Lecture 1

Three-Phase Electric Machine Theory

Objectives:

- Understand the physical construction and winding concepts for three-phase permanent magnet AC machines
- Introduce and explain the machine electrical equations
- Explain the production of torque and rotating magnetic fields

Keywords:

Stator slot

Stator tooth

Distributed Winding

Concentrated Winding

Pole pairs

Faraday's Law

Space vectors

Brushless DC (BLDC)

Trapezoidal BEMF

Permanent Magnet Synchronous Machine (PMSM)

Sinusoidal BEMF

Leakage flux / inductance

Magnetizing flux / inductance

A Note on Variable Labels

Before starting, in an effort to be consistent with literature, we should discuss the conventions commonly used with variable names and labels. In other classes or fields of study, the way we write a variable may not be significant, but in most engineering fields there is a common convention – this is outlined below.

V_s, I_R, etc…	Uppercase italicized variable names denote a constant DC or RMS value – in other words, a single scalar number. These are used to represent the magnitude of something which does not vary with time.
v_s, i_R, etc…	Lowercase italicized variable names denote a continuous-time function or some time-varying signal. We should use these when we talk about things like derivatives, integrals, or any function (e.g. a sine wave) varying in time.
$\mathbf{V_s}$, $\mathbf{I_R}$, etc… or $\vec{V}_s$, $\vec{I}_R$	Uppercase bolded variable names or uppercase italicized variable names with a top-arrow mark designate complex numbers. We use complex numbers to designate vectors (polar numbers with magnitude and phase). These are typically used with phasors, and in sinusoidal steady-state analysis of systems at a specific frequency which does not change.
$\mathbf{v_s}$, $\mathbf{i_R}$, etc… or $\vec{v}_s$, $\vec{i}_R$	Lowercase bolded variable names or lowercase italicized variable names with a top-arrow mark designate time-varying complex numbers. These are usually called space-vectors. They are used to represent magnitude and phase of a time-varying signal which may also be varying at multiple frequencies. We will heavily use space-vectors in this class.

All of the notations above are useful when dealing with different aspects of electric machines or when dealing with specific operating conditions.

Summary / Comparison of Electrical & Mechanical Units

The following table summarizes several electrical and mechanical units together to help visualize their similarities and corresponding units / attributes.

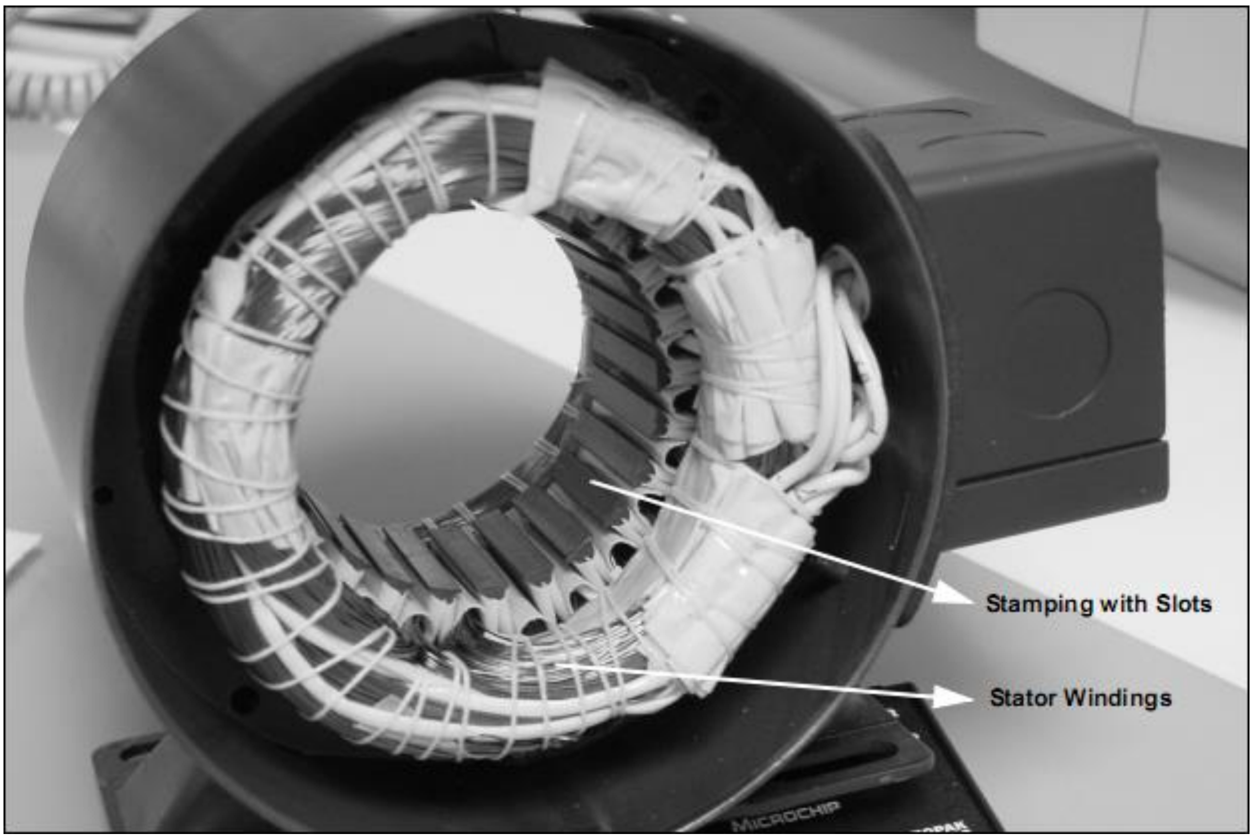
Type	**Category**	**Name**	**Symbol**	**Unit**	**Unit Abbr.**
Force or pressure	Electrical	Voltage	v or V	Volt	V or J/C
	Linear Newtonian	Force	F	Newton	N or J/m or kg·m/s^2
	Rotational Newtonian	Torque	T	Newton-meter	N·m or J/rad or kg·m^2/s^2
Flow rates	Electrical	Current	i or I	Amp	A or C/s
	Linear	Velocity	v	Meters per second	m/s
	Rotational	Angular velocity	ω	Radians per second	rad/s
Resistance to flow	Electrical	Resistance	R	Ohm	Ω or V/A
	Linear	Friction	B	Kilogram per second	kg/s
	Rotational	Rotational friction or drag	D or C	Newton meter seconds per radian	N·m·s/rad or kg·m^2/(rad·s)
Accum. or quantity of substance	Electrical	Charge	q or Q	Coulomb or amp-seconds	C or A·s
	Linear	Position	x or d	Meter	m
	Rotational	Angle	θ	Radian or degree	rad or deg
Storage per unit force or pressure	Electrical	Capacitance	C	Farad	F or C/V or s/Ω
	Linear	Compliance (inverse of spring const.)	1/K	Meters per newton	m/N
	Rotational	Inverse of torsion const.	1/κ	Radians per newton-meter	rad/(N·m) or rad·s^2/(kg·m^2)
Accum. of force or pressure	Electrical	Flux	Φ	Weber or volt-seconds	Wb or V·s
	Linear	Momentum	p	Kilogram meter per second	kg·m/s or N·s
	Rotational	Angular momentum	L	Kilogram meter sq. per radian second	kg·m^2/(rad·s) or N·m·s/rad
Resists change in flow rate	Electrical	Inductance	L	Henry	H or Wb/A or Ω·s
	Linear	Mass	m	Kilogram	kg
	Rotational	Inertia	J or I	Kilogram meter sq. per radian sq.	kg·m^2/rad^2

Reference: http://lpsa.swarthmore.edu/Analogs/ElectricalMechanicalAnalogs.html

Construction of PMAC Machines

Discuss stator and rotor construction

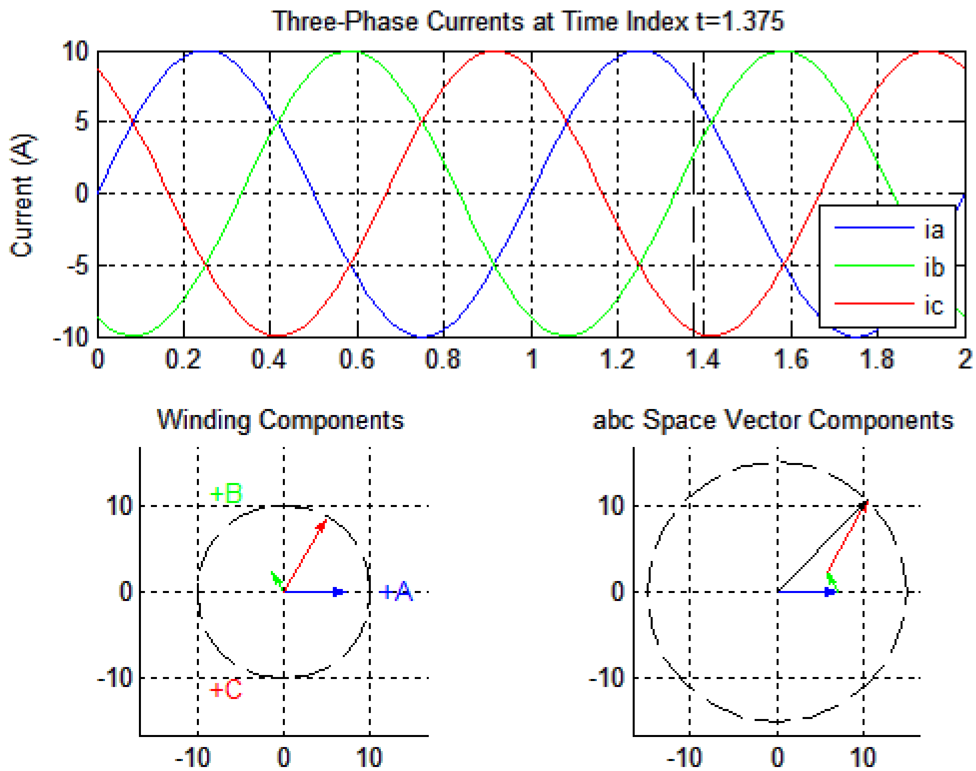
- Slots and teeth in stator for holding wires and minimize air gaps
- Magnets (or windings) are attached or inserted into the rotor
- Discuss the need for steel laminations



Machine Windings

Discuss windings, and how they generate spatially varying fluxes

- Explain distributed vs. concentrated winding configurations and explain their differences in terms of harmonics & construction / cost
- Stress the idea that the coils are spatially varied, and the current is temporally varied – the flux varies in space-time



Animation of rotating MMF vector (MATLAB)

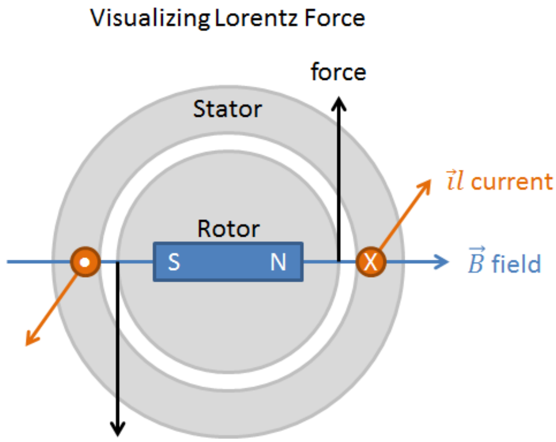
- Mention magnetic pole pairs and illustrate a 4-pole machine compared to a 2-pole machine

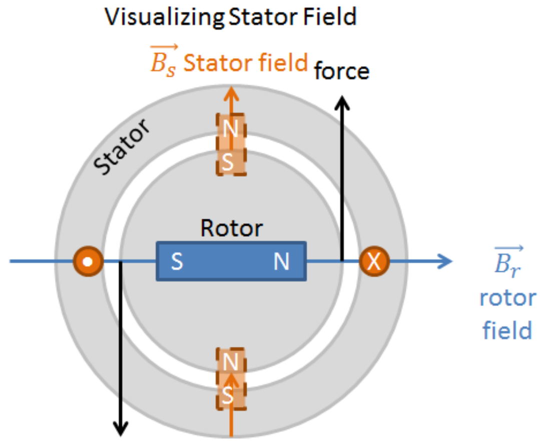
Torque Generation

Discuss torque production using Lorentz Force equation

$$F = B \times il \quad \text{and} \quad T = F \cdot r$$

- Show illustration and discuss how PM field and current vector should be 90-degrees apart for maximum torque production





Machine Voltages & Currents

Start with Faraday's Law for induced voltages

$$v_1(t) = R_s i_1(t) + \frac{d\lambda_1(t)}{dt}$$

- Talk about leakage flux and magnetizing (mutual) flux

$$\lambda_1(t) = L_s i_1(t) + M i_m(t)$$

where $i_m(t)$ is a function of PM and other coils

- In PMAC machines, usually $L_s \ll M$, thus the voltage is

$$v_1(t) = R_s i_1(t) + L_s \frac{di_1(t)}{dt} + \frac{d\lambda_m}{dt}$$

Different Types of PM Machines

Discuss the different types of PM machine names

- Permanent Magnet Synchronous Machine (PMSM) – typically has a sinusoidal BEMF (i.e. the derivative flux term varies sinusoidally).

- Brushless DC (BLDC) Machine – windings are arranged to give a trapezoidal BEMF shape. This makes the square-wave current control method have lower torque ripple and higher power density.