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Innovative design for maximum MMF reduction

By

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Abstract:

This paper accompanies and complements a related companion paper [1]. A reduction in the harmful effects of the space harmonics produced by the stator winding of an induction motor can be obtained by constructional changes to the stator. It is possible to reduce or even eliminate the most significant harmonics, according to the number of slots per pole pair and based on numerical optimization involving both the slot positions and the number of conductors per slot. Importantly, a high winding factor is preserved in the resulting novel stator arrangement. The design of a motor with this arrangement is compared with that of a standard motor, in terms of the cross sections of the stator and rotor, slots and teeth, since various shapes of slots are required to contain the different number of conductors per slot arising from the different shapes of the teeth. A comparison between the main performance characteristics predicted for the two machines demonstrates the operational benefits that are achieved.

Keywords:

Electrical machinery design, space harmonics, machine windings

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1. Introduction:

Previous studies [2-5] have shown that the unwanted effects of the space harmonics produced by the stator mmf of an induction motor can be reduced or almost totally eliminated by optimising both the slot positions and the number of conductors in the slots. The required slot positions and numbers of conductors are calculated using optimisation software [2]. With the mmf waveform required viewed as a step function, results were obtained for a pole pair [2], [3] since they can then easily be adapted to a different number of poles with the same number of slots per pole pair by use of the conversion from geometric angle to electrical angle.

The necessary number of slots is a multiple of 12, and considerations for 24, 36, 48 and 60 slots per pole pair confirm that as the number of slots increases so also does the number of space harmonics that can be eliminated [2], [3]. Although both the slot positions and the number of turns are re-arranged, a high fundamental winding factor is maintained for each solution, in contrast to the harmonic reduction techniques proposed previously that have produced a good harmonic spectrum but at the expense of a low fundamental winding factor [6-8]. All the winding factors presently achieved were confirmed by an alternative routine [9-14].

Implementation of the numerical data obtained for a motor requires new calculation methods and concepts to establish the new stator details. To place different number of conductors in each slot requires various tooth shapes to obtain a constant yoke thickness. For comparative purposes, a standard squirrel cage motor was obtained from the manufacturer together with its numerical data. In this paper, the cross sections of the stator, rotor, slots and teeth of both the conventional and the novel machine are analyzed, and the slot structures and tooth width optimisation method are presented, as well as the calculations and concepts. The effects of the optimization, including a comparison of the equivalent circuit parameters, losses, magnetic quantities, operational data, torque and magnetic analysis results are summarized and the resulting consequent advantages and disadvantages of the novel winding are highlighted [2-5].

2. Optimized MMF Shape:

The general principles, optimized numerical data containing slot positions and number of turns in each slot, harmonic spectra, harmonic winding factors of the optimization method were published elsewhere [2], [3]. The angular distance between the slots and the number of conductors in each slot are not unique and the optimized mmf waveform is given in Figure 1 for an arbitrary current of 1 A, where q is the number of slot per pole per phase. Briefly, this method eliminates or almost eliminates the (q-1) most

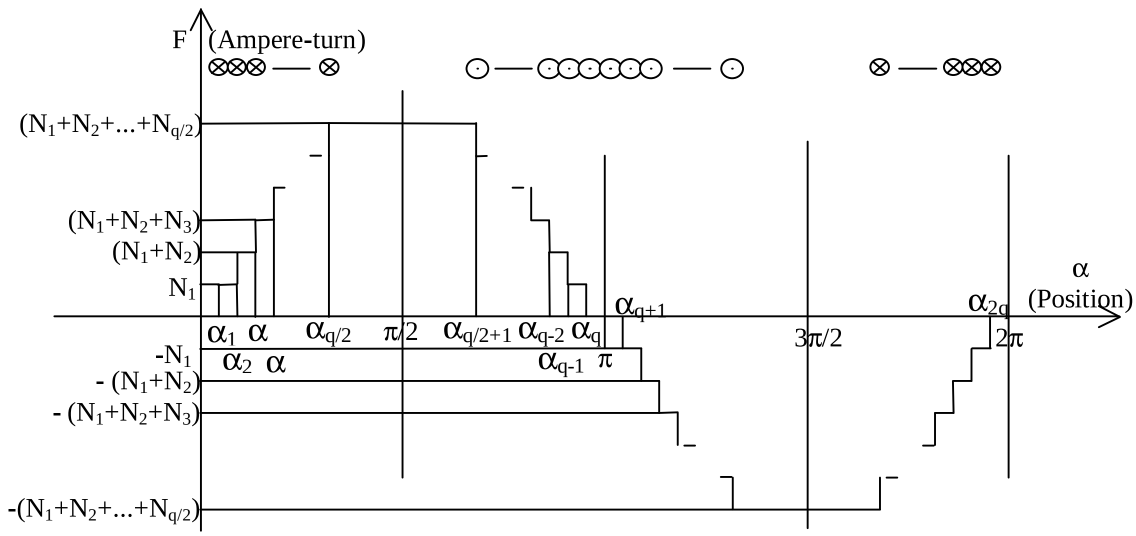

Figure (1): *Optimized mmf waveform for 1 A phase current*

prominent space harmonics excluding multiples of 3, [2], [3], since these do not produce a rotational field [15].

Since the subject of this paper is not the method and the results of optimization, only one harmonic spectrum is given in Figure 2 to demonstrate the benefits of the optimization for 36 slots per pole pair [2], [3]. This spectrum is for the numerical data in Equations 1, 2 and 3, where α is the slot positions, F is the mmf value of the slot for 1 A phase current and N is the number of conductors in a slot.

$$[\alpha]= [\,8° \;\; 25° \;\; 42° \;\; 138° \;\; 155° \;\; 172° \;\; 188° \;\; 205° \;\; 222° \;\; 318° \;\; 335° \;\; 352°\,] \quad (1)$$

$$[F]= [47 \;\; 81 \;\; 100 \;\; 100 \;\; 81 \;\; 47 \;\; -47 \;\; -81 \;\; -100 \;\; -100 \;\; -81 \;\; -47\,] \quad (2)$$

$$[N]= [47 \;\; 34 \;\; 19 \;\; -19 \;\; -34 \;\; -47 \;\; -47 \;\; -34 \;\; -19 \;\; 19 \;\; 34 \;\; 47\,] \quad (3)$$

3.Implementation Of The Numerical Data To A Practical Design:

To analyze the effects of the changes to be made to the conventional machine, a reliable design tool is needed. A design program was prepared, [2], [16], [17], and its reliability checked by comparing the results of the design with that of the standard motor obtained from the manufacturer. A magnetic analysis programme was used to support the results. After obtaining a reliable design program, a winding was designed and implemented into a new design.

The conventional stator structure contains slots of the same size, since they all contain the same number of conductors, but which are different from those of the optimized numerical data. The optimized design requires various slot designs to accommodate the differing numbers of turns. Slot size affects slot leakage reactance, depending on the ratio of slot width to slot depth and also tooth flux densities related to tooth width. It is not desirable to design a stator with different slot depths, since the minimum yoke thickness would then be important for the yoke flux. Before beginning to redesign the stator, the outline of the general design concepts to avoid saturation in all the teeth by calculating a constant width for all teeth and to obtain a unique slot depth by optimizing the tooth flux density are required.

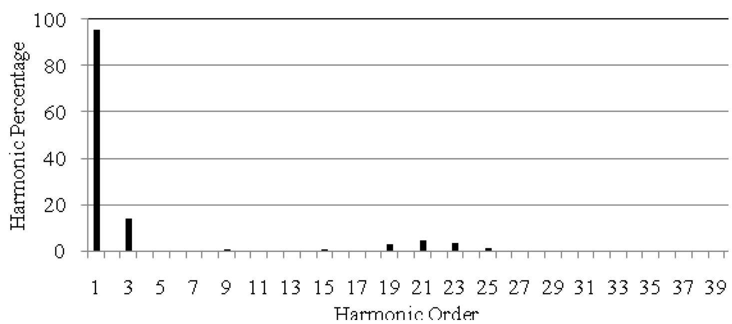

Figure (2): *Optimized harmonic spectrum for the 36 slots per pole pair optimized winding as percentage of the fundamental of the standard machine*

4. Slot Structure and Stator Core for the Conventional Motor:

To ensure a constant tooth width and flux density within the teeth, the stator slots of the conventional motor have a semi-closed entrance, a trapezoidal wedge region, a widening slot width as the slot goes deeper and a circular slot bottom. Details of the slot and tooth shapes are given in Figure 3. The stator and rotor cores are also shown, together with the slot and tooth structure, for a motor with 36 slots, 2 poles, 6 slots per phase per pole and 25 conductors per slot in Figure 4. It can easily be seen that the tooth width is constant and that slots are all the same size, since they all contain the same number of conductors. It must be remembered that there is no change to the rotor.

5.Structure for the Novel Stator Design:

There are q/2 different numbers of conductors in slots in the quarter wave due to the quarter-wave symmetry. There must therefore be q/2 different slot shapes in the stator core including the other two phases, since the numerical results for these are simply displaced by ±120°. To obtain a constant yoke thickness, all slots must have the same slot depth whereas the tooth width between slots must vary. The slots must have different slopes on each side to ensure a constant tooth width between slots and so provide a constant tooth flux density. The main slot quantities are given in Figure 5.

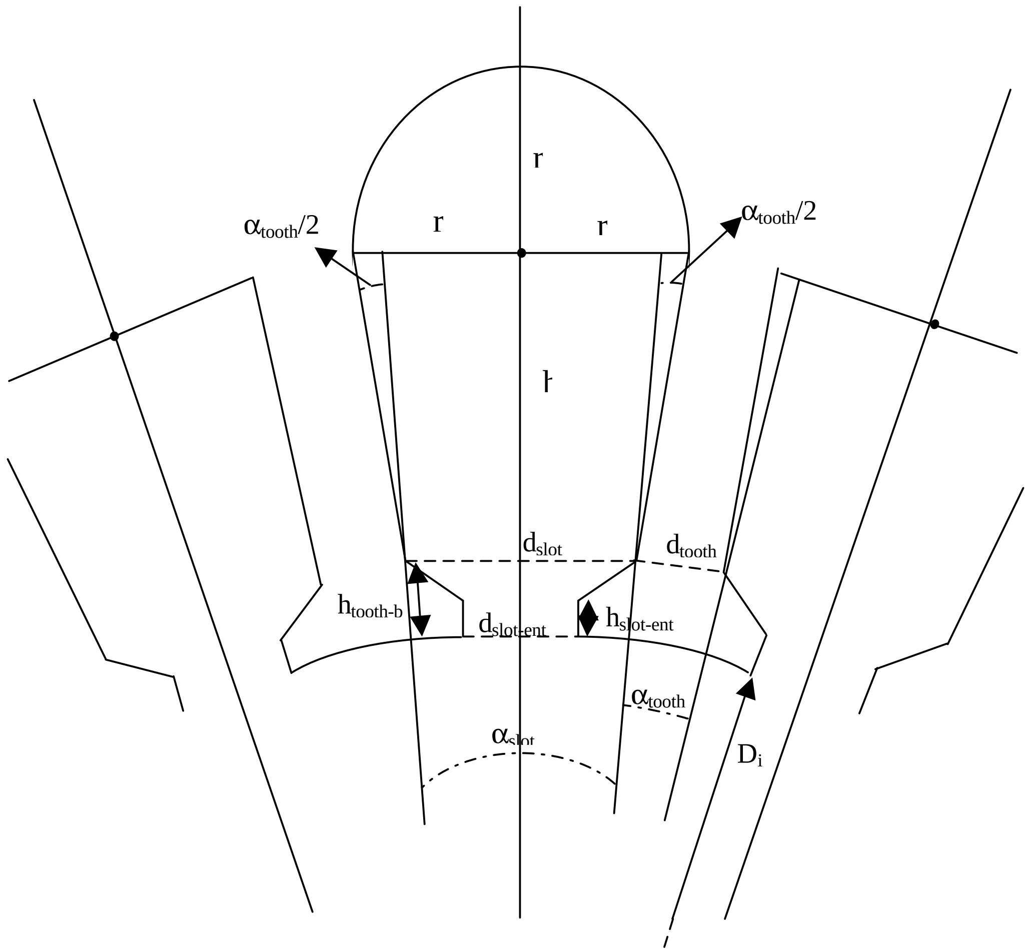

Figure (3): *Details of the slot structure and tooth in the conventional machine*

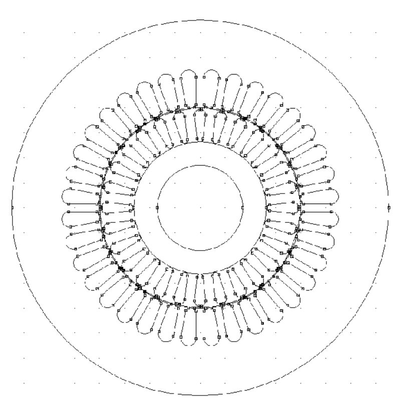

Figure (4): *Cross section of the conventional machine*

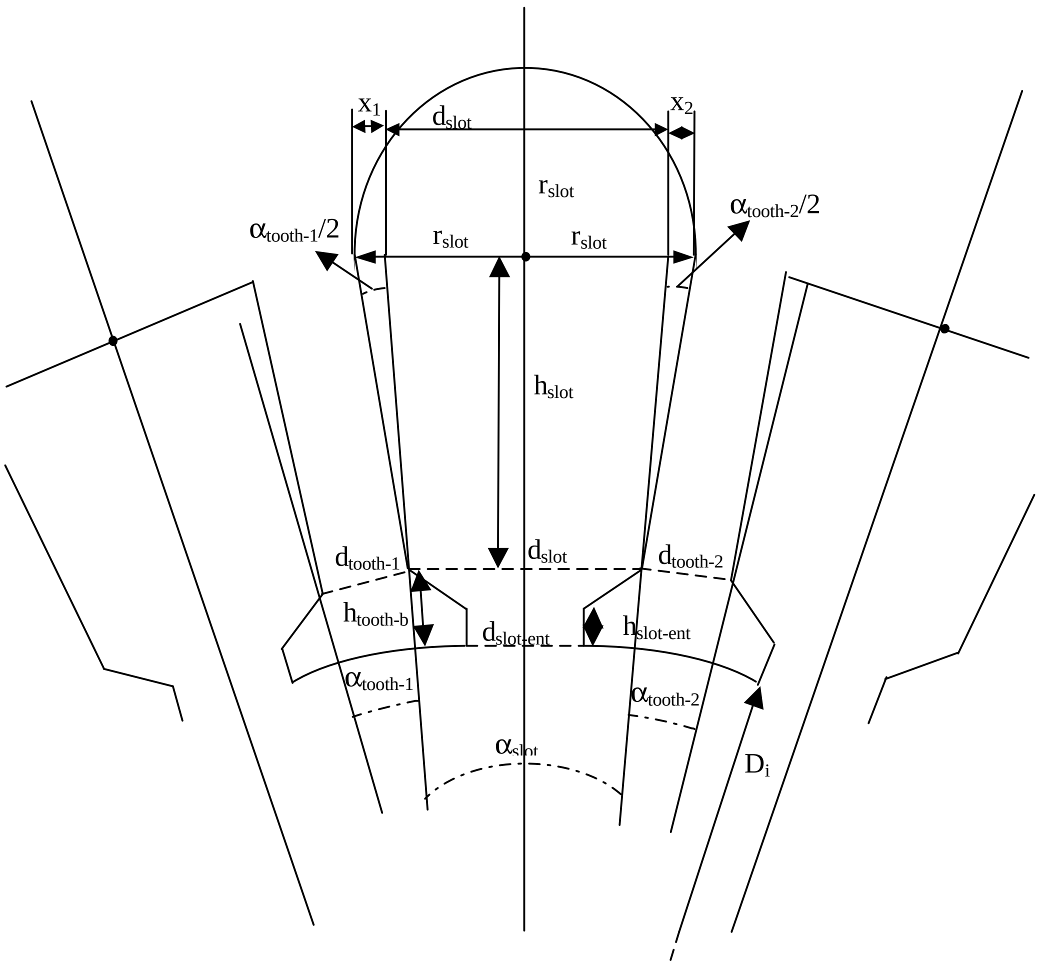

Figure (5): *Slot quantities to obtain a constant tooth width*

6.Slot &Tooth Width Optimization:

The motor was redesigned for 36 slots and 150 turns per phase for comparison with the conventional motor. The slots to be designed contain 35, 26 and 14 conductors in 3 different slot shapes, with no reference to the current direction or to which phase they belong. The overall information for the number of turns in the slots has a repetitive sequence of 35-14-26-26-14-35 resulting in 4 different designs of teeth, which are between slots containing 35&14 conductors, 14&26 conductors, 26&26 conductors and 35&35 conductors, The angular distance between the slot centres are 10º, 7º, 10º, 7º, 10º and 16º and this is also repetitive.

The onset of the optimisation process depends on the prediction of the tooth flux related to the number of conductors in the adjacent slots. The teeth having a greater flux must be wider than the others and the greater flux is produced by more conductors in the adjacent slots. It can easily be seen that the widest tooth must be between slots containing 35 conductors, and the narrowest be between slots containing 26 and 14 conductors. The minimum tooth width to carry the calculated flux can be calculated at the depth where the tooth begins. The depth of the slot entrance and the wedge area thickness were taken to be the same as that of the standard motor.

The distances between the slot axes can be expressed in terms of slot widths, where the tooth begins, and the minimum required tooth widths described above. When the three different slot widths, say 2x, 2y and 2z, are used together with the angular distances between slot centres, 4 equations containing 3 variables are obtained and x, y and z can be calculated by solving the equation system.

The slot area depends on the depth where the end-radius of the slot is proportional to its depth. The slot area is divided into 4 different regions having the dimensions shown in Figure 5, and all regions are described in terms of h_{slot} and r_{slot}. Since these variables are related to one another, the slot area can be expressed as a quadratic equation based on the dimensions of one of them.

In this step, the teeth have the minimum width to carry the tooth flux, but the depths are different from one another. The most risky tooth in terms of saturation is clearly the narrowest, which is between slots containing 26 & 14 conductors. A new optimization file was prepared in Excel to arrange the slot depths, by shortening the longer slot and lengthening the shorter slot, whilst checking that the narrowest tooth width was not less than the critical value. With this calculation method the slot depths are all equal and 3mm longer than in the conventional motor.

The novel design for the stator core together with the unchanged rotor is given in Figure 6. Figure 7 provides a detailed version of Figure 6 drawn for magnetic analysis purposes, including the number of conductors in the slots, material information and circuit information for the conductors.

7.Concepts, Calculations To Change:

In making a comparison in yoke design there are three quantities that can be kept constant which are the yoke flux density or the outer diameter or yoke thickness. All three possibilities were compared and keeping the yoke thickness constant was chosen resulting in an increase in the outer diameter of the rotor, iron weight and also iron loss. The method of calculation was unchanged whichever was chosen [2], [4].

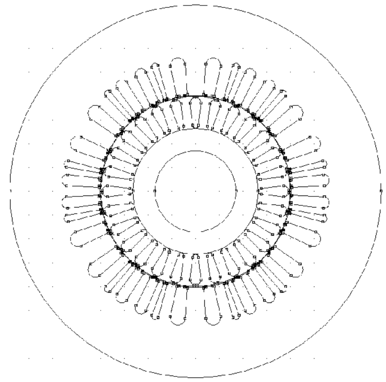

Figure (6): *Cross section of the redesigned motor*

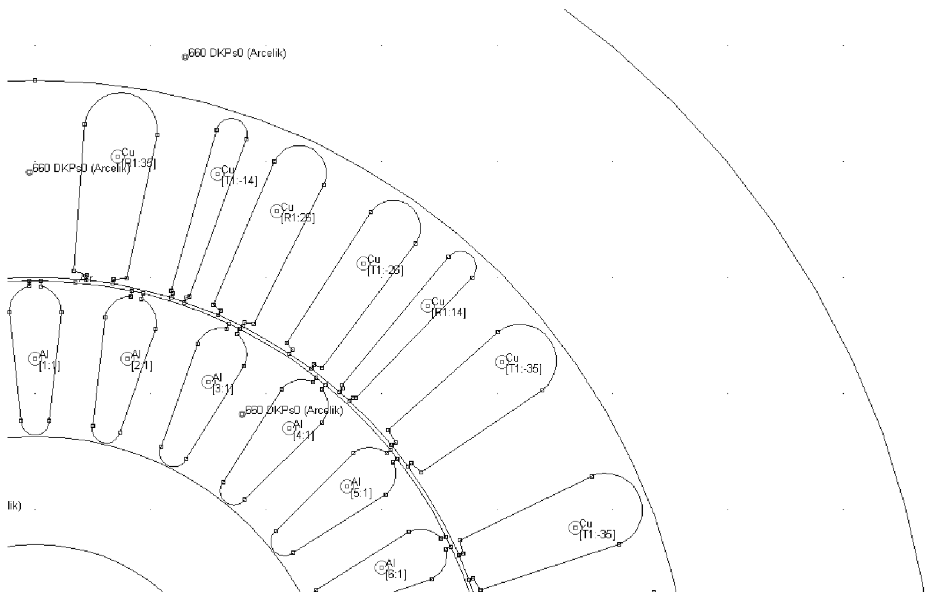

Figure (7): *Zoomed slot shapes including conductor, circuit and material information*

Since the novel winding has a lower fundamental winding factor than the standard winding, to induce the same voltage with the same number of turns in the winding the air gap flux was chosen within the design limits but slightly greater than that of the standard motor. The coil pitches are smaller than those of the standard motor and less copper is used and the formulas related to copper length are adapted accordingly for the coils pitches, the length of turns, conductor length and copper weight [2], [4], [16].

Additionally the iron core along the air gap is smoother than that of the standard motor resulting in a decrease in both the Carter factor of the stator and the ampere-turn requirement of the air-gap. The flux densities of the rotor are increased due to the higher air gap flux density, although there is no change to the rotor [2], [4], [16].

The stator slot leakage reactance was calculated individually for each type of slot and the formula was adapted for the non-uniform slot shapes. The end-coil reactance is decreased due to the decrease in the conductor length, but the slot leakage reactance is increased due to the deeper slots. Overall the stator slot reactance is increased [2], [4], [16].

Since the stator core does not have uniform slot and tooth widths, conventional methods cannot be used in the calculation of the iron volume and consequently the weight. The total tooth volume must be calculated individually for each and then added [2], [4], [16].

8.Particular Results and Comparison:

Only a brief comparison is made here since a detailed comparison is available elsewhere [3-5]. The most beneficial results of the redesign are less copper, a decrease in the copper-loss of 3.72 % and an increase in the efficiency of 0.5%. There is however an increased iron loss of 7.46 % and an increased iron weight of 9.61 % due to the increase in the outer diameter and air gap flux density. The overall weight of motor is increased by 6.67 %. The end-winding leakage reactance is decreased by 21.33% but the total leakage reactance is increased 16.42 %, because of the increase in the slot leakage reactance of 84.3 %. The change in magnetic circuit results in an increase in no-load current by 3.8 % [2-4].

The starting current is increased and the starting torque of the fundamental is decreased, but the overall starting torque including the contributions from the space harmonic is almost the same as that of the standard motor [2], [5], [15].

Both motors are analyzed by a magnetic analysis programme and the results are very promising [2], [4]. The slot and tooth optimization in the novel design to keep the tooth and flux densities within desired limits is useful as can be seen in the magnetic analysis results for both machines in Figure 8. Since deeper slots have to be designed and the teeth have to be wider, the tooth flux density will not be excessive. The effects of the changes can easily be seen in the figure.

9. Conclusions:

In previous studies, it was shown that the disturbing effects of space harmonics can be eliminated by calculating new slot positions and different numbers of slot conductors, for which the required numbers are achieved by optimization software. The corresponding numerical information is analyzed in a design programme, the reliability of which was tested by comparison of its output with data obtained from the manufacturer. The redesign for the optimized numerical information is different from that of a conventional stator, in requiring different slot shapes containing different numbers of conductors. To obtain a constant flux density in the teeth and a constant yoke thickness all slot sizes were optimized by using an optimization file. The basic details of the slot structures were observed for both the conventional and the redesigned stators. The slot optimization method was explained briefly with the cross sections of both stators being drawn. The new calculation methods and concepts were explained, and a brief illustration of the changes to various machine parameters was provided. To support the straightness of the slot optimization and new design, the results of magnetic analysis were given diagrammatically. The new design has satisfactory results after all comparisons and analyses have been made.

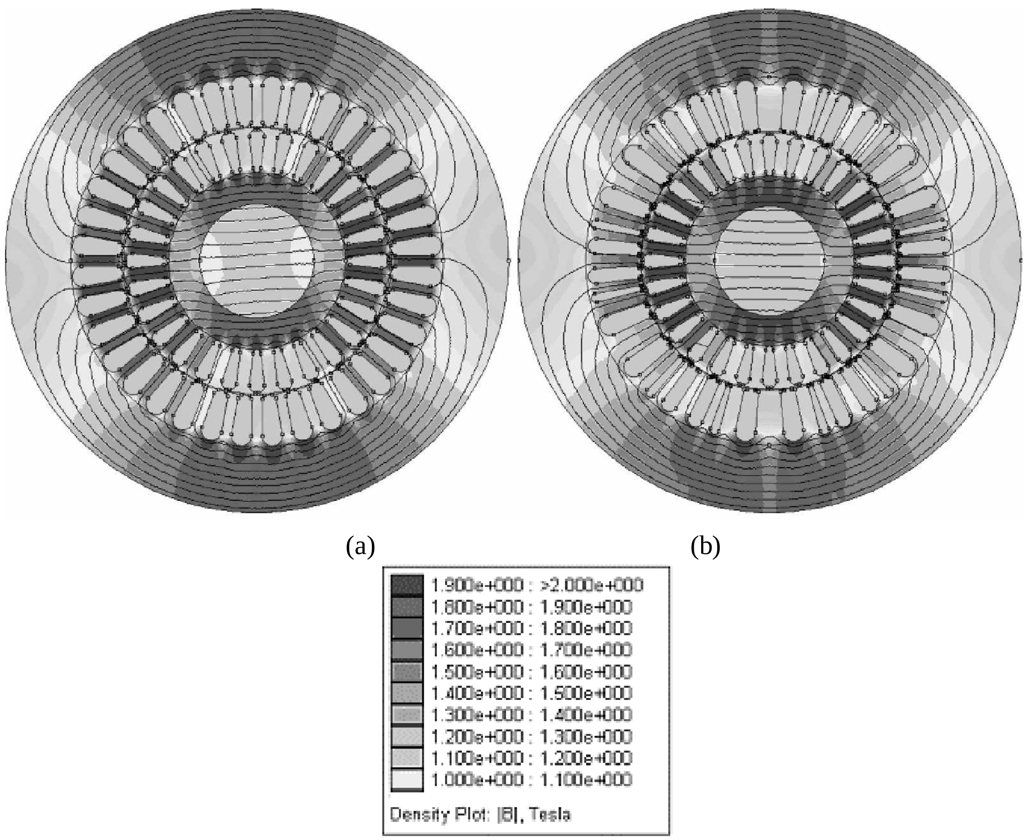

FIGURE (8): *Magnetic analysis results: (a) standard motor (b) motor with novel design*

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