PERFORMANCE ANALYSIS OF A FIVE-PHASE 10-SLOT/4-POLE PERMANENT MAGNET SYNCHRONOUS MOTOR FOR ELECTRIC VEHICLE

NUR SYAHIRAH BINTI ABDUL SANI

UNIVERSITI SAINS MALAYSIA
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by

NUR SYAHIRAH BINTI ABDUL SANI

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LIST OF ABBREVIATIONS

PM	Permanent magnet
PMSM	Permanent magnet synchronous motor
AC	Alternating current
DC	Direct current
EVs	Electric vehicles
HEVs	Hybrid electric vehicles
EMF	Electromagnetic force
EM	Electromagnetic
MMF	Magneto-motive force
UMP	Unbalanced magnetic pull
FFT	Fast Fourier Transform
POT	Magnetic vector potential
ST	Static analysis
RM	Rotating machines analysis
Bmod	Modulus of magnetic flux density
Hmod	Modulus of magnetic field intensity
BA	Bees Algorithm
NdFeB	Neodymium iron boron
PSO	Particle Swarm Optimization
BLDC	Brushless DC
BLAC	Brushless AC

LIST OF SYMBOLS

k_f	Slot fill factor
R_{sh}	Shaft radius
R_r	Rotor outer radius
R_m	Magnet outer radius
R_{so}	Stator outer radius
R_{si}	Stator bore radius
W_{te}	Tooth end width
l_m	Magnet thickness
l_g	Air gap thickness
μ_r	Magnet relative permeability
B_{sat}	Maximum air gap flux density
B_r	Magnet remanence
rpm	Revolution per minute
T	Tesla
N	Newton
W	Watt
V	Volt
A	Ampere
B_g	Average air gap flux density
B	Magnetic flux density
N_P	Number of pole
N_s	Number of slot
N_{ph}	Number of stator turn per phase

k_w	Winding factor
f_e , f	Frequency
$\emptyset_{sp}$	Total flux per stator tooth
E_f	No load rms back EMF
$\emptyset$	Flux Linkage
N	Number of turn
I	Current in the coil
L	Self-inductance
T_c	Cogging torque
dS	Element of the coil surface area vector
N_{scm}	Smallest common multiple for slot and pole number
N_c	Number of turn per coil
A_{slot}	Slot area
d_s	Slot depth
W_{tb}	Stator tooth body height
W_{tt}	Tooth tip height
W_{te}	Tooth end width
W_{ry}	Rotor yoke height
W_{sy}	Stator yoke height
θ_p	Pole pitch
θ_s	Slot pitch
f_{ct}	Cogging torque frequency
n_{syn}	Synchronous speed
$\emptyset_x$	Portion of flux from magnet will enter the tooth pole

ω	Angular speed
P_{out}	Output power consumed
τ	Electromagnetic torque
K_{dn}	Distributed factor
K_{pn}	Pitch factor

ANALISIS PRESTASI 10 LUBANG ALUR/4 KUTUB MAGNET MOTOR SEGERAK MAGNET KEKAL LIMA-FASA BAGI KENDERAAN ELEKTRIK

ABSTRAK

Di antara semua jenis motor elektrik, Motor Segerak Magnet Kekal (MSMK) adalah motor yang paling boleh dipercayai dan cekap dalam aplikasi perindustrian. Ia digunakan secara meluas dalam industri, aplikasi rumah, automotif dan pesawat, kerana penyelenggaraannya yang rendah, kecekapan tinggi, prestasi dinamik yang baik dan kepadatan tork yang tinggi. Projek ini menyiasat pengaruh pelbagai jenis konfigurasi penggulungan dan corak magnetisasi yang berbeza dalam prestasi lima-fasa MSMK. Tiga corak magnetisasi seperti pemagnetan radial, pemagnetan selari dan pemagnetan Halbach pelbagai segmen telah digunakan untuk 10 lubang alur/4 kutub magnet MSMK pada keadaan litar terbuka dan keadaan beban. Kaedah elemen terhingga 2D (FEM) digunakan secara intensif dalam penyiasatan ini untuk membuat model dan meramal ciri-ciri elektromagnetik dan prestasi MSMK. Keputusan analisis elemen terhingga (FEA) terperinci mengenai tork penugalan, voltan fasa teraruh, ketumpatan fluks udara, tork elektromagnet, tarikan magnet yang tidak seimbang dan tork keluaran dianalisis. Tahap voltan fasa teraruh selanjutnya dihitung ke dalam komponen harmoniknya untuk menyiasat prestasi dalam tork output. Selanjutnya, kaedah kecondongan bagi meminimumkan tork penugalan pada MSMK dicadangkan. Hasilnya, MSMK dengan permagnetan selari yang mempunyai pengulungan secara dua lapisan memberikan prestasi motor yang terbaik dari segi voltan fasa teraruh yang tinggi, jumlah gangguan harmonik yang rendah, tork keluaran yang rendah, UMP yang rendah dan tork elektromagnet yang tinggi. Disebabkan ini, MSMK berpotensi untuk

menyediakan penjimatan kos untuk kenderaan elektrik dengan mempunyai konfigurasi penggulungan padat dalam motor pelbagai fasa, yang mampu membolehkan motor berprestasi tinggi dengan jumlah magnet yang lebih kecil.

PERFORMANCE ANALYSIS OF A FIVE-PHASE 10-SLOT/4-POLE PERMANENT MAGNET SYNCHRONOUS MOTOR FOR ELECTRIC VEHICLE

ABSTRACT

Among all types of electrical motors, Permanent Magnet Synchronous Motor (PMSM) is the most reliable and efficient motors in industrial applications. It is widely used in industries, home application, automotive and aircraft, due to its low maintenance, high efficiency, good dynamic performance and high torque density. This project investigates the influence of the various type of winding configuration and different magnetization patterns in the performance of a five-phase PMSM. Three types of magnetization patterns such as radial magnetization, parallel magnetization, and multi-segmented Halbach magnetization are applied to the 10-slot/4-pole PMSM during open-circuit and on-load conditions. A 2D finite element method (FEM) is intensively used in this investigation to model and predict the electromagnetic characteristics and performance of the PMSM. The detailed finite-element analysis (FEA) results on the cogging torque, phase back-EMF, air gap flux density, electromagnetic torque, unbalanced magnetic pull and output torque, are analyzed. The phase back-EMF of the motor is computed further into its harmonic distortions. Further, the skewing method for minimization of cogging torque of PMSM is proposed. As a result, the PMSMs with double layer distributed winding with parallel magnetization gives the best motor performance in terms of high fundamental phase back-EMF, low total harmonic distortion, low peak cogging torque, low UMP and high average electromagnetic torque. Due to this, the PMSM has potential to provide the cost savings for the electric vehicle with a compact winding configuration in multi-

phase motors, which is capable of providing smaller magnet volume with a high-performance motor.

CHAPTER 1

INTRODUCTION

1.1 Background

For the past decade, transportation sector oil consumption has grown at a higher rate than other industrial sectors. This increase was largely derived from the new demand for personal use of vehicles powered by conventional internal combustion engines. With increased awareness of air pollution and rising petroleum prices, electrified vehicles have emerged as promising solutions to replace the conventional vehicles.

Electric Vehicles (EVs) are ideal vehicles for future applications in terms of their zero emissions. However, EVs face several challenges including expensive power electronics, electric propulsion motors, and energy storage systems, which are among the main barriers for their mass commercialization [1].

On the other hand, hybrid electric vehicles (HEVs) combine the advantages of both conventional and electric vehicles and have achieved significant success in the last decade. Electric machines are the vital parts of HEVs in terms of energy conversion. They can either operate as motors to convert electric power into mechanical power, or as generators to generate electricity from mechanical power [1].

Permanent magnet synchronous motors (PMSM) are most capable of competing with Induction Motors for the electric propulsion of HEVs. In fact, they are adopted by well-known automaker for their HEVs. PMSM are very good candidates for HEVs application due to their advantages in compactness which the overall weight and volume are significantly reduced for a given high power density. Furthermore, their high efficiency with an efficient heat lost to the surrounding compared with traditional induction motor, made PMSM more suitable for HEVs application [2].

However, electric vehicle applications require extremely high reliability that made the traditional three-phase PMSM will face with severe challenge. The torque of three phase PMSM drive system will decreases dramatically in case of major failures, such as open circuit of single phase or two phases and short circuit of one phase, which is unacceptable for electric vehicles especially for in-wheel motor driven vehicles [3].

Multiphase drives have additional degrees of freedom compared with traditional three-phase drives. These, degrees of freedom can be used for different purposes, such as additional torque generation or fault tolerance when a part of the system fails [4]. With increase in number of phases in motor, multiphase PMSM can obtain the highest possible reliability. In fact, if one or two phases of motor are out of service due to failure, motor can continue to operate and overcome the fault [5].

Comparing with traditional three-phase PMSM, the multiphase PMSM improves fault-tolerant capability and reliability of the electric vehicle drive system which are important in safety-critical applications. Reduced torque pulsation, improved noise characteristics, and lower copper losses are other advantages of multiphase electric machine drives [6]. The multiphase PMSM drive system offers another solution for the electric vehicle drive system.

The drive model can be described to compose of a five-phase star-connected PMSM and a five-leg voltage source inverter (VSI). The neutral point is not connected and all the phase currents are measured, with consideration that effects of saliency and saturation are negligible [7].

The structure point of PMSM is depending on the position of the magnets on the rotor. The PMSM can be constructed into three general categories, i.e., surface PMSM which have their permanent magnets mounted on the surface of the rotor; inset PMSM in which the permanent magnets are inset or partially inset into the rotor, and interior PMSM which has the permanent magnets buried inside the rotor [8].

In terms of winding point of view, concentrated windings are widely used than distributed winding because of the low manufacturing cost, lower MMF ratio and less copper loss in the motor windings. Although concentrated windings can improve performance due to shorter axial length, its lower resistance gives advantageous in application which is given a priority in lower ampere-turn and small output torque operation [9].

In PMSM, the magnetization pattern of magnet has great influence on the performance of the motor. However, magnetization pattern types of Radial magnetization, Parallel magnetization and Halbach magnetization influence in differences performance of motor.

A radial magnetization has affixed radial component over the angular width of the magnetized magnet area and zero tangential components everywhere. It also has zero magnetization in the air space between magnets. Compared to Halbach magnetizations that have an essentially sinusoidal air gap field distribution. Hence, their induced electromotive force (EMF) waveform is inherently sinusoidal and the cogging torque may be negligible, without resorting to skew or a distributed stator winding [10].

Widely, PMSM can be classified into two types; a sine wave and trapezoidal wave, that depending on the back EMF waveforms. The back EMF is the synthetic voltage of the individual windings due to the flux variation caused by the rotor rotation, and the higher the synthetic voltage is, the better performance the motor possesses [11].

The electric vehicle drive system application requires a minimum vibration and acoustic noise, and smooth operation of the motor. Furthermore, low torque pulsations in motor drives are essential for high-performance speed condition and position control applications where friendly human–machine interactions are desired [12].

Instead due to the inevitable manufacturing error in production, it generates distortions of magnetic energy and additional excitation forces. These manufacturing errors affect magnetic excitation forces. Cogging torque and unbalanced magnetic pull (UMP) are major magnetic excitation forces of PM motors, which generate vibration, noise, and stress of the machine bearings in the motor [13].

Therefore, in this project the performance of five-phase PMSM with various type of winding configuration and different magnetization patterns is investigated and validated by evaluating the cogging torque, phase back-EMF, unbalanced magnetic pull, total harmonic distortions of phase back-EMF and EM torque.

1.2 Problem Statement

Hybrid electric vehicles (HEVs) and electric vehicles (EVs) have been identified to be the most feasible solution to improve fuel economy and reduce emissions in the transportation sector [14]. The EV and HEV applications desire the motors to produce high output torque under steady-state condition. The motor should be capable of achieving high acceleration to attain high speed within short period of time [15].

Since the electric vehicles run at low speed like climbing or accelerating, permanent magnet synchronous motor (PMSM) must provide the higher torque.

When they run at high speed, PMSM must have stronger ability of flux weakening to expand speed [16]. Hence in long term operations, PMSMs are expected to have high energetic efficiency as one of the one most important goal to reach.

In order to improve the performance of PMSM, it is important to fully utilize the magnetic flux produced by permanent magnet. However, it is difficult to control the flux of the permanent, whose magnetic characteristic is influenced by magnetization, magnetic materials and geometric configuration [17].

On the other side, winding factors and consequently the harmonic contents of the electrical quantities involving such machines are determined by the type of windings employed in their construction. Particularly, the harmonic distortions of voltage, currents, flux densities, etc in electrical machines; such as torsional torque, axial and radial forces are producing vibrations; noise and increment in copper and iron losses; which depend on the type of winding-affect in a significant manner on both of the dynamic and steady state performance; and their efficiency [18].

Therefore, the performance of five-phase PMSM design with different winding topologies and magnetization patterns in open-circuit and on-load conditions with and without applied skewing method are compared and analyzed; to identify which design can be implemented for the best performance motor in high EM torque and induced phase back-EMF and provide less cogging torque and unbalanced magnetic pull.

1.3 Research Objectives

The main aim of this research is to design a five-phase 10-slot/4-pole permanent magnet synchronous motor (PMSM). The specific objectives of this project are as follows:-

- To design and calculate the motor dimensions for a five-phase 10-slot/4-pole surface mounted permanent magnet synchronous motor.
- To model and simulate a five-phase 10-slot/4-pole surface mounted permanent magnet synchronous motor using finite element method.
- To analyze and compare the effects of difference winding topology and magnetization patterns on the performance of a five-phase 10-slot/4-pole permanent magnet synchronous motor.

1.4 Scope of Project

The scope of the project is to develop and analyse the performance of five-phase, 10-slot/4-pole, surfaced-mounted permanent magnet synchronous motor (PMSM) using finite element method; that involved with three difference winding types such as distributed winding with double-layer configuration; and concentrated windings with single-layer and double-layer configurations, respectively. Three type magnetization patterns such as radial magnetization, parallel magnetization and multi-segmented Halbach magnetization are applied to the surface-mounted PMSM.

Since the total harmonic distortions and harmonic components of the phase back-EMF are calculated by using Fast Fourier Transform (FFT) in MATLAB. The detailed finite-element analysis (FEA) on the effect of difference winding topologies and magnetization patterns are carried out to evaluate and verify the performance of the designed motors. Additionally, the cogging torque has been analyzed to be reduced by rotor skewing method that applied in the finite-element analysis.

1.5 Outline of the Thesis

This thesis consists of five main chapters in details from introduction to conclusion of this research. Chapter 1 is about the introduction of project which includes and describes the background, problem statement, objectives and scope of project.

In Chapter 2, literature review of the past work by many researchers based on motor topologies, structure topologies, magnetization pattern, phase back-EMF, cogging torque, self-inductance and mutual-inductance, flux linkage, torque ripple, electromagnetic torque, unbalanced magnetic pull (UMP), multiple phases and skewing method are discussed.

Chapter 3 describes the methodology of the project. The methodology clearly explains the methods applied in this project and the steps in Finite Element tool that has been used to simulate and model the performance of motor. In addition, it also includes the project plan and flow chart. Moreover, the descriptions of motor, calculations of motor dimensions, winding layout and procedure to do this project are provided.

Results and Discussion are included in Chapter 4. The simulation results from the FEA software i.e. Opera-2D are given, discussed and analysed in great details. The graphical data and diagram of flux density, EMF, cogging torque, UMP and inductance are obtained. The simulation results between different type motor designs are compared and analyzed.

Finally, Chapter 5 describes the conclusions of this project. The conclusions according to the simulation are made and the motor model which has the best performance is selected. Additionally this chapter also includes the summary of the outcome and future work that can be done to further improve the performance of PMSM.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this paper, a five-phase 10-slot/4-pole permanent magnet synchronous motor (PMSM) is optimally designed to have high dynamic performances such as high efficiency; high steady-state torque; a very high torque; and low rotational inertia for a vehicle purpose. The researchers report various interesting work on PMSM performance. This chapter presents the previous related work with regard to the performances of five-phase PMSM.

The topologies of this PMSM are explained in section 2.2. The type motor and winding topologies are explained in section 2.3 and section 2.4. Hence, winding layout; and self-inductance and mutual-inductance are presented in section 2.5 and section 2.6. The effect of phase back EMF, flux linkage, cogging torque, and unbalanced magnetic pull (UMP) are presented in section 2.7, section 2.8, section 2.9 and section 2.10 respectively.

The few types of magnetization pattern are explained in section 2.11 and advantage of multiple phases is briefly explaining in section 2.12. Finally, the section 2.13 and 2.14 explaining about the type of element that uses in the permanent magnet and the function of skewing method.

2.2 Permanent-Magnet Synchronous motor

Wound-field and a permanent magnet are two types of synchronous motors which widely used in constant speed drives at line frequency as well as in variable speed drive with inverter fed variable frequency supplies. These motors also have lower weight, volume, and inertia compared to dc motors for the same ratings.

Wound-field synchronous motors are well-known in industrial drives requiring constant speed irrespective of load. Separately controllable dc excitation in the form of dc field current is a unique feature in the power factor control of such a motor from the lagging to leading mode [19].

The dc excitation current to the motor is usually fed from a static power semiconductor-based exciter system through brushes and slip rings. When the brushes and slip rings, are not acceptable because of environmental constraints and frequent maintenance requirements, they are replaced by a brushless excitation system having shaft-mounted rectifiers in the ac excitation system, and rotating with the rotor. The field excitation can be provided using permanent magnets.

This permanent magnet ac motor simply known as brushless PMSM [19]. PMSM is capable for the electric propulsion of HEVs. These motors have numbers of advantages such as the weight and volume are significantly reduced for given a high power density; have a higher efficiency, and heat is efficiently dissipated to the surroundings [2].

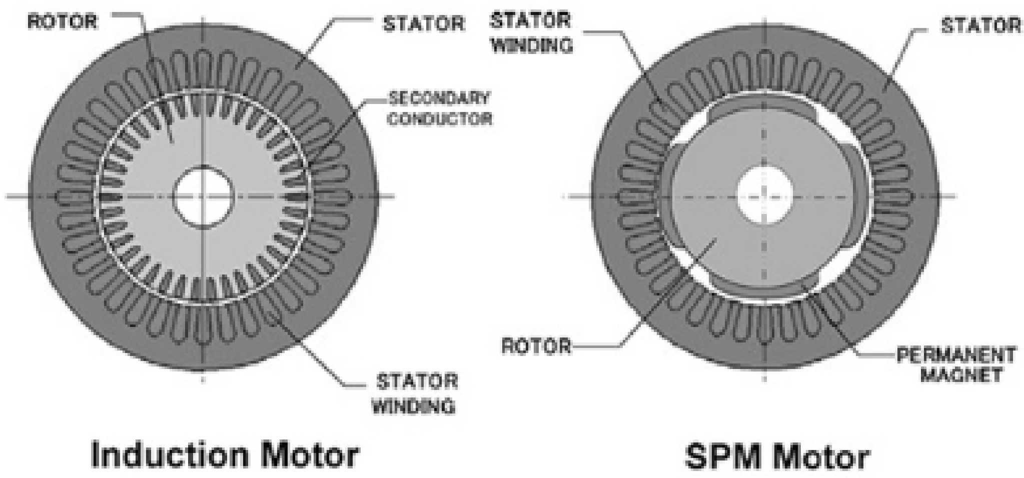

Figure 2.0: Induction motor vs Surface mounted permanent magnet synchronous motor

2.3 Type Motor Topologies

Depending on the location of the magnets on the rotor, typical brushless PMSM can be broadly classified into three kinds, i.e., interior PMSM which have the permanent magnets (PMs) buried inside the rotor; surface PMSM which have their PMs mounted on the surface of the rotor; and inset PMSM in which the PMs are inset or partially inset into the rotor [19].

For the surface-mounted PMSM topology, the PMs are simply mounted on the rotor surface by using epoxy adhesives. Since the permeability of PMs is near to air, the effective air gap is the sum of the actual air gap length and the radial thickness of the PMs. Hence, the corresponding armature-reaction field is small, and the stator winding inductance is low. In addition, since the d-axis and q-axis stator winding inductances are nearly the same, its reluctance torque is almost zero [20]. The surface mounting design tends to yield a small rotor diameter with low inertia, which is conducive to good dynamic performance [19].

For the surface-inset PMSM topology, the PMs are inset into the rotor surface [20]. Thus, it can lead to the q-axis inductance is larger than the d-axis inductance. The saliency will produce significant reluctance torque as well as the magnet torque [19]. Since surface-inset magnet develops reluctance torque; it improves mechanical robustness and also possesses better field weakening capability. Hence, surface-inset magnet provides a lower PM eddy current losses compared to those of surface-mounted magnet topology [21].

For the interior-radial PMSM topology, the PMs are radially magnetized and buried inside the rotor [20]. The interior magnet design offers the advantages of mechanical robustness and a smaller air gap, which allows for a degree of flux weakening when the motors are expected to operate in constant power mode at high speed. In the interior magnet design, it is possible to produce greater flux density than the flux density at the magnet surface [19].

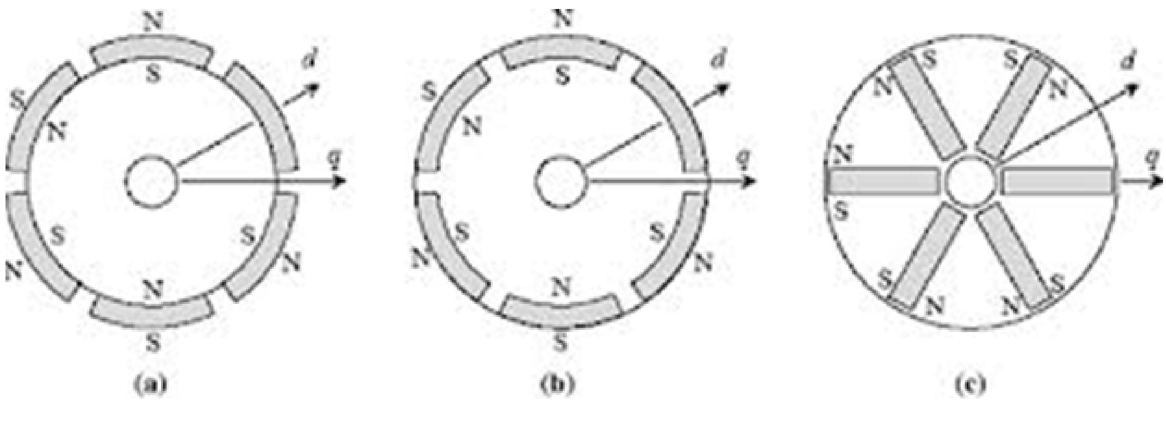

Figure 2.1: PMSM with (a) PMs mounted on the surface of the rotor, (b) PMs are inset into the rotor and (c) PMs buried inside the rotor

2.4 Winding Topologies

There are two winding for PMSM for HEVs; concentrated winding and distributed winding. Both have own merits in terms of influences the motor's performance.

In concentrated winding, the structures of tooth and coil part are independent each other. Therefore, teeth can be divided into each one tooth at the coil winding process, which makes coil fill factor extremely higher. Hence, contribute to a low copper loss with a short axial length application. Furthermore, it's lower resistance gives an advantage to the application which a given a priority in lower ampere-turn and small output torque operation [9]. Due to this, PMSM with concentrated winding has an advantage on the structure of motor which is small, lightweight, short end coil and an easy winding operation.

On the other hand, the PMSM with a distributed winding has a high efficiency and having a low current loss in the PM at a high speed [22]. The higher reluctance torque density gives a distributed winding advantage to available in higher torque regions. In all, the distributed winding motor has better performance in longer core length region [9].

For traction motor which flows large current, eddy current loss of NdFeB Magnet is the critical functioning. To reduce eddy current loss, the distributed winding is good to use. But end turn length of the distributed winding is long, copper loss of the distributed winding is bigger than that of the concentrated winding [23].

2.5 Winding Layout

The effect of winding layout on the shape of flux linkage and back EMF can be described through distribution factor, pitch factor, and winding factor. There is two type of winding layout which is a single layer and double layer. For single layer winding, each slot can only accumulate with one coil, different from double-layer winding that each slot can accumulate with two coil sides which is upper side layer and lower side layer.

2.5.1 Distribution factor

For coil per-phase winding which accommodated in each of slot can be calculated by using Equation 2.1 as below:

$$\text{Slot/Pole/Phase, SSP} = \frac{N_s}{pq} \tag{2.1}$$

where p is number of poles and q is number of phases.

Each coil per-phase will identical have the same number of turns, they will have same RMS value of induced EMF. However, they have progressive time phase difference as these coils are uniformly distributed. The RMS phase EMF is less than the algebraic sum of RMS coil EMF due to the effect of coil distribution which is called distribution factor, K_{dn}. To determine the type of winding of motor design, the ratio of slot/pole has to be considered, in order to achieve the high-performance motor design. For slot/pole less than or equal to 1.5, the motor known as having non-overlapping winding. On the other hand, for slot/pole more than 1.5 the motor known as having overlapping winding.

For overlapping, the distribution factor is shown as below:

$$K_{dn} = \frac{sin\frac{mny}{2}}{msin\frac{ny}{2}} \tag{2.2}$$

where n = 1,3,5,7,… is the harmonic numbers, m is number of coils and y is the coil displacement angle.

For non-overlapping, the distribution factor is shown below:

$$K_{dn} = \frac{resultant\ emf\ vector\ per\ phase}{algebraic\ sum\ of\ emf\ vector\ per\ phase} \quad (2.3)$$

Motor with distributed windings have typically long end windings because the coil of a phase must cross the other phase coils, therefore distributed winding known as overlapping winding. Since the phases are located closely together, more insulation material is used, which will add to the axial build of the end windings [24].

On the other hand, the concentrated winding known as non-overlapping winding because it has phase coils that are wound around separate teeth, which means that the axial build is short. In addition, the single-layer concentrated winding has almost twice the axial end winding build, compared to double-layer windings. This is because the coil around one tooth consists of all conductors in the slot next to it, while for double-layer windings it consists of only half of these conductors.

2.5.2 Pitch Factor

The pitch factor is defined as the ratio of the vector sum of EMF induced in the coil to the arithmetic sum of EMF induced in the coil. For overlapping winding, the pitch factor is equal to 1 when the coil EMF is a sum of the conductor EMF in GO and RETURN conductor.

However, if the coil span is not full pitch coil, the pitch factor is shown as below:

$$K_{pn} = cos\frac{n\theta}{2} \quad (2.4)$$

In contrast, the pitch factor for non-overlapping winding is given:

$$K_{pn} = \; sin \frac{np\pi}{Ns} \tag{2.5}$$

2.5.3 Winding Factor

The winding factor for overlapping and non-overlapping winding is the product of the pitch factor and the distribution factor [24]. The winding factor can be calculated by using Equation 2.5 below:

$$K_w = K_{pn} \; \times \; K_{dn} \tag{2.6}$$

2.6 Self-Inductance and Mutual-Inductance

The stator winding inductances can have a significant effect on the performance of PMSM, as high inductances can cause the torque-speed curve depart from the ideal linear characteristic [25]. The air gap component of inductance in the magnet is mounted adjacent has an only small portion of self-winding inductance and mutual winding inductance. While the slot component of inductance has more effect in self-winding inductance and mutual winding inductance.

However, the ratio of self-inductance and mutual-inductance are depending on the motor design. There are various components of winding inductance that given a different impact to machines, such as non-overlapping winding and an overlapping winding. An overlapping winding result, more sinusoidal magneto-motive force (MMF) distribution and phase back-EMF waveform. While, non-overlapping generally gives lower copper loss, high efficiency and torque density [26].

In addition, synchronous inductances the harmonic leakage inductance, slot leakage inductance and end-leakage inductance component is classified as phase inductance. In fact, the higher slot/pole number ratio will give the lower winding inductance, since the number of series turn per phase reduces [26].

2.7 Phase Back EMF

The most of PM brushless motors can be classified into two types back EMF waveform which is a sine wave and trapezoidal wave. The application with the sine wave motor satisfies less mechanical vibration and low acoustic noise.

The back-EMF is the synthetic voltage of the individual windings due to the flux variation caused by the rotor rotation [11]. Inform of performance, the higher the synthetic voltage lead to better performance for motor possesses. This can be calculated by employing the open-circuit magnetic field distribution on the motor [27].

Back EMF waveforms partly depend on the air-gap flux distribution produced by magnets. In parallel magnetization, for arc shape magnet is given a uniform air-gap permenance and trapezoidal back EMF, it contrasts with a bread loaf magnet that gives a non-uniform air-gap permeance and more sinusoidal back EMF waveform. However, there are no specific criteria to determine the exact magnet shape to form the required sinusoidal back EMF [11]. According [27], the calculation of the magnetic flux linked with each coil is a prerequisite for the induced back-EMF prediction in each phase.

The magnetic flux passing through a surface can be found by

$$\emptyset = \int B.dS \tag{2.7}$$

where B is the magnetic flux density vector distribution passing through the surface and dS is an element of the surface area vector.

The back-EMF can also be found from the Lorentz force law,

$$E = vL \times B \tag{2.8}$$

where v is the tangential velocity between the coil and the flux density.

The no-load RMS back EMF in the stator winding by the magnetic excitation flux of rotor is;

$$E_f = \pi\sqrt{2} f_e k_w N_{ph} \emptyset_{sp} \quad (2.9)$$

where N_{ph} is the number of stator turn per phase, k_w is the winding factor, f_e is the frequency and $\emptyset_{sp}$ is the total flux per stator tooth.

2.8 Flux Linkage

Maximum flux linkages occur when the axis of a magnet is in alignment with the center of the tooth for the coil is wound around a single tooth. The magnetic flux linkage depends on the tooth tip width, W_{tb} which will slightly smaller than the slot pitch [28]. The smaller the number slots, a smaller number of coils are required as the size of the slot is large. The number of a slot has a minor influence on the maximum amplitude flux linkage, as the pole width is decreased the maximum amplitude flux is decreased [8].

The flux linkage can be calculated using Equation 2.9

$$\text{Self-inductance, } L = \frac{N\emptyset}{I} \quad (2.10)$$

Where $\emptyset =$ Flux Linkage

$N =$ Number of turn

$I =$ Current in the coil

2.9 Cogging Torque

The cogging torque is the most important parameter that needs to be considered in the design of PMSM. Cogging torque can be detrimental in PM brushless DC motor as it produces noise, vibration and output ripple which reduced the efficiency of the motor [8]. Cogging torque results from the interaction of permanent magnet MMF harmonics and the air gap permeance harmonics due to slotting.

It manifests itself by the tendency of a rotor to align in a number of stable positions even when the machine is unexcited, and results in a pulsating torque, which does not contribute to the net effective torque [29]. The causes of speed ripple and induce vibrations, particularly at light load and low speed, its reduction is usually a major design goal. The cogging torque can be calculated using Equation 2.8.

$$Cogging\ Torque, T_c = -\frac{\emptyset^2}{2}\frac{dR}{d\theta} \tag{2.11}$$

The Equation 2.10 shown that the cogging torque is directly proportional to the change of radius with respect to the circular angle in radian. The independent of flux direction as the magnet is squared, which produces reluctance variations with the rotor position; it is independent of stator current. When decreasing the pole width, the maximum of cogging torque is reduced, but the frequency of that is increased. Therefore, it is concluded that a change in the angle α would change the cogging torque to a better value outputs [8].

2.10 Unbalanced Magnetic Pull (UMP)

A PMSM are widely implemented in many applications because of its advantages in high magnetic energy that produce high torque density. Due to manufacturing errors, inevitable in their production, generate distortions of magnetic energy and additional excitation forces.

One of the major manufacturing errors is an eccentricity, which happens when the rotor and the stator do not coincide. This error can be classified as dynamic or static eccentricity. Static eccentricity is the state in which the rotor rotates with respect to a fixed center and the air gap between the rotor and the stator is stationary. Dynamic eccentricity is the state in which the rotor rotates around its own center in a whirling motion, and so the position of the minimum air gap revolves around the center of the stator, which changes the magnetic field concurrently [13].

When the rotor is dynamic eccentric, it will produce UMP, but it is smaller than EMF and it can still be omitted [30]. However, UMP is important as it affects the wear on the bearing, as well as noise and vibration content [31]. There has been much research on the cogging torque and UMP generated by dynamic and static eccentricities and uneven magnetization. From J. Y. Song et al. [13] show that the pole harmonics and pole multiple ±n harmonics of the UMP are modulated by the frequency of the unevenly magnetized PM.

The possible sources of UMP and the associated vibration frequencies can be analyzed by developed an analytical model using rotating field theory. The samples of machines are analyzed using finite element analysis to obtain the magnitudes of the UMP and eccentricity of the small rotor explored. In the event of high eccentricity, the UMP will be excessive generating high audible noise (which will lead to developing fault when inspected) or complete rotor pull-over in the air-gap which will cause drive failure [31].

2.11 Magnetisation Patterns

Electromagnetic torque can form from the six different magnetization pattern that is radial sinusoidal amplitude magnetization; ideal Halbach or sinusoidal angle magnetization; radial magnetization; parallel magnetization; Halbach magnetization with fractional pole arc per pole pitch ratio; and two-segment Halbach magnetization. For Halbach magnetization pattern, the electromagnetic torque can be maximized.

In addition, the sinusoidal armature current waveforms with the Halbach magnetization pattern produces maximum torque with zero ripples. By using the radial magnetization pattern with sinusoidal armature current waveform yielding results in zero torque ripples, the electromagnetic torque is almost at minimal compared with other magnetized patterns with the same armature current waveforms.

In the case of internal rotor motors, the parallel magnetization pattern develops slightly higher electromagnetic torque than radial magnetization pattern. However, in the case of external rotor motors, this is totally opposite [27].

Depending on the magnetization orientation for the magnets, the rotor can also be classified into radiation oriented or circumferentially oriented configurations type. For surface type configuration, the only direction of magnetization is the radial. In a brushless PMSM, there is no provision for rotor side excitation control. The control is done only entirely through the stator terminals.

On the other hand for variable speed drive applications, it required the constant torque and constant power operating modes. Since magnetic flux is usually fixed, the air gap flux weakening is achieved by controlling the direct-axis current at high speed. This results in low efficiency at high speed; PM may be subject to irreversible demagnetization condition [19].

2.12 Multiple Phases

The electric vehicle is one of the applications that require extremely high reliability, the conventional three-phase PMSMs are confronted with a severe challenge. Generally, the torque of conventional three-phase PMSM drive system will decrease dramatically in case of major failures, such as the open circuit of a single phase or two phases and short circuit of one phase, which is unacceptable for electric vehicles especially for in-wheel motor-driven vehicle [3]. Due to this, some researchers turned to the investigation of multiphase PMSM system for the better fault-tolerant capability [3]-[6],[15],[32],[33].

Increasing in the number of phases is one of the methods for reducing the amplitude of torque pulsation and increasing its frequency. The multiphase machine provides a significant advantage of fault tolerance feature and improved reliability characteristics compared to conventional three-phase machines. In the five-phase machine, loss of up two phases will not inhibit the motor from continuing operation or even from starting [34]. Multiphase machines can continue operations when the faults occur by using the remaining healthy phases. Improvement of noise characteristics and reducing the stator current per phase without increasing the voltage per phase are other advantages of multiphase machines [15]. These features are very fit for the modern electric drive applications which are energy efficient in variable speed operation underweight and volume constraint.

2.13 Type of Magnet Materials

There are various types of magnet materials with a different characteristic that can use in PMSM. Ferrite is one of the low-cost element that has better linearity in demagnetization. However, the remnance in ferrite magnets is low and more material is required to achieve a flux level in the air gap. Hence, ferrite magnets tend to be used in drives where high dynamic performance is less important than motor cost.

On the other hand, Samarium-Cobalt is high-cost material that has substantially increased residual flux density and coercivity. As a result, it is used in high-performance servo drives, where a high torque to inertia ratio is desirable. A further increase in residual flux density and coercivity has been achieved with the introduction of Neodymium-Iron-Boron magnet material at a lower cost than the Samarium-Cobalt material [19].

2.14 Skewing Method

In work for PMSM to become a high-performance candidate for hybrid and electric vehicle, PMSM application requires minimized the cogging torque value for reduced vibration and acoustic noise, and smooth operation of the motor, that appear due to the mutual attraction between rotor and stator magnetic armature of the motor [12], [35]. Therefore researcher has addressed several methods can be used to minimize cogging torque [12], [35]-[37]. One well-known approach for reduction of cogging torque of PMSM is skewing method.

Skewing may be accomplished with either a skewed stator or a skewed magnet. Both techniques were constructed and resulted in motor with minimum cogging torque. Theoretically, skewing of the stator is simple in term of construction as the stator is made of a thin lamination of the steel. This lamination may simply be twisted before stacked and glued.

The skewing of magnets can be continuous or stepwise. A three-step skew is a good compromise between manufacturing complexity and performance the three step-skew schemes. A three-step skewed motor is modeled as one with three axial slices each shifted by the skew angle. The centered piece is considered to have a zero phase angle (γ =0), while the other two pieces (lagging and leading pieces) have positive and negative phase angles of γ [12].

However, a disadvantage of skewing the stator slots compared to the straight slots solution is the decrease of the e.m.f. due to the skewing factor [35].

2.15 Summary

There are a great number of researchers in literature dealing with the optimum design of PMSM. Hence, various approaches have been adopted by researchers to develop the analytical model for predicting design that given a high dynamic performance for PMSM.