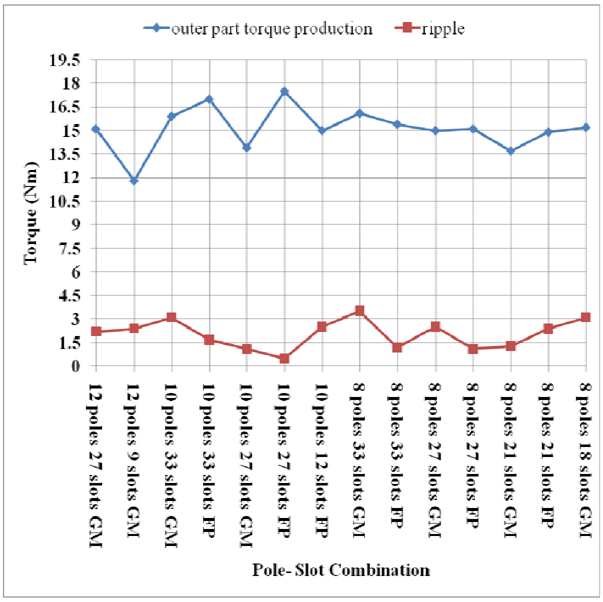

Fig. 9 The electromagnetic torque and the peak to peak ripple torque of the DSCR machine (outer part)

Figs. 6 and 7 show the pole-slot combination that has only 0.08 Nm or less cogging torque at no current. Figs. 8 and 9 show the electromagnetic torque that can be produced by these combinations. The comparison between these combinations considering also the peak to peak ripple torque is also shown in Figs. 8 and 9.

Once the inner and outer parts of the DSCR machine are determined individually, the integrated machine is modeled and examined with no current in both stators' windings. This investigation has been carried out to produce the resultant cogging torque.

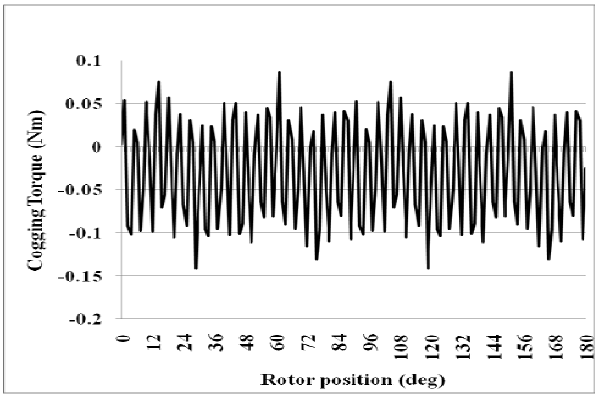

Fig. 10 The resultant cogging torque of the DSCR machine

V. CONCLUSION

The optimization technique based on machine configuration by using the Matlab environment and the DSCR machine design is verified by FEM and presented in this paper.

The main objectives are to minimize the cogging torque, torque ripple and to maximize the electromagnetic torque. The results from the 68 pole-slots combinations showed that the optimal design is 10 pole-27 slots GM for the inner part and 10 poles-27 slots FP for the outer part. Further investigation on the integrated DSCR machine using FEM will be carried out.

APPENDIX

$$q = \frac{s}{N_{ph} N_m} \tag{1A}$$

$$K_{ds} = \frac{\sin\left(\frac{q\gamma}{2}\right)}{q\sin\left(\frac{\gamma}{2}\right)} \tag{2A}$$

$$\gamma = \frac{\pi}{3q} \tag{3A}$$

$$k_{ps} = \sin\left(\frac{\alpha}{2}\right) = \cos\left(\frac{\rho}{2}\right) \tag{4A}$$

$$\rho = \pi - \gamma \tag{5A}$$

$$k_W = k_{ds} * k_{ps} \tag{6A}$$

Where:
S: Number of stator slots
Nm: Number of poles
α: The chording angle
γ: Slot- pitch angle

TABLE IA
THE CALCULATED CURRENT OF THE DSCR MACHINE
INNER PART

Pole- slot Combinations	Number of coils	Number of turns	Current value for 2 phases	Amp. * No. of turns * Cs	Current values for 3 phases
8 pole-21 slots GM	**7**	**12**	**12.86**	**1080**	**11.13**
8 poles- 24 slots FP	**8**	**12**	**11.25**	**1080**	**9.74**
8 poles- 27 slots GM	**9**	**12**	**10.00**	**1080**	**8.66**
8 poles- 27 slots FP	**9**	**12**	**10.00**	**1080**	**8.66**
8 poles- 33 slots GM	**11**	**12**	**8.18**	**1080**	**7.09**
8 poles- 33 slots FP	**11**	**12**	**8.18**	**1080**	**7.09**
10 poles- 24 slots FP	**8**	**12**	**11.25**	**1080**	**9.74**
10 poles- 27 slots FP	**9**	**12**	**10.00**	**1080**	**8.66**
10 poles- 27 slots GM	**9**	**12**	**10.00**	**1080**	**8.66**
10 poles- 33 slots FP	**11**	**12**	**8.18**	**1080**	**7.09**
10 poles- 33 slots GM	**11**	**12**	**8.18**	**1080**	**7.09**

TABLE IIA
THE CALCULATED CURRENT OF THE DSCR MACHINE
OUTER PART

Pole- slot Combinations	Number of coils	Number of turns	Current value for 2 phases	Amp. * No. of turns * Cs	Current value for 3 phases
8 pole-18 slots GM	**6**	**12**	**15**	**1080**	**12.99**
8 poles- 21 slots FP	**7**	**12**	**12.86**	**1080**	**11.13**
8 poles- 21 slots GM	**7**	**12**	**12.86**	**1080**	**11.13**
8 poles- 27 slots FP	**9**	**12**	**10.00**	**1080**	**8.66**
8 poles- 27 slots GM	**9**	**12**	**10**	**1080**	**8.66**
8 poles- 33 slots FP	**11**	**12**	**8.18**	**1080**	**7.09**
8 poles-33 slots GM	**11**	**12**	**8.18**	**1080**	**7.09**
10 poles- 12 slots FP	**4**	**12**	**22.5**	**1080**	**19.49**
10 poles- 27 slots FP	**9**	**12**	**10.00**	**1080**	**8.66**
10 poles- 27 slots GM	**9**	**12**	**10**	**1080**	**8.66**
10 poles- 33 slots FP	**11**	**12**	**8.18**	**1080**	**7.09**
10 poles- 33 slots GM	**11**	**12**	**8.18**	**1080**	**7.09**
12 poles- 9 slots GM	**3**	**12**	**30**	**1080**	**25.98**
12 poles- 27slots GM	**9**	**12**	**10**	**1080**	**8.66**

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