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Influencies of the Slits on Magnetic Flux Density for Induction Motors Having Different Rotor Slot Geometries

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***Abstract*— There are many methods in literature for canalizing of circulating useful flux from stator core to rotor core without radial movements in induction machines. It is obvious to healing of useful flux with decreasing radial moved zig-zag flux and it increases the motor performance. Magnetic barrier, cutout and using of slits are the most used methods for improve the circulating useful flux in the motor. As seen from literature, these methods are used to improve the performances of different motor types. These motor types are, switched reluctance motors, solid rotor motors, hybrid synchronous motors and induction motors etc.**

In this study, slits are applied on the centers of the stator core and rotor core teeth for three phase induction machine. Slit lengths are chosen same with the stator slot lengths. Slit widths are chosen to 0.1 mm for stator and rotor cores. Applied slits are act as air gap barriers and generate a magnetic conditioning for help to decrease the radial zig-zag flux that circulates in the machine. There are 10 different rotor slot geometries are used to simulate the behavior of the magnetic field distribution for different slitted slot geometries. Comparing of the flux densities for conventional and slitted motor structures and airgap magnetic field distributions of different motor geometries are given. From this database, determining of suitable stator and rotor structure for the machine is achieved. Analyzes are conducted with the finite element method based free software FEMM.

Keywords—induction motor; magnetic field analysis; rotor slot geometry; slits

I. INTRODUCTION

Similar with the armature reaction in direct current machines, induction machines are sustained with the rotor magnetic field effect and this influences to magnetic penetration on load conditions. When rotor magnetic field deviates, it causes saturation on stator and rotor teeth and increasing of the leakage flux and harmonic flux [1]. Beside of these primary effects, total loss of the motor increases and efficiency of the motor is decreases. Generally, these losses are called stray losses [2].

Aho et al. compared the two induction motor rotor structures manufactured solid steel. One of the rotor cores is manufactured without slits and covered the electrical conductive material. Another one is manufactured only with slits. Electrical conductive material caused to decrease the rotor losses. Additionally, they showed that electrically conductived motor's air gap magnetic field distribution is better than slitted motor [3].

Karnper and Volshenk researched that the performance of the switched reluctance motor. They produce a rotor prototype which consists of magnetic barriers and seperators. When depth of the magnetic barriers have increased, total shaft torque of the motor has decreased and power factor of the motor has changed a little. They showed that, if width of the two adjacent magnetic barriers decrease from 2 mm to 0.25 mm, shaft torque of the motor increases about %4 and power factor of the motor increases about %4.5. They expressed that decreasing of the rotor separator depth from 14 mm to 5 mm cause the using of %77 more rotor iron material. If choosing the suitable magnetic barrier and separator depth, they expressed that shaft torque of the motor increases about %17.4 [4].

Aho et al. studied the influences of slit depth on an induction motor that fabricated solid steel core. Slitted structure of solid steel core gives better magnetic field distribution but, mechanic strength of the motor decreases. On the other hand, they expressed that, analytical solution of the slitted core magnetic field quite difficult. Their models showed that, increasing slit depth of the motor causes the shaft torque increasing. Simultaneously, power factor of the motor has a significant increase. For increasing the mechanic strength of the motor, it should be used one short one tall slits in structure of the motor core [5].

Zaim studied the influences of slit depth, slit width and slit number on an induction motor that fabricated solid steel core using finite element method. He showed that increasing of the slit depth of the motor supports the shaft torque until for a value. After that value, shaft torque decreases. Width of the slits, influences the shaft torque negatively. Number of the slits affect the shaft torque for two reasons. First reason, narrow slits of the motor supports the shaft torque swiftly until for a value, after that value, shaft torque decreases. Second reason, large slits of the

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motor supports the shaft torque until for a value. After that value, shaft torque decreases swiftly. Choosing suitable number and depth of the slits support the flux lines keep going in to the motor core [6].

Li et al. suggested three different methods for preventing the armature reaction of the hybrid propulsion synchronous motor. One of these methods, locating balancing magnets to pole faces. Thus, shaft torque of the motor increases about %7 and besides airgap flux density of the motor increases about 0.14 T. Second method is adjusting the length of airgap. Reason of this method is increasing of the saturated pole face's airgap which is caused from armature reaction. After this adjustment, distribution of airgap flux gets better trajectory. Besides, shaft torque of the motor increase about %6 and torque ripple of the motor decreases. Third method is locating the slits on solid steel motor core. Reason of this method is reducing the eddy currents and armature reaction effect [7].

Chan and Hamid researched the switched reluctance motor model using finite element method. They have used free FEM software package called FEMM. They have located different number of slits on rotor core and they have investigated its effects on shaft torque and flux density distribution. Five slitted rotor model has given positive effect on performance of the motor. Current and torque graphics showed better waveforms. Output power of the motor has increased about %16 (for fixed phase current peak value). Furthermore, they expressed that adjusting number of the slits helps to control the rotor core saturation [8].

Aho, Nerg and Pyrhonen studied the shaft torque of the motor having slitted rotor core produced solid steel. Increasing the slit number from 28 to 36, electromagnetic torque value upgrades about %6. Besides power factor of the motor changes positively a little. Furthermore, they expressed that, slitted structure causes saturation on rotor core and it affects the motor performance negatively. Slit number also affects the eddy losses [9].

Zaim studied the performance analysis of an induction motor that produced solid steel core using finite element method. Therefore, he used different induction motor models that have different slit number, slit length and slit width. His results showed that increasing of the width of slits for low numbers, support the shaft torque, although decreases the shaft torque for using of high numbers [10].

Nashiki et al. studied on switched reluctance motor for improving its torque ripple value. They located slits on rotor core for create a useful flux on 'd axis'. They investigated the torque ripple for slitted core motor's skewed positions and unskewed positions. Low numbers of slits support the motor efficiency but it causes ripples on torque behavior [11].

Yetgin and Turan, in their study, the motor models reformed with the proposed shape design were analyzed with FEMM software program that uses finite elements method. It was found at the end of the analyses that when the optimum slit width value was 0.10 mm, motor efficiency gave better results compared with other slit width values. The increase in slit width caused saturations in motor teeth and thus caused to worsen the motor efficiency. It was decided at the end of different modeling that the depth of the slits used in the proposed slitted motor models should be almost the same height as stator and rotor height. Optimum slit value was determined as 15.00 mm. At the end of the modeling, 1.869% improvement was obtained in the motor models that had 15.00 mm slit depth and 0.10 mm slit width compared with the efficiency values of reference model at nominal operation point [12].

Yetgin et al., by opening slit in the stator and rotor tooth of the induction motor and reduced the zigzag fluxes, which arise in the air gap of the motor, by 6.123%, ensuring a 2.041% improvement in the coupling flux. With the point measurements in terms of their flux densities, it was illustrated that less strain is present compared to the reference motor [13].

In this study, it is investigated that a new tooth geometry for induction motors. This tooth geometry provides better motor performance for without using high quality core material. Furthermore, it helps to avoid from leakage flux effect, losses, low efficiency problem which causes from magnetic flux decreasing. Besides, increasing about low number of motor efficiency values will improve the global energy saving on industry. In this context, this study is important for gaining economics of energy. For realizing the method, ten different induction motor models have been studied. Slits have been located both stator and rotor cores of each model. Slitted and unslitted models have been simulated with a free finite element software package called FEMM. Simulation results have been discussed and performance benefits of the study has been evaluated respectively.

II. Used Rotor Slot Types

Names of the slot types in this study are, drop, drop + round, rectangle, smooth drop, smooth L, L, contrary trapezoidal, trapezoidal, round + square and round shown in Fig. 1 respectively. Stator slot geometry is fixed for all models called number 11 slot type.

Rotor slot area is defined 68.8 mm^2 and rotor slot height is defined 15 mm for all models. For depending rotor slot shapes, top and bottom width values of the slots, teeth widths, slot opening widths, separator heights etc. will be changed. Furthermore, rotor and airgap flux density values will be changed respectively. This situation affects the motor performance and motor dimensions significantly. For this reason, slot type is one of the important physical parameters for designing electric motors.

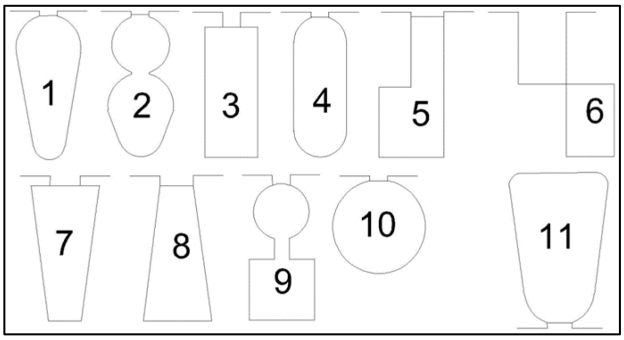

Fig. 1. *Used stator and rotor slot types*

A. *Motor Models*

Motor models are designed with FEMM program. On the program, problem type is planar, dimensional size mm, solver precision 1e^{-008}, minimum triangle angle 30^{0} are defined. Rotor slot winding material is defined aluminum and stator winding materal is defined copper. Core material is defined as magnetic steel. Boundary condition is defined as Dirichlet. Unslitted slot models are shown in Fig. 2 and slitted slot models are shown in Fig. 3 respectively.

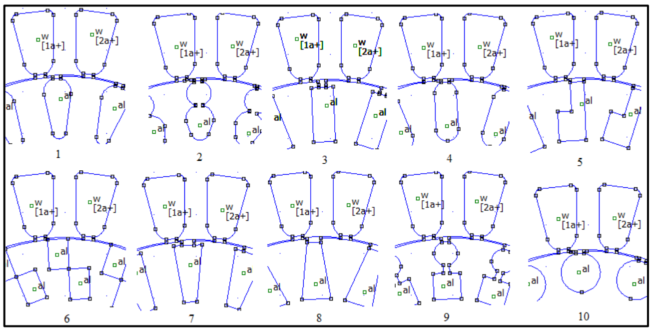

Fig. 2. *Unslitted stator and rotor models*

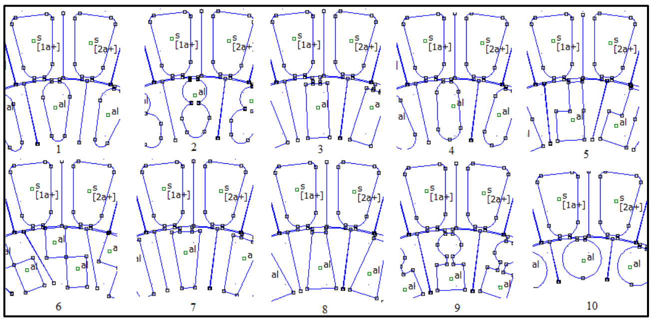

Fig. 3. *Slitted stator and rotor models*

In Fig. 4, it is shown that magnetic field distribution for round + square slot type. In Fig. 5, it is shown that magnetic field distribution for drop rotor slot type.

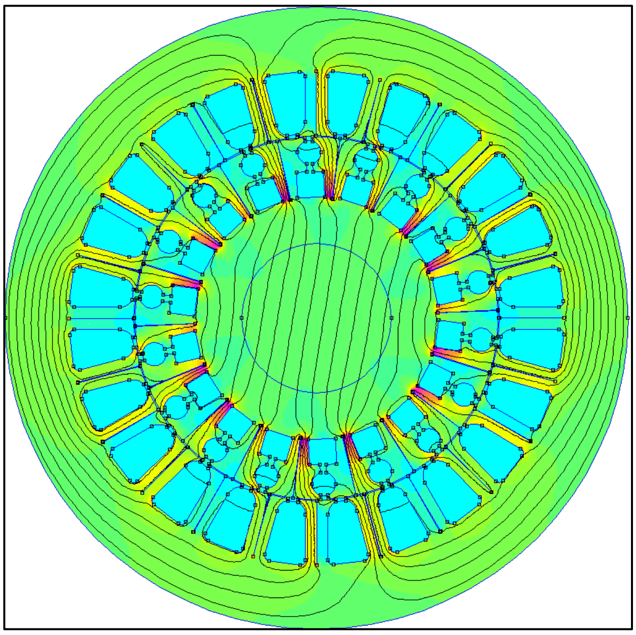

Fig. 4. *Magnetic field distribution for round + square slot type*

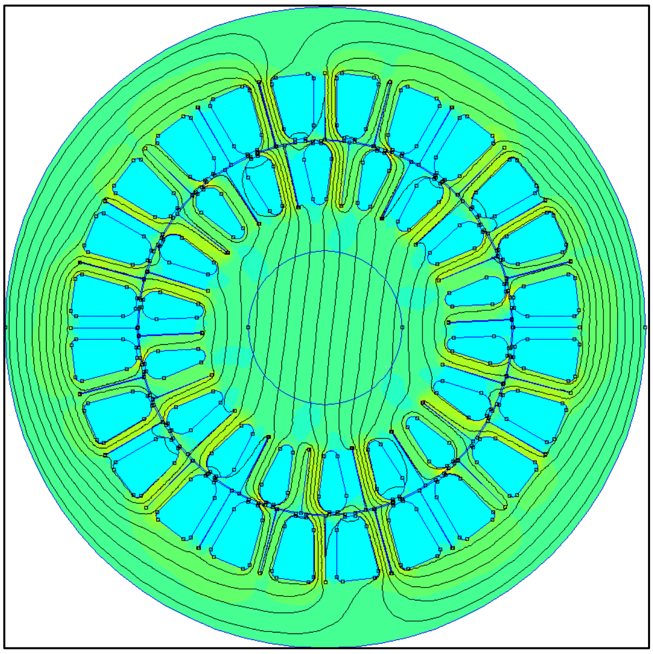

Fig. 5. *Magnetic field distribution for drop rotor slot type*

In Table I, average airgap flux density values are given for slitted and unslitted motor models. There is a little average flux decreasing on the cores for all models.

TABLE I. AVERAGE MAGNETIC FLUX DENSITY VALUES FOR AIR-GAP

Rotor Number	Rotor Models	Average Air-Gap Magnetic Flux Density [T]	
		Unslitted	**Slitted**
1	Drop	0.54412	0.5315
2	Drop + Round	0.55650	0.5312
3	Rectangle	0.54673	0.5324
4	Smooth Drop	0.55621	0.5310
5	Smooth L	0.49716	0.4854

6	L	0.44002	0.4362
7	Reverse Trapezoidal	0.50453	0.5259
8	Trapezoidal	0.49533	0.4837
9	Round+Square	0.56338	0.5333
10	Round	0.55711	0.5311

For all motor models, magnetic flux density values are given for the Cartesian coordinates x = -12 mm and y = 40.8 mm in Table II. As seen from the table, magnetic flux density values are decreasing for the motors having slot types of drop, rectangular and smooth drop. Furthermore, three of the motor models have a parallel slot geometry. A little increasing on flux density for other slot geometries. Primary fact of flux density fluctuations is decreasing of the slit widths. Furthermore, there are saturations on these regions. Because of the increasing the widths of slot openings, there are saturations on the regions between airgap and rotor slots. Furthermore, there are saturations between ends of the slits and tail end points of the slot geometries numbered 5, 6, 8 and 9.

TABLE II. MAGNETIC FLUX DENSITY VALUES FOR CARTESIAN COORDINATES X:-12 MM AND Y: 40.8 MM IN MOTOR CORE REGION

Rotor Number	Rotor Models	Magnetic Flux Density [T]	
		Unslitted	Slitted
1	Drop	**1.84950**	**1.41420**
2	Drop + Round	1.32797	1.32794
3	Rectangle	**1.35676**	**1.33755**
4	Smooth Drop	**1.27117**	**1.24496**
5	Smooth L	0.98762	1.02055
6	L	1.04082	1.05974
7	Reverse Trapezoidal	1.69912	1.92190
8	Trapezoidal	1.01424	1.03712
9	Round + Square	1.32797	1.32794
10	Round	1.84950	1.87968

III. RESULTS

In this study, there are 10 different induction motor models having different slot geometries has been modelled. Slitted and unslitted models have been simulated with the FEMM free software package. Average flux density values obtained from the slitted motor models, a little increasing has been observed. Decreasing of saturations on parallel slot geometries has been observed. Therefore, a little decreasing on core losses. It has been seen that increasing of saturation on narrow points on motor core geometry.

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