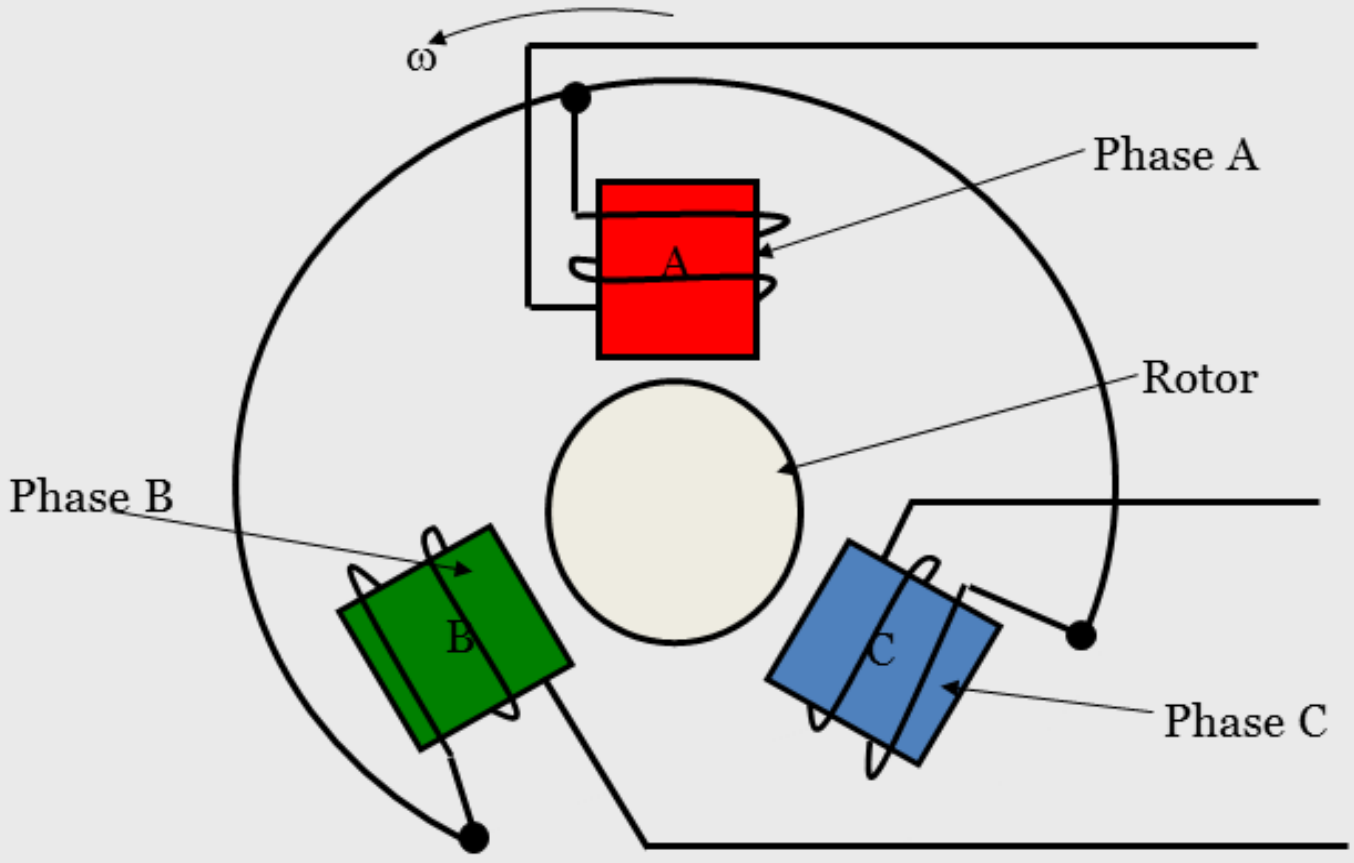
Principles of Electrical Machinery

Dr. Praveen Kumar



DESHYA
Technologies Pvt Ltd

Preface

The primary objective of this book is to develop foundation in the fundamental principles of electric machinery. The book concentrates on the principles of electromechanical energy conversion and its application to electric machinery. An effort is made to develop the theory of operation of machines from electromechanical energy conversion viewpoint. Generally, the operation of electrical machines is better understood using electromagnetic and the analysis of the machine is easier to perform using electrical equivalent circuit. In this book a link between the electromagnetic viewpoint and the equivalent circuit is developed. This link is developed using the principles of electromechanical energy conversion (EMEC).

The chapters 1 and 2 of the book deal with the basics of electric circuits and magnetic circuits. In chapter 3 the principles of EMEC is introduced and its application to singly excited systems is explained. The chapter 4 deals with the electromechanical energy conversion for doubly excited system. Based the principles of EMEC the electrical equivalent circuits of a.c. machines is derived. The common underlying principles of electrical machines are also presented in chapter 4. The chapter 5 explains the working principles of electrical machines and explains the phenomena of rotating magnetic fields and torque production in a.c. machines. The chapters 6 and 7 are dedicated to principles of induction machines and their speed control. The chapter 8 deals with synchronous generators and motor.

The unique feature of this book is extensive use of figures and animations to explain the phenomena occurring in electrical machines. Besides the animations, elaborate explanation of phenomenon is given boxes. The boxes are used ensure that the flow of the text in the book remains intact. Since the book is in electronic format, it helps the reader to navigate through the animations, figures, boxes, etc. in a simple and efficient manner.

It was our endeavour to write and publish an accurate book. However, it is possible that there may still be some typological and numerical errors in the book. It is very likely that the readers might feel that some sections need better explanation. We welcome any comments and suggestions in this regard and will consider them for future revisions.

Copyrights

Preface

Table of Content

Figure 1.8: The network to illustrate superposition theorem.

Figure 1.9a: Equivalent circuit with just the *DC* voltage source.

Figure 1.9b: Equivalent circuit with just the *DC* voltage source.

Figure 1.9c: Equivalent circuit with just the current source.

1.5.5. Thevenin and Norton Equivalent Circuits (figure 1.10)

Figure 1.10: The Network for Thevenin and Norton's Theorem.

Figure 1.11a: The Network for Thevenin Theorem for finding Zth.

Figure 1.11b: The Network for Thevenin Theorem for finding Vth.

Figure 1.12: The Network for Example 1.3.

Figure 1.13: Location of supernode for the network shown in figure 1.12.

Example 1.3

1.6. Three Phase Circuits

1.6.1. Introduction

Figure 1.14a: Single phase 2 wire system.

Figure 1.14b: Single phase 3 wire system.

1.6.2. Transmission Systems

Figure 1.15: Two phase three wire system.

Figure 1.16: Three phase four wire system.

Figure 1.17: Three phase voltages.

1.6.3. Two and Three Phase System

1.6.3.1. Why Three Phase System?

1.6.3.2. Balanced Three Phase Voltages

Figure 1.18: A three phase generator.

1.6.3.3. Balanced Three Phase Systems

Figure 1.19a: Y connection of three phase source.

Figure 1.19b: Delta connection of three phase source.

1.6.3.4. Y and Delta Connections

Figure 1.20a: *abc* or positive sequence.

Figure 1.20b: *acb* or negative sequence.

1.6.4. Three Phase Loads

1.6.4.1. Balanced Three Phase Load

Figure 1.21a: *Y* connected three phase loads.

Figure 1.21b: *Delta* connected three phase loads.

1.6.4.2. Y or Delta Connected Load

4.1. Introduction

4.2. Doubly Excited Magnetic Systems

4.2.1. Doubly excited EMEC System with Linear Motion

Figure 4.1: Doubly excited electromechanical energy conversion system.

Figure 4.2: Path of integration for determining the stored field energy in doubly excited electromechanical energy conversion system.

4.2.2. Doubly excited EMEC System with Rotational Motion

Figure 4.3: Doubly excited rotational electromechanical energy conversion system.

Animation 4.1: The flux is produced by stator and rotor currents. These flux lines see a varying reluctance as the rotor moves.

4.2.3. Analysis of Torque Produced by doubly excited EMEC System

Animation 4.2: Variation of reluctance with rotor position in a doubly excited system.

Figure 4.4: Variation of reluctance with change in rotor position for doubly excited rotational electromechanical energy conversion system.

Animation 4.3: The flux is produced by stator current. These flux lines see a varying reluctance as the rotor moves.

Animation 4.4: The flux is produced by rotor current. These flux lines see a varying reluctance as the rotor moves.

Figure 4.5: Doubly excited rotational electromechanical energy conversion system with cylindrical rotor.

Animation 4.5: Variation of reactance in a cylindrical rotor actuator.

Animation 4.6: The flux is produced by stator current. These flux lines see a constant reluctance as the rotor moves.

Figure 4.6: Doubly excited rotational electromechanical energy conversion system with cylindrical stator and salient pole rotor.

Animation 4.7: Variation of reactance in a salient pole rotor motor with two poles.

Animation 4.8: The flux is produced by current is stator coil and it variation with rotor position.

Animation 4.9: The flux is produced by current is rotor coil and its variation with rotor position.

Animation 4.10: The flux is produced by current is stator and rotor coils and it variation with rotor position.

Figure 4.7: Doubly excited rotational electromechanical energy conversion system with cylindrical stator and cylindrical rotor.

Animation 4.11: Variation of mutual inductance in a single phase machine.

Animation 4.12: The flux is produced by stator and rotor current.

Animation 4.13: The flux lines due to current in stator coil.

Animation 4.14: The flux lines due to current in the rotor coil.

4.3. Single Phase Non-Salient Machine

Figure 4.8: Single phase non salient pole motor.

Figure 4.9: Variation of mutual inductance with change in rotor position.

Animation 4.15: Flux linked by rotor coils in a two phase machine.

Box 4.1

Figure 4.B1.1: Single phase motor with stator coil excited by a DC source.

Figure 4.B1.2: Flux lines in produced by direct current in the stator coil.

Figure 4.B1.3a: Position of the rotor coil when the rotor has moved by 90 degrees mechanically.

Figure 4.B1.3b: Position of the rotor coil when the rotor has moved by 135 degrees mechanically.

Figure 4.B1.3c: Position of the rotor coil when the rotor has moved by 180 degrees mechanically.

Figure 4.B1.4: Flux linked by rotor coil with change is rotor position.

4.4. Two Phase Non-Salient Machine

Figure 4.10: Two phase non salient pole motor.

Figure 4.11: Variation of mutual inductance in two phase non salient pole motor.

Animation 4.16: Flux linked in two phase machine.

Box 4.2

Figure 4.B2.1: Two phase cylindrical rotor motor.

Figure 4.B2.2a: Flux seen by rotor coils at the initial position.

Figure 4.B2.2b: Flux seen by rotor coils when the rotor moves by 45 degrees mechanically.

Figure 4.B2.3: Flux linked by rotor coils due to excitation of phase A of stator.

Figure 4.B2.4: Flux seen by rotor coils when the phase B of the stator is excited by direct current.

Figure 4.B2.5: Flux linked by rotor coils due to excitation of phase A of stator.

4.5. Two Phase Non-Salient Synchronous Machine

Box 4.3

Figure 4.B3.1: Equivalent circuit of a synchronous machine.

Figure 4.B3.2a: Phasor diagram of a synchronous machine for $\delta > 0$.

Figure 4.B3.2b: Phasor diagram of a synchronous machine for $\delta < 0$.

4.6. Two Phase Non-Salient Induction Machine

Figure 5.8a: The direction of *MMF* produced by phase A winding at time instant t1.
Figure 5.8b: The direction of *MMF* produced by phase B winding at time instant t1.
Figure 5.8c: The direction of *MMF* produced by phase C winding at time instant t1.
Figure 5.8d: The direction of resultant *MMF* produced by phase A,
B and C windings at time instant t1.
Figure 5.9a: The direction of *MMF* produced by phase A winding at time instant t2.
Figure 5.9b: The direction of *MMF* produced by phase B winding at time instant t2.
Figure 5.9c: The direction of *MMF* produced by phase C winding at time instant t2.
Figure 5.9d: The direction of the resultant *MMF* produced by all the three phases at time instant t2.
Figure 5.10a: The direction of *MMF* produced by phase A winding at time instant t3.
Figure 5.10b: The direction of *MMF* produced by phase B winding at time instant t3.
Figure 5.10c: The direction of *MMF* produced by phase C winding at time instant t3.
Figure 5.10d: The direction of resultant *MMF* produced by the three phases at time instant t3.
Figure 5.11a: The direction of *MMF* produced by phase A winding at time instant t4.
Figure 5.11b: The direction of *MMF* produced by phase B winding at time instant t4.
Figure 5.11c: The direction of *MMF* produced by phase C winding at time instant t4.
Figure 5.11d: The direction of resultant *MMF* produced by the three phases at time instant t4.
Figure 5.12a: The direction of *MMF* produced by phase A winding at time instant t5.
Figure 5.12b: The direction of *MMF* produced by phase B winding at time instant t5.
Figure 5.12c: The direction of *MMF* produced by phase C winding at time instant t5.
Figure 5.12d: The direction of resultant *MMF* produced by the three phases at time instant t5.
Figure 5.13a: The direction of *MMF* produced by phase A winding at time instant t6.
Figure 5.13b: The direction of *MMF* produced by phase B winding at time instant t6.

Figure 5.13c: The direction of *MMF* produced by phase C winding at time instant t6.

Figure 5.13d: The direction of resultant *MMF* produced by the three phases at time instant t6.

Animation 5.1: The direction of magnetic field produced by coils of phase A.

Animation 5.2: The direction of magnetic field produced by coils of phase B.

Animation 5.3: The direction of magnetic field produced by coils of phase C.

Animation 5.4: The direction of resultant magnetic field produced by all the three phases.

Animation 5.5: The direction of magnetic field produced by each phase and all phases taken together.

5.5.2. Rotating Magnetic Field (4 poles) produced by a Machine Having Distributed Coils

Figure 5.14: Winding scheme of a 12 slot stator that produces four poles.

Figure 5.15a: The direction of resultant *MMF* produced by current in phase A at time instant t1.

Figure 5.15b: The direction of resultant *MMF* produced by current in phase B at time instant t1.

Figure 5.15c: The direction of resultant *MMF* produced by current in phase C at time instant t1.

Figure 5.15d: The direction of resultant *MMF* produced by current in all the three phases at time instant t1.

Figure 5.15e: The flux lines due to currents in all the three phases at time instant t1.

Animation 5.6: The direction of magnetic field produced by coils of phase A in a four pole machine.

Animation 5.7: The direction of magnetic field produced by coils of phase B in a four pole machine.

Animation 5.8: The direction of magnetic field produced by coils of phase C in a four pole machine.

Animation 5.9: The direction of magnetic field produced by coils of three phases and their resultant flux.

Figure 5.16a: The direction of resultant *MMF* produced by current in phase A at time instant t2.

Figure 5.16b: The direction of resultant *MMF* produced by current in phase B at time instant t2.

Figure 5.16c: The direction of resultant *MMF* produced by current in phase C at time instant t2.

Figure 5.16d: The direction of resultant *MMF* produced by current in all the three phases at time instant t2.

Figure 5.16e: The flux lines due to currents in all the three phases at time instant t2.

Figure 5.17a: The direction of resultant *MMF* produced by current in phase A at time instant t3.

Figure 5.17b: The direction of resultant *MMF* produced by current in phase B at time instant t3.

Figure 5.17c: The direction of resultant *MMF* produced by current in phase C at time instant t3.

Figure 5.17d: The direction of resultant *MMF* produced by current in all the three phases at time instant t3.

Figure 5.17e: The flux lines due to currents in all the three phases at time instant t3.

Figure 5.18a: The direction of resultant *MMF* produced by current in phase A at time instant t4.

Figure 5.18b: The direction of resultant *MMF* produced by current in phase B at time instant t4.

Figure 5.18c: The direction of resultant *MMF* produced by current in phase C at time instant t4.

Figure 5.18d: The direction of resultant *MMF* produced by current in all the three phases at time instant t4.

Figure 5.18e: The flux lines due to currents in all the three phases at time instant t4.

Figure 5.19a: The direction of resultant *MMF* produced by current in phase A at time instant t5.

Figure 5.19b: The direction of resultant *MMF* produced by current in phase B at time instant t5.

Figure 5.19c: The direction of resultant *MMF* produced by current in phase C at time instant t5.

Figure 5.19d: The direction of resultant *MMF* produced by current in all the three phases at time instant t5.

Figure 5.19e: The flux lines due to currents in all the three phases at time instant t5.

Figure 5.20a: The direction of resultant *MMF* produced by current in phase A at time instant t6.

Figure 5.20b: The direction of resultant *MMF* produced by current in phase B at time instant t6.

Figure 5.20c: The direction of resultant *MMF* produced by current in phase C at time instant t6.

Figure 5.20d: The direction of resultant *MMF* produced by current in all the three phases at time instant t6.

Figure 5.20e: The flux lines due to currents in all the three phases at time instant t6.

Box 5.1

Figure 5.B1.1: Winding scheme of a 12 slot stator that produces four poles.

Figure 5.B1.2a: Hall effect sensor and only coil 1 of phase A is excited.

Figure 5.B1.2b: Flux density in the air gap periphery when coil 1 of phase A is excited.

Figure 5.B1.3a: Hall effect sensor and only coil 2 of phase A is excited.

Figure 5.B1.3b: Flux density in the air gap periphery when coil 2 of phase A is excited.

Figure 5.B1.4a: Hall effect sensor and only coil 3 of phase A is excited.

Figure 5.B1.4b: Flux density in the air gap periphery when coil 3 of phase A is excited.

Figure 5.B1.5a: Hall effect sensor and only coil 4 of phase A is excited.

Figure 5.B1.5b: Flux density in the air gap periphery when coil 4 of phase A is excited.

Figure 5.B1.6: Magnetic flux density in the air gap due to the current in all the coils of phase A at time instant t1.

Figure 5.B1.7: Magnetic flux density in the air gap due to the current in all the coils of phase B at time instant t1.

Figure 5.B1.8: Magnetic flux density in the air gap due to the current in all the coils of phase C at time instant t1.

Figure 5.B1.9: Magnetic flux density in the air gap due to all the three phases at time instant t1.

Figure 5.B1.10: Resultant magnetic flux density in the air gap due to all the three phases at time instant t1.

Figure 5.B1.11: Magnetic flux density in the air gap due to all the three phases at time instant t2.

Figure 5.B1.12: Resultant magnetic flux density in the air gap due to all the three phases at time instant t2.

Figure 5.B1.13: Magnetic flux density in the air gap due to all the three phases at time instant t3.

Figure 5.B1.14: Magnetic flux density in the air gap due to all the three phases at time instant t4.

Figure 5.B1.15: Magnetic flux density in the air gap due to all the three phases at time instant t5.

Figure 5.B1.16: Magnetic flux density in the air gap due to all the three phases at time instant t6.

Figure 5.B1.17: Resultant flux density in the air gap at time instant t3.

Figure 5.B1.18: Resultant flux density in the air gap at time instant t4.

Figure 5.B1.19: Resultant flux density in the air gap at time instant t5.

Figure 5.B1.20: Resultant flux density in the air gap at time instant t6.

Figure 5.B1.21: The resultant flux density is the air gap at different instants of time.

5.6. How to Create the Second Magnetic Field?

5.6.1. Synchronous Machines

Figure 5.21: A simple salient pole synchronous machine. The coils on the rotor carry direct current and produce the magnetic field.

5.6.2. Permanent Magnet Synchronous Machines (*PMSM*)

Figure 5.22: A permanent magnet synchronous machine. The two permanent magnets on the rotor produce the magnetic field.

5.6.3. Induction Machine (*IM*)

5.7. Why Should the Number of Poles on Stator Equal to the Number of Poles on Rotor?

Figure 5.23: A 2 pole stator and 4 pole rotor configuration.

5.8. Electrical and Mechanical Angle

Figure 5.24: A simple salient pole synchronous machine. The stator has saliency and rotor is cylindrical. The stator coils are excited by current source and as rotor moves an *EMF* is induced in the rotor coil.

Figure 5.25: Induced *EMF* in the rotor (at a constant speed of rotation) as function of rotor position.

Animation 5.10: Flux linked by rotor coil in a two pole machine.

Animation 5.11: *EMF* induced in the rotor coil of a two pole machine.

Figure 5.26: Stator with four salient poles. The direct current in the stator coils produces four poles.

Figure 5.27: Induced *EMF* in the rotor (at a constant speed of rotation) as function of rotor position. In one complete rotation of rotor (that is 360degrees), two cycles of *EMF* is induced.

Animation 5.12: *EMF* induced in the rotor coil of a four pole machine.

5.9. Summary

Chapter 6: Fundamentals of Induction Mchine

6.1. Introduction

6.2. Fluxes and *MMF* in Induction Motor

6.2.1. Fluxes and *MMF* in 2 Pole Cage Rotor Induction Motor

Figure 6.1: A cage rotor induction motor with 12 slot stator and 16 slot rotor.

Figure 6.2: Stator winding scheme to produce two poles.

Animation 6.1: Construction of a 3-phase Induction Motor.

Animation 6.2: Flux lines in a two pole machine.

Figure 6.3a: Flux lines due to stator currents at time instant t1.

Figure 6.3b: Magnetic flux density in the air gap as measure by the Hall effect sensor at time instant t1.

Animation 6.3: Air gap field distribution in a two pole machine at time instant t1.

Figure 6.4a: Flux lines due to stator currents at time instant t2.

Figure 6.4b: Magnetic flux density in the air gap as measure by the Hall effect sensor at time instant t2.

Animation 6.4: Air gap field distribution in a two pole machine at time instant t2.

Figure 6.5a: Flux lines due to stator currents at time instant t3.

Figure 6.5b: Magnetic flux density in the air gap as measure by the Hall effect sensor at time instant t3.

Animation 6.5: Air gap field distribution in a two pole machine at time instant t3.

Figure 6.6a: Flux lines due to stator currents at time instant t4.

Figure 6.6b: Magnetic flux density in the air gap as measure by the Hall effect sensor at time instant t4.

Animation 6.6: Air gap field distribution in a two pole machine at time instant t4.

Figure 6.7a: Flux linked by rotor bars at time instant t1.

Figure 6.7b: Flux linked by rotor bars at time instant t2.

Figure 6.7c: Flux linked by rotor bars at time instant t3.

Figure 6.7d: Flux linked by rotor bars at time instant t4.

Figure 6.8a: Induced *EMF* in the rotor bar at time instant t1.

Figure 6.8b: Induced *EMF* in the rotor bar at time instant t2.

Animation 6.7: Flux enclosing the bar of rotors.

Figure 6.8c: Induced *EMF* in the rotor bar at time instant t3.

Figure 6.8d: Induced *EMF* in the rotor bar at time instant t4.

Animation 6.8: Induced E.M.F. in the bars of the rotor.

Figure 6.9a: Current in the rotor bars at time instant t1.

Figure 6.9b: Current in the rotor bars at time instant t2.

Figure 6.9c: Current in the rotor bars at time instant t3.

Figure 6.9d: Current in the rotor bars at time instant t4.

Animation 6.9: Current distribution in the bars of the rotor.

Box 6.1

Figure 6.B1.1a: Direction of bar current at time instant t1.

Figure 6.B1.1b: Direction of bar current at time instant t2.

Figure 6.B1.1c: Direction of bar current at time instant t3.

Figure 6.B1.1d: Direction of bar current at time instant t4.

Figure 6.10a: Magnetic field created by current in the rotor bars at time instant t1.

Figure 6.10b: Magnetic field created by current in the rotor bars at time instant t2.

Figure 6.10c: Magnetic field created by current in the rotor bars at time instant t3.

Figure 6.10d: Magnetic field created by current in the rotor bars at time instant t4.

Figure 6.11a: Direction of torque acting on rotor due to the interaction between stator and rotor magnetic fields at time instant t1.

Figure 6.11b: Direction of torque acting on rotor due to the interaction between stator and rotor magnetic fields at time instant t2.

Figure 6.11c: Direction of torque acting on rotor due to the interaction between stator and rotor magnetic fields at time instant t3.

Figure 6.11d: Direction of torque acting on rotor due to the interaction between stator and rotor magnetic fields at time instant t4.

Animation 6.10: Air gap field, Flux linkage, induced E.M.F. and bar currents without taking rotor inductance in the account.

Figure 6.12: The phasor diagram of a cage rotor induction with rotor inductance neglected.

Figure 6.13: Induced *EMF* in the rotor bars with rotor inductance taken into account.

Figure 6.14: The current in the rotor bars with rotor inductance taken into account.

Figure 6.15: The phasor diagram of a cage rotor induction with rotor inductance taken into account.

Animation 6.11: Air gap field, Flux linkage, induced E.M.F. and bar currents with taking rotor inductance in the account.

6.2.2. Fluxes and MMF in 4 Pole Cage Induction Motor

Figure 6.16: A four pole cage rotor induction motor with its winding scheme for stator.

Animation 6.12: Flux lines in a four pole machine.

Figure 6.17a: Flux lines due to balanced three phase current in the stator windings at time instant t1.

Figure 6.17b: Magnetic flux density along the periphery of the air gap.

Animation 6.13: Air gap field distribution in a four pole machine at time instant t1.
Figure 6.18: Flux lines due to balanced three phase current in the stator windings at time instant t2.
Figure 6.19: Flux lines due to balanced three phase current in the stator windings at time instant t3.
Figure 6.20: Flux lines due to balanced three phase current in the stator windings at time instant t4.
Animation 6.14: Air gap field distribution in a four pole machine at time instant t2.
Animation 6.15: Air gap field distribution in a four pole machine at time instant t3.
Animation 6.16: Air gap field distribution in a four pole machine at time instant t4.
Figure 6.21a: Flux linked by rotor bars at time instant t1.
Figure 6.21b: Flux linked by rotor bars at time instant t2.
Figure 6.21c: Flux linked by rotor bars at time instant t3.
Figure 6.21d: Flux linked by rotor bars at time instant t4.
Figure 6.22a: Induced *EMF* in rotor bars at time instant t1.
Figure 6.22b: Induced *EMF* in rotor bars at time instant t2.
Figure 6.22c: Induced *EMF* in rotor bars at time instant t3.
Figure 6.22d: Induced *EMF* in rotor bars at time instant t4.
Figure 6.23a: Current in the rotor bars at time instant t1.
Figure 6.23b: Current in the rotor bars at time instant t2.
Figure 6.23c: Current in the rotor bars at time instant t3.
Figure 6.23d: Current in the rotor bars at time instant t4.
Figure 6.24a: Magnetic field due to current in the rotor bars at time instant t1.
Figure 6.24b: Magnetic field due to current in the rotor bars at time instant t2.
Figure 6.24c: Magnetic field due to current in the rotor bars at time instant t3.
Figure 6.24d: Magnetic field due to current in the rotor bars at time instant t4.
Animation 6.17: Magnetic field and current at different rotor position for a given slip.
Figure 6.25: The angular displacement between the stator and rotor magnetic fields at different time instants.
Figure 6.26a: Magnetic field due to current in the rotor bars, taking into account the rotor inductance, at time instant t1.
Figure 6.26b: Magnetic field due to current in the rotor bars, taking into account the rotor inductance, at time instant t2.
Figure 6.26c: Magnetic field due to current in the rotor bars, taking into account the rotor inductance, at time instant t3.

Figure 6.26d: Magnetic field due to current in the rotor bars, taking into account the rotor inductance, at time instant t4.

6.2.3. Fluxes and *MMF* in 2 Pole Wound Rotor Induction Motor

Figure 6.27: Cross section of a wound rotor induction motor. In this machine, the rotor has a winding similar to stator instead of bars.

Figure 6.28: The end terminals of the rotor winding and their connection to the slip rings.

Figure 6.29: Axes of three phases of rotor in a wound rotor induction motor.

Figure 6.30a: Flux linked by the three coils of phase A.

Figure 6.30b: Flux linked by the three coils of phase B.

Figure 6.30c: Flux linked by the three coils of phase C.

Figure 6.31a: The *EMF* induced in each of the three coils of phase A.

Figure 6.31b: The *EMF* induced in each of the three coils of phase B.

Figure 6.31c: The *EMF* induced in each of the three coils of phase C.

Figure 6.32: Resultant *EMF* in each phase of rotor.

Figure 6.33: Current in each phase of rotor.

Figure 6.34a: The location of the stator field at time instant t1.

Figure 6.34b: The location of the rotor field, due to currents in the rotor winding, at time instant t1.

Figure 6.35a: The location of the stator field at time instant t2.

Figure 6.35b: The location of the rotor field, due to currents in the rotor winding, at time instant t2.

Figure 6.36a: The location of the stator field at time instant t3.

Figure 6.36b: The location of the rotor field, due to currents in the rotor winding, at time instant t3.

Figure 6.37a: The location of the stator field at time instant t4.

Figure 6.37b: The location of the rotor field, due to currents in the rotor winding, at time instant t4.

Figure 6.38a: Magnetic flux lines in a four pole wound rotor induction motor at time instant t1.

Figure 6.38b: Magnetic flux lines in a four pole wound rotor induction motor at time instant t2.

Figure 6.38c: Magnetic flux lines in a four pole wound rotor induction motor at time instant t3.

Figure 6.38d: Magnetic flux lines in a four pole wound rotor induction motor at time instant t4.

Figure 6.38e: Magnetic flux lines in a four pole wound rotor induction motor at time instant t5.

6.3. Rotor Action

6.4. Rotor *EMF* and Equivalent Circuit

Figure 6.39: Electrical equivalent circuit of rotor.

6.5. Complete Equivalent Circuit

Figure 6.40: Electrical equivalent circuit of stator.

Figure 6.41: Per phase electrical equivalent circuit of the induction motor.

6.6. Simplification of Equivalent Circuit

Figure 6.42: Simplified per phase electrical equivalent circuit of the induction motor.

6.7. The Electromagnetic Torque-Speed Characteristics of an Induction Motor: A Physical View

Figure 6.43a: Magnitudes of stator and rotor magnetic fields at no load.

Figure 6.43b: Magnitudes of stator and rotor magnetic fields at full load.

6.7.1. Variation of B_{gap}

Figure 6.44a: Air gap field versus rotor speed.

6.7.2. Variation of B_2

Figure 6.44b: Magnetic field in the air gap due to rotor current versus speed.

6.7.3. Variation of δ

Figure 6.44c: Variation of load angle with speed.

Figure 6.44d: Typical torque versus speed of induction motor.

6.8. Thevenin's equivalent circuit

Figure 6.45: Thevenin's equivalent circuit.

Figure 6.46a: Thevenin's equivalent circuit.

Figure 6.46b: Thevenin's modified equivalent circuit.

6.8.1. Maximum Torque

Figure 6.47a: Torque versus slip curve for different values of rotor resistance.

Figure 6.47b: Torque versus slip curve for increasing values of applied voltage.

Figure 6.47c: Torque versus slip curve for increasing values of stator resistance.

Figure 6.47d: Torque versus slip curve for increasing values of stator reactance.

Figure 6.47e: Torque versus slip curve for increasing values of rotor reactance.

6.8.2. Starting Torque

Figure 8.4a: Location of stator and rotor magnetic field at time instant t1.

Figure 8.4b: Location of stator and rotor magnetic field at time instant t2.

Figure 8.4c: Location of stator and rotor magnetic field at time instant t3.

Figure 8.4d: Location of stator and rotor magnetic field at time instant t4.

Figure 8.4e: Location of stator and rotor magnetic field at time instant t5.

Figure 8.4f: Location of stator and rotor magnetic field at time instant t6.

Figure 8.5a: Location of stator and rotor magnetic field at time instant t1.

Figure 8.5b: Location of stator and rotor magnetic field at time instant t2.

Figure 8.5c: Location of stator and rotor magnetic field at time instant t3.

Figure 8.5d: Location of stator and rotor magnetic field at time instant t4.

Figure 8.5e: Location of stator and rotor magnetic field at time instant t5.

Figure 8.5f: Location of stator and rotor magnetic field at time instant t6.

Figure 8.6a: Location of stator and rotor magnetic field at time instant t1.

Figure 8.6b: Location of stator and rotor magnetic field at time instant t2.

Figure 8.6c: Location of stator and rotor magnetic field at time instant t3.

Figure 8.6d: Location of stator and rotor magnetic field at time instant t4.

Figure 8.6e: Location of stator and rotor magnetic field at time instant t5.

Figure 8.6f: Location of stator and rotor magnetic field at time instant t6.

8.5.1 Cylindrical rotor synchronous machine

Figure 8.7: Distribution of the stator and rotor magnetic field along the air gap periphery at a given point of time.

Animation 8.1: Construction of a 3-phase Cylindrical rotor synchronous machine.

Figure 8.8: Induced *EMF* in three phases of the stator winding as a function of rotor position. The rotor rotates at angular speed of ωr.

Figure 8.9: A synchronous generator connected to a resistive load.

Figure 8.10a: The resultant magnetic field in synchronous machine.

Figure 8.10b: The induced *EMF* and current in phase A. Since the inductance is neglected, the induced *EMF* and the current are in phase.

Figure 8.11: The induced *EMF* and current in phase A. Since the inductance is considered, the current lags the induced *EMF*.

Figure 8.12a: A synchronous generator connected to an inductive load.

Figure 8.12b: The induced *EMF* and current in phase A. The load connected to the stator terminals is purely inductive and hence, the current lags the induced *EMF* by 90°. The stator resistance is neglected.

Figure 8.12c: Since the load across the stator terminals is purely inductive, the armature field and the rotor field oppose each other. The armature field is demagnetizing in nature.

Figure 8.13a: A synchronous generator connected to a capacitive load.

Figure 8.13b: The induced *EMF* and current in phase A. The load connected to the stator terminals is purely capacitive and hence, the current leads the induced *EMF* by 90°. The stator resistance is neglected.

Figure 8.13c: Since the load across the stator terminals is purely capacitive, the armature field and the rotor field are in same direction. The armature field is magnetizing in nature.

8.5.2 Salient rotor synchronous machine

Figure 8.14: Construction of a six pole salient pole synchronous generator.

Animation 8.2: Construction of a 3-phase Salient rotor synchronous machine.

Figure 8.15a: The magnetic field created by the stator winding is along the x-axis and the rotor poles are also aligned along x-axis. Hence, the flux lines of the stator pole face low reluctance.

Figure 8.15b: The magnetic field created by the stator winding is along the y-axis and the rotor poles are also aligned along x-axis. Hence, the flux lines of the stator pole face high reluctance.

Figure 8.16a: The armature current and induced *EMF* relation in case of lagging power factor load.

Figure 8.16b: The armature current and induced *EMF* relation in case of leading power factor load.

Box 8.1

Figure 8.B1.1: The rotor is aligned along the x-axis and the coil axis is also aligned along the *x-axis*.

Figure 8.B1.2: Flux linkage and *EMF* waveform for a complete rotation of the rotor in case the rotor field axis was initially aligned with the *x-axis*.

Figure 8.B1.3: The rotor is aligned along the *y-axis* and the coil axis is also aligned along the *x-axis*.

Figure 8.B1.4: Flux linkage and *EMF* waveform for a complete rotation of the rotor in case the rotor field axis was initially aligned with the *y-axis*.

8.6. Phasor diagram of a synchronous machine

Figure 8.17: The phasor diagram of a cylindrical rotor synchronous generator for a lagging power factor load.

Figure 8.18: Flux linkage and *EMF* waveform for a complete rotation of the rotor in case the rotor field axis was initially aligned with the *y-axis*.

Figure 8.19: The per phase equivalent circuit of three phase synchronous generator.

Figure 8.20a: The phasor diagram of a cylindrical rotor synchronous generator for a lagging power factor load and neglecting the drop across armature.

Figure 8.20b: The phasor diagram of a cylindrical rotor synchronous generator for a leading power factor load and neglecting the drop across armature.

8.7. Power and torque in synchronous generators

Figure 8.21: The phasor diagram of a cylindrical rotor synchronous generator for a lagging power factor load and neglecting the drop across armature. This phasor diagram is used to determine the power delivered by the generator.

Figure 8.22: Variation of power delivered by the generator as a function load angle.

8.8. Stand alone operation of synchronous generators

Figure 8.23: The phasor diagram of a cylindrical rotor synchronous generator. Here it is assumed that Φrotor >> Φarm and hence,Eairgap >> Ef and Φairgap ≈ Φrotor.

Figure 8.24: The per unit equivalent circuit of a synchronous generator feeding a load.

8.8.1. Varying load with unity power factor

8.8.2. Varying load with lagging power factor

Figure 8.25b: Variation of *Vt* with increase in *Ia* for a lagging power factor load.

8.8.3. Varying load with leading power factor

Figure 8.25c: Variation of *Vt* with increase in *Ia* for a leading power factor load.

8.9. Voltage regulation of an alternator

Figure 8.26: As the load at a fixed power factor increases, the field excitation current is increased so that Vt remains constant. In this case *EMF* increases due to increase in filed excitation current.

8.10. Compounding characteristics of the synchronous generators

Figure 8.27a: Synchronous generator phasor diagram for constant terminal voltage and feeding a lagging power factor load. In this case *Ef* > 1 *p.u.*

Figure 8.27b: Synchronous generator phasor diagram for constant terminal voltage and feeding a unity power factor load. In this case*Ef* is slightly greater than *1 p.u.*

Figure 8.27c: Synchronous generator phasor diagram for constant terminal voltage and feeding a leading power factor load. In this case *Ef* > 1*p.u.*

Figure 8.28: The compounding characteristics of a synchronous generator.

8.11. Basic principle of operation of synchronous motor

Figure 8.29: Construction of synchronous motor.

8.12. Equivalent circuit of synchronous motor

Figure 8.30a: The equivalent circuit of three phase synchronous motor.