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Comparison of Magnetic Flux Density for Six-Phase and Three-Phase Induction Motor using COMSOL Multiphysics

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Abstract

The basic design of induction motors has not changed in the last years, with latest and good insulation materials, pre-simulation for design, computer optimization techniques in design and using automated manufacturing devices have resulted in motors of less cost per kW, heating reduction and smaller physical size. Due to standards by International of physical dimensions and frame sizes the motors from most manufacturers are physically interchangeable and they have similar performance characteristics, dimensions and electrical distribution of multiphase coils are affecting on magnetic field density, because of difficulty in measuring magnetic flux in each point of the machine computer simulations help in machine design to demonstrate and adjustments in magnetic flux distribution. Three-phase and six-phase induction motor electromagnetic models are developed in two-dimensions in the finite element method based software-tool Computer Solutions (COMSOL) Multiphysics. Frequency domain simulation result obtained magnetic field density comparison between three phase and six phase induction motors.

Introduction

Induction motor consists of a stationary part and a rotating part called stator and rotor. Conventional induction motor stator has one set of three phase windings while the stator of six-phase induction motor contains two sets of separate three phase windings which displaced by specific angle with each other. Mathematical models as well as the concept of three-phase and six-phase induction machines are developed [1]. The criterion for selecting the starting points of each phases and a generalized formula is suggested for the selection of number of slots required for n-phase alternating current machine design [2]. Better winding coefficient and increased power output and torque could be acquired by designing dual Stator Winding Induction Machine (DSWIM) with two separate sets of three phase stator windings [3]. Six-phase induction motor use in industrial drives presents several advantages over the conventional three-phase motor such as magnetic flux harmonic reduction, improved reliability, minimization of torque pulsations and reduction on the power ratings for the static converter [4]. Also as the three-phase motors, six-phase dual stator winding induction motor could be fed from an independent variable-voltage variable-frequency (VVVF) and zero-speed operation has been achieved by independently controlling the two sets of stator currents [5]. Simulation of induction motor leads to precise design and this can be achieved with the help of programming and simulation. simulation software helps in design with different parameter modifications, moreover supports in analyzing the effects of different parameter variations easily and to design of induction motor effectively [6]. The two-dimensional model in the COMSOL Multiphysics software is a good tool for study of induction motor behavior under various conditions, speed, torque and current values are depending on the accuracy of identification and calculation of induction motor parameters, geometry and material properties [7]. Flux density in the air-gap and torque performance of the double three-phase motor have been investigated by using FE software, theoretical/conventional analysis calculation and practical measurement [8]. The air-gap field density of the six-phase induction motor have been studied using trapezoidal wave phase current [9]. In this paper stator of two different induction motors designed and their flux distributions are simulated by using COMSOL Multiphysics to demonstrate modification in maximum flux density.

Design of Induction Motor Stator

There are essential equations in designing the stator of induction motor [6], [10] and [11].

For full pitch, $pitch\ factor\ (K_p) = 1$

Motor output power (P_{out}) is obtained by:

$$P_{out} = HP\ x\ 746 \tag{1}$$

Where HP is motor horse power.

The motor input apparent power (KVA_i) can be calculated as:

$$KVA_i = \frac{P_{out}}{\eta\ x\ pf} \tag{2}$$

The output coefficient (C_o) is determined by:

$$C_o = 1.11\ \pi^2\ B_{av}\ ac\ K_w\ 10^{-3} \tag{3}$$

Where B_{av} is average flux density and ac is ampere conductor per meter.

Synchronous speed of the motor in revolution per second (N_{ss}) can be obtained by:

$$(N_{ss}) = \frac{f}{P/2} \tag{4}$$

Where f is the supply frequency.

Diameter and length of the stator could be found is as below:

$$DSi^2L = \frac{input\ KVA}{C_o\ x\ N_{ss}} \tag{5}$$

$$DSi^3 = \frac{DSi^2L\ x\ P}{\pi\ x\ L/\tau} \tag{6}$$

$$DSi = \sqrt[3]{DSi^3} \tag{7}$$

$$L = \frac{DSi^2L}{DSi^2} \tag{8}$$

Where DSi is stator inner diameter, L is stator length and τ is pole pitch.

Magnetic flux ($\emptyset$) is obtained by:

$$\emptyset = \frac{B_{av}\ x\ \pi\ x\ DSi\ x\ L}{P} \tag{9}$$

Number of turns per phase (T_{ph}) is determined by:

$$T_{ph} = \frac{V_{ph}}{4.44\ x\ K_w\ x\ f\ x\ \emptyset} \tag{10}$$

Where V_{ph} is per phase voltage.

Number of total conductors (Z_t) is found as:

$$Z_t = 2 \ x \ n \ x \ T_{ph} \tag{11}$$

And number of conductors per stator slot (ZSs) is as below:

$$ZSs = \frac{Z_t}{Ss} \tag{12}$$

Rated per phase current (I_{ph}) is determined by:

$$I_{ph} = \frac{KVA_i}{n \ x \ V_{ph}} \tag{13}$$

And current density (J) is calculated as:

$$J = \frac{I_{ph}}{Acu} \tag{14}$$

Area of conductors per stator slot (ASc) is equal to:

$$ASc = ZSs \ x \ Acu \tag{15}$$

Where Acu is area of one conductor.

And area of the stator slot (ASs) is found by:

$$ASs = \frac{Asc}{1 - spf} \tag{16}$$

Where spf is space factor.

Diameter of one stator slot (DSs) is determined by:

$$DSs = 2 \ x \sqrt{\frac{Ass}{\pi}} \tag{17}$$

The outer diameter of the stator (DSo) is found as:

$$DSo = DSi + 2 \ x \ (2 \ x \ DSs) \tag{18}$$

Air gap length ($Lg1$) is determined by:

$$Lg1 = 0.2 + 2 \ x \sqrt{DSi \ x \ L} \tag{19}$$

And outer diameter of the rotor (DRo) is calculated by:

$$DRo = DSi - 2 \ x \ Lg1 \tag{20}$$

A. Three Phase Induction Motor

For three-phase induction motor the equations will be as below.

Number of slot per pole per phase (S_{spp}) is calculated as:

$$S_{spp} = \frac{Ss}{3 \ x \ P} \tag{21}$$

Where P is number of poles and Ss is number of stator slots.

The slot electrical angle (α_e) is determined as:

$$\alpha_e = \frac{180 \ x \ P}{Ss} \tag{22}$$

And the distribution factor (K_d) is equal to:

$$K_d = \frac{sin(S_{spp}\ x\ \frac{\alpha_e}{2})}{S_{spp}\ x\ sin\frac{\alpha_e}{2}} \quad (23)$$

The winding factor (K_w) found as:

$$K_w = K_p\ x\ K_d \quad (24)$$

Number of total conductors (Z_t) is found as:

$$Z_t = 2\ x\ 3\ x\ T_{ph} \quad (25)$$

Rated per phase current (I_{ph}) is calculated by:

$$I_{ph} = \frac{KVA_i}{3\ x\ V_{ph}} \quad (26)$$

B. Six Phase Induction Motor

There are some differences between the stator of six-phase induction motor and three-phase induction motor. Equations for six-phase induction motor will be as below.

Number of slot per pole per phase (S_{spp}) is calculated as:

$$S_{spp} = \frac{Ss}{6\ x\ P} \quad (27)$$

While for six phase, 4 pole, 24 slot stator, number of slot per pole per phase is equal to one, so the distribution factor will be equal to one.

$K_d = 1$

$K_w = 1$

Number of total conductors (Z_t) is found as:

$$Z_t = 2\ x\ 6\ x\ T_{ph} \quad (28)$$

Rated per phase current (I_{ph}) is calculated by:

$$I_{ph} = \frac{KVA_i}{6\ x\ V_{ph}} \quad (29)$$

Fig. 1 shows the main dimensions of both motors.

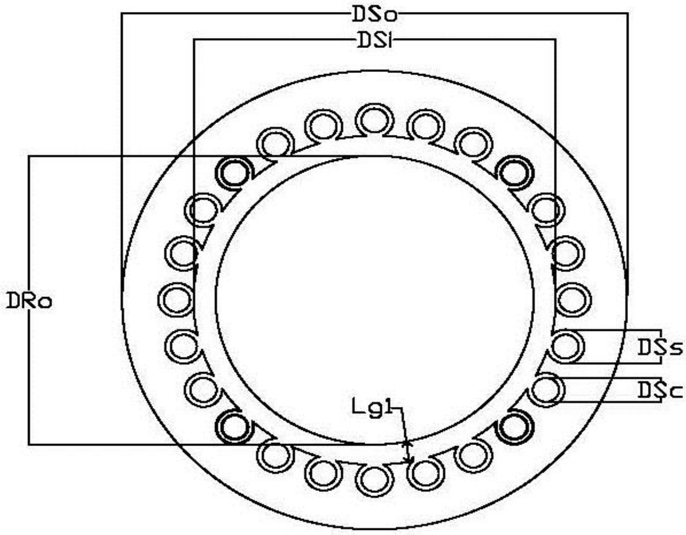


Figure-1: dimensions representation of the induction motor.

Results of stator design

The induction motor to be designed has the following specifications: 2 horse power (HP), 4 pole (P), supply frequency of 50 Hertz (f), supply voltage 400 Volt (V_L), efficiency of 80% (η), full pitch, 0.825 full load power factor (pf), unity ratio of pole length to pole pitch (L/τ), 0.25 space factor (spf), 24 stator slots (Ss), average flux density (B_{av}) of 0.44 Wb/m^2, electrical loading (ac) of 18000 ac/m.

For three phase winding, 20 Standard Wire Gauge (SWG) enameled copper coil is used.
Diameter of the conductor (D_c) = 0.914mm.
Area of the conductor (A_{cu}) = 0.656118 mm^2.
The results of design the stator of three phase induction motor are illustrated in Table (1).

Table-1: design data for 2 HP stator of three phase induction motor

Parameter	Value	Unit
DSo	157	Millimeters
DSi	112.6879193	Millimeters
DSs	10.83174626	Millimeters
DSc	8.123809697	Millimeters
Tph	316	Turns
ZSs	79	Conductor
Iph	3.262903794	Ampere
J	4.9730405	A/mm^2
Lg1	0.3	Millimeters
DRo	112.0879193	Millimeters

For the six phase winding, 22 SWG enameled copper coil is used.
Diameter of the conductor (D_c) = 0.711 mm.
Area of the conductor (A_{cu}) = 0.397035265 mm^2.
The results of design the stator of six phase induction motor are illustrated in Table (2).

Table-2: design data for 2 HP stator of six phase induction motor

Parameter	Value	Unit
DSo	159	Millimeters
DSi	111.3931845	Millimeters
DSs	11.80250482	Millimeters
DSc	8.851878614	Millimeters
Tph	310	Turns
ZSs	155	Conductor
Iph	1.631451897	Ampere
J	4.109085618	A/mm^2
Lg1	0.3	Millimeters
DRo	110.7931845	Millimeters

Per-phase current in six-phase stator is half of the three phase, with reduced current lower cross-section area of wire can be used, so the standard wire gauge has been changed from 20 to 22, and current density in the six-phase windings are about 82% of the three-phase windings, the ratio of current density is as below.

$$Current\ Density\ ratio = \frac{J_{six-phase}}{J_{three-phase}} = 0.826272 \qquad (30)$$

Number of turns and conductors should be calculated as an integer number, after rounding number of turns for each phase of the three-phase motor is 316 turns, while for each phase of the six-phase is 310 turns, this slight difference is mainly because of the winding factor. As shown the previous tables there is a huge variance between number of conductors per slot which is 79 conductors per slot for three-phase stator and 155 conductors per slot for six-phase stator. But as the cross-section area of 22 SWG wire is smaller than 20 SWG the ratio of number of conductors per slot is as below.

$$Conductor\ per\ slot\ ratio = \frac{ZSs_{six-phase}}{ZSs_{three-phase}} = 1.962025 \tag{31}$$

Simulation of Magnetic flux density

COMSOL Multiphysics is a powerful interactive environment for modeling and solving all kinds of scientific and engineering problems. The software provides a powerful integrated desktop environment with a Model Builder where you get full overview of the model and access to all functionality. With COMSOL Multiphysics conventional models can be easily extended for one type of physics into Multiphysics models that solve coupled physics phenomena and do so simultaneously. Accessing this power does not require an in-depth knowledge of mathematics or numerical analysis. Using the built-in physics interfaces and the advanced support for material properties, it is possible to build models by defining the relevant physical quantities such as material properties, loads, constraints, sources, and fluxes rather than by defining the underlying equations. These variables, expressions, or numbers can be applied directly to solid and fluid domains, boundaries, edges, and points independently of the computational mesh. COMSOL Multiphysics then internally compiles a set of equations representing the entire model. COMSOL Multiphysics creates sequences to record all steps that create the geometry, mesh, studies and solver settings, and visualization and results presentation [12].

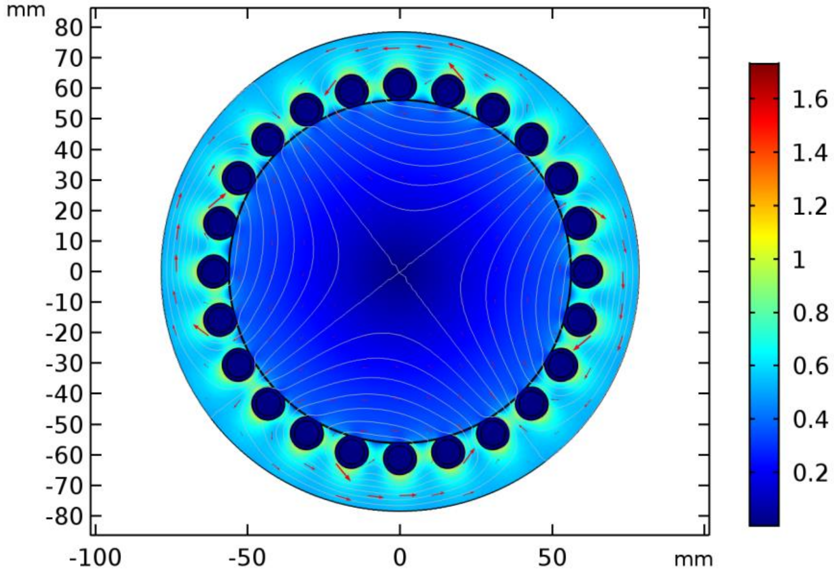
Finite element analysis is conducted in the three-phase and six-phase machines by using COMSOL Multiphysics to demonstrate the variation of the fundamental flux component without consideration of slot shape, slot wedges and rotor bars. With the same average flux density, the maximum apparent flux density ratio from the six-phase stator to the three-phase stator is shown in equation (32). the maximum real flux density ratio from the six-phase stator to the three-phase stator is shown in equation (33). It means that the magnetic flux in the six-phase motor distributed better than the three-phase motor, its why the maximum apparent flux density is less in the six-phase motor by approximately 0.5% and real flux density is less by 0.8%. The real flux density is due to actual flux through a tooth. The apparent flux density is due to total flux that has to be passed through the tooth. Since some of the flux passes through slot, the real flux density is always less than the apparent flux density. Fig. 2 shows the apparent flux distribution for both three-phase and six-phase machines. Fig.3 shows the real flux density for both machines. colors from dark blue to read indicate the magnetic flux density for each point and arrows indicate the direction of magnetic flux. Flux density measurements are in Tesla.

In COMSOL Multiphysics expression for apparent magnetic flux density is
mf.normB
and for real magnetic flux density is
sqrt(real(mf.Bx)^2+real(mf.By)^2)

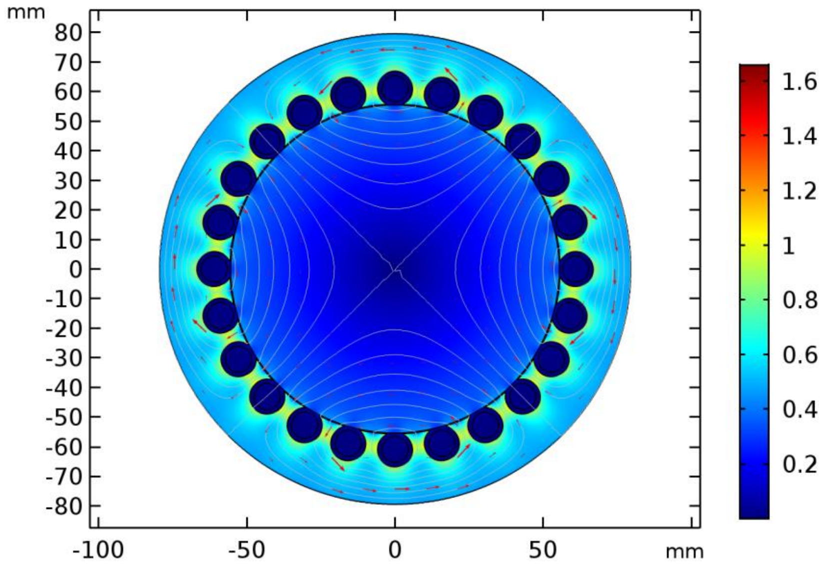
$$B_{max}\ apparent\ ratio = \frac{B_{max}\ apparent\ in\ six-phase}{B_{max}\ apparent\ in\ three-phase} = 0.958758 \tag{32}$$

$$B_{max}\ real\ ratio = \frac{B_{max}\ real\ in\ six-phase}{B_{max}\ real\ in\ three-phase} = 0.923981 \tag{33}$$

Where (B_{max}) is maximum flux density.

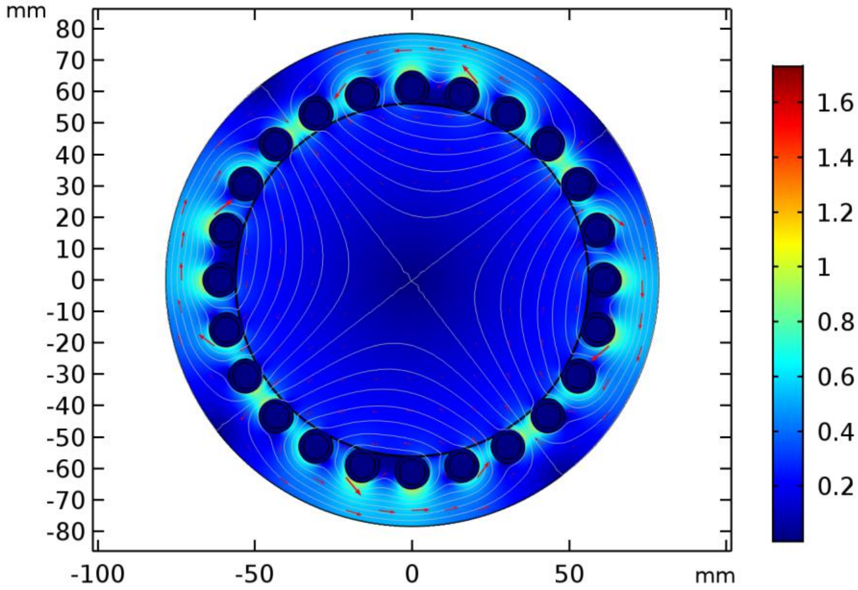


(a)

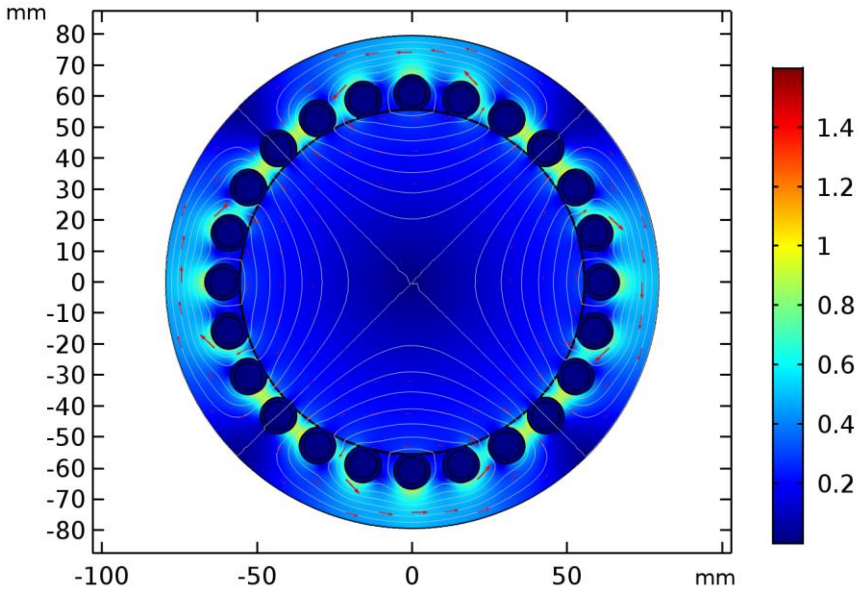


(b)

Figure-2: Distribution of apparent magnetic flux; (a) Three-phase, (b) Six-phase.



(a)



(b)

Figure-3: Distribution of real magnetic flux; (a) Three-phase, (b) Six-phase.

By using six phase windings on the same dimensions of the three phase motor maximum apparent flux density ratio will be 0.96, and maximum real flux density ratio will be 0.93, which shows that even with the same dimensions of the three-phase motor, six-phase windings are better in flux distribution.

Conclusion

The demand of induction motor design for research and flux density modification purposes was the motivation behind this study. The scope of the paper is computer simulation help for the design of induction motors in its basic form useful to design adjustment. The simulated six-phase stator provides good support for the multi-phase motor, while the magnetic flux distribution is better than three-phase motor. The design procedure and the flux distribution modifications provide better efficiency for the motor operation. The present work has concentrated on the magnetic flux density simulation of three-phase and six-phase induction motor which can be extended for designing energy efficient machines as a future scope.

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