METU EE7566
Electric Drives in Electric and Hybrid Electric Vehicles

Emine Bostancı

Office: C-107

Requirements in Traction Applications

- High torque and power density
- High torque at low speeds for starting, acceleration, and hill climbing
- High power at high speeds for cruising
- Intermittent overload capability (twice the rated power)
- High efficiency over a wide speed range especially for regenerative braking
- Wide constant power speed range (CPSR)
- Fast dynamic response
- Operation in demanding conditions as frequent start/stop
- Operation in harsh environmental conditions such as dust, water, cold and hot temperatures
- Low frequency service and maintenance
- Ruggedness and robustness
- Fault tolerance and safety
- Comfort (proper acoustics)
- Low cost

Fundamentals of Electric Machines

An electric machine is a power converter. When used as a motor, it converts electrical power in the form of current and voltage to mechanical power at the shaft in the form of speed and torque. This conversion process is reversible. It can convert mechanical power into electrical power as well. In that case, the machine works as a generator.

All magnetic forces are the result of the fact that the magnetic field lines tend to shorten, minimum energy state.

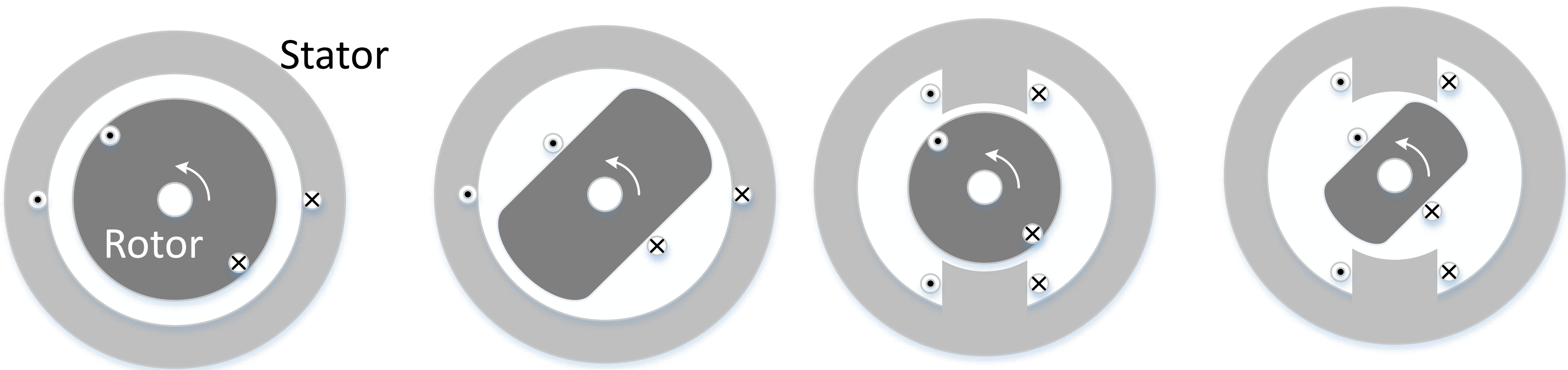
Torque production can be related to two different mechanisms:

- **Reluctance force:** Force caused by the change in magnetic resistance (reluctance)
- **Lorentz force:** Force on a current-carrying conductor in a magnetic field

Electric Machines Overview

<u>Electromagnetic torque:</u> Two magnetic fields try to align themselves, at least one of them should be controllable

<u>Reluctance torque:</u> System tries to decrease the reluctance, magnetic saliency and controllable magnetic field



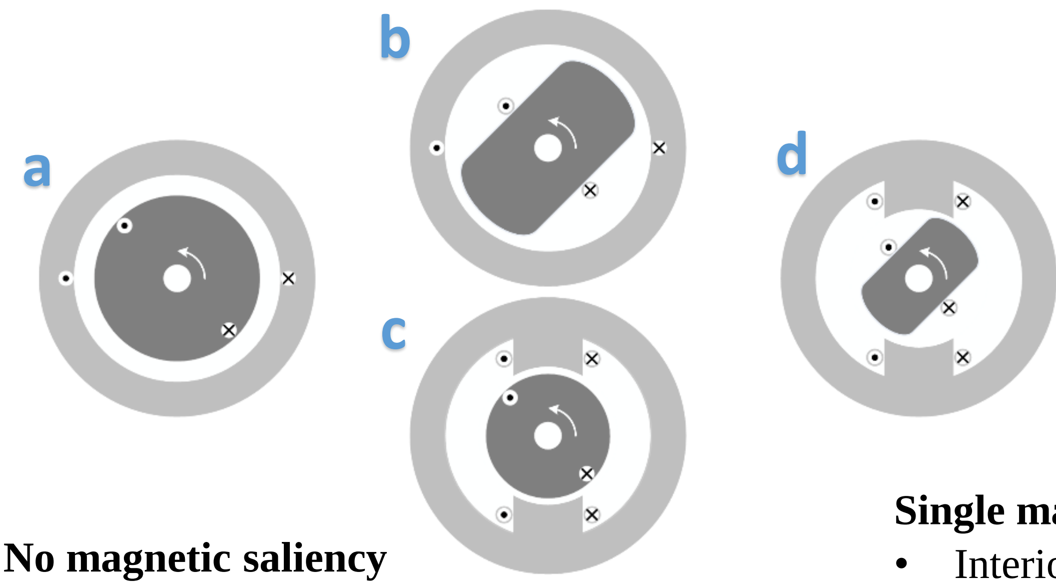
No magnetic saliency

Single magnetic saliency

Double magnetic saliency

Electric Machines Overview

No magnetic saliency	Single mag. saliency	Double mag. saliency



No magnetic saliency

- Induction machine (IM)
- Round rotor synchronous machine (SM)
- Surface mount permanent magnet synchronous machine (SM-PMSM)

Single magnetic saliency

- Interior permanent magnet synchronous machine (IPMSM)
- Synchronous reluctance machine (SyncRel)
- Salient pole synchronous machines (SP-SM)

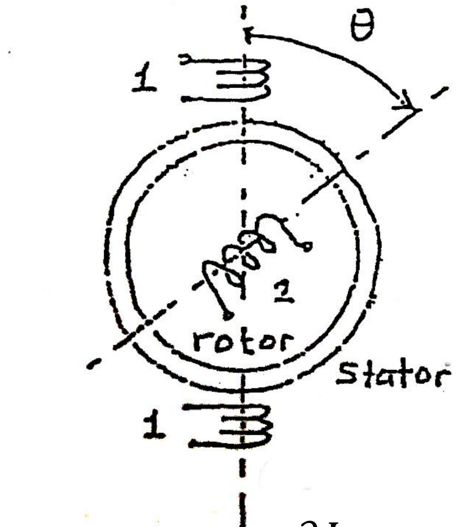
Double magnetic saliency

- Switched reluctance machine (SRM)

➢ The production of a constant average torque is that the stator and rotor fields are standing still to each other, independent of the type of the machine. If both fields (stator & rotor) are rotating at different speeds, a pulsating torque is produced.

Electric Machines Overview

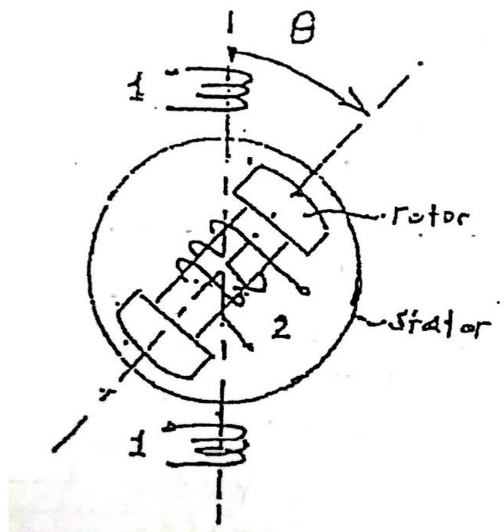
a **No magnetic saliency**



$$T = i_1 i_2 \frac{\partial L_{12}}{\partial \theta}$$

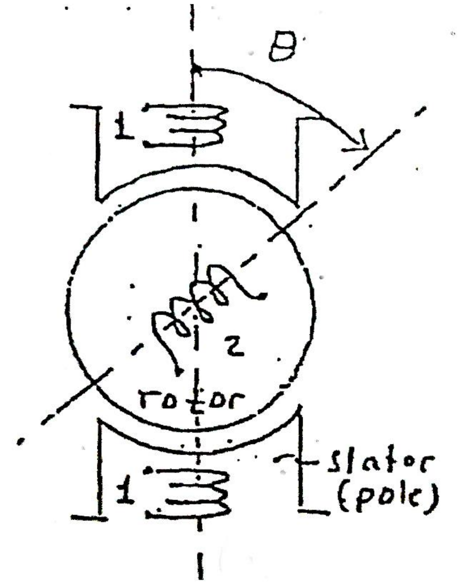
(L_{11} and L_{22} constant)

b **Single magnetic saliency**



$$T = \frac{1}{2} i_1^2 \frac{\partial L_{11}}{\partial \theta} + i_1 i_2 \frac{\partial L_{12}}{\partial \theta}$$ (L_{22} constant)

c **Single magnetic saliency**

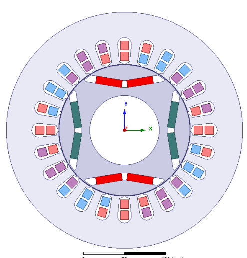


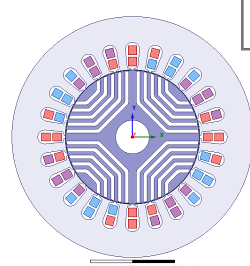
$$T = \frac{1}{2} i_2^2 \frac{\partial L_{22}}{\partial \theta} + i_1 i_2 \frac{\partial L_{12}}{\partial \theta}$$

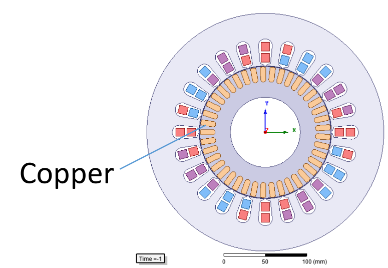
(L_{11} constant)

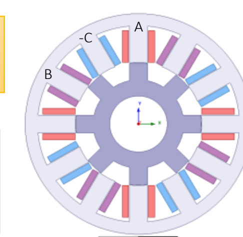
Typical Machine Types

- Stationary Field
  - DC-Machines
    - PM-excited
    - Electrically excited
- Rotating Field
  - Synchronous
    - Radial flux
      - Stator with rotating field winding
        - PM-excited
          - Trapezoidal excitation
          - Sinusoidal excitation
        - Electrically excited
        - Salient pole
      - Modular windings
        - PM-excited
        - Electrically excited
    - Axial flux
    - Transversal flux
  - Asynchronous
    - Rotor with slip rings
    - Squirrel-cage rotor
- Switched field
  - Salient pole



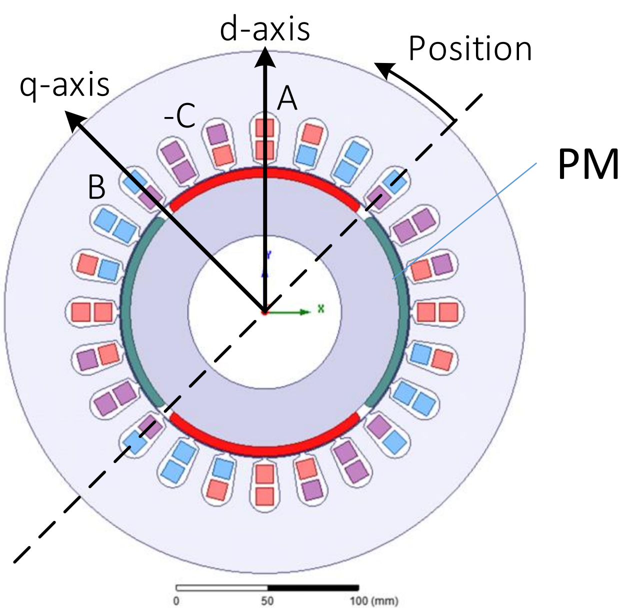




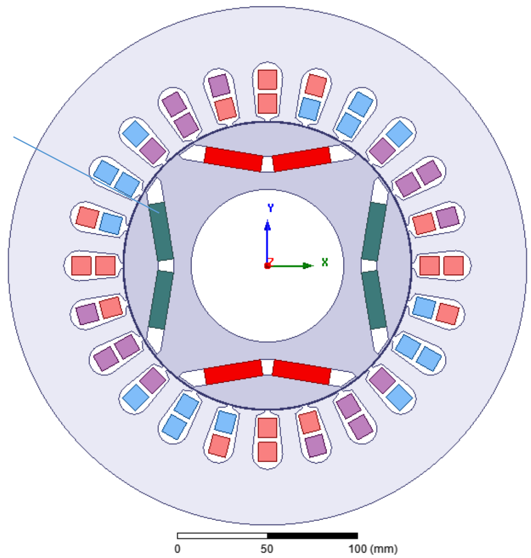


Typical Machine Types

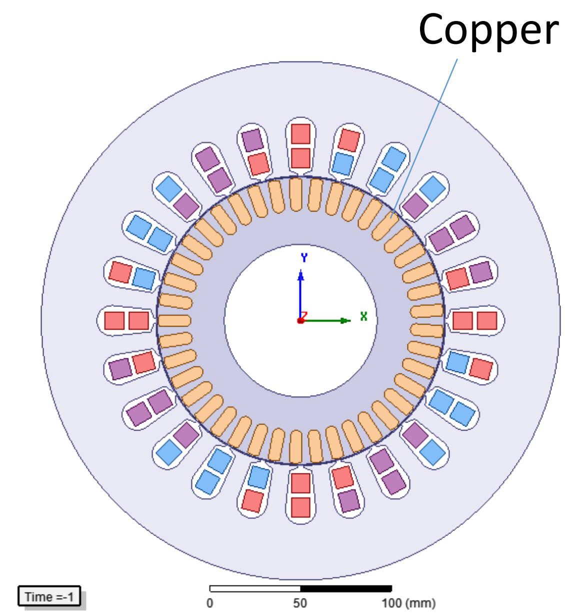
3-phase Rotating Field Machines



Surface mounted PM synchronous machine



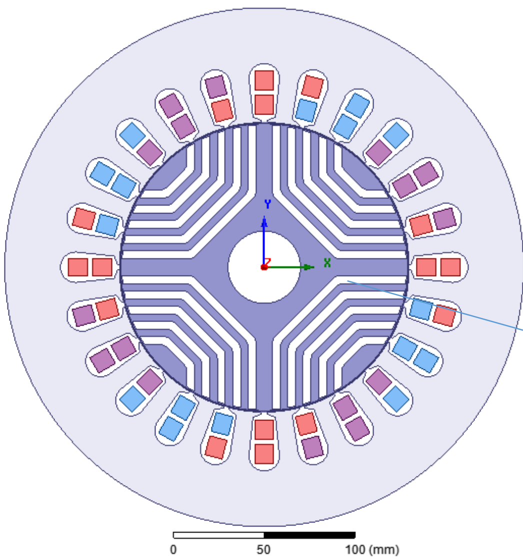
Interior PM synchronous machine



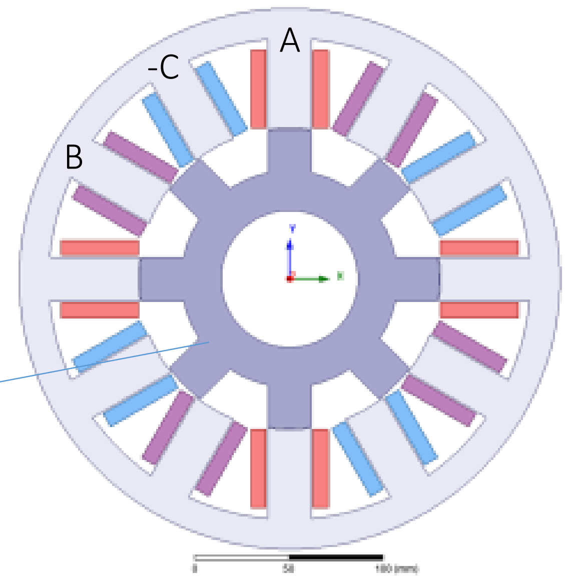
Induction machine

Typical Machine Types

Machines only with Reluctance Torque



Salient rotor



Synchronous reluctance motor
(Rotating Field)

Switched reluctance machine

Elementary AC Machine Example

Source: Electric Machinery by Fitzgerald, Kingsley and Umans.

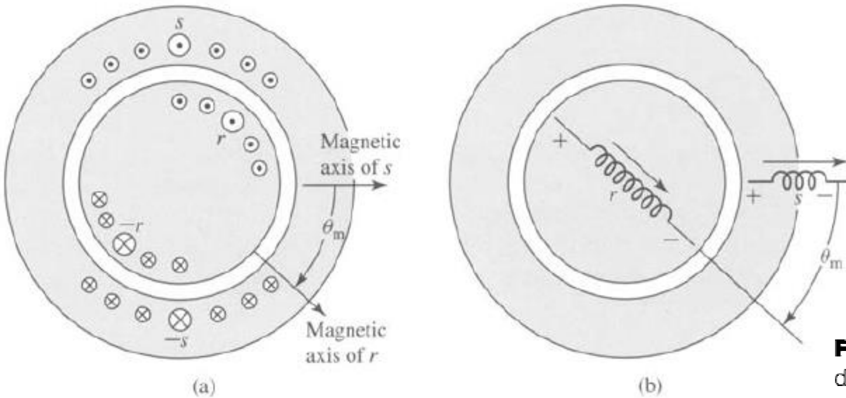


Figure 4.34 Elementary two-pole machine with smooth air gap: (a) winding distribution and (b) schematic representation.

EXAMPLE 4.6

Consider the elementary two-pole, two-winding machine of Fig. 4.34. Its shaft is coupled to a mechanical device which can be made to absorb or deliver mechanical torque over a wide range of speeds. This machine can be connected and operated in several ways. For this example, let us consider the situation in which the rotor winding is excited with direct current I_r and the stator winding is connected to an ac source which can either absorb or deliver electric power. Let the stator current be

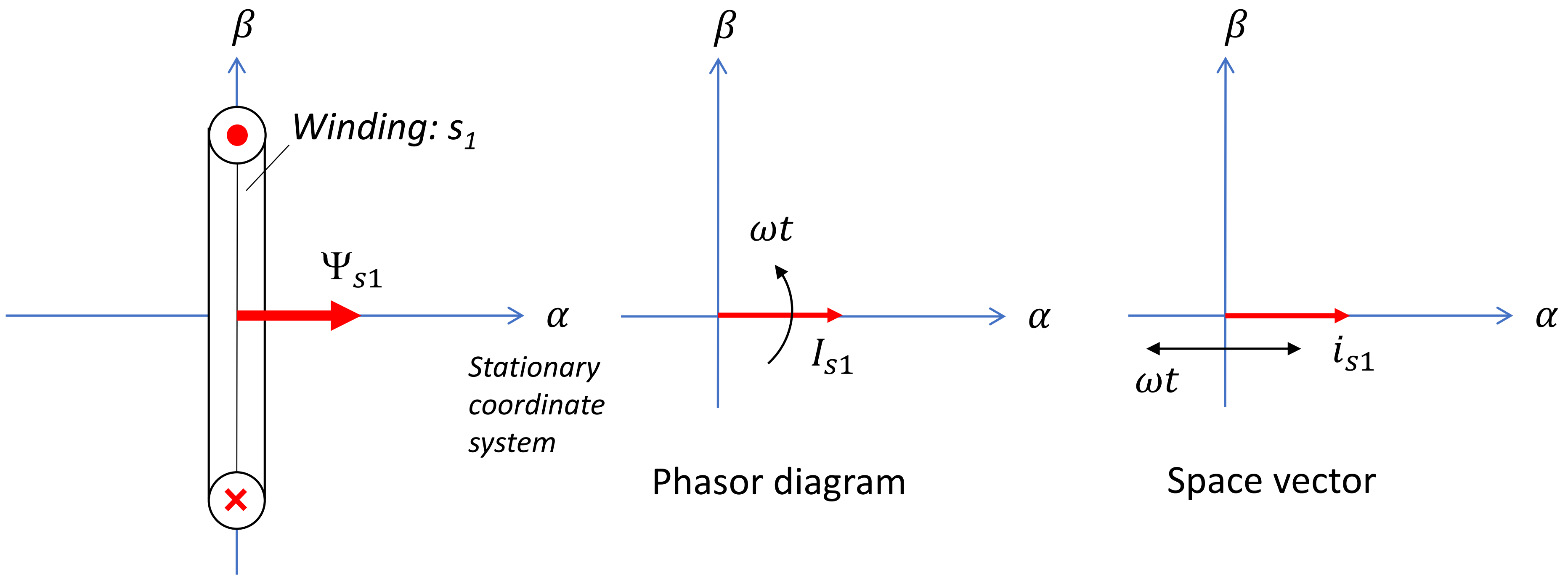
$$i_s = I_s \cos \omega_e t$$

where $t = 0$ is arbitrarily chosen as the moment when the stator current has its peak value.

a. Derive an expression for the magnetic torque developed by the machine as the speed is varied by control of the mechanical device connected to its shaft.
b. Find the speed at which average torque will be produced if the stator frequency is 60 Hz.
c. With the assumed current-source excitations, what voltages are induced in the stator and rotor windings at synchronous speed ($\omega_m = \omega_e$)?

Creating Rotating Field & Space Vector and Coordinate Transformations

Creating a Rotating Field – 1-Phase



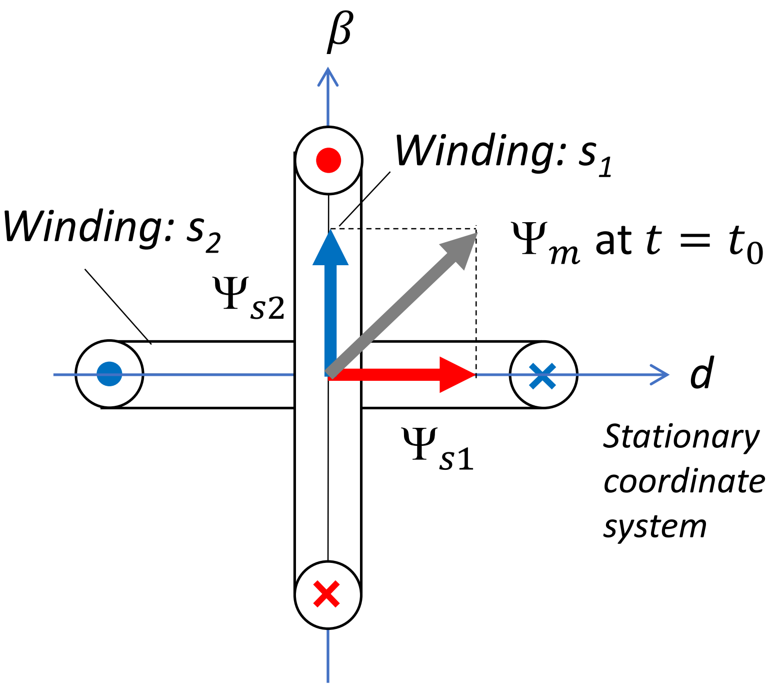
Phasor diagram

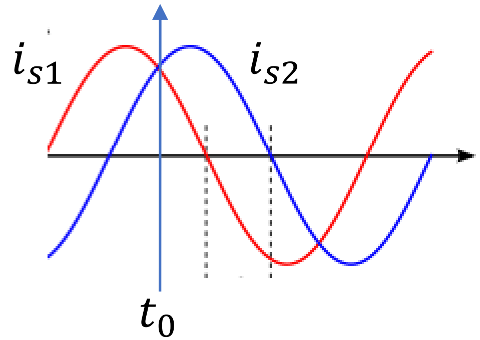
Space vector

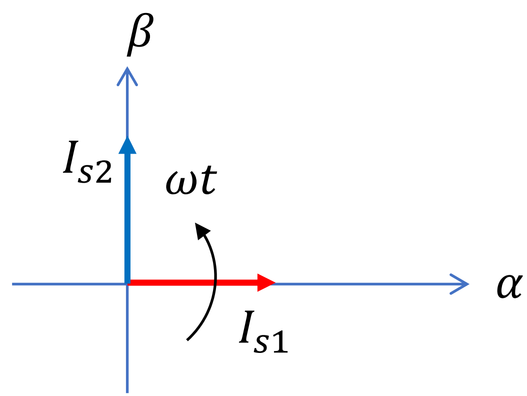
$$\Psi_{s1}(t) = \Psi_m(\mathrm{t}) = \Psi_d(\mathrm{t})$$

$$i_{s1}(t) = \sqrt{2}\, I_{s1} \cos(\omega t)$$

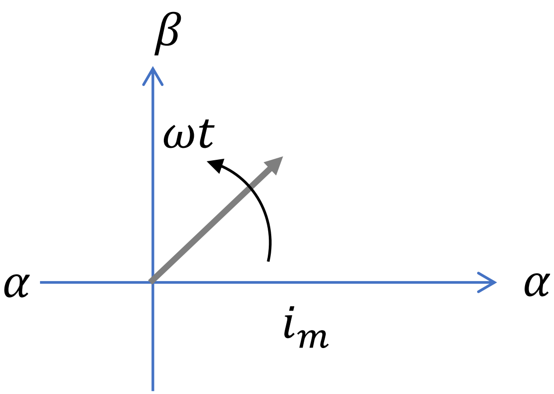
Creating a Rotating Field – 2-Phase







Phasor diagram



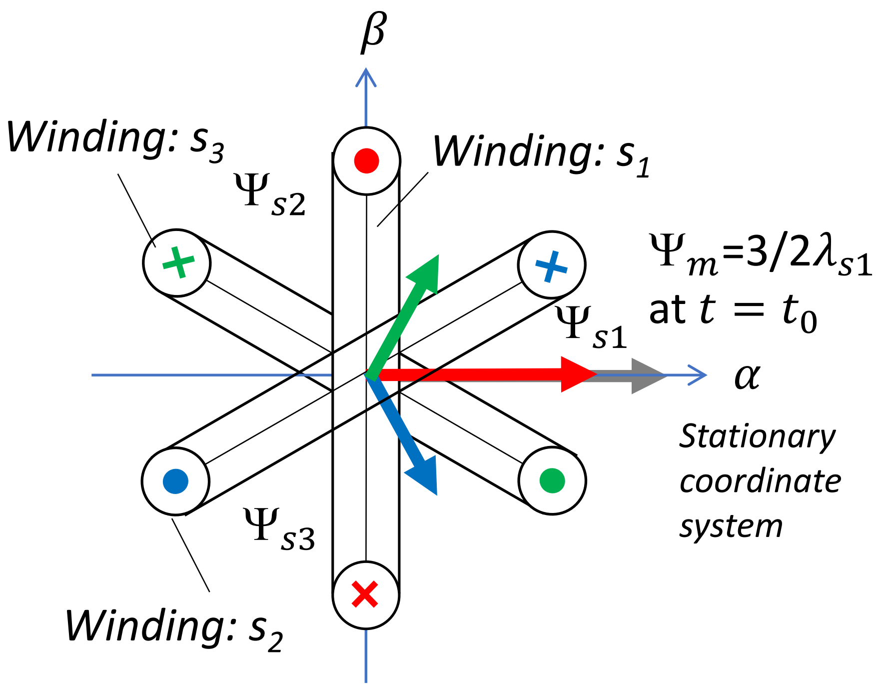
Space vector

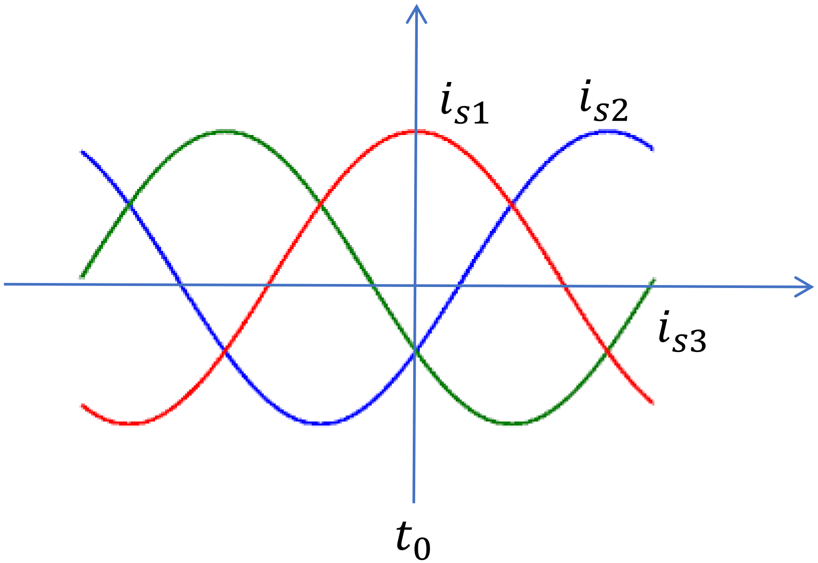
$$i_{s1}(t) = \sqrt{2}\, I_{s1} \cos(\omega t)$$

$$i_{s2}(t) = \sqrt{2}\, I_{s2} \cos\left(\omega t - \frac{\pi}{2}\right)$$

$$\Psi_m(\mathrm{t}) = \overrightarrow{\Psi_{s1}}(t) + \overrightarrow{\Psi_{s2}}(t) = \Psi_m\ cos(\omega \mathrm{t}) + \mathrm{j}\Psi_m sin(\omega \mathrm{t}) = \Psi_m\ e^{j\omega t}$$

Creating a Rotating Field – 3-Phase





$$i_{s1}(t) = \sqrt{2}\, I_{s1}\cos(\omega t)$$

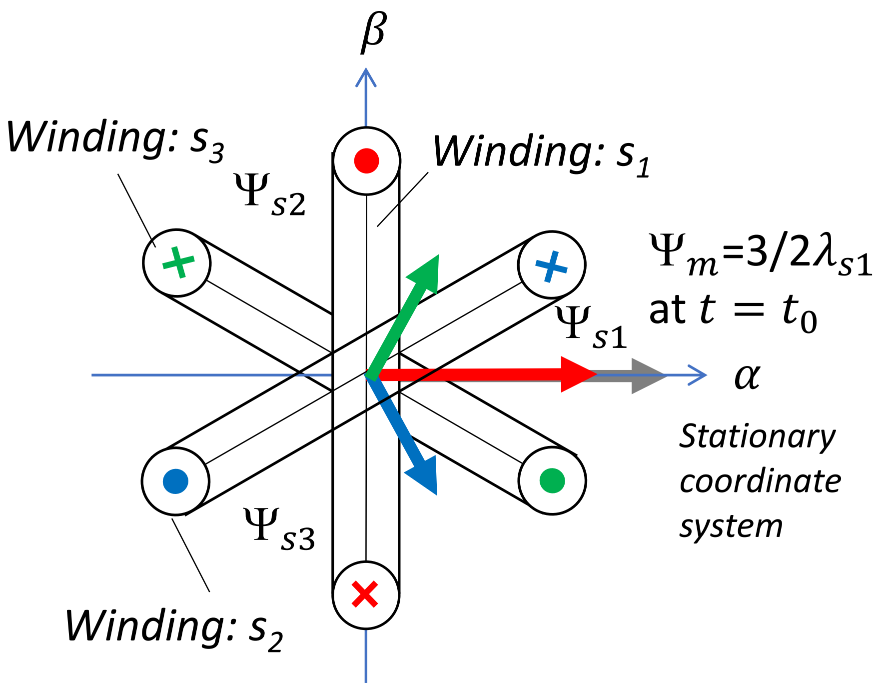
$$i_{s2}(t) = \sqrt{2}\, I_{s1}\cos\left(\omega t - \frac{2\pi}{3}\right)$$

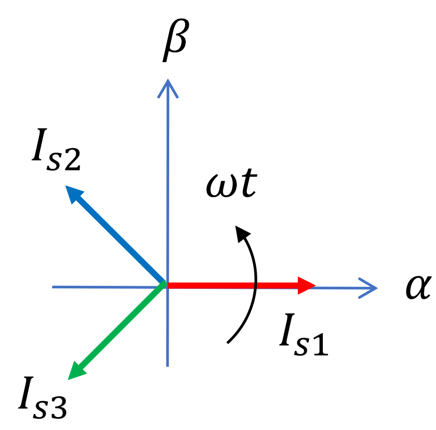
$$i_{s3}(t) = \sqrt{2}\, I_{s1}\cos\left(\omega t - \frac{4\pi}{3}\right) = \sqrt{2}\, I_{s1}\cos\left(\omega t + \frac{2\pi}{3}\right)$$

$$\Psi_m(\mathrm{t}) = \overrightarrow{\Psi_{s1}}(t) + \overrightarrow{\Psi_{s2}}(t) + \overrightarrow{\Psi_{s3}}(t)$$

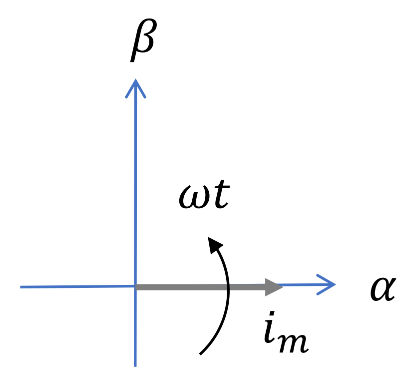
$$= \Psi_{s1}\, e^{j0} + \Psi_{s2} e^{j\frac{2\pi}{3}} + \Psi_{s3} e^{j\frac{4\pi}{3}} = \Psi_m e^{j\omega t}$$

Creating a Rotating Field – 3-Phase





Phasor diagram



Space vector

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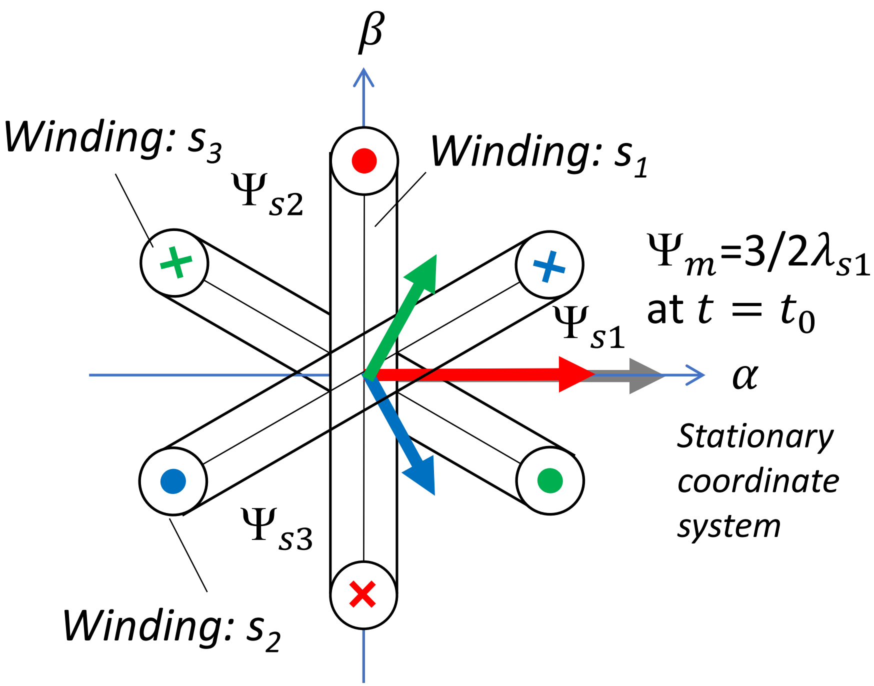
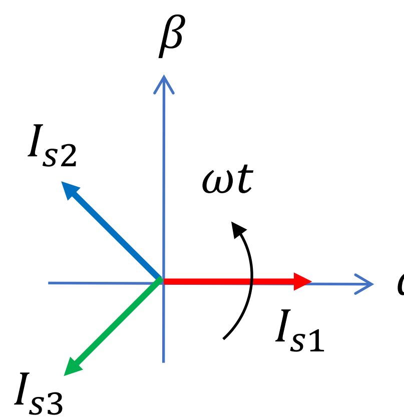
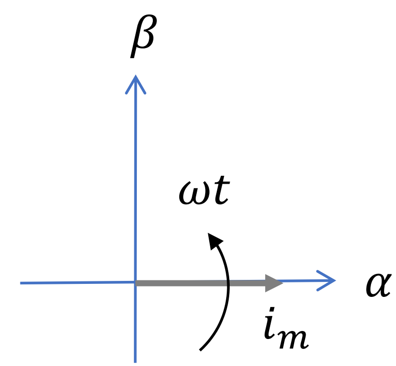
Creating a Rotating Field – 3-Phase





Phasor diagram



Space vector

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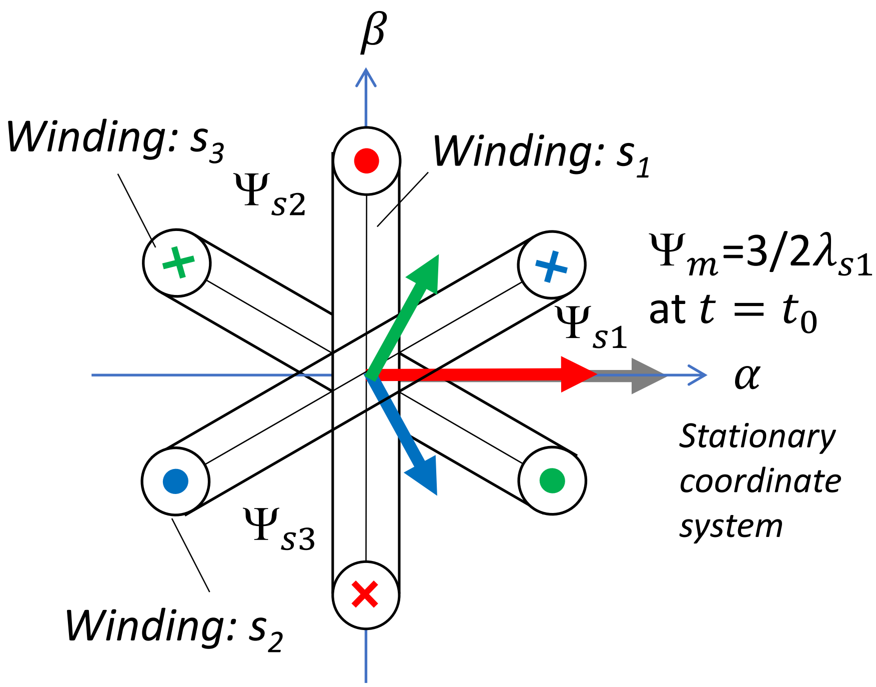
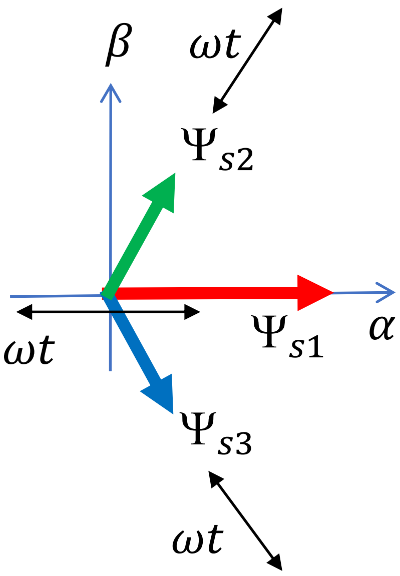
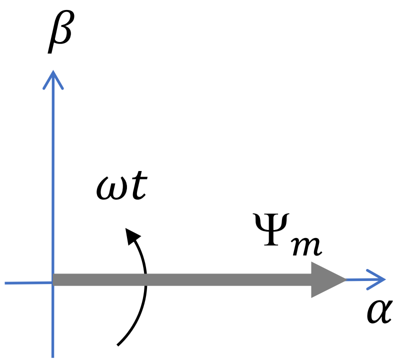
Creating a Rotating Field – 3-Phase





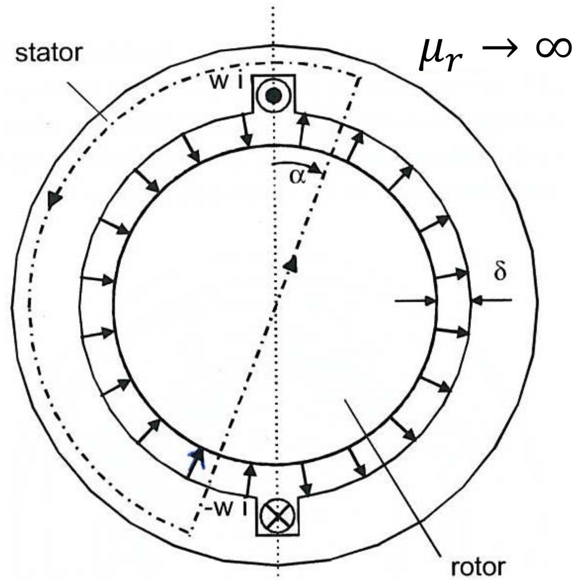


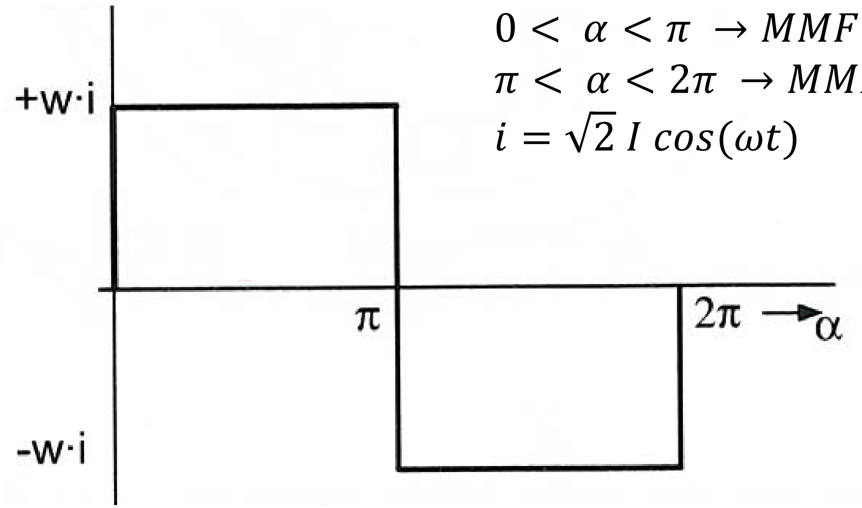
$$\Psi_m(\mathrm{t}) = \overrightarrow{\Psi_{s1}}(t) + \overrightarrow{\Psi_{s2}}(t) + \overrightarrow{\Psi_{s3}}(t)$$

$$= \Psi_{s1}\, e^{j0} + \Psi_{s2} e^{j\frac{2\pi}{3}} + \Psi_{s3} e^{j\frac{4\pi}{3}} = \Psi_m e^{j\omega t}$$

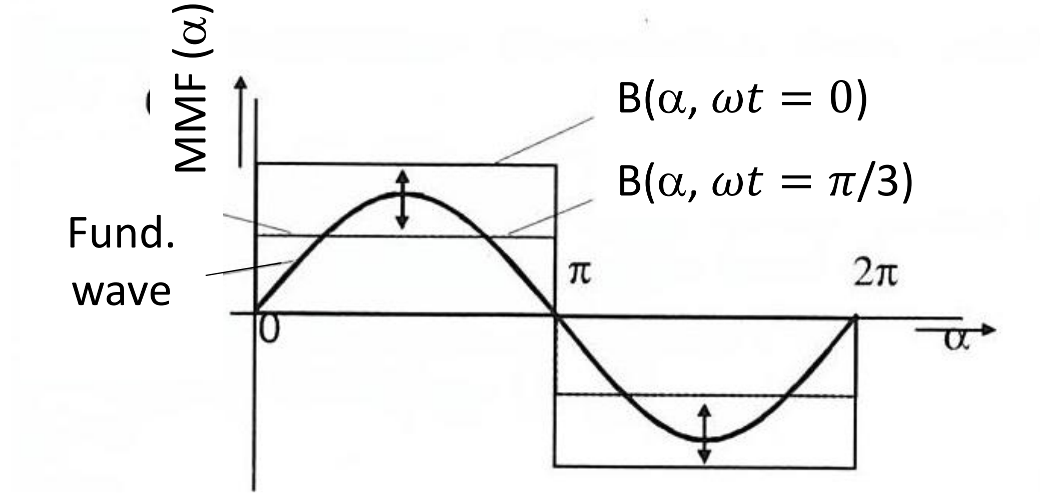
Animations: http://people.ece.umn.edu/users/riaz/animations/listanimations.html

1-Phase Magnetic Air-gap B-Field

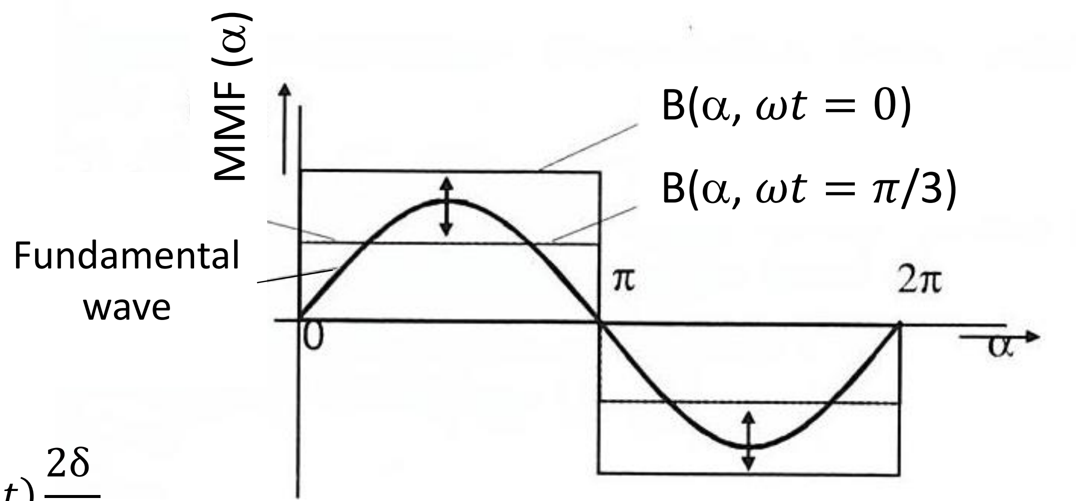




$0 < \ \alpha < \pi \ \rightarrow MMF = w\ i$
$\pi < \ \alpha < 2\pi \ \rightarrow MMF = -w\ i$
$i = \sqrt{2}\ I\ cos(\omega t)$



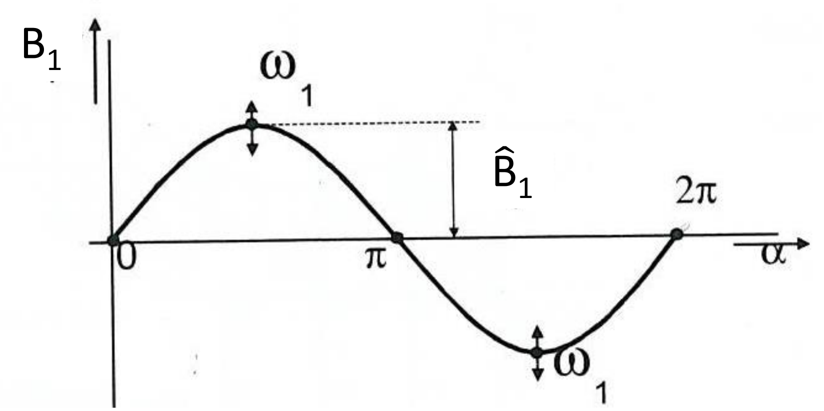
1-Phase Magnetic Field Distribution



$$\mathrm{MMF} = \mathrm{H}(\alpha)2\delta = \frac{\mathrm{B}(\alpha)}{\mu_0}2\delta$$

$$0 < \alpha < \pi \rightarrow \mathrm{B}(\alpha, t) = w\,\sqrt{2}\,I\,cos(\omega t)\frac{2\delta}{\mu_0}$$

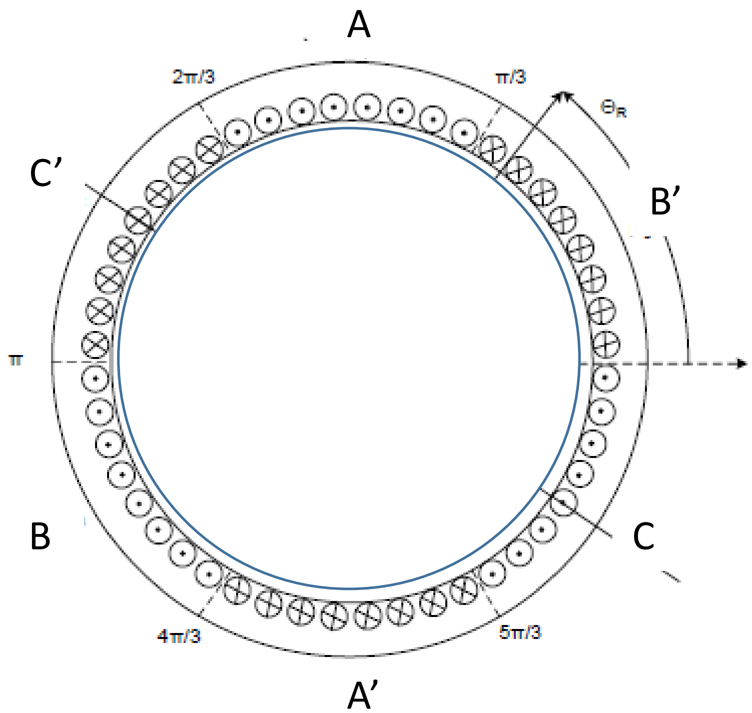
$$\pi < \alpha < 2\pi \rightarrow \mathrm{B}(\alpha, t) = -w\,\sqrt{2}\,I\,cos(\omega t)\frac{2\delta}{\mu_0}$$



Fundamental wave:

$$\mathrm{B}(\alpha, t) = w\,\sqrt{2}\,I\,cos(\omega t)\frac{\mu_0}{2\delta}\frac{4}{\pi}\sin(\alpha)$$

3-Phase Magnetic Air-gap B-Field



$$B_{A1}(\alpha,t) = w\,\sqrt{2}\,I\,cos(\omega t)\,\frac{\mu_0}{2\delta}\frac{4}{\pi}\sin(\alpha)$$

$$B_{A1}(\alpha,t) = B_1 cos(\omega t)\,\sin(\alpha)$$

$$B_{B1}(\alpha,t) = B_1 cos\left(\omega t - \frac{2\pi}{3}\right)\sin(\alpha - \frac{2\pi}{3})$$

$$B_{C1}(\alpha,t) = B_1 cos\left(\omega t - \frac{4\pi}{3}\right)\sin(\alpha - \frac{4\pi}{3})$$

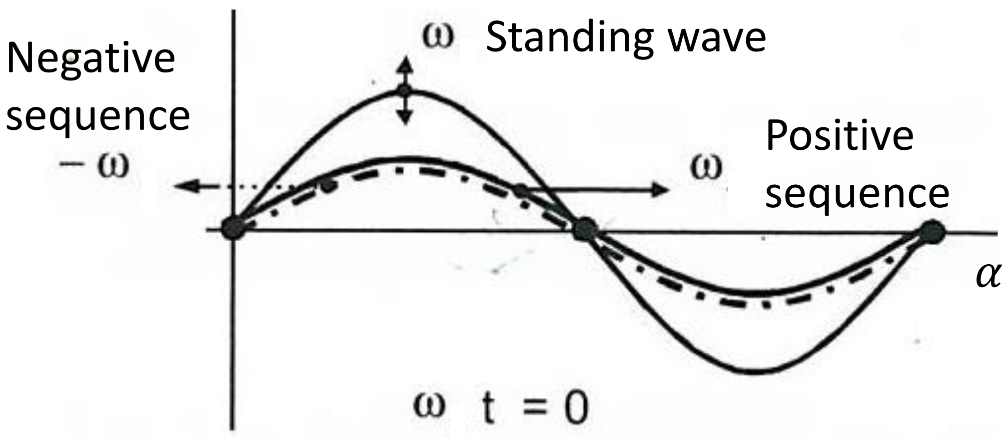
Fundamental component of the flux density distribution created by phase C.

$$i_{s1}(t) = \sqrt{2}\,I_{s1}\cos(\omega t)$$

$$i_{s2}(t) = \sqrt{2}\,I_{s1}\cos\left(\omega t - \frac{2\pi}{3}\right)$$

$$i_{s3}(t) = \sqrt{2}\,I_{s1}\cos\left(\omega t - \frac{4\pi}{3}\right) = \sqrt{2}\,I_{s1}\cos\left(\omega t + \frac{2\pi}{3}\right)$$

3-Phase Magnetic Air-gap B-Field



$$B_{A1}(\alpha,t) = w\,\sqrt{2}\,I\,cos(\omega t)\,\frac{\mu_0}{2\delta}\frac{4}{\pi}\sin(\alpha)$$

$$B_{A1}(\alpha,t) = B_1 cos(\omega t)\,\sin(\alpha)$$

$$B_{B1}(\alpha,t) = B_1 cos\left(\omega t - \frac{2\pi}{3}\right)\sin(\alpha - \frac{2\pi}{3})$$

$$B_{C1}(\alpha,t) = B_1 cos\left(\omega t - \frac{4\pi}{3}\right)\sin(\alpha - \frac{4\pi}{3})$$

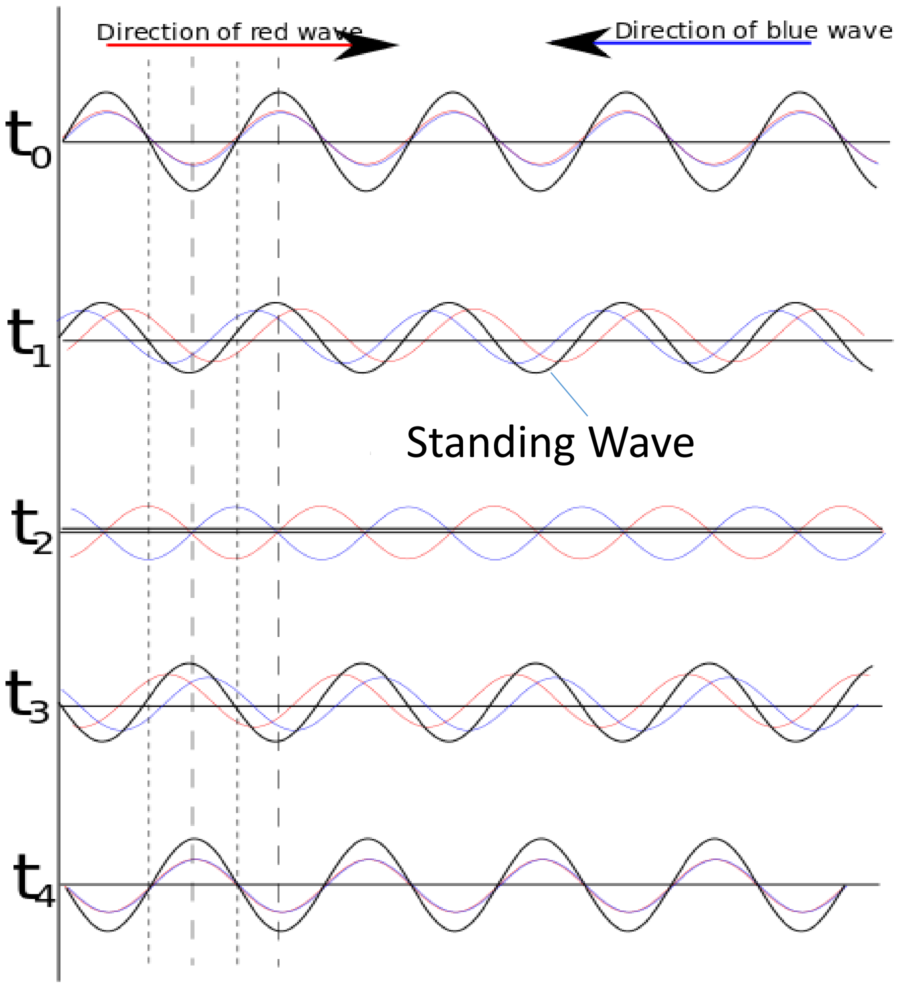
$$\underbrace{\frac{B_1}{2}\sin(\alpha - \omega t)}_{\text{Positive sequence}} + \underbrace{\frac{B_1}{2}\sin(\alpha + \omega t))}_{\text{Negative sequence}}$$

$B_{A1}(\alpha,t)$, $B_{B1}(\alpha,t)$ and $B_{C1}(\alpha,t)$ are the fundamental waves. The air-gap flux density distribution depends on

- position due to distribution of the winding conductors, $sin(\alpha)$
- time due to time-varying phase currents, $cos(\omega t)$.

Animation: https://upload.wikimedia.org/wikipedia/commons/7/7d/Standing_wave_2.gif

3-Phase Magnetic Air-gap B-Field



$$\mathrm{B_{A1}}(\alpha,t) = w\sqrt{2}\,I\,cos(\omega t)\,\frac{2\delta}{\mu_0}\frac{4}{\pi}\sin(\alpha)$$

$$\mathrm{B_{A1}}(\alpha,t) = B_1 cos(\omega t)\,\sin(\alpha)$$

$$\mathrm{B_{B1}}(\alpha,t) = B_1 cos\left(\omega t - \frac{2\pi}{3}\right)\sin(\alpha - \frac{2\pi}{3})$$

$$\mathrm{B_{C1}}(\alpha,t) = B_1 cos\left(\omega t - \frac{4\pi}{3}\right)\sin(\alpha - \frac{4\pi}{3})$$

$$\mathrm{B_{A1}}(\alpha,t) = \frac{B_1}{2}\,(\sin(\alpha - \omega t) + \sin(\alpha + \omega t))$$

$$\mathrm{B_{B1}}(\alpha,t) = \frac{B_1}{2}\,(\sin(\alpha - \omega t) + \sin(\alpha + \omega t - 4\pi/3))$$

$$\mathrm{B_{C1}}(\alpha,t) = \frac{B_1}{2}\,(\sin(\alpha - \omega t) + \sin(\alpha + \omega t - 8\pi/3))$$

$$\Rightarrow \mathbf{B_m}\,(\boldsymbol{\alpha}, \boldsymbol{t}) = \frac{\mathbf{3}\,\boldsymbol{B_1}}{\mathbf{2}}\,\mathbf{sin}(\boldsymbol{\alpha} - \boldsymbol{\omega t})$$

Generating Rotating Field

Standing wave animation

$$Standing\ wave\ (pulsating\ wave) = A\ cos(\omega_e t)\sin(\alpha)$$

$$A\ cos(\omega_e t)\sin(\alpha) = \underbrace{\frac{A}{2}\sin(\alpha - \omega_e t)}_{\text{Positive sequence}} + \underbrace{\frac{A}{2}\sin(\alpha + \omega_e t)}_{\text{Negative sequence}}$$

3-phase system (positive sequence phase b is lagging phase a by 120 deg):

$$Phase\ 1 \Rightarrow \frac{A}{2}\sin(\alpha - \omega_e t) + \frac{A}{2}\sin(\alpha + \omega_e t)$$

$$Phase\ 2 \Rightarrow \frac{A}{2}\sin\left((\alpha - \frac{2\pi}{3}) - (\omega_e t - \frac{2\pi}{3})\right) + \frac{A}{2}\sin\left((\alpha - \frac{2\pi}{3}) + (\omega_e t - \frac{2\pi}{3}\right)$$

$$Phase\ 3 \Rightarrow \frac{A}{2}\sin\left((\alpha + \frac{2\pi}{3}) - (\omega_e t + \frac{2\pi}{3})\right) + \frac{A}{2}\sin\left((\alpha + \frac{2\pi}{3}) + (\omega_e t + \frac{2\pi}{3})\right)$$

$$= 3\frac{A}{2}\sin(\alpha - \omega_e t)$$

A constant wave with **3/2** times amplitude of the standing wave is generated.

Creating a Rotating Field – 5-Phase Case

Assignment not to be collected: Show that how we can produce a rotating field in a five phase system.

a) Draw the winding diagram of a 2-pole 10-slot 5-phase stator structure, show positive and negative coil sides of each phase. What is the spatial phase shift between phases?

b) Write down the phase currents assuming that Phase A has the following current. What is the electrical phase shift between phase currents?

$$I_A = I_{max}\, cos(\omega_e t)$$

a) Write down the positive and negative MMF sequences created by each phase. Assume that Phase A creates the following MMF waveform. Where ω_e is the electrical frequency and α is the spatial position.

$$Acos(\omega_e t)\sin(\alpha)$$

a) Show that we can create a rotating fields rotating both in positive and negative directions. How do we change the direction of the resultant rotating field.

b) Draw MMF space vectors created by each phase on $\alpha\beta - plane$ and show the resultant rotating MMF space vector **at time equal to 0**.

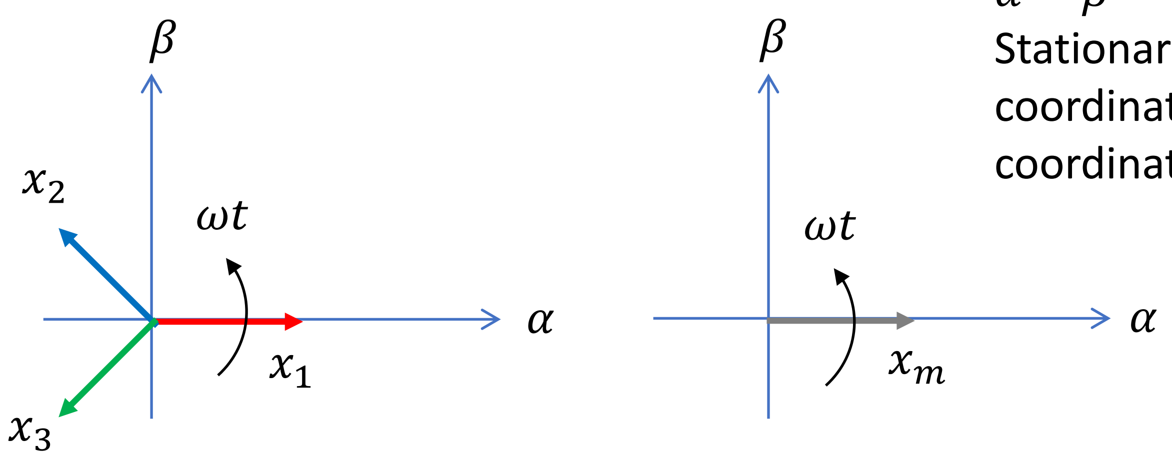
c) What is the amplitude of the resultant rotating field in terms of A? Compare it with a 3-phase system discussed during lectures.

Space Vector Transformation

Since 3-phase systems are highly used, a transformation from 3-phase system into 2-phase quantities is beneficial.

A general quantity x that may represent current, voltage and flux linkage.

Space vectors represent a physical interpretation for flux (linkages) but not for other quantities.



Phasor diagram

Space vector

$\alpha - \beta$
Stationary coordinates (stator coordinates)

$$x_m = \left\{ x_1 + \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2} \right) x_2 + \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2} \right) x_3 \right\} = x_{m-\alpha} + jx_{m-\beta}$$

Space Vector Transformation (Clarke's Transformation)

$$x_m = \mathbf{\frac{2}{3}} \left\{ x_1 + \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2} \right) x_2 + \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2} \right) x_3 \right\} = x_{m-\alpha} + jx_{m-\beta}$$

Amplitude invariant:

$$\begin{bmatrix} x_\alpha \\ x_\beta \\ x_0 \end{bmatrix} = 2/3 \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ -1/2 & \sqrt{3}/2 & 1 \\ -1/2 & -\sqrt{3}/2 & 1 \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \\ x_0 \end{bmatrix}$$

$$\rightarrow p_{3-phase} = 3/2\, p_{2-phase}$$

In electric machine analysis we use amplitude invariant transformation.

Amplitude invariant means that amplitude of 3-phase quantities and 2-phase quantities are going to be same.

Space Vector Transformation (Clarke's Transformation)

Assignment not to be collected: For amplitude invariant transformation, show that power of 3-phase system is 3-phase system is 3/2 times the power of the 2-phase system that is → $p_{3-phase} = 3/2\ p_{2-phase}$

Hint:

$$p_{3-phase} = v_1\ i_1 + v_2\ i_2 + v_3\ i_3 = \mathrm{Re}\{v\ i^*\}$$

$$p_{2-phase} = \mathrm{Re}\left\{\ (v_\alpha + j\ v_\beta)\ \ (i_\alpha - j\ i_\beta)\right\} = v_\alpha\ \ i_\alpha + v_\beta\ i_\beta$$

$System\ is\ balanced$!

Space Vector Transformation (Clarke's Transformation)

$$x_m = \sqrt{\frac{\mathbf{2}}{\mathbf{3}}}\left\{x_1 + \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right)x_2 + \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right)x_3\right\} = x_{m-\alpha} + jx_{m-\beta}$$

Power invariant:

$$\begin{bmatrix} x_\alpha \\ x_\beta \\ x_0 \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & 0 & 1/\sqrt{2} \\ -1/2 & \sqrt{3}/2 & 1/\sqrt{2} \\ -1/2 & -\sqrt{3}/2 & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} x_\alpha \\ x_\beta \\ x_0 \end{bmatrix}$$

Power

$\rightarrow p_{3-phase} = p_{2-phase}$

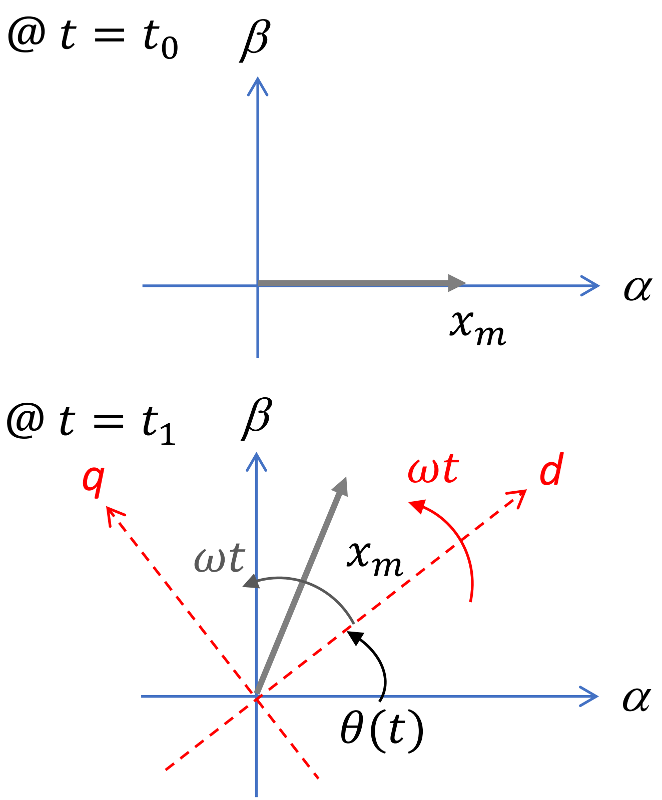
If we use power invariant transformation, the powers of 3-phase system and 2-phase system are going to be the same. But amplitues are going to be different.

$$p_{3-phase} = v_1\, i_1 + v_2\, i_2 + v_3\, i_3 = \mathrm{Re}\{v\, i^*\}$$

$$p_{2-phase} = \mathrm{Re}\{\,(v_\alpha + j\, v_\beta)\,\,(i_\alpha - j\, i_\beta)\} = v_\alpha\,\, i_\alpha + v_\beta\, i_\beta$$

Coordinate Transformation (Park's Transformation)

- Transformation between stationary and rotatory coordinates



Space vector

Rotatory coordinates → Stationary coordinates

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix}$$

Stationary coordinates → Rotatory coordinates

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} x_d \\ x_q \end{bmatrix}$$

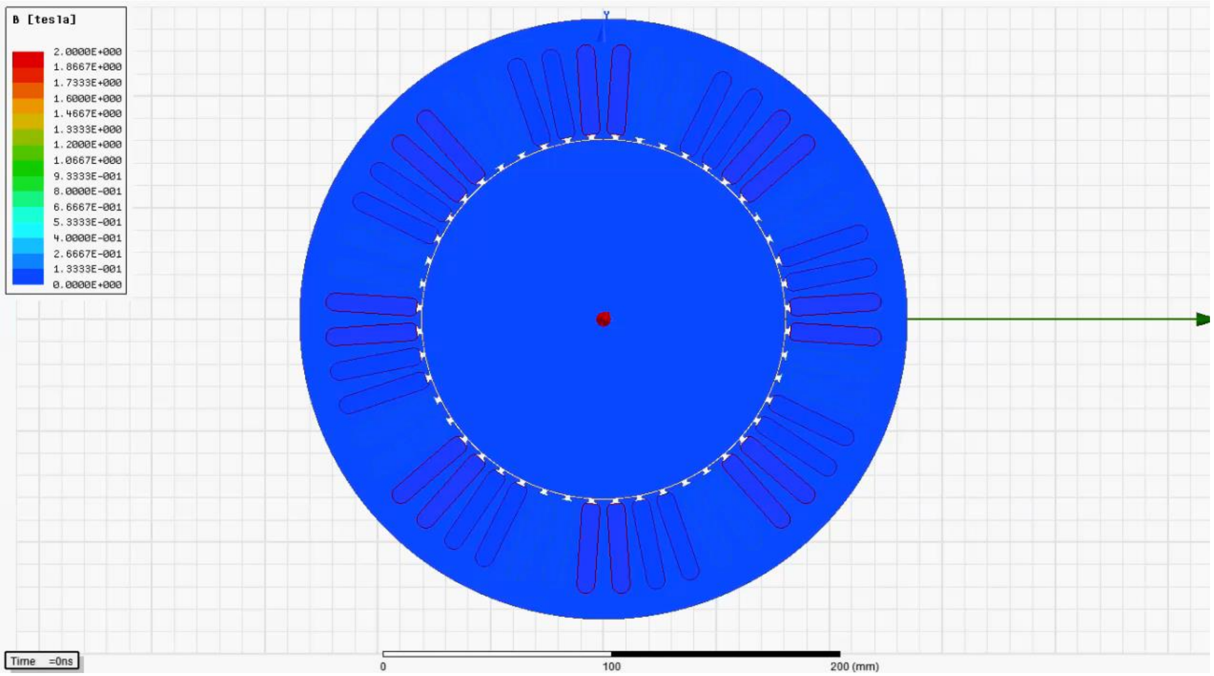
$\alpha\beta$: Stationary coordinate system
i.e. Stator reference frame

dq: Rotatory coordinate system,
i.e. Rotor reference frame

$\theta(t)$: angle between coordinate systems

Simulation of Standing Wave and Rotating Field with Ansys/Maxwell

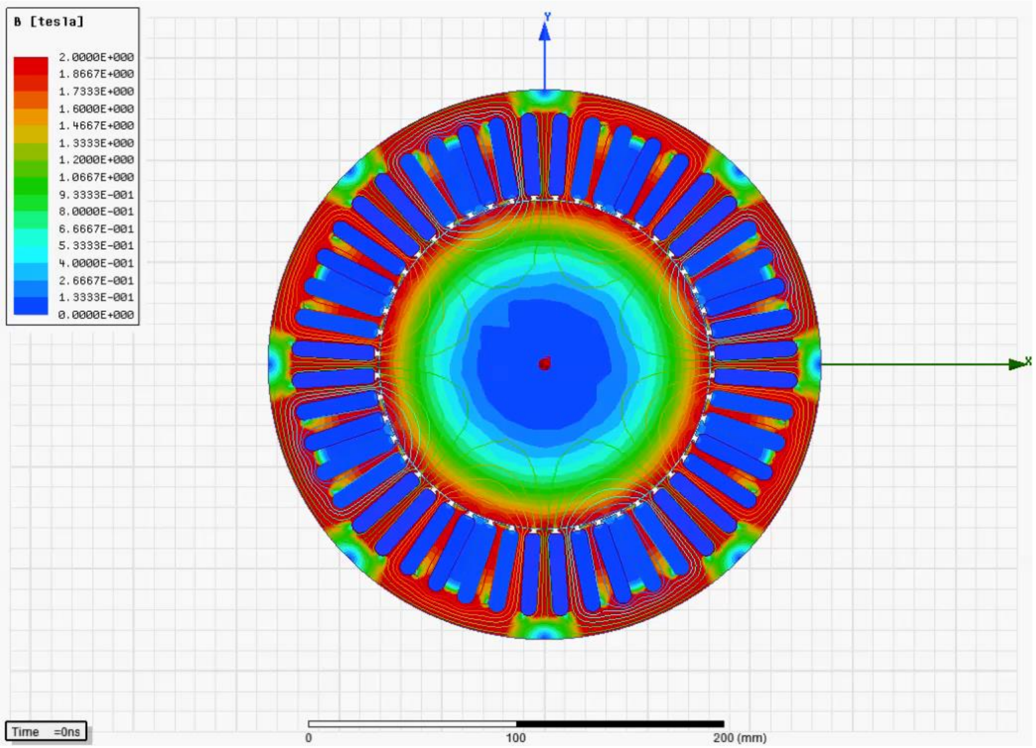
Standing Wave (Linear material)



$i_{s1}(t) = 100\cos(\omega t - \pi/2)$ and $i_{s2}(t) = i_{s3}(t)$= 0

Simulation of Standing Wave and Rotating Field with Ansys/Maxwell

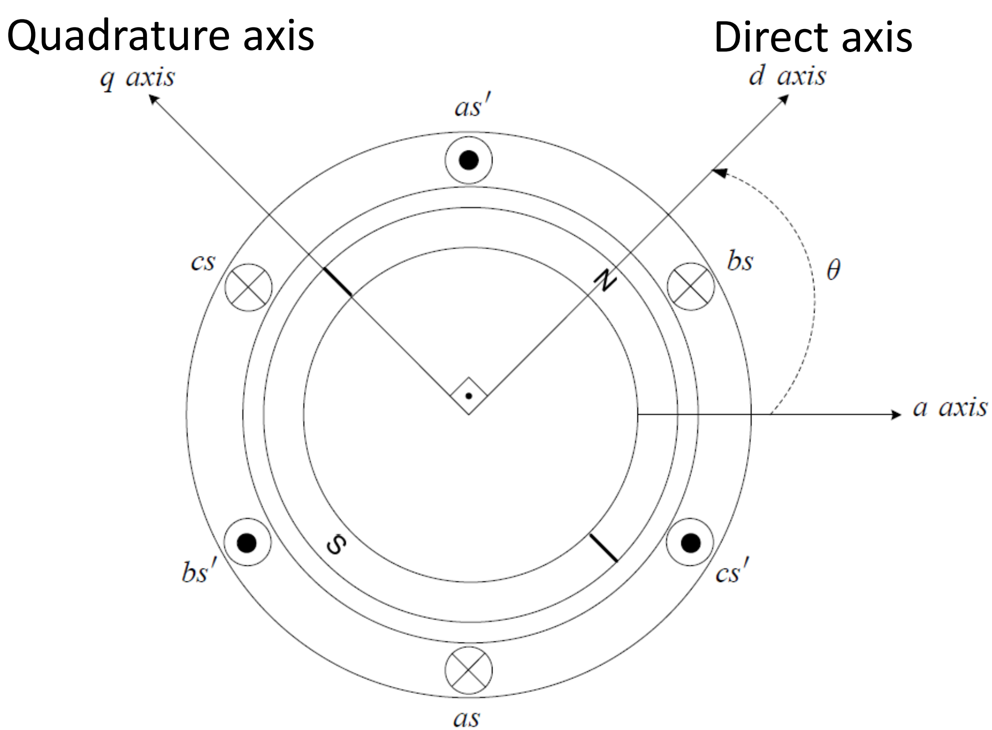
Rotating Field (Linear material)



$i_{s1}(t) = 100\sin(\omega t)$, $i_{s2}(t) = 100\sin\left(\omega t - \frac{2\pi}{3}\right)$, and $i_{s3}(t) = 100\sin\left(\omega t - \frac{4\pi}{3}\right)$

Permanent Magnet Synchronous Machines (PMSM)

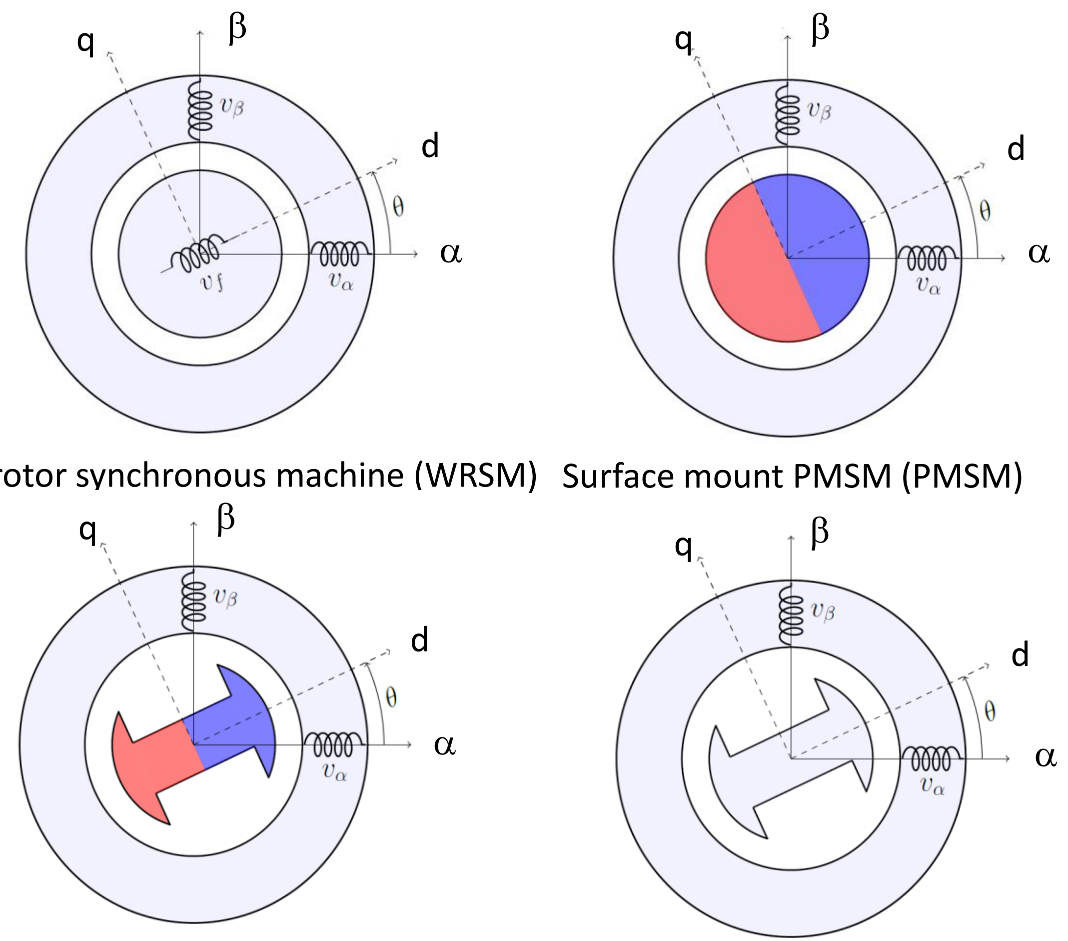
Stationary and Rotatory Coordinates



Definition of αβ coordinates for

$i_{as1}(t) = 100\cos(\omega t)$, $i_{bs2}(t) = 100\cos\left(\omega t - \frac{2\pi}{3}\right)$ and $i_{cs3}(t) = 100\cos\left(\omega t - \frac{4\pi}{3}\right)$

Stationary and Rotatory Coordinates



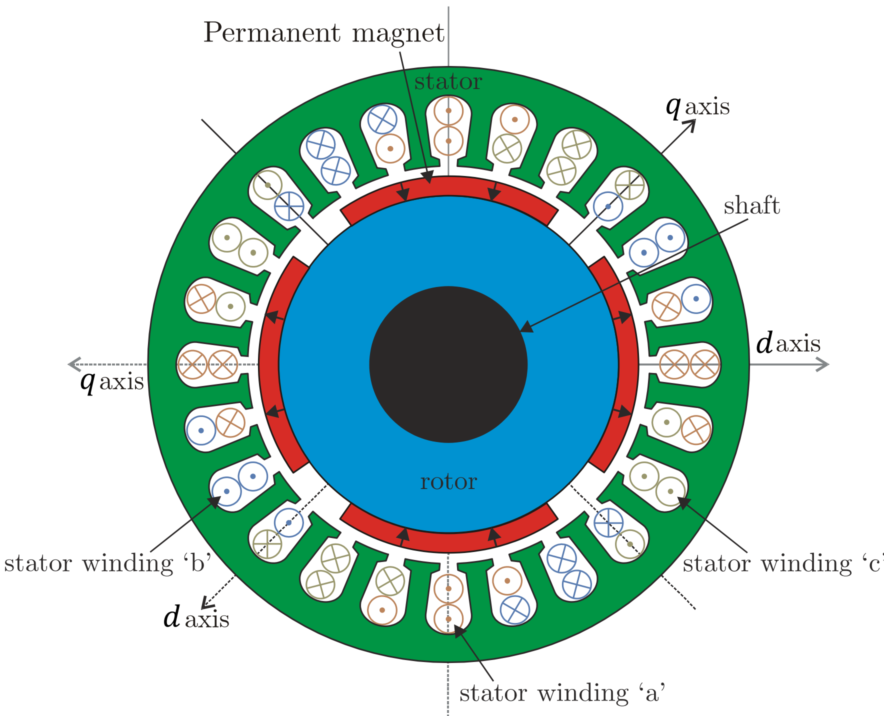
Wound rotor synchronous machine (WRSM) Surface mount PMSM (PMSM)

Interior PMSM (IPMSM)

Synchronous reluctance machine (SynRM)

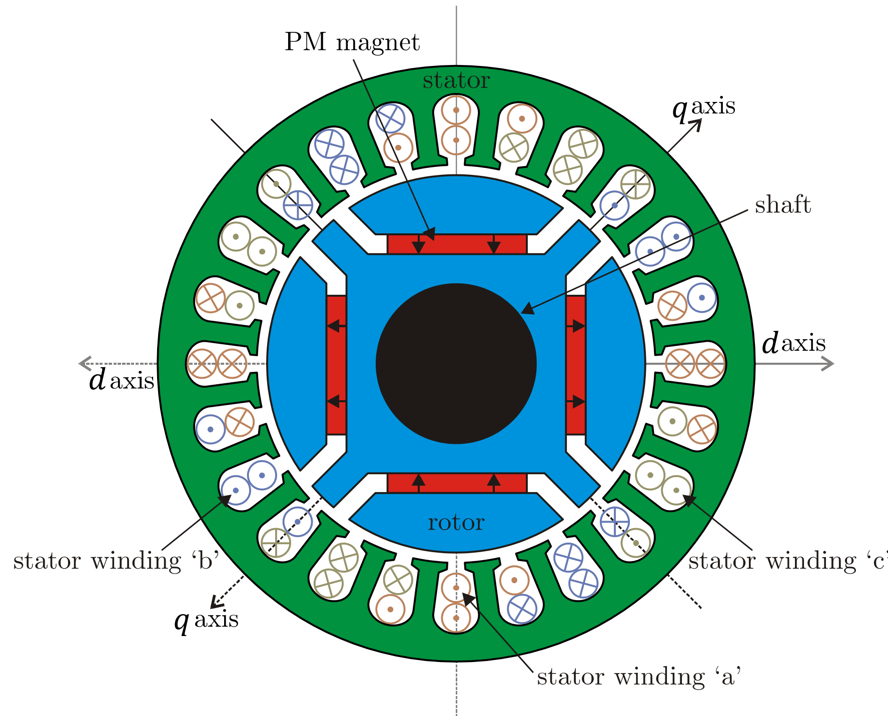
http://arxiv.org/pdf/1512.03666.pdf

Permanent Magnet Synchronous Machines (PMSM)



p = 2; four pole machine

Surface Mount(ed) PM SM - SMPMSM

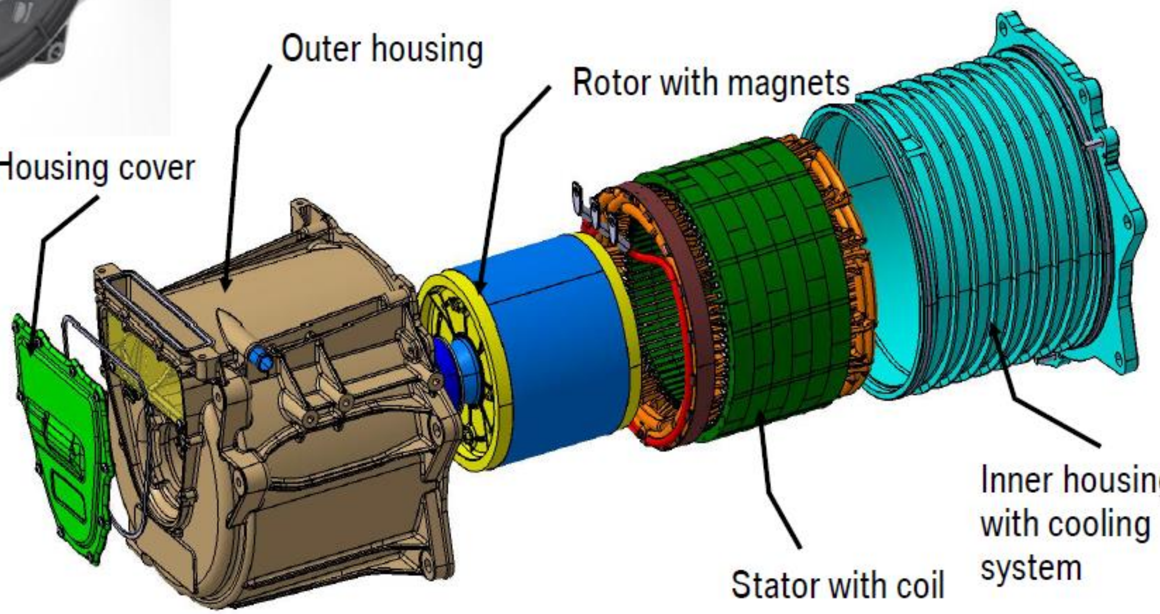


$p = 2$; four pole machine with interior permanent magnets

Interior PM SM - IPMSM

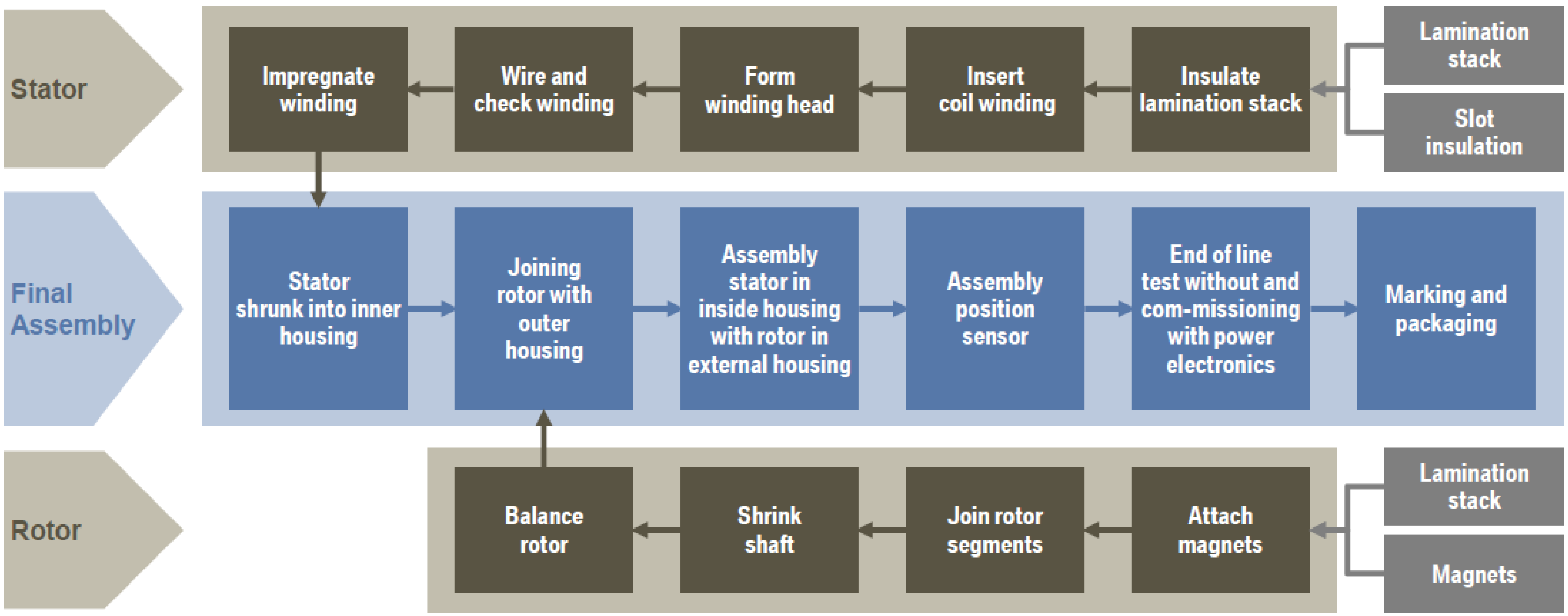
BMW i3 Electric Machine

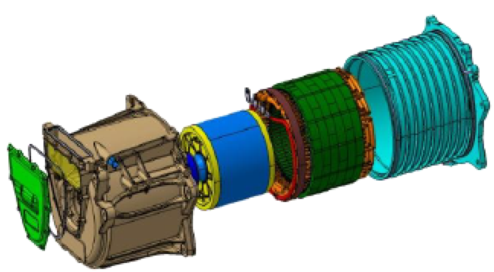
– Optimum ratio of power vs. weight
– Maximum torque during start-up
– High degree of efficiency over a wide operating range.



Source

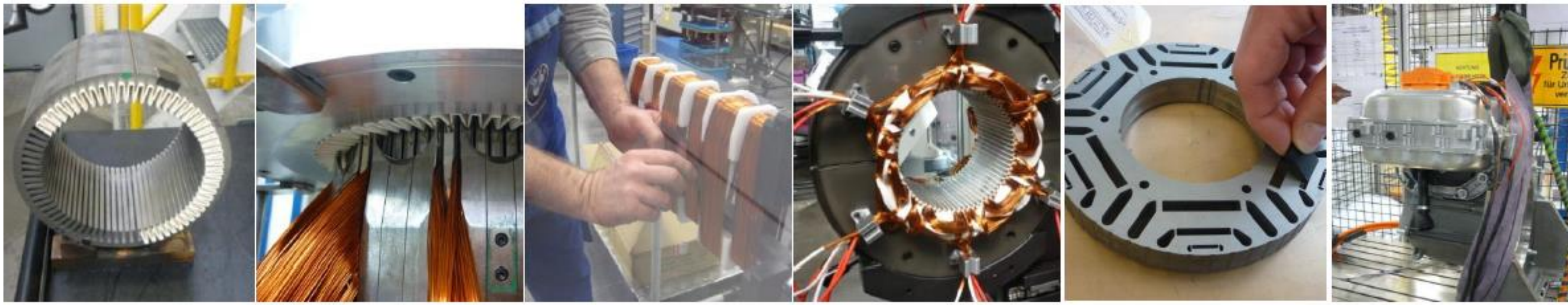
Production Steps of the Electric Machine





Source

Challenges in Production



- High output **flexibility** of the production system required in case of rapid variations in demand.
- Optimized **manufacturing processes** to improve efficiency and power/weight ratio:
  - Winding →Slot filling factor.
  - Forming and connecting the winding head.
  - Minimize packaging space.
- Production-orientated design of **isolation concepts** in large series:
  Material of primary and secondary isolation, impregnation process, phase separation and –isolation.
- Reliable handling of **magnets**.
- **Measurement and testing** technologies: Standards and automation.

Source

Derivation of Phase Voltage Equation in 2-phase Coordinates

Voltage equation in αβ coordinates, $v_s = R_s i_s + \frac{d\Psi}{dt}$

$where\ v_s = v_\alpha + j v_\beta,\ i_s = i_\alpha + j\ i_\beta, and\ \Psi_s = \Psi_\alpha + j\Psi_\beta.$

$$\Psi = \Psi_s + \Psi_{PM} = L_s i_s + \Psi_{PM} = (\underbrace{L_{s\sigma}}_{\text{Leakage}} + \underbrace{L_{ms}}_{\text{Main}}) i_s + \underbrace{\Psi_{PM}}_{\text{PM flux linking stator}}$$

Voltage equation in dq coordinates

$$v_s^r e^{j\theta_s^r} = R_s i_s^r e^{j\theta_s^r} + \frac{d\Psi^r}{dt} e^{j\theta_s^r} = R_s i_s^r e^{j\theta_s^r} + j\frac{d\theta_s^r}{dt}\Psi^r e^{j\theta} + \frac{d\Psi^r}{dt} e^{j\theta_s^r}$$

$v^r{}_s = R_s i^r{}_s + j\frac{d\theta_s^r}{dt}\Psi^r + \frac{d\Psi^r}{dt}$, where electrical speed: $\omega = \frac{d\theta_s^r}{dt}$ and rotor speed $\Omega = \omega/\underbrace{pp}_{\text{Pole pair number}}$

$$v^r{}_s = R_s i^r{}_s + j\omega(L_s i^r{}_s + \Psi^r_{PM}) + \frac{d(L_s i^r{}_s + \Psi^r_{PM})}{dt}$$

$$v^r{}_s = \underbrace{R_s i^r{}_s}_{\text{Resistive V-drop}} + \underbrace{j\omega(L_s i^r{}_s)}_{\text{Inductive V-drop}} + \underbrace{j\omega(\Psi^r_{PM})}_{\text{Back-emf}} + \underbrace{\frac{d(L_s i^r{}_s)}{dt}}_{\text{Transient inductive V-drop}} + \cancelto{0}{\frac{d(\Psi^r_{PM})}{dt}}$$

$$v^r{}_s = v_d + \mathrm{j}\ v_q = R_s\ (i_d + \mathrm{j}\ i_q) + j\omega(i_d + \mathrm{j}\ i_q) + j\omega(\Psi^r_{PM}) + \frac{d\big(L_s(i_d + \mathrm{j}\ i_q)\big)}{dt}$$

Derivation of Phase Voltage Equation in 2-phase Coordinates

$$v^{r}{}_{s} = v_d + \mathrm{j}\, v_q = R_s\ (i_d + \mathrm{j}\, i_q) + j\omega(i_d + \mathrm{j}\, i_q) + j\omega(\Psi^{r}_{PM}) + \frac{d\big(L_s(i_d + \mathrm{j}\, i_q)\big)}{dt}$$

In dq plane, we have only DC values during steady state operation.

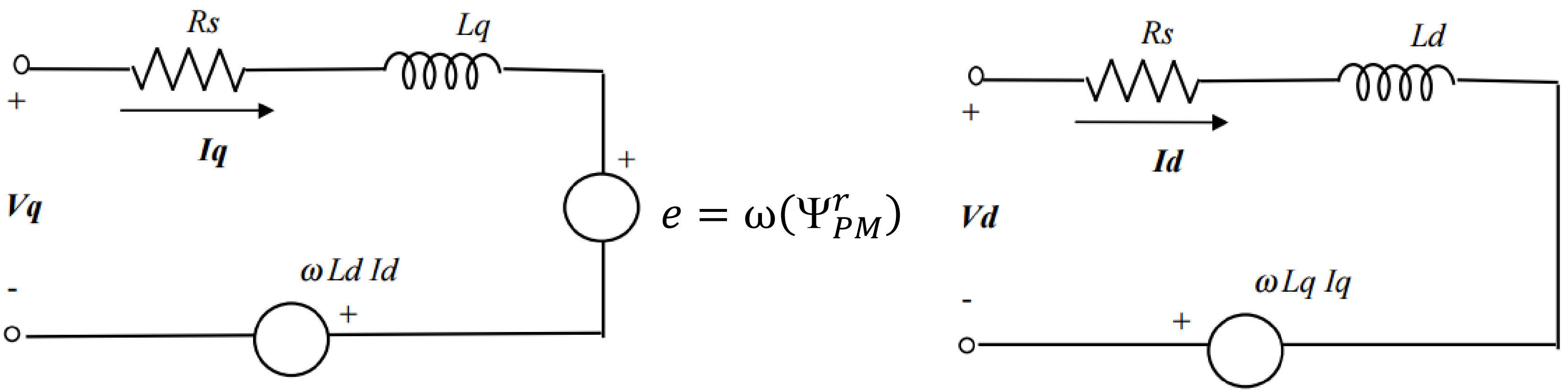
$$v_d = R_s\ i_d - \omega L_s i_q + \frac{d(L_s i_d)}{dt}$$

$$v_q = R_s\ i_q + \omega L_s i_d + \omega(\Psi^{r}_{PM}) + \frac{d\big(L_s i_q\big)}{dt}$$

Equivalent Circuit Model

$$v_d = R_s\ i_d - \omega L_s i_q + \frac{d(L_s i_d)}{dt}$$

$$v_q = R_s\ i_q + \omega L_s i_d + \omega(\Psi_{PM}^r) + \frac{d\left(L_s i_q\right)}{dt}$$



Dal Y. Ohm, Dynamic Model Of
PM Synchronous Motors

Power and Torque Equations

$$v_d = R_s\ i_d - \omega L_q i_q + \frac{d(L_d i_d)}{dt}$$

$$v_q = R_s\ i_q + \omega L_d i_d + \omega \Psi^r_{PM} + \frac{d\left(L_q i_q\right)}{dt}$$

$$P = P_{losses} + P_{stored} + P_{mech} = \ v_1\ i_1 + v_2\ i_2 + v_3\ i_3$$

$$= \mathrm{Re}\left\{\ (v_d + j\ v_q)\ \ (i_d - j\ i_q)\right\} = \frac{3}{2}\ (v_d\ \ i_d + v_q\ i_q)$$

$$P_{mech} = \frac{3}{2}\omega\left(\Psi^r_{PM} - (L_q - L_d)i_d\right)i_q$$

$$T_{mech} = \frac{3}{2}pp\left(\Psi^r_{PM} - (L_q - L_d)i_d\right)i_q$$

Torque in SMPMSM vs. IPMSM

SMPMSM

$$T_{mech} = \frac{3}{2}pp\big(\Psi_{PM} - (L_q - L_d)i_d\big)i_q, \text{ where } L_q = L_d$$

$$T_{mech} = \frac{3}{2}pp\Psi_{PM}i_q$$

➔ Only reactance (magnet) torque

IPMSM

$$T_{mech} = \frac{3}{2}pp\big(\Psi_{PM} - (L_q - L_d)i_d\big)i_q, \text{ where } L_q > L_d$$

$$T_{mech} = \frac{3}{2}pp\big(\Psi_{PM} - (L_q - L_d)i_d\big)i_q$$

➔ Reactance (magnet) torque and reluctance torque

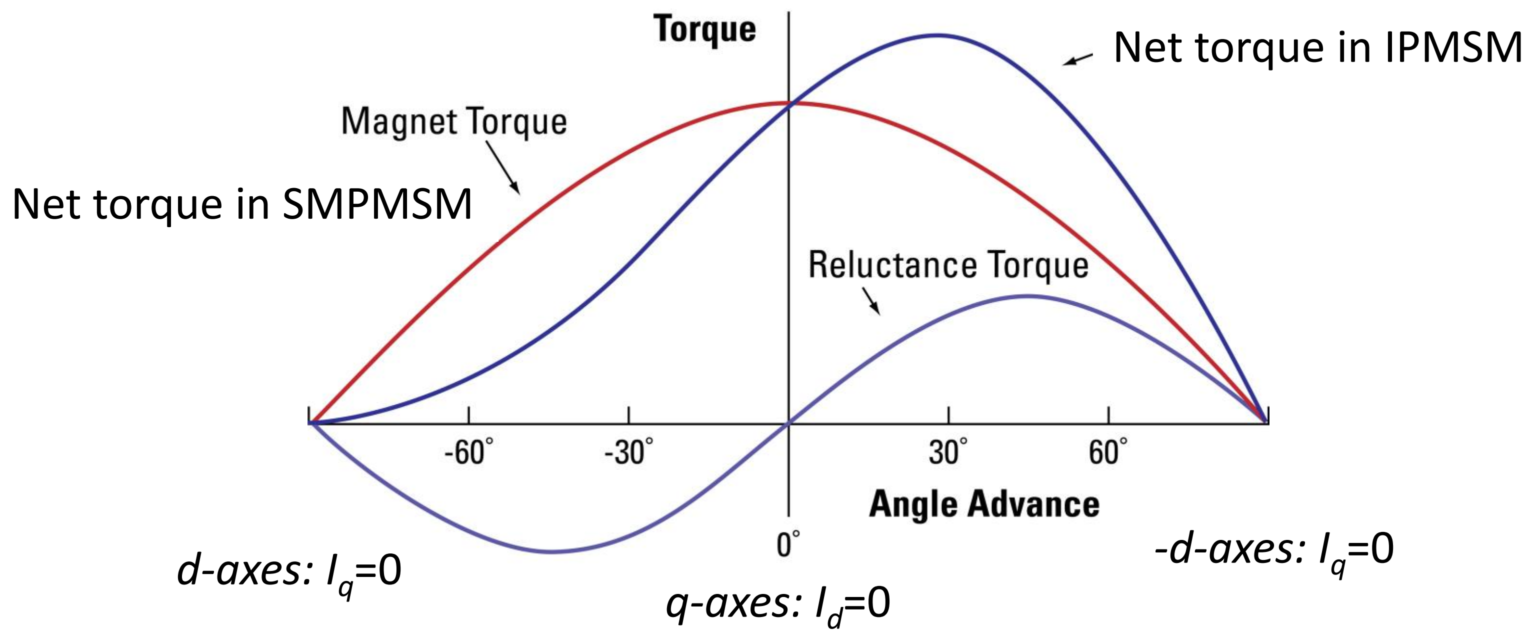
Torque in SMPMSM vs. IPMSM

SMPMSM

$T_{mech} = \frac{3}{2} pp \Psi_{PM} i_q$ ➔ Only reactance (magnet) torque

IPMSM

$T_{mech} = \frac{3}{2} pp\left(\Psi_{PM} - (L_q - L_d) i_d\right) i_q$ ➔ Reactance (magnet) torque and reluctance torque



Space Vector Representation

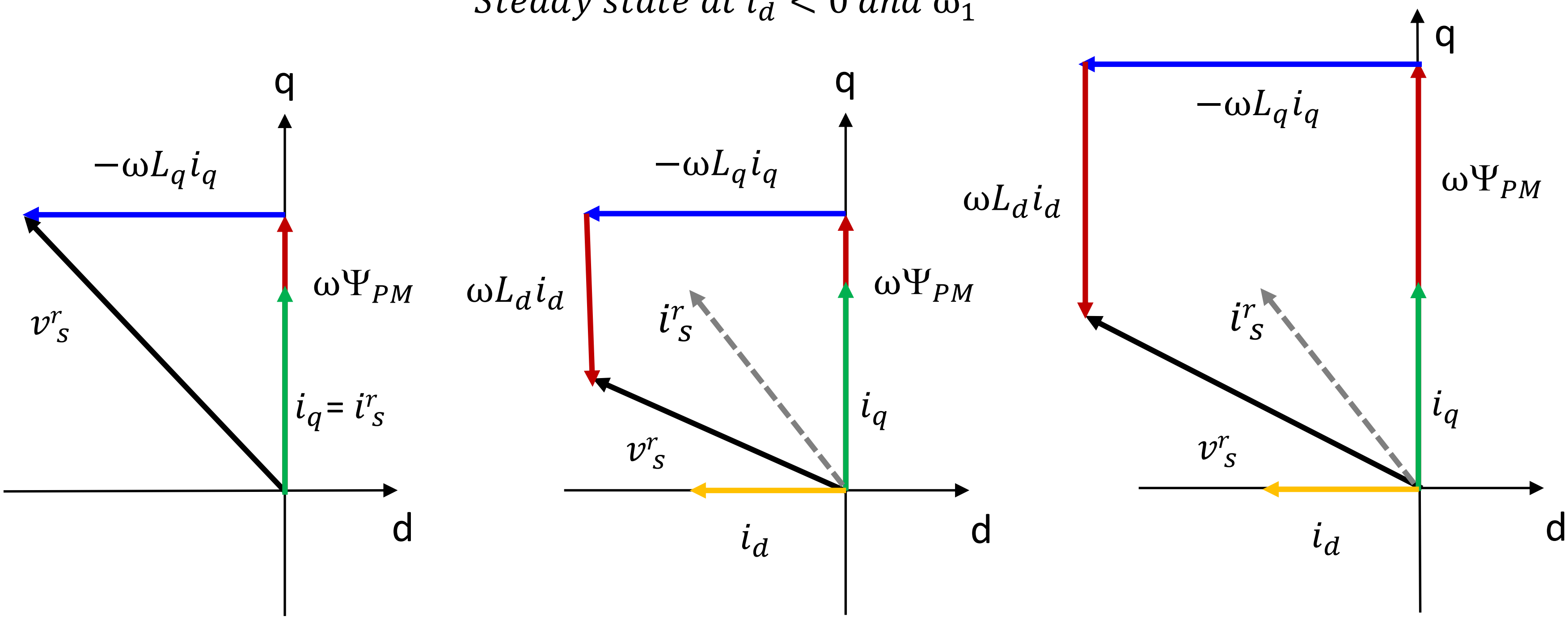
$$v_d = R_s\ i_d - \omega L_q i_q + \frac{d(L_d i_d)}{dt}$$

$$v_q = R_s\ i_q + \omega L_d i_d + \omega \Psi_{PM}^r + \frac{d\left(L_q i_q\right)}{dt}$$

$Steady\ state\ at\ i_d = 0\ and\ \omega_1$

$Steady\ state\ at\ i_d < 0\ and\ \omega_2 > \omega_1$

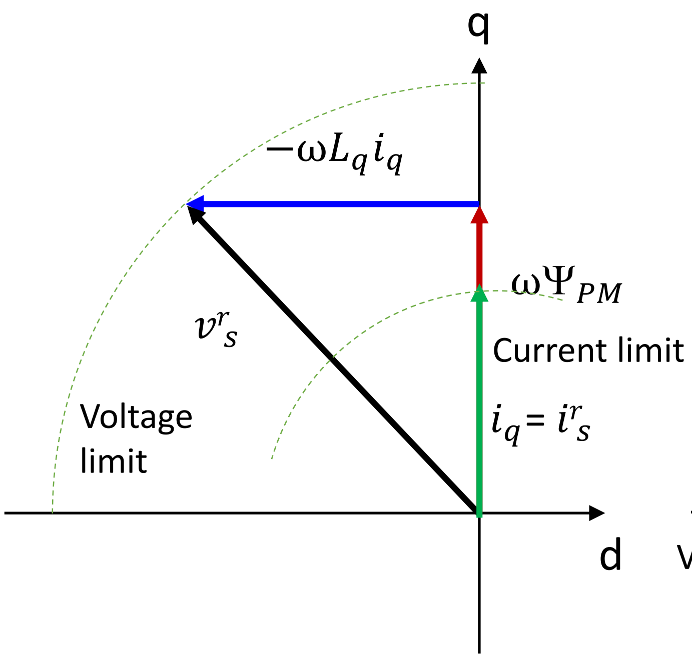
$Steady\ state\ at\ i_d < 0\ and\ \omega_1$

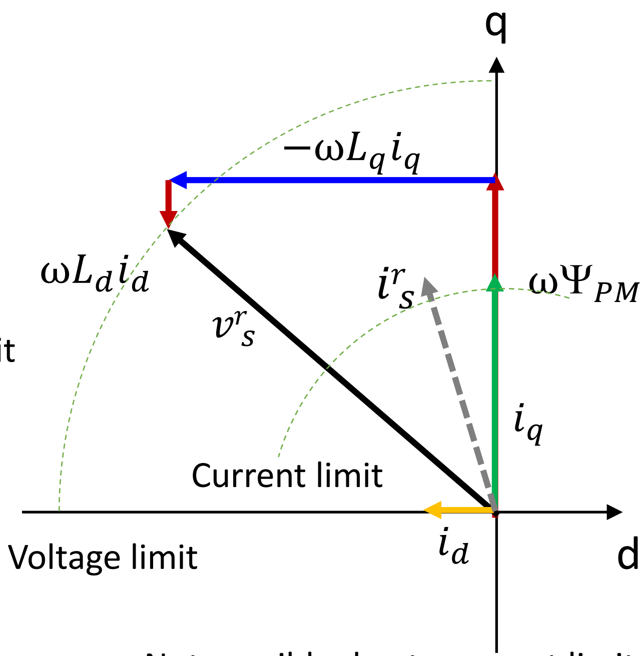


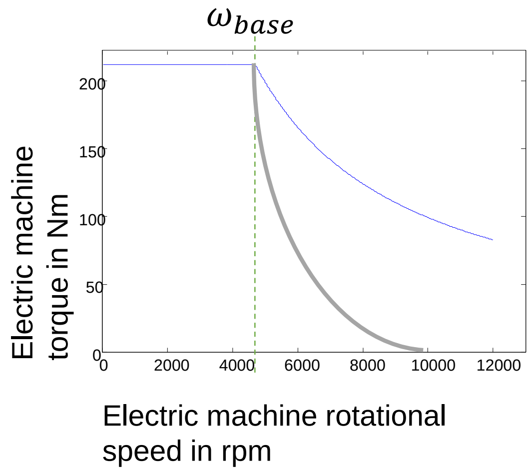
Voltage Limits and Field Weakening Operation in SMPMSM

$Steady\ state\ at\ i_q = i_{s-max}, i_d = 0\ and\ \omega = \omega_{base}$

$Steady\ state\ at\ i_q = i_{s-max}, i_d < 0\ and\ \omega > \omega_{base}$





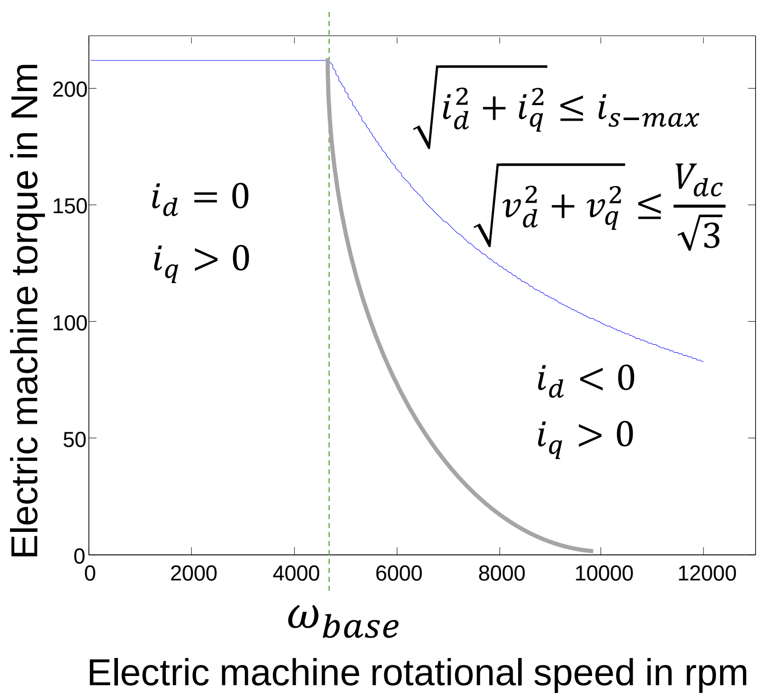


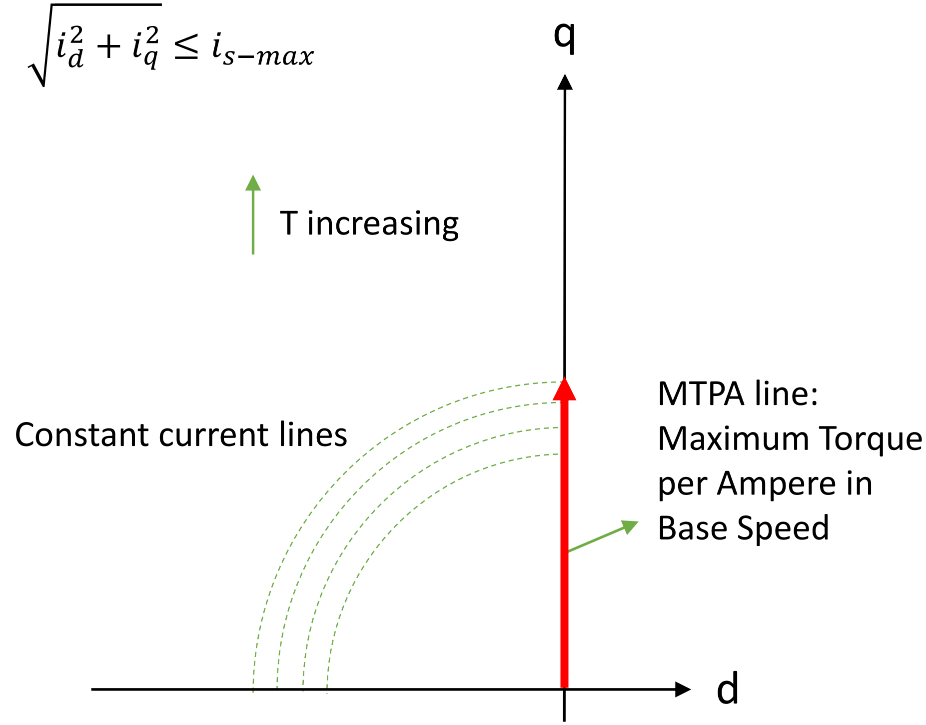
Above base speed, maximum torque is reduced and terminal voltage is limited by producing a $-\Psi_d$ by stator excitation, that can be produced by $-i_d$. Field weakening term originates from wound rotor machine, in which the field excitation is controllable. On the other hand, in PMSMs an opposing flux to the PM flux is generated to reduce the flux linkage in phase windings without demagnetizing PMs.

Maximum Torque per Ampere Operation in SMPMSM

$$T_{mech} = \frac{3}{2} pp \Psi_{PM} i_q$$

$$\sqrt{i_d^2 + i_q^2} \leq i_{s-max}$$





Limits in PMSM

Limiting Factors:

- DC-link voltage
- Current capability
- Temperature (Cooling capability)

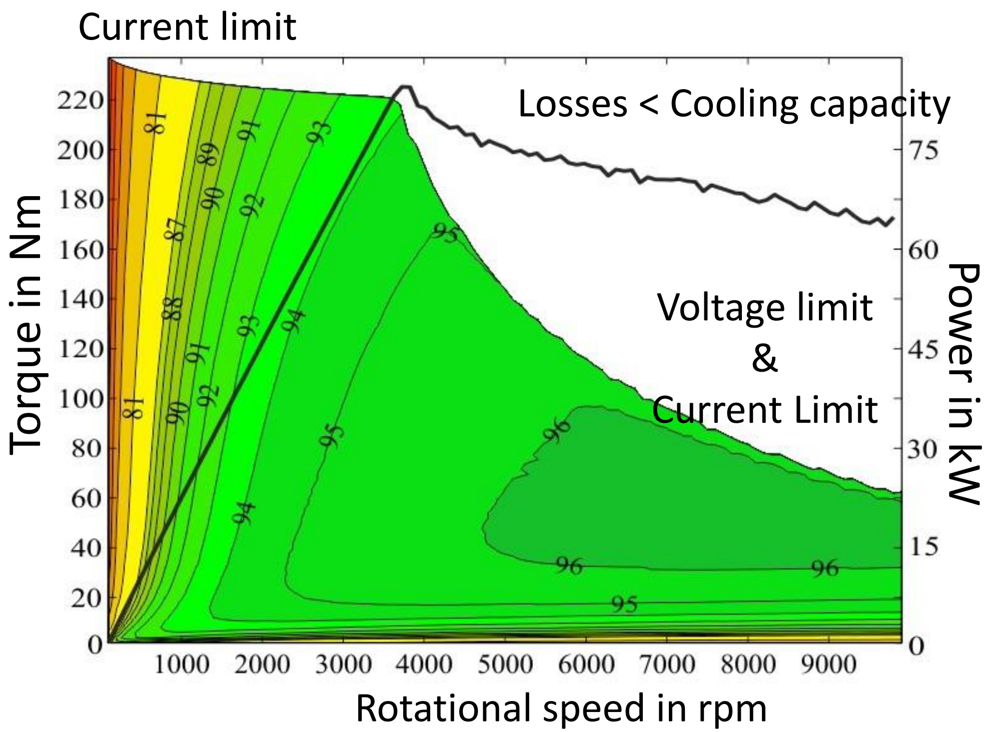
$$v_d = R_s\, i_d - \omega L_q i_q$$
$$v_q = R_s\, i_q + \omega L_d i_d + \omega \Psi^{\mathrm{r}}_{PM}$$

$$\sqrt{i_d^2 + i_q^2} \le i_{s-max} \;\; and \;\; \sqrt{v_d^2 + v_q^2} \le \frac{V_{dc}}{\sqrt{3}}$$

$$\sqrt{\left(-\omega L_q i_q\right)^2 + \left(\omega L_d i_d + \omega \Psi^r_{PM}\right)^2} \le \frac{V_{dc}}{\sqrt{3}}$$

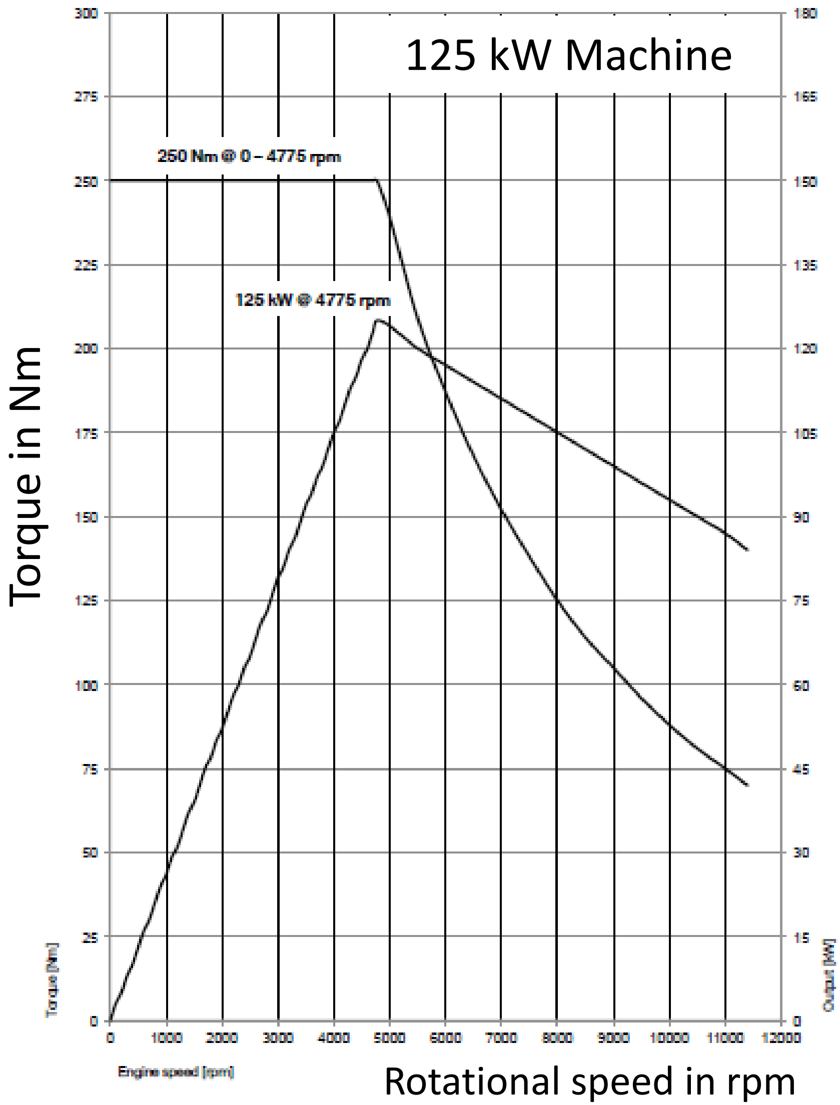
$$\sqrt{\left(-L_q i_q\right)^2 + \left(L_d i_d + \Psi^r_{PM}\right)^2} \le \frac{V_{dc}}{\omega\sqrt{3}}$$

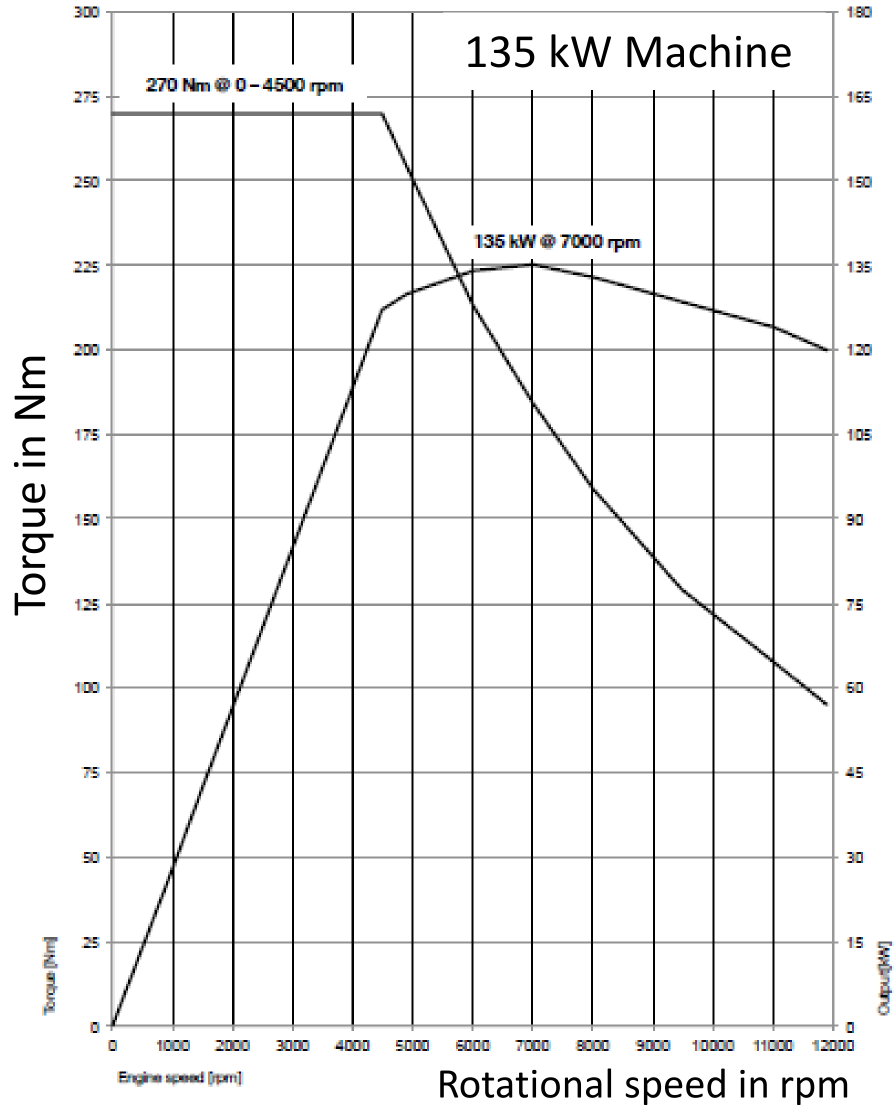
Assumption: SV-PWM



http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6556123

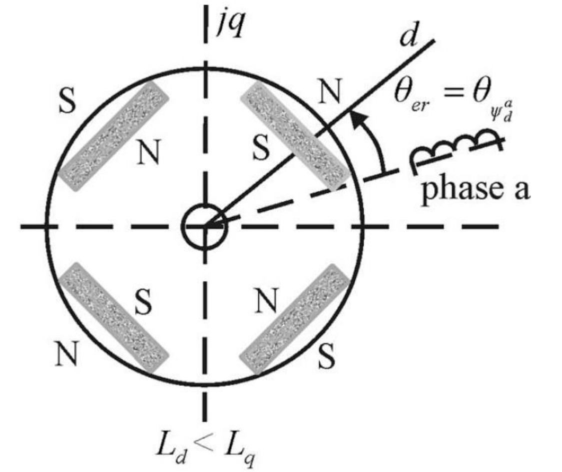
BMW i3 EM Torque-Speed Characteristics





Self- and Mutual Inductances

$$\begin{bmatrix} \Psi_1 \\ \Psi_2 \\ \Psi_3 \end{bmatrix} = \underbrace{\begin{bmatrix} L_{aa} & M_{ab} & M_{ac} \\ M_{ba} & L_{bb} & M_{bc} \\ M_{ca} & M_{cb} & L_{cc} \end{bmatrix}}_{\text{Inductance matrix: } L \text{ self inductance and } M \text{ mutual inductance}} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix}$$



$$L_s = L_{s\sigma} + L_{ms} = L_{s\sigma} + L_{s1} + L_{s2} =$$

$$\underbrace{\begin{bmatrix} L_{s\sigma} & 0 & 0 \\ 0 & L_{s\sigma} & 0 \\ 0 & 0 & L_{s\sigma} \end{bmatrix}}_{\text{Leakage}} + \underbrace{\begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix}}_{\text{Constant}} + \underbrace{\begin{bmatrix} M_2\cos(2\theta) & M_2\cos(2\theta - \frac{2\pi}{3}) & M_2\cos(2\theta + \frac{2\pi}{3}) \\ M_2\cos(2\theta - \frac{2\pi}{3}) & M_2\cos(2\theta + \frac{2\pi}{3}) & M_2\cos(2\theta) \\ M_2\cos(2\theta + \frac{2\pi}{3}) & M_2\cos(2\theta) & M_2\cos(2\theta - \frac{2\pi}{3}) \end{bmatrix}}_{\text{Position dependent}}$$

$M = L\cos(\frac{2\pi}{3}) = -0.5\,L$

$M_2 < 0$ and $|L| > |M_2|$

Self- and Mutual Inductances

$$\begin{bmatrix} \Psi_1 \\ \Psi_2 \\ \Psi_3 \end{bmatrix} = \begin{bmatrix} L_{aa} & M_{ab} & M_{ac} \\ M_{ba} & L_{bb} & M_{bc} \\ M_{ca} & M_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix}$$

$$\mathrm{T}\begin{bmatrix} \Psi_1 \\ \Psi_2 \\ \Psi_3 \end{bmatrix} = \mathrm{T}\begin{bmatrix} L_{aa} & M_{ab} & M_{ac} \\ M_{ba} & L_{bb} & M_{bc} \\ M_{ca} & M_{cb} & L_{cc} \end{bmatrix}\mathrm{T}^{-1}\,\mathrm{T}\begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} \Rightarrow \begin{bmatrix} \Psi_d \\ \Psi_q \\ \Psi_0 \end{bmatrix} = \underbrace{\mathrm{T}\begin{bmatrix} L_{aa} & M_{ab} & M_{ac} \\ M_{ba} & L_{bb} & M_{bc} \\ M_{ca} & M_{cb} & L_{cc} \end{bmatrix}\mathrm{T}^{-1}}_{\text{Inductances in dq coordinates}} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix}$$

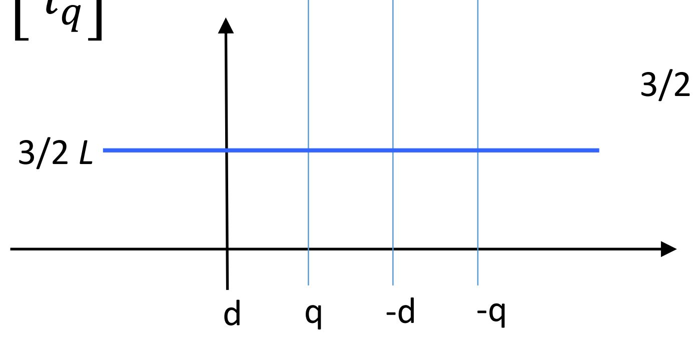
$$\begin{bmatrix} \Psi_d \\ \Psi_q \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix},$$

we **assume** that d and q axes are magnetically decoupled.

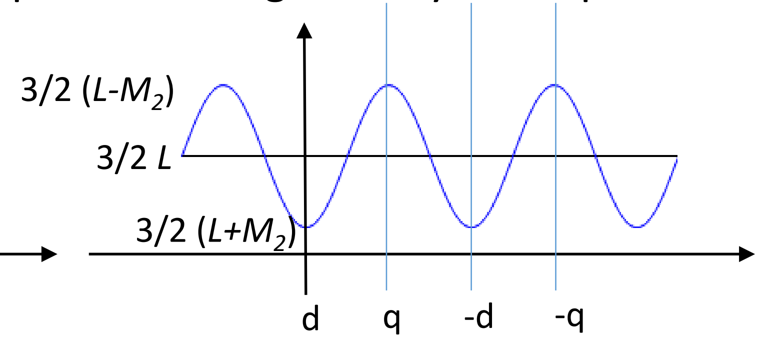
$$L_d = \frac{3}{2}(L + M_2)$$

$$L_q = \frac{3}{2}(L - M_2)$$

where $M_2 < 0$



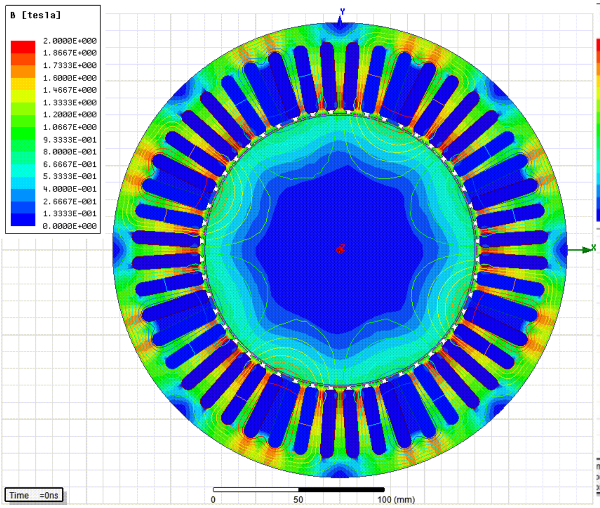
SMPMSM



IPMSM

Simulation of an IPMSM

Stator rotating field

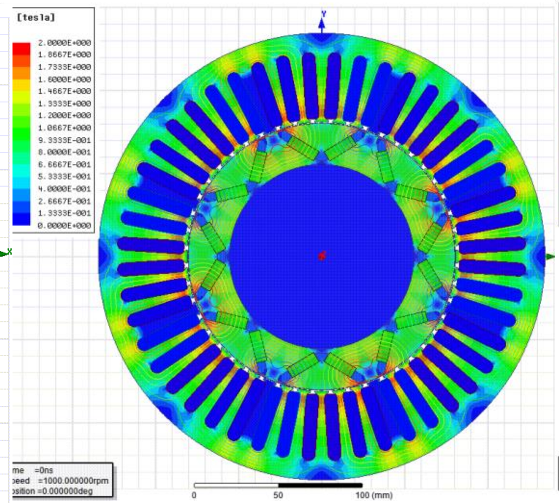


$i_{s1}(t) = 100\sin(\omega t)$,

$i_{s2}(t) = 100\sin\left(\omega t - \frac{2\pi}{3}\right)$, and

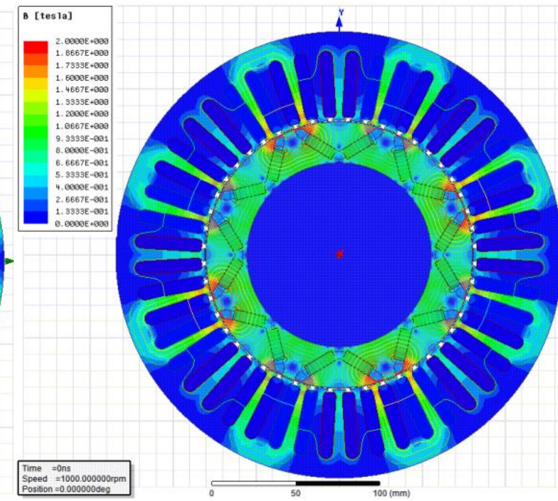
$$i_{s3}(t) = 100\sin\left(\omega t - \frac{4\pi}{3}\right)$$

Rotating rotor with PMs



$i_{s1}(t) = i_{s2}(t) = i_{s3}(t) = 0$

Stator rotating field & rotating rotor with PMs



$i_{s1}(t) = 100\sin(\omega t)$,

$i_{s2}(t) = 100\sin\left(\omega t - \frac{2\pi}{3}\right)$, and

$$i_{s3}(t) = 100\sin\left(\omega t - \frac{4\pi}{3}\right)$$

Extra Materials

PMSM production: **BMW i3 Electric Motor Production**

Animations:
http://people.ece.umn.edu/users/riaz/animations/listanimations.html