Design of Multi Phase Induction motor for Electric Vehicle application

M.Tech Thesis

by

Mayank Gupta

CENTRE FOR ELECTRIC VEHICLE AND INTELLIGENT TRANSPORT SYSTEMS

INDIAN INSTITUTE OF TECHNOLOGY INDORE

May 2025

Design of Multi Phase Induction motor for Electric Vehicle application

A THESIS

Submitted in partial fulfillment of the

requirements for the award of the degree

of

Master of Technology

by

Mayank Gupta

2302106002

CENTRE FOR ELECTRIC VEHICLE AND

INTELLIGENT TRANSPORT SYSTEMS

INDIAN INSTITUTE OF TECHNOLOGY

INDORE

May 2025

INDIAN INSTITUTE OF TECHNOLOGY INDORE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Design of Multi Phase Induction motor for Electric Vehicle application** in the partial fulfillment of the requirements for the award of the degree of **Master of Technology** and submitted in the **Center for Electric Vehicle and Intelligent Transport System, Indian Institute of Technology Indore,** is an authentic record of my own work carried out during the period from July 2024 to May 2025 under the supervision of **Prof. B Prathap Reddy**, Indian Institute of Technology Indore, India.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Signature of the Student with Date

(Mayank Gupta)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

03/06/2025

Signature of Thesis Supervisor with Date

(Prof. B Prathap Reddy)

ACKNOWLEDGEMENT

First and foremost, I would like to express my heartfelt gratitude to my supervisor, **Prof. B Prathap Reddy**, for his invaluable guidance, constant support, and insightful suggestions throughout the course of this research. His encouragement and expertise have been instrumental in shaping both the direction and the quality of this work.

I would also like to thank my friends specially **Shreyansh, Shreya and Tuse** and **peers at IIT Indore** for their continuous support, helpful discussions, and for creating a collaborative and motivating environment that made this journey enriching and enjoyable.

Lastly, I am deeply thankful to my parents and family for their unconditional love, patience, and unwavering support. Their encouragement has been my strongest pillar throughout my academic journey.

This thesis would not have been possible without the contribution and support of all these individuals.

Mayank Gupta

Dedicated to My Family

ABSTRACT

The growing demand for robust, fault-tolerant, and high-performance electric drives in industrial, automotive, and renewable energy applications has intensified interest in multiphase induction machines. Unlike conventional three-phase motors, multiphase systems offer advantages such as reduced torque ripple, enhanced fault tolerance, and higher power density. However, with the increase in phase number and variations in winding configuration, analyzing the magnetic field behavior becomes increasingly complex, particularly in terms of the spatial distribution of magnetomotive force (MMF).

This thesis presents a comprehensive investigation into the MMF distribution of multiphase induction motors, with a primary focus on deriving **generalized equations for resultant MMF** under various winding and connection schemes. The study begins with an introduction to the fundamental operating principles of multiphase induction machines, outlining their advantages, applications, and the challenges involved in their analytical modeling.

The second chapter explores the concept of **space harmonics**, which arise due to discrete winding distribution, slotting, and other machine asymmetries. These harmonics are analyzed for their influence on MMF waveform distortion, torque ripple, and losses. A mathematical foundation is laid to represent MMF in terms of spatial Fourier series, enabling harmonic analysis for various phase configurations.

Following this, a detailed **literature review** focuses on the MMF distribution of conventional **three-phase windings** in induction motors. Prior analytical and simulation-based research is examined, highlighting the limitations of existing models when extended to multiphase and asymmetrical systems.

The core contribution of this thesis lies in the systematic development of **generalized MMF equations** for a wide range of phase numbers and configurations:

- Generalized expressions for MMF are derived for **odd-phase systems** (3, 5, 7, 9, 11...), for common neutral connection.

- Generalized expressions for MMF are derived for **even-phase systems** (4, 6, 8,

10, 12...), for common neutral connection.

- A unified expression for the **resultant MMF for any phase number** is then formulated, integrating both odd and even phase systems under a single analytical framework for common neutral connection .

The thesis further advances into more complex configurations involving **Asymmetrical isolated neutral connections**. Separate generalized MMF models are derived for:

- **Asymmetrical isolated neutral connections in odd-phase systems** (e.g., 9, 15, 21, 27...).
- **Asymmetrical isolated neutral connections in even-phase systems** (e.g., 6, 12, 18, 24, 30...).

In contrast,**Symmetrical isolated neutral connections**, separate generalized MMF models are derived for:

- **Symmetrical isolated neutral connections in odd-phase systems** (e.g., 9, 15, 21, 27...).
- **Symmetrical isolated neutral connections in even-phase systems** (e.g., 6, 12, 18, 24, 30...).

To validate the theoretical models, the thesis includes a **performance comparison of two different double-layer winding layouts** for a standard three-phase induction motor. The layouts are evaluated using both analytical MMF modeling and electromagnetic simulation tools. Key performance metrics such as harmonic content, MMF waveform smoothness, and flux linkage profiles are compared to provide insights into winding optimization.

And the last chapter is about **% reduction in stator copper loss in Multiphase induction machine as compared to Three phase inducitn machine**.

Contents

List of Figures

List of Tables

Acronyms

MMF Magnetomotive force

Chapter 1

INTRODUCTION

1.1 Introduction

Multiphase induction motors have garnered increasing attention in recent years due to their inherent advantages over conventional three-phase machines. These advantages include improved fault tolerance, reduced torque pulsations, enhanced power sharing capabilities, and greater flexibility in winding configurations. Such features are particularly desirable in safety-critical and high-performance applications such as aerospace, electric vehicles, wind turbines, and naval propulsion systems.

The magnetomotive force (MMF) produced by the stator windings is a critical factor in determining the torque, efficiency, and harmonic behavior of the machine. In three-phase machines, the MMF distribution is well understood and established. However, as the number of phases increases and new connection schemes such as isolated neutral configurations are introduced, the spatial MMF distribution becomes increasingly complex and requires a generalized analytical framework.

This thesis focuses on developing generalized MMF equations for multiphase induction machines, taking into account for Common neutral connection, Asymmetrical isolated neutral connection and symmetrical isolated neutral connection winding configurations for both odd and even phase systems. The study includes both theoretical modeling and practical insights through comparative analysis of different winding layouts.

1.2 Motivation

The increasing adoption of multiphase motors in modern applications demands accurate and efficient modeling tools for design and analysis. Traditional MMF models are often limited to three-phase systems and cannot easily be extended to cover arbitrary phase numbers or isolated neutral configurations.

Furthermore, the lack of generalized equations for MMF distribution across both symmetrical and asymmetrical systems results in fragmented research efforts and difficulty in standardizing design approaches. This gap becomes more prominent in isolated neutral systems, where unbalanced conditions and harmonic distortions are more pronounced.

Therefore, a comprehensive and unified framework is needed to analyze the MMF of multiphase machines under all major configurations. This thesis aims to address that gap by formulating general MMF equations that apply to both odd and even phase numbers and accommodate common neutral ,asymmetrical and symmetrical windings with isolated neutral connection.

1.3 Objectives

The main objectives of this thesis are as follows:

- To review the operating principles of multiphase induction machines and identify key factors affecting MMF distribution.
- To analyze the effects of space harmonics on the MMF waveform and its implications for machine performance.
- To study and summarize existing literature on MMF modeling for conventional three-phase windings.
- To derive generalized equations for the resultant MMF of induction machines with common neutral connection :
  - Odd number of phases (e.g., 3, 5, 7, 9, 11, ...)
  - Even number of phases (e.g., 4, 6, 8, 10, 12, ...)
  - All phase numbers in a unified formulation
- To develop generalized MMF expressions for asymmetrical winding systems with isolated neutral connections for:
  - Odd-phase systems (e.g., 9, 15, 21, ...)
  - Even-phase systems (e.g., 6, 12, 18, ...)
- To formulate MMF expressions for symmetrical isolated neutral systems for:
  - Odd-phase systems (e.g., 9, 15, 21, ...)
  - Even-phase systems (e.g., 6, 12, 18, ...)
- To compare the MMF performance of two different double-layer winding layouts in three-phase induction motors.

- To validate the derived equations through graphical analysis and simulation, and provide design insights based on the results.

- % reduction in stator copper loss in Multiphase induction machine as compared to Three phase inducitori machine

1.4 Operating Principles of Multiphase Induction Machines and Key Factors Affecting MMF Distribution

Multiphase induction machines extend the concept of the conventional three-phase induction motor by employing more than three stator phases, typically 5, 6, 9, 12, or higher. The basic working principle remains the same, a rotating magnetic field is generated by the stator, which induces currents in the rotor according to Faraday's law of electromagnetic induction. These rotor currents interact with the stator magnetic field to produce torque.

1.4.1 Stator and Rotor Construction

Multiphase machines usually feature a symmetrical arrangement of stator windings distributed in multiple slots per pole per phase. The rotor may be of squirrel cage or wound type. The stator windings are distributed such that each phase is electrically displaced by $360°/m$ degrees, where m is the number of phases. For instance, in a five-phase motor, the phase displacement is 72°, and in a nine-phase motor, it is 40°.

1.4.2 Production of Rotating Magnetic Field

The stator windings, when supplied with balanced multiphase sinusoidal currents, produce a rotating magnetic field in the air gap. The fundamental component of the MMF rotates synchronously at a speed given by:

$$n_s = \frac{120f}{P}$$

where f is the supply frequency and P is the number of poles.

The amplitude and quality of the resulting MMF wave depend on:

- The number of phases (m)
- Winding configuration and distribution
- Slot and pole combination
- Harmonics introduced due to winding and slotting

1.4.3 Key Factors Affecting MMF Distribution

The magnetomotive force (MMF) distribution in multiphase machines is influenced by several factors, including:

1. **Number of Phases:** Increasing the number of phases reduces the harmonic content in the MMF waveform and allows for better torque smoothness and fault tolerance.
2. **Winding Distribution:** The distribution factor and pitch factor determine the harmonic spectrum of the MMF. Properly distributed windings minimize harmonics and improve the fundamental MMF.
3. **Slotting Effect:** The interaction between stator slots and magnetic fields introduces slot harmonics that can distort the MMF waveform and cause

torque pulsations.

4. **Connection Scheme:** Star, delta, open-end, or isolated neutral connections impact the symmetry of the phase currents and the resulting MMF. Isolated neutral systems particularly require careful analysis due to the absence of current redistribution paths.

5. **Imbalance and Asymmetry:** Any imbalance in winding impedance or supply voltages leads to unbalanced MMF distribution, which can introduce negative sequence and zero sequence components.

6. **Presence of Harmonics:** Both time and space harmonics affect the MMF waveform. Space harmonics arise due to slotting and winding design, while time harmonics are due to inverter-fed supplies.

1.4.4 Benefits of Multiphase Machines

Some of the key benefits associated with multiphase induction machines include:

- Increased fault tolerance—machine can continue operating with one or more phases disconnected
- Reduced torque pulsations due to smoother MMF waveforms
- Higher power output for the same frame size due to better copper utilization
- Improved noise and vibration characteristics

1.4.5 Need for Generalized MMF Modeling

Due to the increasing complexity in winding design and the use of various connection types (symmetrical/asymmetrical, isolated/star/delta), a unified method to analyze MMF distribution is essential. This forms the core motivation of the current thesis, where generalized MMF equations are developed for both symmetrical and asymmetrical multiphase induction machines.

Chapter 2

Space Harmonics

The term ”space harmonics” describes the harmonic elements of a motor's magnetic field distribution that result from the stator's shape and winding configuration. The motor's performance may be impacted by these harmonics, leading to problems including noise, higher losses, and torque ripple. It is essential to comprehend space harmonics in order to optimize motor design and raise overall efficiency.

2.1 Origin of Space harmonics

In electric motors, the winding of the stator generates a rotating magnetic field. Ideally, this field should be sinusoidal. However, due to the physical structure of the windings (such as the distribution and placement of coils), the magnetic field becomes distorted, introducing harmonics.

1. **Fundamental Component (1st Harmonic):** The main rotating magnetic field produced by the motor.

2. **Higher-Order Harmonics (2nd, 3rd, 5th, etc.):** These are unwanted components that distort the field and affect motor operation.

2.1.0.1 Factors responsible for origin of Space harmonics

1. **Slotting of Stators:** Space harmonics may be produced as a result of the magnetic field discontinuities introduced by stator slots.

   The harmonic spectrum is greatly influenced by the number of slots and how they are arranged.

2. **Distribution of Windings:** The harmonic content of coils is influenced by their winding type (concentrated, distributed).

3. **Number of Poles:** The harmonic profile is also affected by the motor's pole count. Certain harmonics may become more noticeable if the pole number is a non-integer multiple of the slot number.

4. **Pitch of Slots and Coils:** The harmonic content is influenced by the pitch of the coils and stator slots. Harmonic distortion is frequently lessened by a higher pitch.

2.2 Importance of Winding configuration in Space Harmonic Analysis :

An induction motor's winding arrangement has a significant impact on the distribution and magnitude of space harmonics. The stator winding configuration causes the magnetic field to be non-sinusoidal, which results in space harmonics. Unwanted consequences including vibration, torque ripple, higher losses, and electromagnetic interference (EMI) can result from these harmonics. Thus, it is crucial to comprehend how various winding topologies affect space harmonics in order to maximize motor performance, particularly in applications such as electric vehicles (EVs), where high efficiency and smooth operation are necessary.

2.3 Types of Winding and its effect on Space Harmonics :

1. **Concentrated Winding:** All of the coil turns are positioned in one slot in concentrated winding. Each slot of this kind of winding has a high coil density.

   Effect on Space Harmonics :

   (a) **Higher Harmonics:** In general, concentrated windings produce more space harmonics, particularly low-order harmonics. These windings provide a more distorted magnetic field, which raises the harmonic content noticeably.

   (b) **Increased Vibration and Torque Ripple**: Concentrated windings produce a greater torque ripple as a result of the non-sinusoidal magnetic field, which may result in noise and mechanical vibrations. Because of this, they are less appropriate for uses like electric vehicles (EVs) where smoothness is crucial.

   (c) **Decreased Efficiency:** The motor's overall efficiency is decreased as a result of the high harmonic content, which raises core losses.

   (d) **Applications:** Common in small motors and applications where compactness is more important than smooth operation or efficiency (e.g., in some small household appliances).

2. **Distributed Winding :** Instead of being concentrated in a single slot, the coils in a distributed winding are dispersed among several slots. The most popular kind of winding seen in contemporary induction motors is this one.

Effect on Space Harmonics :

(a) **Diminished Harmonics :** There are less space harmonics as a result of the magnetic field being smoothed by distributed windings. The motor's magnetic field becomes more sinusoidal by distributing the windings over several slots, which lowers the lower-order harmonics (5th, 7th, etc.).

(b) **Enhanced Efficiency:** Lower core losses and increased efficiency are the results of the lower harmonic content. This is especially advantageous in high-performance applications where energy economy is crucial, such as electric vehicles.

(c) **Lower Torque Ripple and Vibration:** The more even magnetic field reduces torque ripple, resulting in smoother operation and lower mechanical vibrations, improving the driving experience and motor lifespan.

(d) **Applications:** Widely used in industrial motors, electric vehicles (EVs), and high-performance motors where efficiency and smooth operation are essential.

3. **Fractional Slot Winding :** The number of stator slots in a fractional-slot winding is not an integer multiple of the number of poles. The purpose of this winding arrangement is to limit the impacts of harmonics produced by pole-slot interactions and to lower the harmonic content.

   Effect on Space Harmonics :

   (a) **Diminished Harmonics :** By moving the harmonic frequencies and lowering their peak values, fractional-slot winding lessens the effect of space harmonics, particularly low-order harmonics (such the fifth and seventh harmonics). This lessens the torque ripple.

   (b) **Smoother Operation:** When harmonics are minimized, motors operate more smoothly and produce less noise and vibration.

   (c) **Increased Efficiency:** Lower core losses and increased motor efficiency are the results of a more uniform harmonic distribution.

   (d) **Applications:**

   Used in high-performance motors, including electric vehicles (EVs), where low vibration, smooth torque, and high efficiency are critical.

   Also used in wind power generation and other industrial applications requiring smooth motor operation.

4. **Double-layer windings :** Double-layer windings increase torque capacity by having two layers of windings in each stator slot.

   Effect on Space Harmonics :

   (a) **Diminished Harmonics:** Since a more uniform distribution of the magnetic field smoothes out the waveform and lessens the intensity of space harmonics, double-layer winding aids in the reduction of harmonic distortion.

   (b) **Reduced Torque Ripple:** Better performance, particularly at lower speeds, results from a smoother magnetic field that lessens torque ripple.

   (c) **Increased Reliability and Efficiency:** The motor's overall longevity and efficiency are increased as a result of reduced core losses and heat caused by harmonic distortion.

   (d) **Applications:** Used in electric cars and high-power industrial motors where low harmonic distortion and high efficiency are essential.

2.4 Types of Neutral Connections :

Neutral connections play a critical role in the performance and harmonic characteristics of multi-phase electric machines. Based on how the neutral points of different phase groups are treated, winding connections can be categorized as follows:

2.4.1 Types of Neutral Connections

In multi-phase electric machines, the neutral connection topology significantly influences the machine's performance, harmonic content, and fault tolerance. Neutral connections are broadly categorized as follows:

1. **Same Neutral Connection**

   In this configuration, all phase windings share a common neutral point. It is simpler to implement and is often used in balanced systems. However, it offers limited flexibility in controlling individual phase groups or mitigating specific harmonics.

2. **Isolated Neutral Connection**

   Here, each phase group or subset has its own neutral point, offering better isolation, control flexibility, and harmonic reduction. Isolated neutral configurations are further divided into:

   (a) **Symmetrical Connection**

   The phase windings are grouped such that each subset is symmetrical and balanced. The phase displacement between adjacent phases remains uniform. This configuration is useful for applications requiring harmonic mitigation through phase shifting.

(b) **Asymmetrical Connection**

In this case, the phase groups are arranged with unequal displacement, leading to asymmetry. This can be useful for suppressing specific harmonic orders or achieving particular control characteristics.

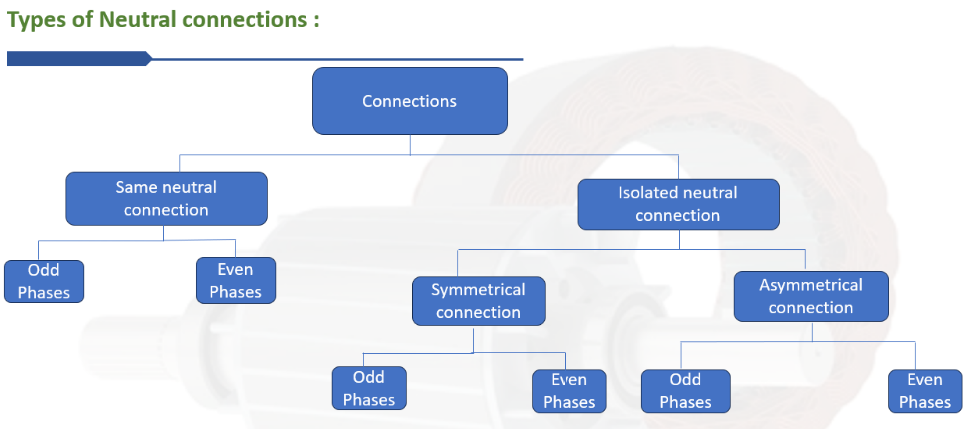


Figure 2.1: Types of Neutral connections

2.4.2 Same Neutral Connection :

In this type of configuration, all phase windings share a common neutral point. This connection is widely used due to its simplicity and ease of implementation.

2.4.2.1 Odd Phase

For machines with an m number of phases, the phase displacement is calculated as:

$$\text{Phase displacement} = \frac{360°}{\text{Number of Phases}} = \frac{360°}{m}$$

where m should be greater than 2.

For Five phase machine phase displacment is :

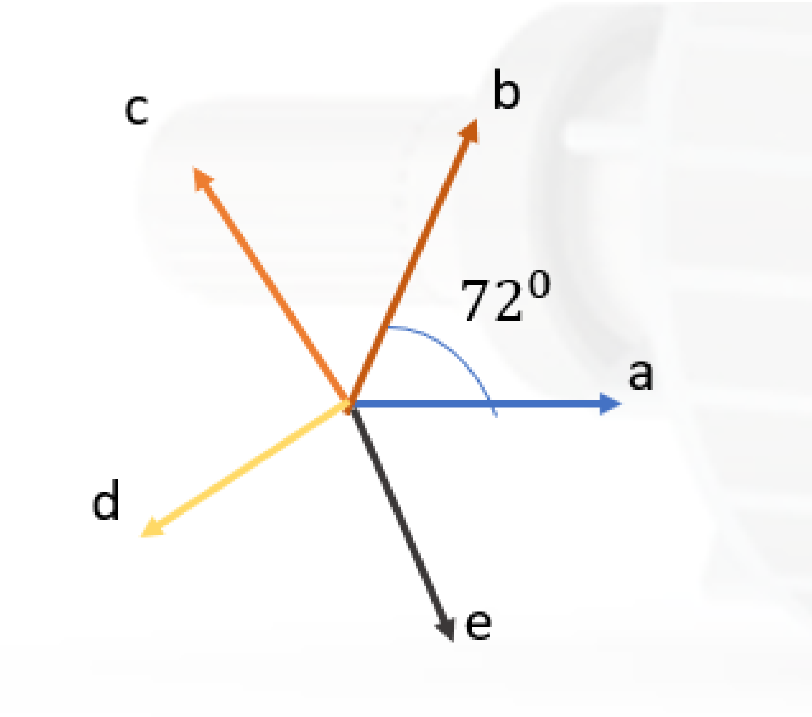


Figure 2.2: Five phase same neutral connection

$$\text{Phase displacement} = \frac{360^\circ}{\text{Number of Phases}} = \frac{360^\circ}{5} = 72^\circ$$

As shown in the diagram, all five phases are spaced 72° apart and share the same neutral point n_1.

2.4.2.2 Even Phase

Foe Six phase machine phase displacment is :

$$\text{Phase displacement} = \frac{360^\circ}{6} = 60^\circ$$

As shown in the diagram, all six phases are spaced 60° apart and share the same neutral point n_1.

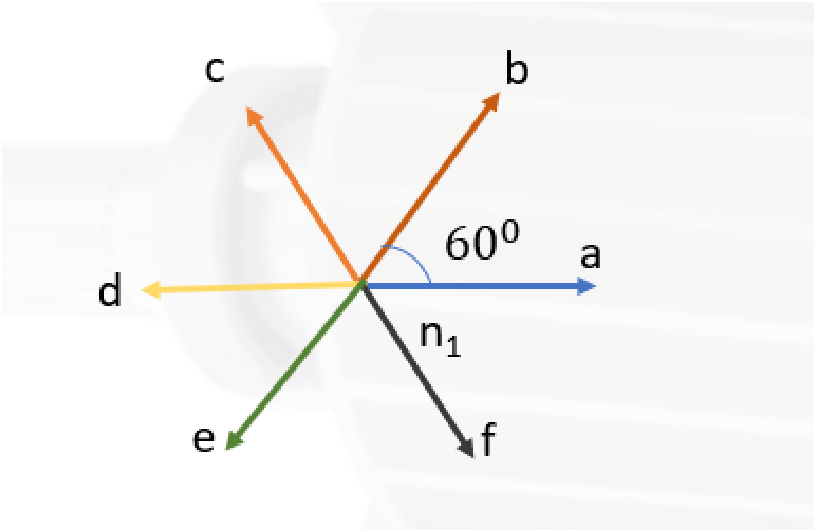


Figure 2.3: Six phase same neutral connection

2.4.3 Isolated Neutral Connection :

In isolated neutral configurations, each group of windings (or phase pairs) has its own independent neutral point. This approach provides better insulation, allows fault isolation, and is beneficial in reducing specific space harmonics.

2.4.3.1 Symmetrical isolated neutral Connection :

Phase displacement for isolated neutral asymmetrical connection is :

$$\text{Phase displacement} = \frac{360^\circ}{m}$$

2.4.3.2 Six phase machine with symmetrical isolated neutral connection :

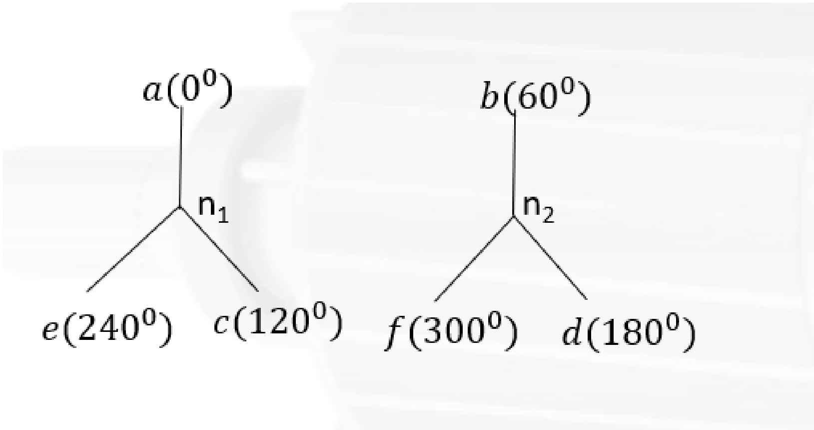


Figure 2.4: Six phase isolated neutral symmetrical connection

Phase displacement for Six phase isolated neutral symmetrical connection is :

$$\text{Phase displacement} = \frac{360°}{6} = 60°$$

Phase shift between phase a, phase b for the Asymmetrical isolated neutral Six phase connection 60 degree.

2.4.3.3 Asymmetrical isolated neutral Connection :

Phase displacement for isolated neutral asymmetrical connection is :

$$\text{Phase displacement} = \frac{360^\circ}{2m}$$

2.4.3.4 Six phase machine with asymmetrical isolated neutral connection :

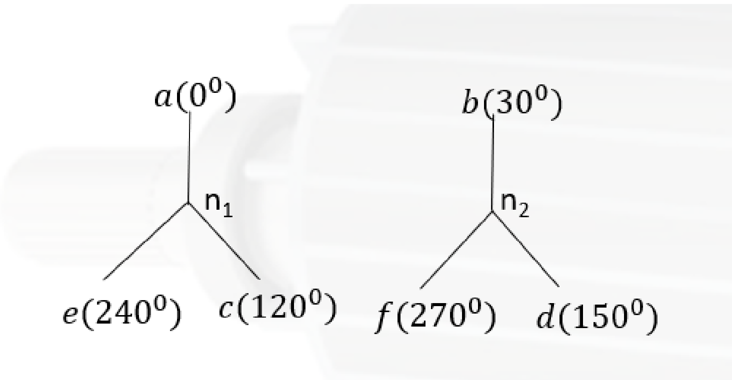


Figure 2.5: Six phase isolated neutral asymmetrical connection

Phase displacement for Six phase isolated neutral asymmetrical connection is :

$$\text{Phase displacement} = \frac{360^\circ}{2*6} = 30^\circ$$

Phase shift between phase a, phase b for the Asymmetrical isolated neutral Six phase connection 30 degree.

Chapter 3

Literature Review of MMF Distribution of Three Phase winding of Induction Motor

3.1 Introduction

An extensive overview of the literature on the MMF distribution in induction motor three-phase windings is presented in this chapter. It lists the main conclusions from earlier studies, describes the various approaches taken in the computation of MMF, and describes how winding parameters and phase connections affect the harmonic content of MMF. The impact of space harmonics and winding designs, including dispersed, concentrated, and distributed windings, are specifically examined in order to shape the air-gap MMF. Additionally, the impact of neutral connection methods on MMF symmetry and harmonic suppression is examined, including same neutral and isolated neutral topologies in upcoming chapters.

In addition to employing coil pitch adjustments to eliminate undesirable harmonics, windings are generally distributed across multiple slots to more effectively utilize the stator surface area and reduce harmonic content.

Figure 3.1 shows one phase of a two-layer winding in which a concentrated coil of N_t turns is distributed into three coils per pole, each with a full pitch.The phase A conductors are distributed in six slots under one pole is shown in figure 3.1.

Each pair of connected coils contributes a rectangular MMF distribution,

The maximum MMF of each rectangular component is given by:

$$\text{MMF}_{\text{max}} = \frac{N_t I}{2Q}$$

where:

- N_t is the number of turns per phase,
- I is the phase current,
- Q is the number of coils per pole (3 in this example).

The $q = 2Q$ coil sides collectively form a phase belt, which is a fundamental concept in winding representation and harmonic analysis. Each successive coil side is displaced from its neighbor by an angle γ. From the analysis, it follows that the MMF distribution generated by the winding is a summation of the individual rectangular MMF waves of these coil sides [1].

$$f_a = \frac{4}{\pi}\left(\frac{N_t I}{2Q}\right)\frac{\cosh\left(\frac{h\gamma}{2}\right)}{h} \tag{3.1}$$

$$f_b = \frac{4}{\pi}\left(\frac{N_t I}{2Q}\right)\frac{\cosh\left(\frac{\gamma}{2}+\gamma\right)}{h} \tag{3.2}$$

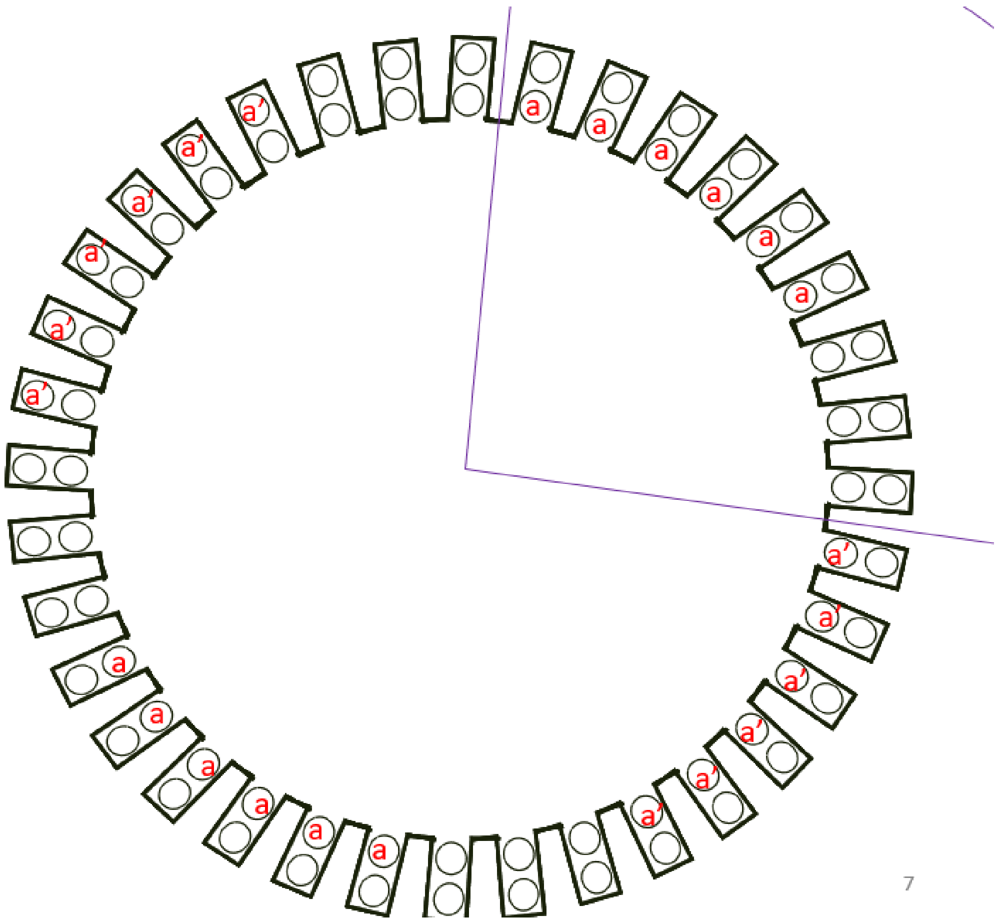


Figure 3.1: Three phase double layer distributed winding

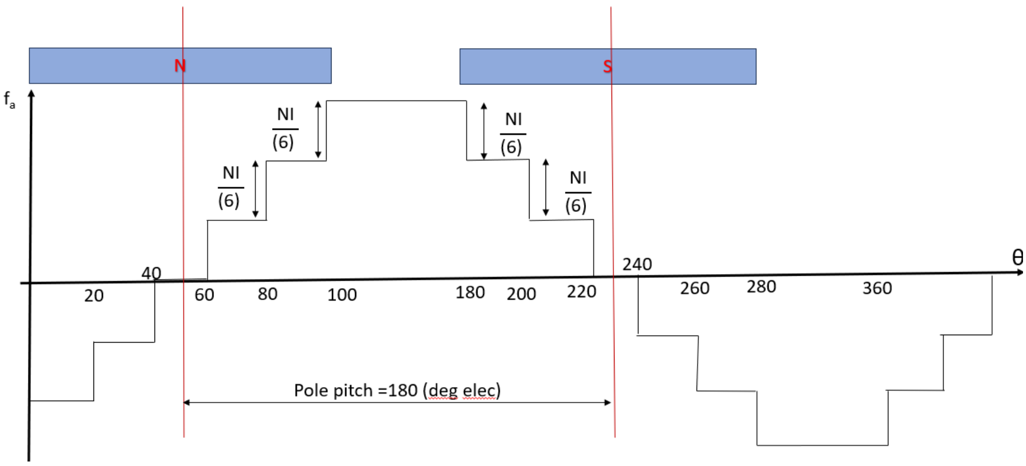


Figure 3.2: Resultant MMF of the Three phase machine

$$f_c = \frac{4\pi N_t I}{2Q} \cdot \frac{\cosh\left(\frac{\gamma}{2} + 2\gamma\right)}{h} \tag{3.3}$$

$$Q_{\text{inner}} = \frac{4}{\pi}\left(\frac{N_t I}{2Q}\right)\left(\frac{\cosh\left(\frac{\gamma}{2} + (Q-1)\gamma\right)}{h}\right) \tag{3.4}$$

So the per phase MMF can be calculated by adding the equation shown below,

$$F_{\text{ph}} = f_a + f_b + f_c + \cdots + f_Q \tag{3.5}$$

$$F_{ph} = \frac{4\pi N_t I}{2h} \cdot \frac{\sin\left(\frac{hQ\gamma}{2}\right)}{Q\sin\left(\frac{h\gamma}{2}\right)} \cdot \cos\left(\frac{hQ\gamma}{2}\right) \tag{3.6}$$

3.1.1 MMf Distribution for Three Phase Winding

When the machine gets energized with three symmetrically wound coils, the net MMF operating on the magnetic circuits equals the sum of the individual coils' MMFs. Assuming that the three coils are coiled identically.

The MMFs of windings a, b, and c may be written by physically placing them in the machine at 120 degree intervals.

$$F_a = \frac{4}{\pi}\left(\frac{N_{\text{t}}\, i_a}{P}\right) \sum_{h=1,5,7,11,\ldots} \frac{k_h \sin(\theta)}{h} \tag{3.7}$$

$$F_b = \frac{4}{\pi}\left(\frac{N_{\text{t}}\, i_b}{P}\right) \sum_{h=1,5,7,11,\ldots} \frac{k_h \sinh\left(\theta - \frac{2\pi}{3}\right)}{h} \tag{3.8}$$

$$F_c = \frac{4}{\pi}\left(\frac{N_{\text{t}}\, i_c}{P}\right) \sum_{h=1,5,7,11,\ldots} \frac{k_h \sinh\left(\theta - \frac{4\pi}{3}\right)}{h} \tag{3.9}$$

where,

$$i_a = I_s \cos(\omega_e t) \tag{3.10}$$

$$i_b = I_s \cos\left(\omega_e t - \frac{2\pi}{3}\right) \tag{3.11}$$

$$i_c = I_s \cos\left(\omega_e t - \frac{4\pi}{3}\right) \tag{3.12}$$

where Is is the peak value of the current.

$$F_{\mathrm{R}} = F_a + F_b + F_c \tag{3.13}$$

$$F_R = \left(\frac{3}{2}\right)\left(\frac{4}{\pi}\right)\left(\frac{N_{\mathrm{t}} \cdot I_s}{P}\right)\left[\sum_{h=1,7,13,\ldots} \frac{k_h}{h} \sin\left(\theta - \omega_e t\right) + \sum_{h=5,11,17,\ldots} \frac{k_h}{h} \sin\left(\theta + \omega_e t\right)\right] \tag{3.14}$$

[1]

The above equation represents the Resultant MMF for Three phase machine

A balanced, three-phase operation of a machine with a practical winding distribution containing odd harmonics results in an MMF that rotates positively and negatively.Each of these MMF's is of constant amplitude and rotate in the forward direction for h=1,7,13,19,... and in the negative direction for h = 5, 11, 17,.. Harmonic components corresponding to h=3, 9, etc.are not present if the machine has no neutral return, that is, no zero sequence component.

Chapter 4

Generalized Resultant MMF equations for common Neutral Connection in Odd phase and Even phase Induction Machine

4.1 Introduction

This chapter presents a generalized formulation for the resultant magnetomotive force (MMF) in multiphase systems with common neutral connections, covering both:

- **Odd-phase systems** (e.g., 3, 5, 7, 9.....)
- **Even-phase systems** (e.g., 4, 6, 8, 10, 12.....)

The major goal is to expand the classical MMF equations, which were originally designed for three-phase systems, so that they may be used to machines with more odd-number phase configurations.

4.2 Problem Statement

The conventional theoretical foundation for analyzing the magneto-motive force (MMF) in electric machines is predominantly based on three-phase systems. The classical MMF equation assumes a 120-degree phase shift between phases and utilizes symmetrical winding configurations suitable only for three-phase machines. When applied to multiphase machines, this conventional MMF model becomes inadequate because it does not account for varying phase angles, different phase numbers, and asymmetrical winding distributions that are often used in higher-phase machines.

In current literature, a comprehensive and generalized MMF equation that is valid for arbitrary phase systems—whether odd or even—remains underdeveloped. Most existing models either oversimplify the problem by extending three-phase assumptions or restrict their applicability to specific phase numbers.

The absence of a generalized MMF formulation poses significant challenges in the accurate analysis of space harmonics, torque ripple, and electromagnetic losses in multiphase machines. These aspects are critical for machine design optimization, thermal management, and power converter control strategies.

Hence, the core problem addressed in this thesis is the development of a generalized MMF equation applicable multiphase induction motors with a odd number of phases (such as 3, 5, 7, 9, 11....) and **even number of phases (such as 6, 8, 10, 12, 14....)** having common neutral connection. The ultimate goal is to enable precise analytical modeling, simulation, and optimization of multiphase electric machines for modern high-performance applications.

4.3 Generalized Equation of Resultant MMF for Odd Number of Phases (3, 5, 7, 9, 11...) in Induction Machine

[2]

4.3.1 Mathematical formulation for Odd phase induction machine with common neutral connection :

Let the machine have m phases. The MMF for each phase k can be expressed as:

$$F_k = \frac{4}{\pi}\left(\frac{N_\mathrm{t} i_k}{P}\right) \sum_{h=1,5,7,11,...} \frac{k_h \sinh\left(h\left(\theta - \frac{2(k-1)\pi}{m}\right)\right)}{h} \tag{4.1}$$

$$F_1 = \frac{4}{\pi}\left(\frac{N_\mathrm{t}\, i_1}{P}\right) \sum_{h=1,5,7,11,...} \frac{k_h \sin\left(h(\theta)\right)}{h} \tag{4.2}$$

$$F_2 = \frac{4}{\pi}\left(\frac{N_\mathrm{t}\, i_2}{P}\right) \sum_{h=1,5,7,11,...} \frac{k_h \sin\left(h\left(\theta - \frac{2\pi}{m}\right)\right)}{h} \tag{4.3}$$

$$F_3 = \frac{4}{\pi}\left(\frac{N_\mathrm{t}\, i_3}{P}\right) \sum_{h=1,5,7,11,...} \frac{k_h \sin\left(h\left(\theta - \frac{4\pi}{m}\right)\right)}{h} \tag{4.4}$$

$$F_{m-1} = \frac{4}{\pi}\left(\frac{N_\mathrm{t}\, i_{m-1}}{P}\right) \sum_{h=1,5,7,11,...} \frac{k_h \sin\left(h\left(\theta - \frac{2(m-2)\pi}{m}\right)\right)}{h} \tag{4.5}$$

$$F_m = \frac{4}{\pi}\left(\frac{N_\mathrm{t}\, i_m}{P}\right) \sum_{h=1,5,7,11,...} \frac{k_h \sin\left(h\left(\theta - \frac{2(m-1)\pi}{m}\right)\right)}{h} \tag{4.6}$$

where,

$$i_1 = I_s \cos(\omega_e t) \tag{4.7}$$

$$i_2 = I_s \cos\left(\omega_e t - \frac{2\pi}{3}\right) \tag{4.8}$$

$$i_3 = I_s \cos\left(\omega_e t - \frac{4\pi}{m}\right) \tag{4.9}$$

$$i_k = I_s \cos\left(\omega_e t - \frac{2\pi(k-1)}{m}\right) \tag{4.10}$$

So the Resultant MMF of the M phase machine is the addition of the individual phases MMF's show below,

$$F_m = F_1 + F_2 + F_3 + \ldots + F_m \tag{4.11}$$

The phase currents are given as:

The resultant MMF is the sum of MMFs of all m phases:

$$F_R = \frac{4}{\pi} \cdot \left(\frac{N_{\mathrm{t}} \;\cdot I_S}{P}\right) \cdot \sum_{h=1,3,5,7} \frac{K_h}{h}$$
$$\Bigg[\quad \left\{1 + \left(\sum_{k=2}^{\frac{(m-1)}{2}+1} 2\cos\left(\frac{2(k-1)\pi}{m}\right)\cos\left(\frac{2h(k-1)\pi}{m}\right)\right)\sin(h\theta)\cos(\omega t)\right\}$$
$$- \left\{\left(\sum_{k=2}^{\frac{(m-1)}{2}+1} 2\sin\left(\frac{2(k-1)\pi}{m}\right)\sin\left(\frac{2h(k-1)\pi}{m}\right)\right)\cos(h\theta)\sin(\omega t)\right\}\Bigg]$$

This is the required generalized equation of resultant MMF in induction machine for the calculation of the space harmonics having common neutral for odd number phases.

Where:

- N_{t} : Number of turns per phase
- i_k : Instantaneous current in the k^{th} phase
- P : Number of pole pairs
- k_h : Winding factor
- m : Number of phases
- h : Harmonic order (only odd harmonics, e.g., $h = 1, 3, 5, \ldots$)
- θ : Electrical space angle

Here:

$$k_h = k_{ph} \cdot k_{dh} \cdot k_{\chi h} \cdot k_{sh} \tag{4.12}$$

- k_h : Winding factor
- k_{ph} : Pitch factor
- k_{dh} : Distribution factor
- $k_{\chi h}$: Skew factor
- k_{sh} : Slot opening factor

4.4 Generalized Equation of Resultant MMF for Even Number of Phases (4, 6, 8, 10, 12...) in Induction Machine

4.4.1 Mathematical formulation for Even phase Induction machine :

Let the machine have m phases. The MMF for each phase k can be expressed as:

$$F_k = \frac{4}{\pi}\left(\frac{N_t \cdot i_k}{P}\right)\sum_{h=1,5,7,...}\frac{k_h \sin\left(h\left(\theta - \frac{2\pi(k-1)}{m}\right)\right)}{h} \tag{4.13}$$

Phase currents are:

$$i_k = I_s \cos\left(\omega_e t - \frac{2\pi(k-1)}{m}\right) \tag{4.14}$$

$$F_k = \frac{4}{\pi}\left(\frac{N_\mathrm{t} i_k}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sinh\left(h\left(\theta - \frac{2(k-1)\pi}{m}\right)\right)}{h} \tag{4.15}$$

$$F_1 = \frac{4}{\pi}\left(\frac{N_\mathrm{t}\, i_1}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h(\theta)\right)}{h} \tag{4.16}$$

$$F_2 = \frac{4}{\pi}\left(\frac{N_\mathrm{t}\, i_2}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h\left(\theta - \frac{2\pi}{m}\right)\right)}{h} \tag{4.17}$$

$$F_3 = \frac{4}{\pi}\left(\frac{N_\mathrm{t}\, i_3}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h\left(\theta - \frac{4\pi}{m}\right)\right)}{h} \tag{4.18}$$

$$F_{m-1} = \frac{4}{\pi}\left(\frac{N_\mathrm{t}\, i_{m-1}}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h\left(\theta - \frac{2(m-2)\pi}{m}\right)\right)}{h} \tag{4.19}$$

$$F_m = \frac{4}{\pi}\left(\frac{N_{\mathrm{t}}\, i_m}{P}\right) \sum_{h=1,5,7,11,...} \frac{k_h \sin\left(h\left(\theta - \frac{2(m-1)\pi}{m}\right)\right)}{h} \tag{4.20}$$

where,

$$i_1 = I_s \cos\left(\omega_e t\right) \tag{4.21}$$

$$i_2 = I_s \cos\left(\omega_e t - \frac{2\pi}{3}\right) \tag{4.22}$$

$$i_3 = I_s \cos\left(\omega_e t - \frac{4\pi}{m}\right) \tag{4.23}$$

$$i_k = I_s \cos\left(\omega_e t - \frac{2\pi(k-1)}{m}\right) \tag{4.24}$$

So the Resultant MMF of the m phase machine is the addition of the individual phases MMF's show below,

$$F_m = F_1 + F_2 + F_3 + \ldots + F_m \tag{4.25}$$

The phase currents are given as:

$$i_k = I_s \cos\left(\omega_e t - \frac{2\pi(k-1)}{m}\right) \tag{4.26}$$

$$F_R = \frac{4}{\pi} \cdot \left(\frac{N_{\mathrm{t}} \ \cdot I_S}{P} \right) \cdot \sum_{h=1,3,5,7} \frac{K_h}{h}$$
$$\Bigg[\quad \left\{ 2 + \left(\sum_{k=2}^{\frac{m}{2}} 2\cos\left(\frac{2(k-1)\pi}{m}\right)\cos\left(\frac{2h(k-1)\pi}{m}\right)\right)\sin(h\theta)\cos(\omega t) \right\}$$
$$- \left\{ \left(\sum_{k=2}^{\frac{m}{2}} 2\sin\left(\frac{2(k-1)\pi}{m}\right)\sin\left(\frac{2h(k-1)\pi}{m}\right)\right)\cos(h\theta)\sin(\omega t) \right\} \Bigg]$$

This is the required generalized equation of resultant MMF in induction machine for the calculation of the space harmonics having common neutral for even number phases.

Where:

- N_{t} : Number of turns per phase
- i_k : Instantaneous current in the k^{th} phase
- P : Number of pole pairs
- k_h : Winding factor
- m : Number of phases
- h : Harmonic order (only odd harmonics, e.g., $h = 1, 3, 5, \ldots$)
- θ : Electrical space angle

Here:

$$k_h = k_{ph} \cdot k_{dh} \cdot k_{\chi h} \cdot k_{sh} \tag{4.27}$$

- k_h : Winding factor
- k_{ph} : Pitch factor
- k_{dh} : Distribution factor
- $k_{\chi h}$: Skew factor
- k_{sh} : Slot opening factor

4.5 Conclusion

Hence, the core problem addressed in this chapter is the development of a generalized MMF equation applicable multiphase induction motors with **odd number of phases (such as 3, 5, 7, 9, 11...)** as well as **even number of phases (such as 4, 6, 8, 10, 12...)**.

Chapter 5

Unified MMF Equation for Multiphase Induction Machine across All phase numbers having Common Neutral connection

5.1 Introduction

In previous chapters, we derived and analyzed the MMF equations for odd-phases and even-phases for induction machines separately. Chapter 4 presented a mathematical formulation for space harmonics in machines with an odd number of phases and even number of phases both such as **(3, 5, 7, 9....)** and **(4, 6, 8, 10....)** respectively .

To enable a unified approach for space harmonic analysis and MMF distribution across any arbitrary phase number, this chapter introduces a comprehensive generalization of the MMF equation that is applicable to all phase numbers **(1, 2, 3, 4, 5, 6, 7, 8, 9, 10,......)**

5.2 Problem Statement

While the previous chapters formulations have addressed mathematical formulation applicable for odd phases and even phases separately. So there is need of one single formula thar is applicable for **any arbitrary phase (1, 2, 3, 4, 5, 6, 7, 8, 9, 10,......)**.

The major goal is to expand the classical MMF equations, which were originally designed for three-phase systems, so that they may be used to machines with any arbitrary phase number. This formulation should be capable of incorporating varying phase shifts, winding configurations (such as distributed and concentrated windings), and space harmonic effects. The ultimate goal is to enable precise analytical modeling, simulation, and optimization of multiphase electric machines for modern high-performance applications.

5.2.1 Advantage of Generalization of formula

- Enables direct computation for any number of phases.
- Simplifies the analytical process.
- Enhances applicability in machine design and simulation tools.

5.3 Generalized Equation of Resultant MMF for any arbitary Phase (1, 2, 3, 4, 5, 6, 7, 8, 9, 10,......) in Induction Machine

5.3.1 Mathematical formulation

Let the machine have m phases. The MMF for each phase k can be expressed as:

$$F_R = \frac{4}{2\pi}\left(\frac{N_{\mathrm{t}}\ I_S}{P}\right)\sum_{h=1,3,5}\frac{K_h}{h}\left[\left\{I_m\sum_{k=1}^{m}\exp\left(j\left(\theta+\omega t-\frac{2(k-1)\pi}{m(h+1)}\right)\right)\right\}\right.$$
$$\left.+\left\{I_m\sum_{k=1}^{m}\exp\left(j\left(\theta-\omega t-\frac{2(k-1)\pi}{m(h-1)}\right)\right)\right\}\right]$$

$$F_R = \frac{4}{2\pi}\cdot\left(\frac{N_{\mathrm{t}}\ I_S}{P}\right)\sum_{h=1,3,5}\frac{K_h}{h}\left[I_m\left\{e^{j(\theta+\omega t)}\sum_{k=1}^{m}e^{j\left(\frac{2(k-1)\pi}{m}(h+1)\right)}\right\}\right.$$
$$\left.+\ I_m\left\{e^{j(\theta-\omega t)}\sum_{k=1}^{m}e^{j\left(\frac{2(k-1)\pi}{m}(h-1)\right)}\right\}\right]$$

This is the required generalized equation of resultant MMF in induction machine for the calculation of the space harmonics having common neutral for any arbitrary phase.

Where:

- N_{t} : Number of turns per phase
- i_k : Instantaneous current in the k^{th} phase
- P : Number of pole pairs
- k_h : Winding factor
- m : Number of phases
- h : Harmonic order (only odd harmonics, e.g., $h = 1, 3, 5, \ldots$)
- θ : Electrical space angle

Here:

$$k_h = k_{ph} \cdot k_{dh} \cdot k_{\chi h} \cdot k_{sh} \tag{5.1}$$

- k_h : Winding factor
- k_{ph} : Pitch factor
- k_{dh} : Distribution factor
- $k_{\chi h}$: Skew factor
- k_{sh} : Slot opening factor

5.3.2 Conclusion :

By combining the methodologies developed in 4, this chapter provides a universal formulation for MMF analysis in multiphase machines for common neutral connection. This comprehensive equation forms the basis for advanced studies in machine harmonics and paves the way for efficient multiphase electric machine designs.

Hence, the core problem addressed in this chapter is the development of a generalized MMF equation applicable multiphase induction motors with a **any arbitrary phase (such as 1,2,3,4,5,6,7,8,9,10,11...)**.

Chapter 6

Generalized Resultant MMF Equations for Asymmetrical Isolated Neutral Connections in Odd phase and Even phase Induction Machine

6.1 Introduction

This chapter presents a generalized formulation for the resultant magnetomotive force (MMF) in Asymmetrical multiphase systems with isolated neutral connections, covering both:

- **Odd-phase systems** (e.g., 9, 15, 21, 27.....)
- **Even-phase systems** (e.g., 6, 12, 18, 24, 30.....)

In the study of multiphase induction machines, winding arrangement is crucial in determining the magnetic field distribution, harmonic content, and overall machine performance. When working for both odd number of phases (e.g., 9, 15, 21, 27, 33...) and even number of phases (e.g., 6, 12, 18, 24, 30..), asymmetrical isolated neutral connection becomes an effective solution for harmonic reduction and performance optimization.

the asymmetrical isolated configuration intentionally introduces unequal phase displacement among different phase groups. This leads to an asymmetric MMF distribution which can be strategically used to suppress selected harmonic components or to tailor the machine's dynamic response for specialized control requirements. Though this introduces complexity in analysis, it offers advanced degrees of freedom in the design of modern multiphase drives and machines.

6.2 Problem Statement

The investigation of space harmonics in such systems necessitates a more generalized technique to calculating magnetomotive force (MMF). While the MMF equations common neutral multiphase systems are explained in chapter 4. The available literature does not provide a thorough mathematical formulation that describes the behavior of asymmetrical isolated neutral systems.

6.2.1 Such a generalized equation is essential for:

- Analyzing air gap MMF (Magneto-Motive Force) distributions
- Estimating space harmonic amplitudes
- Designing winding configurations that minimize undesirable harmonics in high-performance multiphase drives

The behavior of the resulting magnetomotive force (MMF), which controls the torque output and the spatial distribution of magnetic flux in the air gap, is a crucial component of machine performance. Asymmetrical windings and isolated neutral configurations are common in real-world applications, which have a substantial impact on the MMF profile. Conventional models frequently assume balanced windings and symmetrical connections.

In the analysis and design of multiphase electric machines, the configuration of the neutral connection plays a critical role in determining the machine's electromagnetic performance, harmonic behavior, and control capabilities. While same-neutral (common-neutral) configurations are widely used for their simplicity, isolated neutral connections have gained increasing relevance in advanced machine applications due to their inherent flexibility and harmonic mitigation capabilities.

6.3 Isolated Neutral Connection :

Refers to a configuration where each group of phase windings, or each subset of a multiphase system, has its own independent neutral point. This arrangement allows for improved control over individual phase groups, enhanced fault tolerance, and significant opportunities for space harmonic suppression.

Isolated neutral configurations can be categorized further into two major types based on the symmetry of phase displacement and structural layout:

6.3.1 (a) Symmetrical Isolated Neutral Connection :

In this type, the phase windings are grouped such that each subset forms a balanced and symmetrical configuration. The electrical displacement between adjacent phases remains uniform across all groups. Such arrangements are particularly effective in achieving uniform magnetic field distribution and are often utilized to cancel specific harmonics by exploiting phase-shifting techniques. This configuration supports harmonic mitigation strategies and is well-suited for high-performance, high-reliability applications.

6.3.2 (b) Asymmetrical Isolated Neutral Connection :

Unlike the symmetrical case, the asymmetrical isolated configuration intentionally introduces unequal phase displacement among different phase groups. This leads to an asymmetric MMF distribution which can be strategically used to suppress selected harmonic components or to tailor the machine's dynamic response for specialized control requirements. Though this introduces complexity in analysis, it offers advanced degrees of freedom in the design of modern multiphase drives and machines.

Overall, isolated neutral connections offer a more modular and analytically rich approach to electric machine design, especially in the context of space harmonic control, fault-tolerant operation, and custom waveform synthesis. Their use is expanding in aerospace, traction, and renewable energy systems where performance, efficiency, and robustness are critical.

6.4 Nine Phase machine with Isolated neutral Asymmetrical connection :

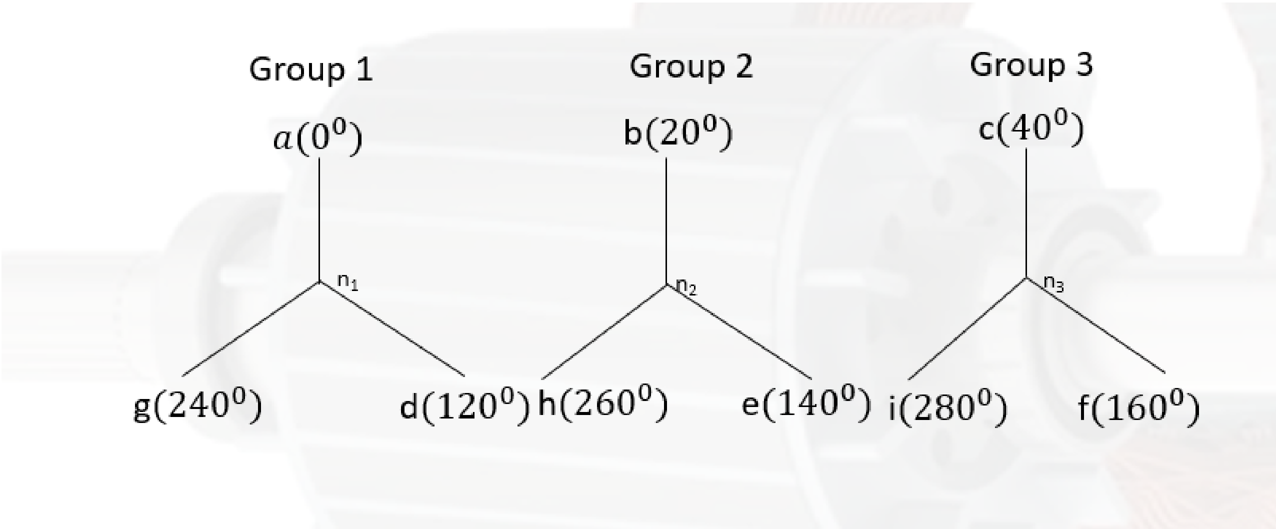


Figure 6.1: Nine phase asymmetrical isolated neutral connection

Nine phase machine is divided into group of three sets (G_1, G_2, G_3). Each individual group has three phases and has a phase shift of 120(degree).

Phase shift between phase a, phase b, phase c for the Asymmetrical isolated neutral connection is :

$$\text{Phase displacement} = \frac{360^\circ}{2m}$$

Phase shift between phase a, phase b, phase c for the Asymmetrical isolated neutral for Nine phase connection is :

$$\text{Phase displacement} = \frac{360^\circ}{2 * 9} = 20^\circ$$

Group 1

$$F_a = \frac{4}{\pi}\left(\frac{N_{\mathrm{t}}\, i_1}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h(\theta)\right)}{h} \tag{6.1}$$

$$F_d = \frac{4}{\pi}\left(\frac{N_{\mathrm{t}}\, i_2}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h\left(\theta - \frac{2\pi}{3}\right)\right)}{h} \tag{6.2}$$

$$F_g = \frac{4}{\pi}\left(\frac{N_{\mathrm{t}}\, i_3}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h\left(\theta - \frac{4\pi}{3}\right)\right)}{h} \tag{6.3}$$

$$F_1 = F_a + F_d + F_g$$

(6.4)

Group 2

$$F_b = \frac{4}{\pi}\left(\frac{N_{\mathrm{t}}\, i_b}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h(\theta - \frac{\pi}{9}\right)}{h} \tag{6.5}$$

$$F_e = \frac{4}{\pi}\left(\frac{N_{\mathrm{t}}\, i_e}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h\left(\theta - \frac{7\pi}{9}\right)\right)}{h} \tag{6.6}$$

$$F_h = \frac{4}{\pi}\left(\frac{N_{\mathrm{t}}\, i_h}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h\left(\theta - \frac{13\pi}{9}\right)\right)}{h} \tag{6.7}$$

$$F_2 = F_b + F_e + F_h \tag{6.8}$$

Group 3

$$F_c = \frac{4}{\pi}\left(\frac{N_t\, i_c}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h(\theta - \frac{2\pi}{9}\right)}{h} \tag{6.9}$$

$$F_f = \frac{4}{\pi}\left(\frac{N_t\, i_f}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h\left(\theta - \frac{8\pi}{9}\right)\right)}{h} \tag{6.10}$$

$$F_i = \frac{4}{\pi}\left(\frac{N_t\, i_i}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h\left(\theta - \frac{14\pi}{9}\right)\right)}{h} \tag{6.11}$$

$$F_3 = F_c + F_f + F_i \tag{6.12}$$

Now

$$F_R = F_1 + F_2 + F_3 \tag{6.13}$$

$$\begin{aligned} F_R = \frac{1}{2}\cdot\left(\frac{4}{\pi}\right)\cdot\left(\frac{NI_S}{P}\right)\cdot\Bigg\{\sum_{h=1,3,5}\frac{K_h}{h}\Big[&(1 + 2\cos(20)\cos(h\cdot 20) + 2\cos(40)\cos(h\cdot 40) \\ &+ 2\cos(120)\cos(h\cdot 120) + 2\cos(260)\cos(h\cdot 260)\sin(h\theta)\cos(\omega t)\Big] \\ &- \sum_{h=1,3,5}\frac{K_h}{h}\Big(2\sin(20)\sin(h\cdot 20) + 2\sin(40)\sin(h\cdot 40) \\ &+ 2\sin(120)\sin(h\cdot 120) + 2\sin(260)\sin(h\cdot 260)\Big)\cos(h\theta)\sin(\omega t)\Bigg\} \end{aligned}$$

For M phase machine with Isolated asymmetrical neutral connection

$$
\begin{aligned}
F_r = \frac{1}{2}\left(\frac{4}{\pi}\right)\left(N\,\frac{I_s}{P}\right) \sum_{h=1,3,5} \frac{K_h}{h} \Bigg[& \left\{ 1 + \sum_{K=2}^{G} 2\cos\!\left(\frac{(K-1)\pi}{m}\right) \cos\!\left(\frac{h\,(K-1)\pi}{m}\right) \right\} \\
& + \sum_{K\,=\,m-(G-1)} 2\cos\!\left(\frac{(K-1)\pi}{m}\right) \cos\!\left(\frac{h\,(K-1)\pi}{m}\right) \\
& + \sum_{K\,=\,2\,\left(m-(G-1)\right)}^{2\left(m-(G-1)\right)\,-\,\left(2\,m-\frac{m-1}{2}\right)} 2\cos\!\left(\frac{(K-1)\pi}{m}\right) \cos\!\left(\frac{h\,(K-1)\pi}{m}\right) \cos(h\theta)\,\sin(\omega t) \Bigg] \\
- \sum_{h=1,3,5} \frac{K_h}{h} \Bigg[& \sum_{K=2}^{G} 2\sin\!\left(\frac{(K-1)\pi}{m}\right) \sin\!\left(\frac{h\,(K-1)\pi}{m}\right) \\
& + \sum_{K\,=\,m-(G-1)} 2\sin\!\left(\frac{(K-1)\pi}{m}\right) \sin\!\left(\frac{h\,(K-1)\pi}{m}\right) \\
& + \sum_{K\,=\,2\,\left(m-(G-1)\right)}^{2\left(m-(G-1)\right)\,-\,\left(2\,m-\frac{m-1}{2}\right)} 2\sin\!\left(\frac{(K-1)\pi}{m}\right) \sin\!\left(\frac{h\,(K-1)\pi}{m}\right) \sin(h\theta)\,\cos(\omega t) \Bigg].
\end{aligned}
$$

Where:

- G : Total number of group
- N_{t} : Number of turns per phase
- i_k : Instantaneous current in the k^{th} phase
- P : Number of pole pairs
- k_h : Winding factor
- m : Number of phases
- h : Harmonic order (only odd harmonics, e.g., $h = 1, 3, 5, \ldots$)
- θ : Electrical space angle

Here:

$$k_h = k_{ph} \cdot k_{dh} \cdot k_{\chi h} \cdot k_{sh} \tag{6.14}$$

- k_h : Winding factor
- k_{ph} : Pitch factor
- k_{dh} : Distribution factor
- $k_{\chi h}$: Skew factor
- k_{sh} : Slot opening factor

6.5 Generalized Equation of Resultant MMF of Asymmetrical Isolated neutral connection for even Phases (6,12,18,24,30...)

6.5.1 Six Phase machine with Asymmetrical Isolated neutral connection :

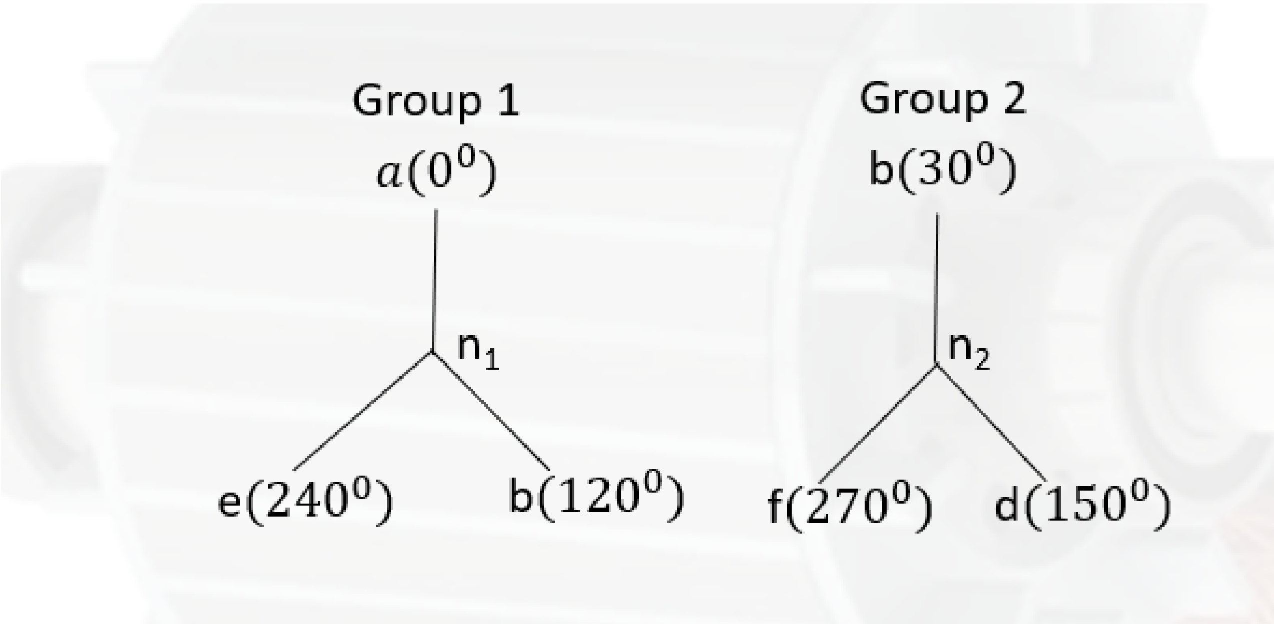


Figure 6.2: Nine phase asymmetrical isolated neutral connection

Six phase machine is divided into group of two sets (G_1, G_2). Each individual group has three phases and has a phase shift of 120(deg).

Phase shift between phase a, phase b for the Asymmetrical isolated neutral connection is :

$$\text{Phase displacement} = \frac{360°}{2m}$$

Phase shift between phase a, phase b, phase c for the Asymmetrical isolated neutral for Nine phase connection is :

$$\text{Phase displacement} = \frac{360^\circ}{2*6} = 30^\circ$$

Group 1

$$F_a = \frac{4}{\pi}\left(\frac{N_t\, i_a}{P}\right)\sum_{h=1,5,7,11,\ldots}\frac{k_h \sin\left(h(\theta)\right)}{h} \tag{6.15}$$

$$F_c = \frac{4}{\pi}\left(\frac{N_t\, i_c}{P}\right)\sum_{h=1,5,7,11,\ldots}\frac{k_h \sin\left(h\left(\theta - \frac{2\pi}{3}\right)\right)}{h} \tag{6.16}$$

$$F_e = \frac{4}{\pi}\left(\frac{N_t\, i_e}{P}\right)\sum_{h=1,5,7,11,\ldots}\frac{k_h \sin\left(h\left(\theta - \frac{4\pi}{3}\right)\right)}{h} \tag{6.17}$$

$$F_1 = F_a + F_c + F_e$$

(6.18)

Group 2

$$F_b = \frac{4}{\pi}\left(\frac{N_t\, i_b}{P}\right)\sum_{h=1,5,7,11,\ldots}\frac{k_h \sin\left(h(\theta - \frac{\pi}{6}\right)}{h} \tag{6.19}$$

$$F_e = \frac{4}{\pi}\left(\frac{N_t\, i_e}{P}\right)\sum_{h=1,5,7,11,\ldots}\frac{k_h \sin\left(h\left(\theta - \frac{5\pi}{6}\right)\right)}{h} \tag{6.20}$$

$$F_h = \frac{4}{\pi}\left(\frac{N_t\, i_h}{P}\right) \sum_{h=1,5,7,11,\ldots} \frac{k_h \sin\left(h\left(\theta - \frac{3\pi}{2}\right)\right)}{h} \tag{6.21}$$

$$F_2 = F_b + F_d + F_f \tag{6.22}$$

Now

$$F_R = F_1 + F_2 \tag{6.23}$$

$$F_r = \frac{1}{2}\cdot\left(\frac{4}{\pi}\right)\cdot\left(\frac{NI_S}{P}\right)\cdot$$

$$\Bigg[\ \sum_{\substack{h=1\\ h \text{ odd}}}^{\infty} \frac{K_h}{h}\left(1 + 2\cos(30^\circ)\cos(h\cdot 30^\circ) + 2\cos(120^\circ)\cos(h\cdot 120^\circ)\right)\sin(h\theta)\cos(\omega t)$$

$$-\,(\sum_{\substack{h=1\\ h \text{ odd}}}^{\infty} \frac{K_h}{h}\left(2\sin(30^\circ)\sin(h\cdot 30^\circ) + 2\sin(120^\circ)\sin(h\cdot 120^\circ)\right)$$

$$+\sin(270^\circ)\sin(h\cdot 270^\circ)\cdot\cos(h\theta)\sin(\omega t))\Bigg]$$

6.5.2 Conclusion

A thorough mathematical model for the generalized resultant MMF in asymmetrical even-phase electrical machines with isolated neutral connections has been developed in this chapter. The study fills a major gap in multiphase machine modeling by concentrating on phase configurations of odd number of phases (3, 5, 7, 9....) as well as even number of phases (6, 12, 18, 24....) particularly for systems that operate under asymmetrical winding and non-standard phase angles. The behavior of space harmonics and their impact on the dispersion of the magnetic field are well captured by the derived equation.

Chapter 7

Generalized Resultant MMF Equations for Symmetrical Isolated Neutral Connections in Odd phase and Even phase Induction Machine

7.1 Introduction

This chapter presents a generalized formulation for the resultant magnetomotive force (MMF) in symmetrical multiphase systems with isolated neutral connections, covering both:

- **Odd-phase systems** (e.g., 9, 15, 21, 27.....)
- **Even-phase systems** (e.g., 6, 12, 18, 24, 30.....)

In the study of multiphase induction machines, winding arrangement is crucial in determining the magnetic field distribution, harmonic content, and overall machine performance. When working for both odd number of phases (e.g., 9, 15, 21, 27, 33...) and even number of phases (e.g., 6, 12, 18, 24, 30..), a symmetrical isolated neutral connection becomes an effective solution for harmonic reduction and performance optimization.

Unlike common neutral systems, isolated neutral systems have independent neutral points for each phase group. In a symmetrical arrangement, the phases are uniformly separated in the electrical space domain, which ensures consistent phase displacement across the winding pattern. This symmetry leads in equal magnetic field contributions from each phase group, which, when properly integrated, can lead to considerable cancellation of space harmonics.

7.2 Problem Statement

The investigation of space harmonics in such systems necessitates a more generalized technique to calculating magnetomotive force (MMF). While the MMF equations common neutral multiphase systems are explained in chapter 3 and chapter 4. The available literature does not provide a thorough mathematical formulation that describes the behavior of symmetrical isolated neutral systems.

7.2.1 Such a generalized equation is essential for:

- Analyzing air gap MMF (Magneto-Motive Force) distributions
- Estimating space harmonic amplitudes
- Designing winding configurations that minimize undesirable harmonics in

high-performance multiphase drives.

7.2.2 Symmetrical Isolated Neutral Connection :

In this type, the phase windings are grouped such that each subset forms a balanced and symmetrical configuration. The electrical displacement between adjacent phases remains uniform across all groups. Such arrangements are particularly effective in achieving uniform magnetic field distribution and are often utilized to cancel specific harmonics by exploiting phase-shifting techniques. This configuration supports harmonic mitigation strategies and is well-suited for high-performance, high-reliability applications.

7.3 Nine Phase machine with Isolated neutral Symmetrical connection :

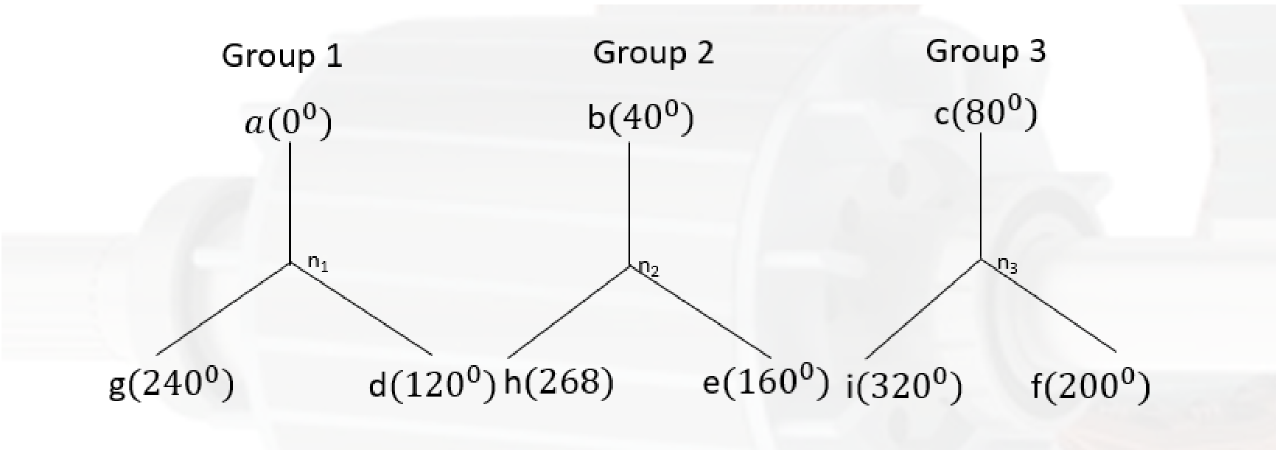


Figure 7.1: Nine phase asymmetrical isolated neutral connection

Nine phase machine is divided into group of three sets (G_1, G_2, G_3). Each individual group has three phases and has a phase shift of 120(deg).

Phase shift between phase a, phase b, phase c for the Asymmetrical isolated neutral connection is :

$$\text{Phase displacement} = \frac{360^\circ}{m}$$

Phase shift between phase a, phase b, phase c for the Asymmetrical isolated neutral for Nine phase connection is :

$$\text{Phase displacement} = \frac{360^\circ}{9} = 40^\circ$$

Group 1

$$F_a = \frac{4}{\pi}\left(\frac{N_t\, i_1}{P}\right) \sum_{h=1,5,7,11,\ldots} \frac{k_h \sin\left(h(\theta)\right)}{h} \tag{7.1}$$

$$F_d = \frac{4}{\pi}\left(\frac{N_t\, i_2}{P}\right) \sum_{h=1,5,7,11,\ldots} \frac{k_h \sin\left(h\left(\theta - \frac{2\pi}{3}\right)\right)}{h} \tag{7.2}$$

$$F_g = \frac{4}{\pi}\left(\frac{N_t\, i_3}{P}\right) \sum_{h=1,5,7,11,\ldots} \frac{k_h \sin\left(h\left(\theta - \frac{4\pi}{3}\right)\right)}{h} \tag{7.3}$$

$$F_1 = F_a + F_d + F_g$$

(7.4)

Group 2

$$F_b = \frac{4}{\pi}\left(\frac{N_t\, i_b}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h(\theta - \frac{2\pi}{9}\right)}{h} \tag{7.5}$$

$$F_e = \frac{4}{\pi}\left(\frac{N_t\, i_e}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h\left(\theta - \frac{8\pi}{9}\right)\right)}{h} \tag{7.6}$$

$$F_h = \frac{4}{\pi}\left(\frac{N_t\, i_h}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h\left(\theta - \frac{14\pi}{9}\right)\right)}{h} \tag{7.7}$$

$$F_2 = F_b + F_e + F_h \tag{7.8}$$

Group 3

$$F_c = \frac{4}{\pi}\left(\frac{N_t\, i_c}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h(\theta - \frac{4\pi}{9}\right)}{h} \tag{7.9}$$

$$F_f = \frac{4}{\pi}\left(\frac{N_t\, i_f}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h\left(\theta - \frac{10\pi}{9}\right)\right)}{h} \tag{7.10}$$

$$F_i = \frac{4}{\pi}\left(\frac{N_t\, i_i}{P}\right)\sum_{h=1,5,7,11,...}\frac{k_h \sin\left(h\left(\theta - \frac{16\pi}{9}\right)\right)}{h} \tag{7.11}$$

$$F_3 = F_c + F_f + F_i \tag{7.12}$$

Now

$$F_R = F_1 + F_2 + F_3 \tag{7.13}$$

$$F_r = \frac{1}{2} \cdot \left(\frac{4}{\pi}\right) \cdot \left(\frac{NI_S}{P}\right)$$
$$\Bigg[\sum_{\substack{h=1 \\ h \text{ odd}}}^{\infty} \frac{K_h}{h}\Big(1 + 2\cos(40^\circ)\cos(h \cdot 40^\circ) + 2\cos(80^\circ)\cos(h \cdot 80^\circ)$$
$$+ 2\cos(120^\circ)\cos(h \cdot 120^\circ) + 2\cos(160^\circ)\cos(h \cdot 160^\circ)\Big) \cdot \sin(h\theta) \cdot \cos(\omega t)$$
$$- (\sum_{\substack{h=1 \\ h \text{ odd}}}^{\infty} \frac{K_h}{h}\Big(2\sin(40^\circ)\sin(h \cdot 40^\circ) + 2\sin(80^\circ)\sin(h \cdot 80^\circ)$$
$$+ 2\sin(120^\circ)\sin(h \cdot 120^\circ) + 2\sin(160^\circ)\sin(h \cdot 160^\circ)\Big) \cdot \cos(h\theta) \cdot \sin(\omega t)\Bigg]$$

7.4 Generalized Equation of Resultant MMF of Symmetrical Isolated neutral connection for Odd Phases (9,15,21,27...)

$$F_r = \frac{4}{\pi} \cdot \left(\frac{N \cdot I_S}{P}\right) \cdot \sum_{h=1,3,5,7} \frac{K_h}{h}$$
$$\Bigg[\left\{1 + \left(\sum_{k=2}^{\frac{(m-1)}{2}+1} 2\cos\left(\frac{2(k-1)\pi}{m}\right)\cos\left(\frac{2h(k-1)\pi}{m}\right)\right)\sin(h\theta)\cos(\omega t)\right\}$$
$$- \left\{\left(\sum_{k=2}^{\frac{(m-1)}{2}+1} 2\sin\left(\frac{2(k-1)\pi}{m}\right)\sin\left(\frac{2h(k-1)\pi}{m}\right)\right)\cos(h\theta)\sin(\omega t)\right\}\Bigg]$$

7.5 Generalized Equation of Resultant MMF of Symmetrical Isolated Neutral connection for even Phases (6,12,18,24,30...)

7.5.0.1 Six Phase machine with Symmetrical Isolated neutral Symmetrical connection :

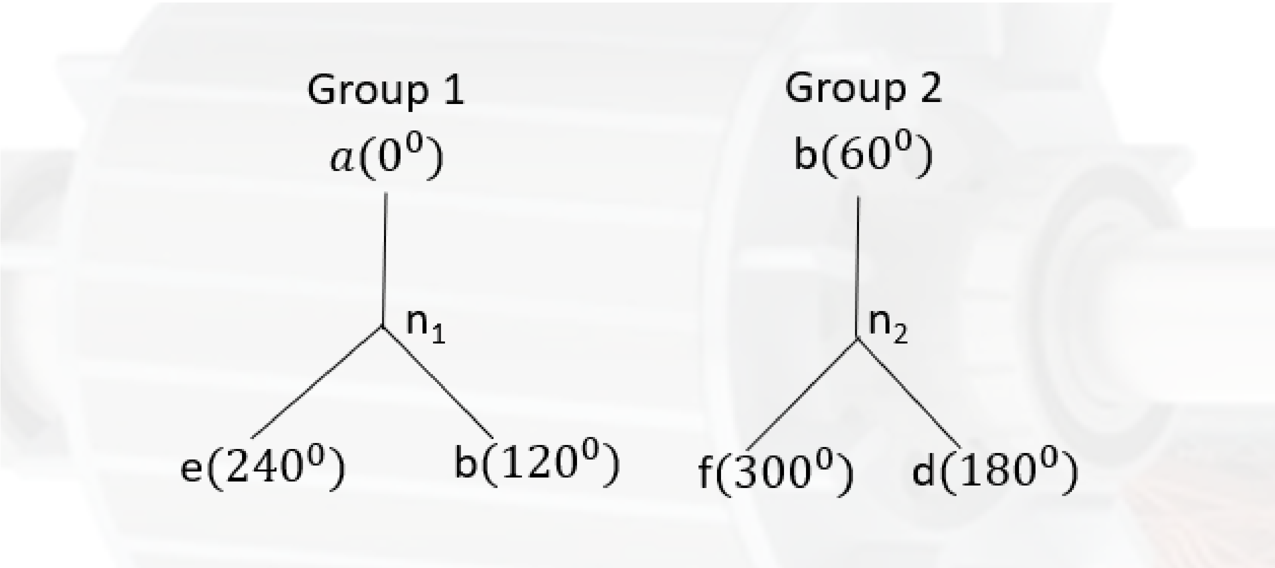


Figure 7.2: Nine phase asymmetrical isolated neutral connection

Six phase machine is divided into group of two sets (G_1, G_2). Each individual group has three phases and has a phase shift of 120(deg).

7.5.0.2 Phase shift between phase a, phase b for the Symmetrical isolated neutral connection is :

$$\text{Phase displacement} = \frac{360^\circ}{m}$$

$$\text{Phase displacement} = \frac{360^\circ}{6} = 60^\circ$$

Group 1

$$F_a = \frac{4}{\pi}\left(\frac{N_t\, i_a}{P}\right)\sum_{h=1,5,7,11,\ldots}\frac{k_h \sin\left(h(\theta)\right)}{h} \tag{7.14}$$

$$F_c = \frac{4}{\pi}\left(\frac{N_t\, i_c}{P}\right)\sum_{h=1,5,7,11,\ldots}\frac{k_h \sin\left(h\left(\theta-\frac{2\pi}{3}\right)\right)}{h} \tag{7.15}$$

$$F_e = \frac{4}{\pi}\left(\frac{N_t\, i_e}{P}\right)\sum_{h=1,5,7,11,\ldots}\frac{k_h \sin\left(h\left(\theta-\frac{4\pi}{3}\right)\right)}{h} \tag{7.16}$$

$$F_1 = F_a + F_c + F_e$$

(7.17)

Group 2

$$F_b = \frac{4}{\pi}\left(\frac{N_t\, i_b}{P}\right)\sum_{h=1,5,7,11,\ldots}\frac{k_h \sin\left(h(\theta-\frac{\pi}{3}\right)}{h} \tag{7.18}$$

$$F_e = \frac{4}{\pi}\left(\frac{N_t\, i_e}{P}\right)\sum_{h=1,5,7,11,\ldots}\frac{k_h \sin\left(h\left(\theta-\frac{\pi}{1}\right)\right)}{h} \tag{7.19}$$

$$F_f = \frac{4}{\pi}\left(\frac{N_t\, i_f}{P}\right)\sum_{h=1,5,7,11,\ldots}\frac{k_h \sin\left(h\left(\theta-\frac{5\pi}{3}\right)\right)}{h} \tag{7.20}$$

$$F_2 = F_b + F_d + F_f \tag{7.21}$$

Now

$$F_R = F_1 + F_2 \tag{7.22}$$

$$F_r = \cdot \left(\frac{4}{\pi}\right) \cdot \left(\frac{NI_S}{P}\right) \cdot \Bigg[\sum_{h=1,3,5,7} \frac{K_h}{h} \left(2 + 2\cos(60^\circ)\cos(h \cdot 60^\circ) + 2\cos(120^\circ)\cos(h \cdot 120^\circ)\right)\sin(h\theta)\cos(\omega t) - \Big(\sum_{h=1,3,5,7} \frac{K_h}{h} \left(2\sin(60^\circ)\sin(h \cdot 60^\circ) + 2\sin(120^\circ)\sin(h \cdot 120^\circ)\right) \cdot \cos(h\theta)\sin(\omega t)\Big)\Bigg]$$

7.5.1 Generalized Equation of Resultant MMF of Symmetrical Isolated neutral connection for even Phases (6,12,18,24,30...)

$$F_r = \frac{4}{\pi} \cdot \left(\frac{N \cdot I_S}{P}\right) \cdot \sum_{h=1,3,5,7} \frac{K_h}{h}$$

$$\Bigg[\quad \left\{ 2 + \left(\sum_{k=2}^{\frac{m}{2}} 2\cos\left(\frac{2(k-1)\pi}{m}\right) \cos\left(\frac{2h(k-1)\pi}{m}\right) \right) \sin(h\theta)\cos(\omega t) \right\}$$

$$- \left\{ \left(\sum_{k=2}^{\frac{m}{2}} 2\sin\left(\frac{2(k-1)\pi}{m}\right) \sin\left(\frac{2h(k-1)\pi}{m}\right) \right) \cos(h\theta)\sin(\omega t) \right\} \Bigg]$$

7.6 Conclusion

The resulting magneto-motive force (MMF) for multiphase induction machines with symmetrical isolated neutral connections has been generalized and provided in this chapter. The analytical model developed here addresses a key gap in the existing literature by extending MMF equations to even-phase systems beyond the conventional three-phase configuration.

Chapter 8

Performance Comparison of the Two different double layer Winding layouts of Three Phase Induction Motor

8.1 Objective :

a) An electric motor's magnetic field distribution and overall performance are heavily influenced by its winding design. In this goal, we examine and compare two possible winding patterns for a three-phase, four-pole motor with 36 stator slots. Each arrangement is studied in terms of the per-phase Magneto Motive Force (MMF) waveform, which has significant effects on torque generation, harmonic content, and vibration.

b) To evaluate and compare the machine performance characteristics of two different winding configurations (Winding Layout 1 and Winding Layout 2) under identical operating conditions using Altair Flux Motor software.

8.2 Motor Specifications

- Number of slots: 36
- Number of poles: 4
- Number of phases: 3
- Winding type: Double layer, distributed winding

Slot Angle and Distribution :

The angular distance between adjacent slots, known as the slot angle, is given by:

$$\gamma = \frac{180 \times P}{S} = \frac{180 \times 4}{36} = 20^\circ \text{ (electrical)}$$

The number of slots per pole per phase (q) is calculated as:

The slot per pole per phase determines how the windings are distributed around the stator or rotor. A higher SPP means that the windings are more spread out, which can lead to a smoother and more sinusoidal distribution of the magnetomotive force (MMF). Mathematically,

$$q = \frac{S}{P \times \text{Ph}} = \frac{36}{4 \times 3} = 3$$

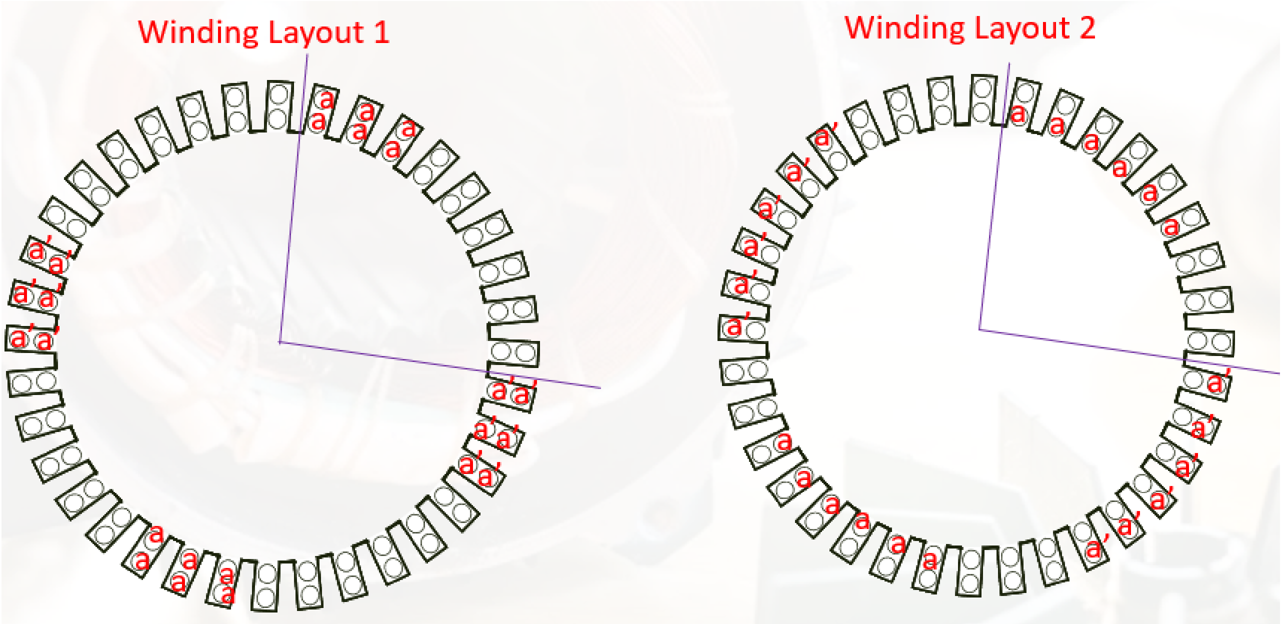


Figure 8.1: Winding layouts of two different winding configuration

8.3 Winding Layouts

Two different winding layouts are considered, both with the same number of slots, poles, and phases, but differing in the coil distribution and placement.

8.3.0.1 Winding Layout 1

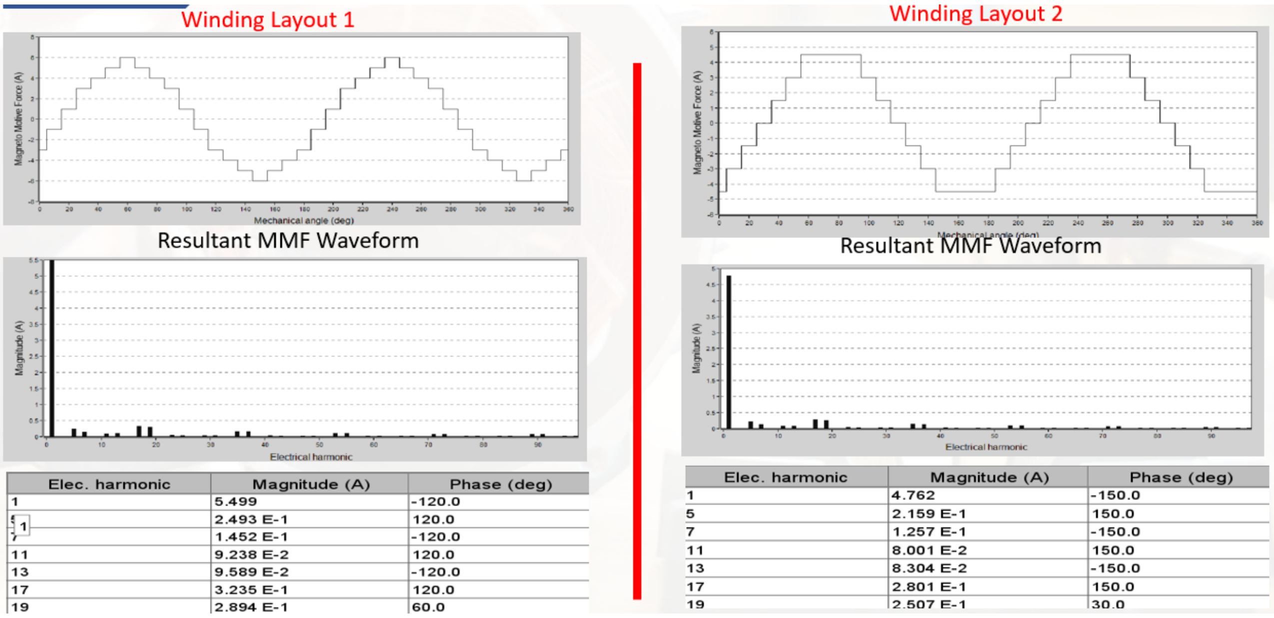
All the conductors of phase A under one pole are distributed in three slots.

8.3.0.2 Winding Layout 2

All the conductors of phase A under one pole are distributed in six slots.

8.4 MMF Waveform Analysis

Each layout's Resultant MMF waveform shows the spatial total of the ampere-turns that each coil contributed. The MMF profile is smoother and more sinusoidal when the winding pattern is of superior quality.



Elec. harmonic	Magnitude (A)	Phase (deg)
1	5.499	-120.0
5	2.493 E-1	120.0
7	1.452 E-1	-120.0
11	9.238 E-2	120.0
13	9.589 E-2	-120.0
17	3.235 E-1	120.0
19	2.894 E-1	60.0

Elec. harmonic	Magnitude (A)	Phase (deg)
1	4.762	-150.0
5	2.159 E-1	150.0
7	1.257 E-1	-150.0
11	8.001 E-2	150.0
13	8.304 E-2	-150.0
17	2.801 E-1	150.0
19	2.507 E-1	30.0

Figure 8.2: Resultant MMF Waveforms of two different winding configuration

8.4.1 Observations

- **Layout 1:** Produces a stepped MMF waveform with moderate harmonic content.
- **Layout 2:** Exhibits a more refined MMF distribution, closer to a sinusoidal shape, implying lower harmonic distortion and better torque quality.

8.4.2 Observations

- **Layout 1:** Exhibits a more refined MMF distribution, closer to a sinusoidal shape, implying lower harmonic distortion and better torque quality.
- **Layout 2:** Produces a stepped MMF waveform with moderate harmonic content.

8.5 Performance Evaluation of Different Winding Layouts

8.5.0.1 T(Slip) Performance Mapping Test in Altair Flux Motor software

The primary aim of the **"Performance Mapping – Sine wave – Motor – T(Slip)"** test is to characterize the electromechanical behavior of the machine across a defined operating speed range under motor mode operation. This test is vital for:

- Evaluating torque production against slip.
- Determining electromagnetic efficiency zones.
- Generating a map of key performance indicators (KPIs) such as:
  - Torque,
  - Stator current,
  - Magnetic flux density,
  - Core loss,
  - Electromagnetic efficiency.

8.5.1 Machine Operating Conditions

- Frequency, $f = 50\,\text{Hz}$
- Number of poles, $P = 4$
- Supply line voltage, $V = 415\,\text{V}$
- % slip, $S = 5\%$

8.5.2 Machine Performance - User Working Point Test

The measured performance parameters in steady state are presented and discussed below.

Winding Layout 1

Power supply frequency	50 Hz
Mechanical Torque	15.073 Nm
Mechanical Power	2249.342 W
Machine efficiency	84.06 %
Slip	5 %
Line current	4.31 A
Line voltage	415
Speed	1425 rpm
Machine electrical power	2644.302 W
Apparent Power	3097.706 VA
Machine total loss	394.959 W
Power factor	0.853
Flux density , Average Rectified Value	0.504

Winding Layout 2

Power supply frequency	50 Hz
Mechanical Torque	19.0 Nm
Mechanical Power	2836.06 W
Machine efficiency	82.28 %
Slip	5 %
Line current	5.6 A
Line voltage	415
Speed	1425 rpm
Machine electrical power	3446.806 W
Apparent Power	4026.01 VA
Machine total loss	610.74 W
Power factor	0.856
Flux density , Average Rectified Value	0.326

Figure 8.3: Machine Performance - User Working Point Test

8.5.3 Machine Performance - Starting Torque , Motering Mode :

Winding Layout 1

Power supply frequency	50 Hz
Mechanical Torque	14.01 Nm
Mechanical Power	0 W
Machine efficiency	-
Slip	100 %
Line current	14.255 A
Line voltage	415
Speed	0 rpm
Machine electrical power	5122.217 W
Apparent Power	10246.84 VA
Machine total loss	5122.217 W
Power factor	0.49
Flux density , Average Rectified Value	0.504

Winding Layout 2

Power supply frequency	50 Hz
Mechanical Torque	16.42 Nm
Mechanical Power	0.0 W
Machine efficiency	-
Slip	100%
Line current	17.89 A
Line voltage	415
Speed	0 rpm
Machine electrical power	7132.984 W
Apparent Power	12808.44 VA
Machine total loss	7132.984 W
Power factor	0.55
Flux density , Average Rectified Value	0.499

Figure 8.4: Machine Performance - Starting Torque , Motering Mode

8.5.4 Machine Performance - Breakdown Torque , Motering Mode :

Winding Layout 1

Power supply frequency	50 Hz
Mechanical Torque	22.054 Nm
Mechanical Power	2886.901 W
Machine efficiency	62.191 %
Slip	16.667 %
Line current	9.031 A
Line voltage	415
Speed	1250 rpm
Machine electrical power	4641.997 W
Apparent Power	6491.71 VA
Machine total loss	1755.906 W
Power factor	0.715
Flux density , Average Rectified Value	0.41

Winding Layout 2

Power supply frequency	50 Hz
Mechanical Torque	26.47Nm
Mechanical Power	3464.93W
Machine efficiency	57.35 %
Slip	16.667 %
Line current	11.441 A
Line voltage	415
Speed	1250 rpm
Machine electrical power	6040.965 W
Apparent Power	8223.64 VA
Machine total loss	2576.036 W
	W
Power factor	0.73
Flux density , Average Rectified Value	0.445

Figure 8.5: Machine Performance - Breakdown Torque , Motering Mode

8.5.5 Torque Vs Slip and Efficiency Vs Slip Curve :

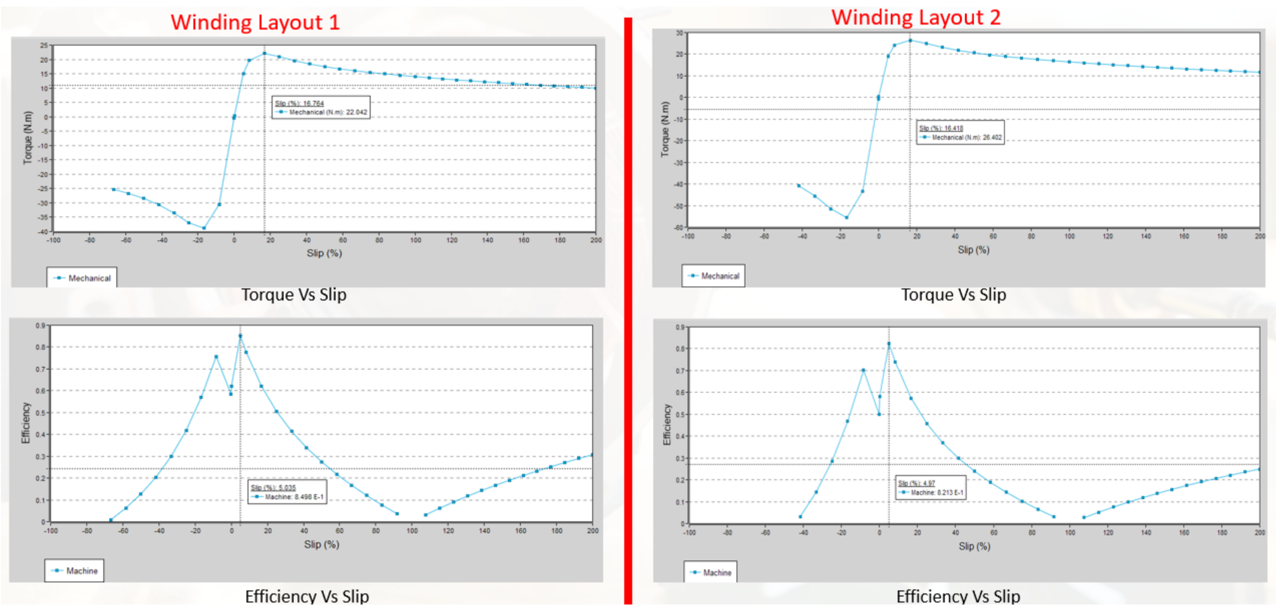


Figure 8.6: Torque Vs Slip and Efficiency Vs Slip Curve

Conclusion :

If the primary goal is to achieve higher mechanical torque and power output, then Winding Layout 2 is clearly better. It delivers significantly more rotational force and can do more work.

If efficiency is the top priority, and you want to minimize energy consumption and losses, then Winding Layout 1 has a slight edge due to its higher machine efficiency and lower total losses.

Winding Layout 2 comes at the cost of higher current draw, higher electrical power consumption, and higher losses. This might be a concern for the sizing of your power supply, wiring, and thermal management.

The higher flux density in Winding Layout 1 could have implications for saturation and core losses, but without more context on the motor design and materials, it's difficult to say definitively.

Which configuration is better :

For applications demanding maximum performance (torque and power), Winding Layout 2 is superior.

For applications where energy efficiency and minimizing losses are paramount, Winding Layout 1 is a better choice.

8.5.6 Transient behavior of Magnetic filed density for both different configuration :

Magnetic flux density distribution and harmonic content in the airgap of electrical machines have significant effects on machine performance parameters such as torque ripple, noise, vibration, and efficiency. This section examines and compares the flux density waveforms and harmonic spectra for two different winding arrangements, known as Winding Layout 1 and Winding Layout 2.

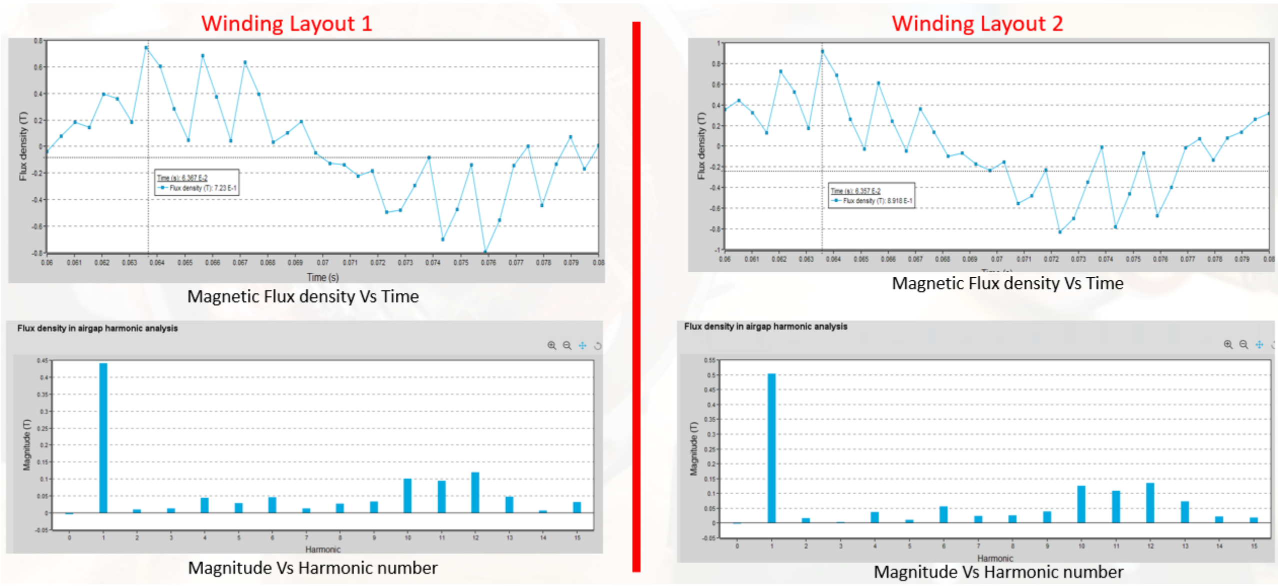


Figure 8.7: Magnetic filed Vs Time

8.5.7 Conclusion

From the flux density and harmonic analysis, it is evident that while both winding layouts generate effective magnetic flux for torque production, Winding Layout 2 provides high ripple in magnetic flux density as compared to winding layout 1.

8.5.8 Transient behavior of Torque for both different configuration

Torque output is one of the most important performance factors in electric machines. Torque generation characteristics—smoothness, peak values, and harmonic distortion—have a direct influence on machine efficiency, vibration, noise, and drive system performance. This chapter provides a comparative examination of the torque response of two alternative stator winding configurations: Winding Layout 1 and Winding Layout 2, using both time-domain.

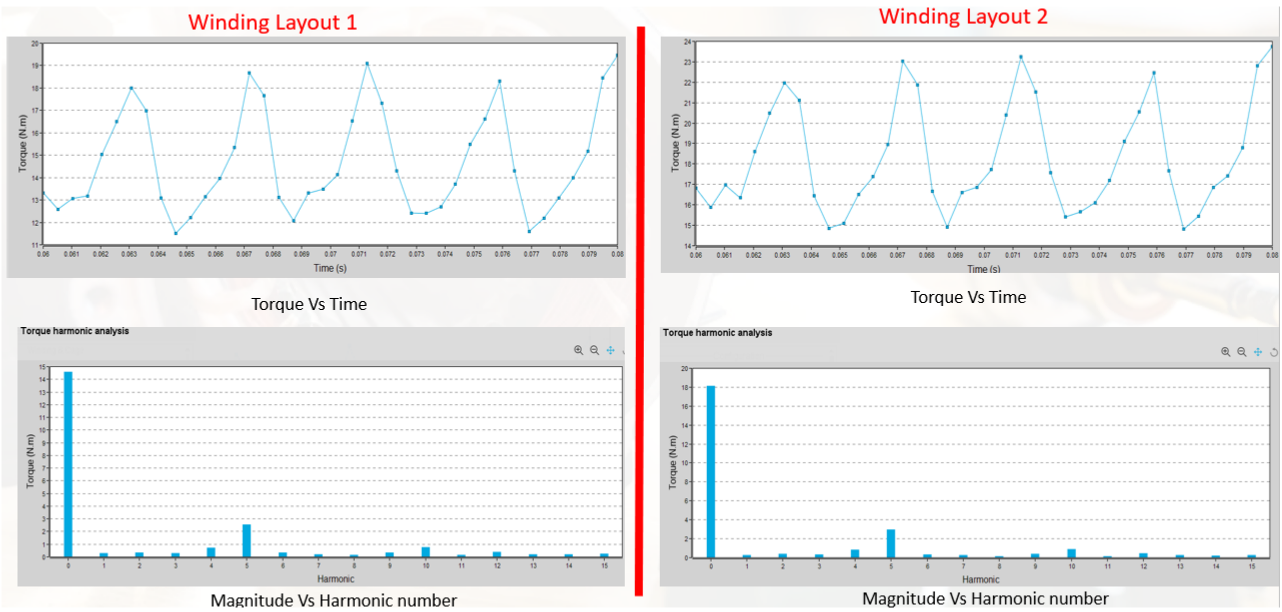


Figure 8.8: Torque Vs Time

Winding layout 2 offers high Torque fluctuation as compared to winding layout 1.

8.5.8.1 Isovalues Comparison Between Two Winding Layouts

This section compares the magnetic flux density distribution in different parts of the motor for **winding Layout 1** and **winding Layout 2**. Isovalue charts are used to evaluate magnetic performance by graphically representing the flux density distribution inside the stator, rotor, and airgap areas.

Flux Density Distribution

Figure 11 and figure 12 and show the Magnetic flux density distributions for Winding Layout 1 and Layout 2, respectively. The color-coded isovalues illustrate the intensity and spread of magnetic flux density (in Tesla, T).

- **Winding Layout 1**: The flux density reaches a peak value of approximately **1.954 T**, with regions of strong magnetic concentration observed near the stator teeth and rotor poles.
- **Winding Layout 2**: Shows a slightly higher peak flux density of approximately **2.039 T**, with a more uniform flux spread in the rotor.

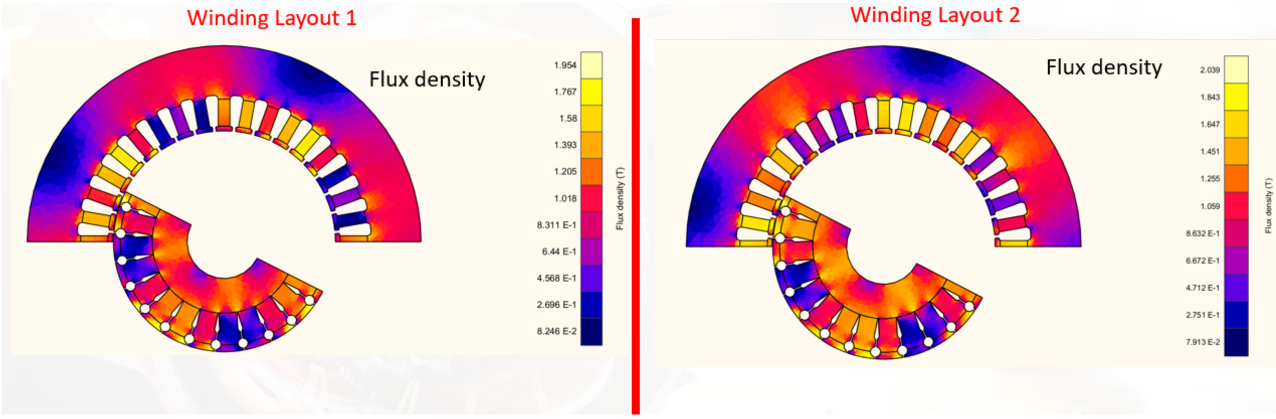


Figure 8.9: Isovalues

Winding Layout 1

Flux density in iron					
Stator tooth,max (T)	1.337	Stator foot,max (T)	2.241	Stator yoke,max (T)	1.102
Stator tooth, mean(T)	0.483	Stator foot,mean(T)	0.449	Stator yoke,max (T)	0.352

Winding Layout 2

Flux density in iron					
Stator tooth,max (T)	1.388	Stator foot,max (T)	2.326	Stator yoke,max (T)	1.278
Stator tooth, mean(T)	0.573	Stator foot,mean(T)	0.503	Stator yoke,max (T)	0.394

Figure 8.10: Magnetic flux density distributions for Winding Layout 1 and Layout 2

8.5.9 Motor - Efficiency Map Scalar Control (V-f) Test

Positioning and Objective of the Efficiency Map Scalar Test

The objective of the test "Performance Mapping – Sine wave – Motor – Efficiency map scalar" is to thoroughly evaluate the electromagnetic and electromechanical behavior of an electric machine across a defined Torque-Speed operating area. This area is typically bounded by:

- Maximum line-line voltage,
- Rated power supply frequency,
- Maximum line current, and
- Maximum rotational speed of the machine.

This test is particularly useful for scalar-controlled machines, where a scalar control mode (also known as V/f control) is employed. Unlike vector control, scalar control maintains a fixed voltage-to-frequency ratio to regulate machine speed and torque.

Torque-Speed Operating Principle

The machine's performance is mapped across the torque-speed plane, starting from zero speed up to the machine's maximum operational speed. This involves two distinct regions:

- **Constant Torque Region (Below Base Speed):**
  - In this region, the machine delivers maximum torque.
  - Voltage and frequency increase proportionally (V/f = constant).
  - The torque remains constant until the base speed N_{base} is reached.
- **Constant Power Region (Above Base Speed):**
  - Beyond N_{base}, the machine cannot maintain the same V/f ratio.
  - Torque starts to decrease inversely with speed while power remains constant.
  - This region is critical for high-speed applications where reduced torque is acceptable.

8.5.10 Machine Performance - Base Speed Test

Winding Layout 1

Power supply frequency	50 Hz
Mechanical Torque	14.46 Nm
Mechanical Power	2180.14 W
Machine efficiency	87.51 %
Slip	4.044%
Line current	3.91 A
Line voltage	415
Speed	1439.33 rpm
Machine electrical power	2491.15 W
Apparent Power	2814.44VA
Machine total loss	311.01 W
Power factor	0.885

Winding Layout 2

Power supply frequency	50 Hz
Mechanical Torque	13.54Nm
Mechanical Power	1946.4266 W
Machine efficiency	82.97 %
Slip	8.485%
Line current	3.91 A
Line voltage	415
Speed	1372.72 rpm
Machine electrical power	2345.85 W
Apparent Power	2814.35 VA
Machine total loss	399.42 W
Power factor	0.833

Figure 8.11: Machine Performance - Base Speed

8.5.11 Machine Performance - Maximum Speed Test

Winding Layout 1

Power supply frequency	50 Hz
Mechanical Torque	1.543 Nm
Mechanical Power	969.68 W
Machine efficiency	93.42%
Slip	2.21%
Line current	1.799 A
Line voltage	415
Speed	6000 rpm
Machine electrical power	1037.891 W
Apparent Power	1293.13 VA
Machine total loss	68.21 W
Power factor	0.80

Winding Layout 2

Power supply frequency	50 Hz
Mechanical Torque	1.046 Nm
Mechanical Power	657.632 W
Machine efficiency	84.01 %
Slip	7.179%
Line current	2.21 A
Line voltage	415
Speed	6000 rpm
Machine electrical power	782.74 W
Apparent Power	1592.50 VA
Machine total loss	125.11 W
Power factor	0.49

Figure 8.12: Machine Performance - Maximum Speed

8.5.12 Torque Vs Speed and Efficiecy Vs Speed Curve

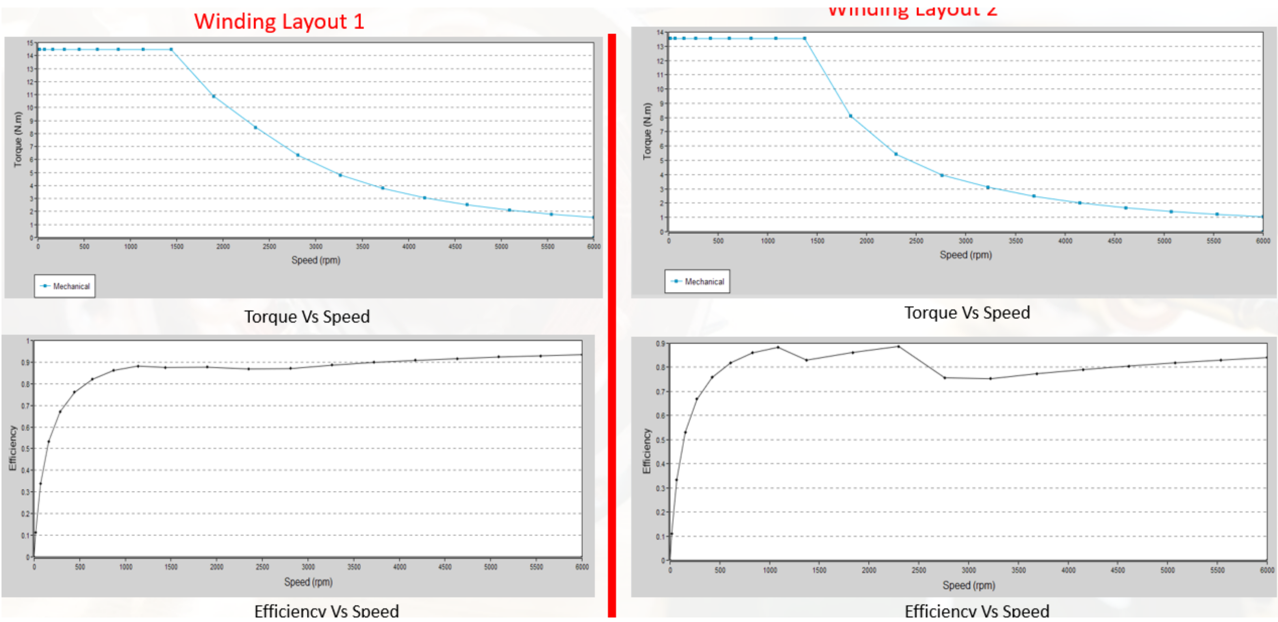


Figure 8.13: Torque Vs Speed and Efficiecy Vs Speed Curve

8.5.13 Conclusion

- **Higher Performance:** Layout 1 provides significantly higher mechanical torque and power output at the same speed.
- **Greater Efficiency:** The machine efficiency of Layout 1 is substantially higher, meaning less energy is wasted as heat.
- **Lower Slip:** The much lower slip in Layout 1 suggests a more effective utilization of the magnetic field and potentially better stability at this operating point.
- **Lower Current Draw:** Layout 1 requires less line current to achieve its higher performance, which is beneficial for reducing resistive losses in the wiring and the motor windings.
- **Lower Losses:** The total losses in Layout 1 are significantly lower, contributing to its higher efficiency and potentially longer lifespan.
- **Better Power Factor:** The power factor of Layout 1 is considerably higher, indicating a more efficient use of the supplied electrical power and a lower reactive power demand.

Chapter 9

Percentage reduction in stator joule loss in Nine phase machine as compared to Three phase machine

9.0.1 Introduction

In electric machines, particularly in high-performance and multi-phase applications, efficiency and loss reduction are critical. Stator copper (Joule) losses are one of the most significant contributors to overall power loss. This section compares stator copper losses in a typical Three phase motor versus a Nine phase motor, focusing on the influence of the winding factor K_w.

9.0.2 Objective

Compute the percentage decrease in stator Joule loss while utilizing a 9-phase motor instead of a 3-phase motor, considering winding distribution and slot/pole/phase configurations.

Given Data

- Frequency, $f = 50\,\text{Hz}$
- Number of poles, $P = 4$
- Number of stator slots, $S = 36$

Slot Angle :

The slot angle refers to the angular displacement between adjacent slots in the stator . Mathematically,

$$\gamma = \frac{180 \times P}{S} = \frac{180 \times 4}{36} = 20^\circ$$

Number of Slots per Pole per Phase :

The slot per pole per phase determines how the windings are distributed around the stator or rotor. A higher SPP means that the windings are more spread out, which can lead to a smoother and more sinusoidal distribution of the magnetomotive force (MMF). Mathematically,

$$q = \frac{S}{P \times \text{Phases}}$$

For 3-phase motor:

$$q_{3\phi} = \frac{36}{4 \times 3} = 3$$

For 9-phase motor:

$$q_{9\phi} = \frac{36}{4 \times 9} = 1$$

Distribution Factor K_d :

The distribution factor shows how much the total EMF generated by a distributed winding is reduced compared to a concentrated winding.

$$K_d = \frac{\sin\left(\frac{q \cdot \gamma}{2}\right)}{q \cdot \sin\left(\frac{\gamma}{2}\right)}$$

For 3-phase motor:

$$K_{d3} = \frac{\sin\left(\frac{3 \cdot 20}{2}\right)}{3 \cdot \sin\left(\frac{20}{2}\right)} = \frac{\sin(30^\circ)}{3 \cdot \sin(10^\circ)} \approx \frac{0.5}{3 \cdot 0.1736} \approx 0.925$$

For 9-phase motor:

$$K_{d9} = \frac{\sin\left(\frac{1 \cdot 20}{2}\right)}{1 \cdot \sin\left(\frac{20}{2}\right)} = \frac{\sin(10^\circ)}{\sin(10^\circ)} = 1$$

Stator Copper Loss Relationship :

Stator copper loss is proportional to the square of the winding factor K_w, which includes the distribution factor K_d [3]: Mathematically,

$$P_{\text{stator}} \propto K_w^2$$

Relative Comparison:

$$\frac{P_{S9}}{P_{S3}} = \frac{K_{d9}}{K_{d3}} = \frac{1}{0.925}$$

Percentage Reduction in Stator Loss:

$$\frac{P_{S9} - P_{S3}}{P_{S3}} \times 100 = \left(\frac{0.925 - 1}{1} \right) \times 100 = -7.5\%$$

9.0.3 Conclusion :

The 9-phase motor demonstrates a reduction in stator copper losses by approximately 7.5% compared to a conventional 3-phase motor, under identical slot and pole conditions. This improvement is primarily due to a higher winding factor, as the distribution of coils becomes more uniform with more phases.

Chapter 10

Conclusion and Future work

10.1 Conclusion

- A comprehensive and unified mathematical framework has been developed for analyzing the magnetomotive force (MMF) in multiphase induction machines, accommodating both odd and even phase numbers.
- Generalized MMF equations have been systematically derived for a wide spectrum of winding configurations and neutral connection schemes, including:
  - Common neutral systems,
  - Asymmetrical isolated neutral systems (odd/even phase counts),
  - Symmetrical isolated neutral systems (odd/even phase counts).
- The formulation enables precise characterization of MMF spatial distributions and associated harmonic content, facilitating improved machine modeling and performance prediction.
- The influence of space harmonics, resulting from slotting and winding distribution, is thoroughly examined to evaluate their effects on torque ripple,

waveform distortion, and losses.

- To validate theoretical models, performance comparisons between different double-layer winding layouts for three-phase induction machines are conducted using both analytical and simulation-based approaches.
- Approximately 7.5% reduction in stator copper losses by in Nine phase induction machine as compared to a conventional Three phase machine, under identical slot and pole conditions.

10.2 Future work

1. Nine phase motor detail analysis including Torque Slip characteristics
2. Validation with Hardware Prototypes of the Nine phase induction Machine
3. Performance Evaluation with different Winding Configurations for multiphase induction mac
4. Mathemetical equation for Stator Surface Current Density for Multi-layer Windings

References

[1] T. A. Lipo, *Introduction to AC machine design.* John Wiley & Sons, 2017.

[2] V. Kindl, R. Cermak, Z. Ferkova, and B. Skala, "Review of time and space harmonics in multi-phase induction machine," *Energies*, vol. 13, no. 2, p. 496, 2020.

[3] S. Williamson and S. Smith, "Pulsating torque and losses in multiphase induction machines," in *Conference Record of the 2001 IEEE Industry Applications Conference. 36th IAS Annual Meeting (Cat. No. 01CH37248)*, vol. 2. IEEE, 2001, pp. 1155–1162.