ELEC 344
7th Tutorial Additional Slides

Midterm Result &
Induction Machine

November 18, 2016
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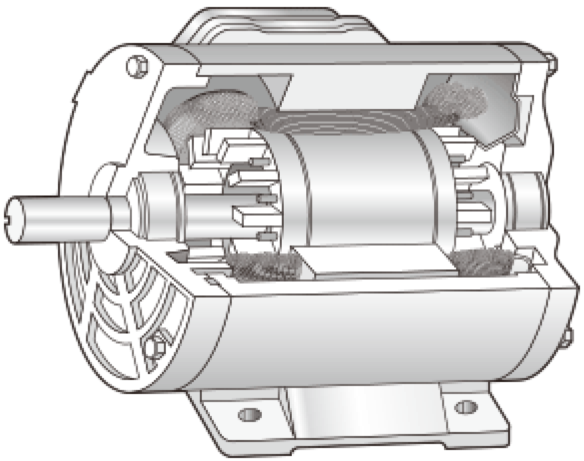
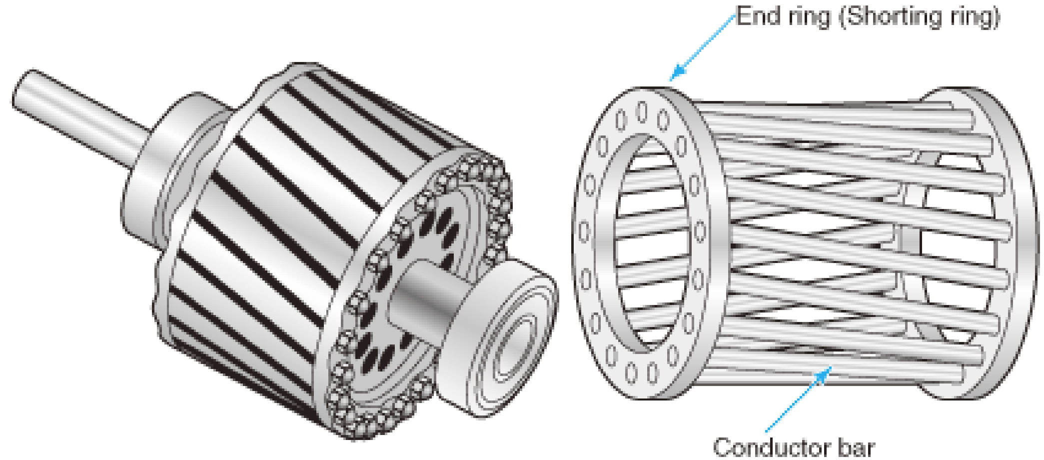
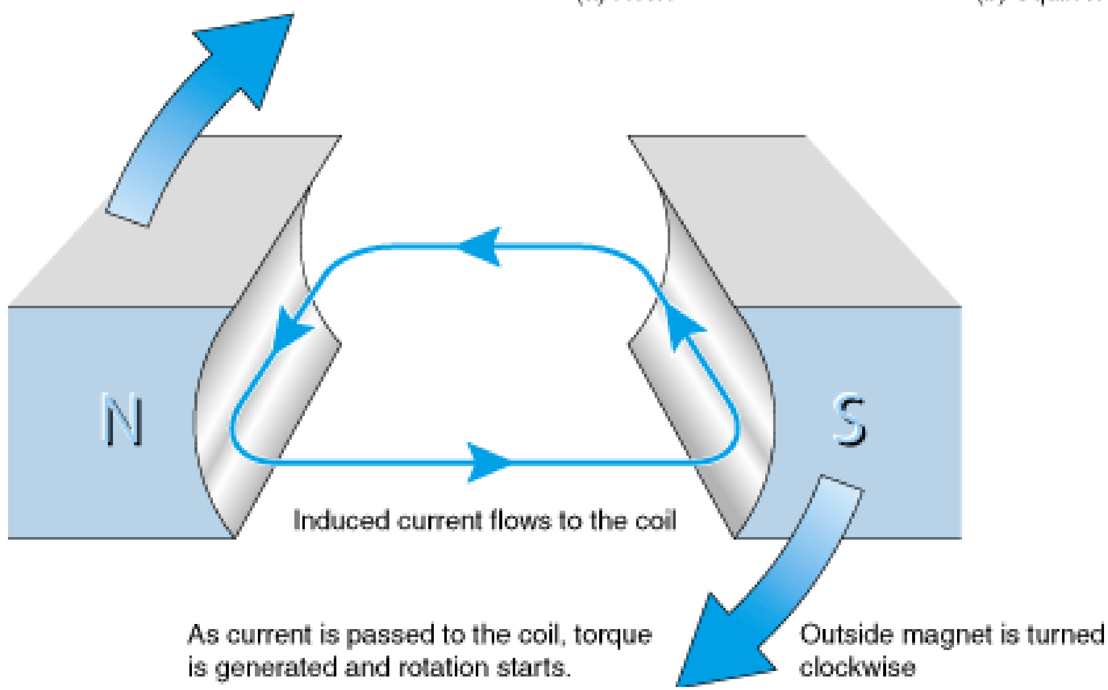
The University of British Columbia

1. Structure of Induction Machine

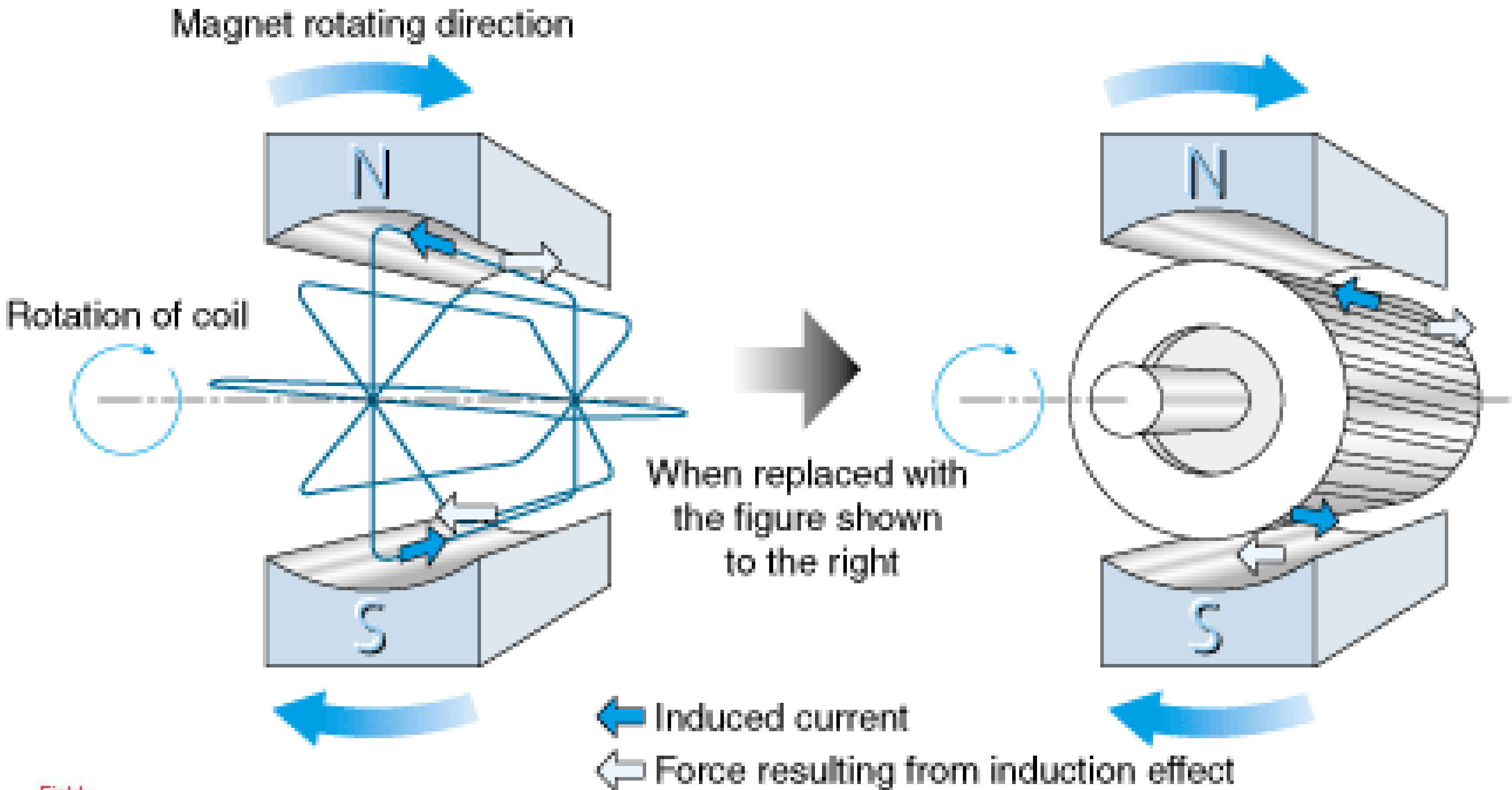


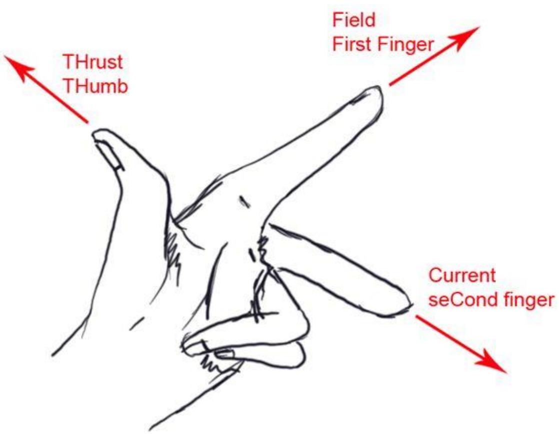


(a) Rotor (b) Squirrel-cage conductor



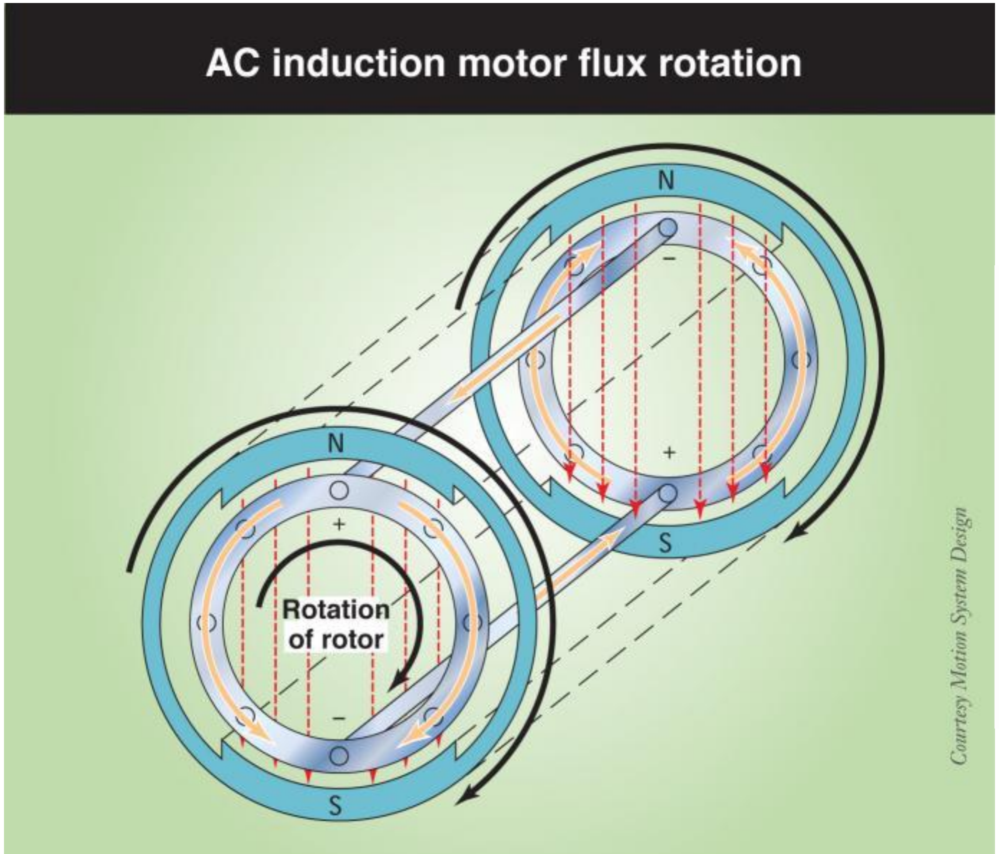
2. *Working principle of induction motors*

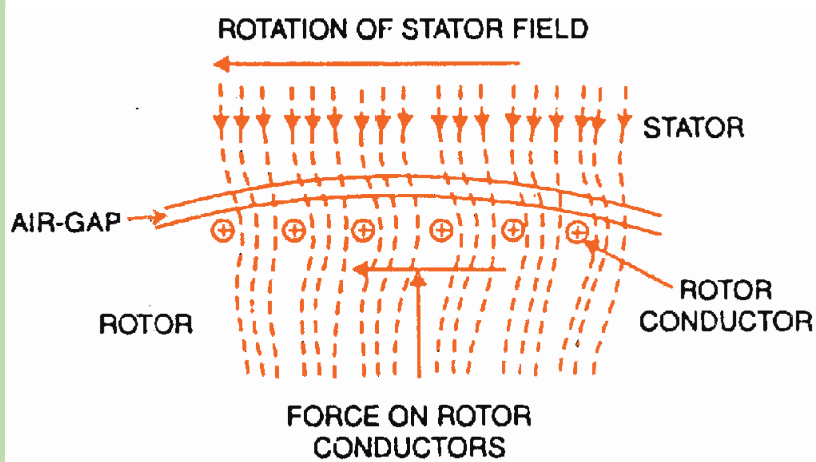




$$E_{ind} = (v \times B) \bullet l$$

2. Working principle of induction motors





Current is induced in the rotor’s conducting bars, and associated magnetic fields interact with those of the stator. This causes the rotor to follow the field generated by the stator, to rotate the output shaft.

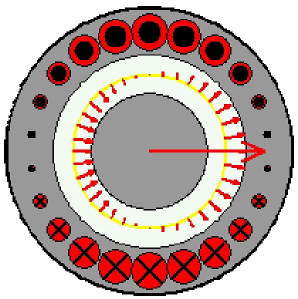
2. Working principle of induction motors

1. Three-phase power supply to Stator windings
2. MMF vector $\mathbf{F}_{net}$ produced ($\mathbf{B}_S$)
   - Constant magnitude
   - Rotates in space
3. Voltage induced in Rotor bars (just like a transformer)
   - $E_{ind} = (v \times B) \bullet l$
   - Due to the speed difference between $\mathbf{F}_{net}$ and rotor
4. Current flows in Rotor bars
5. Rotor current flow produces a rotor magnetic filed $\mathbf{B}_R$
6. Torque is induced such that the speed difference between $\mathbf{F}_{net}$ ($\mathbf{B}_S$) and the rotor
   - $\mathbf{F} = i\,(\mathbf{l} \times \mathbf{B})$ - induced force on rotor bar
   - $T_{ind} = (\mathbf{r} \times \mathbf{F}) = k\mathbf{B}_R \times \mathbf{B}_S$
7. The resulting torque is counterclockwise
8. The rotor accelerates in that direction.

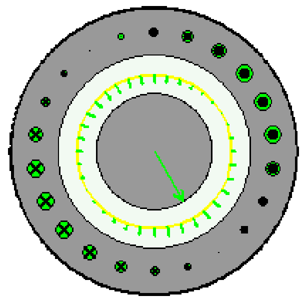
Note:

- To produce torque in an induction motor, current must flow in the rotor
- To induce current flow in the rotor, the rotor speed must be slightly slower than the synchronous speed
- The difference between the <u>synchronous speed</u> (R.P.M) and the <u>rotor speed (rated speed)</u> (R.P.M) is called the slip speed.

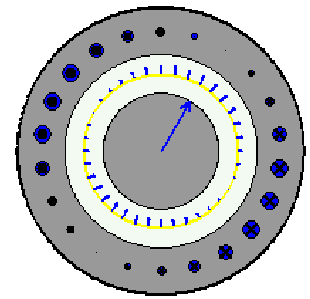
3. Torque Production



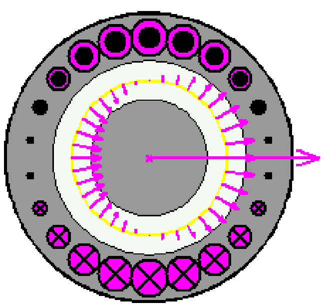
Phase A



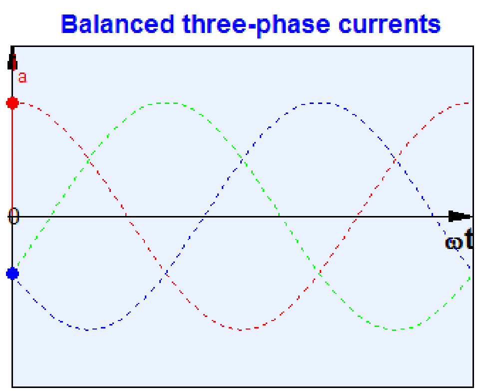
Phase B

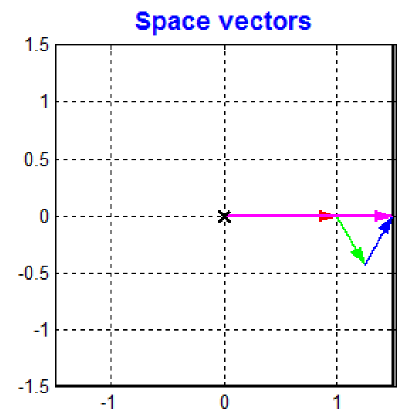


Phase C



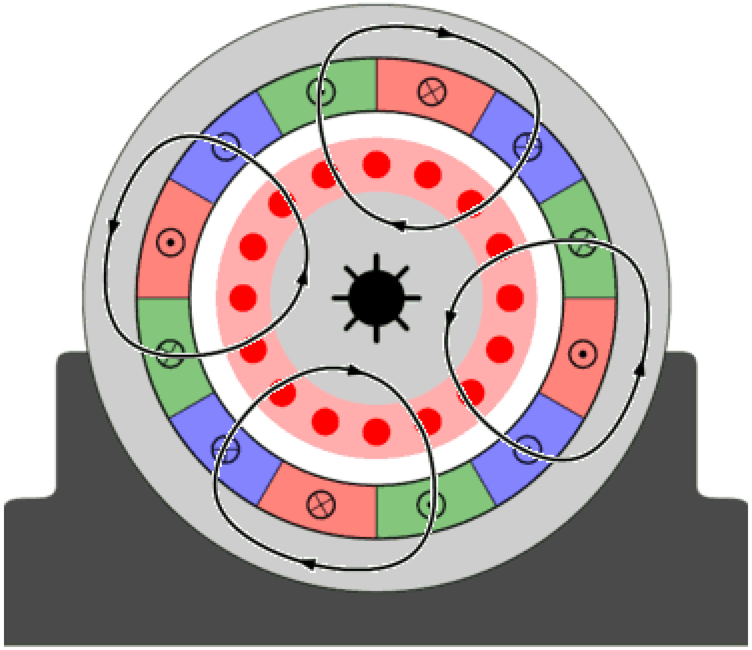
Resultant

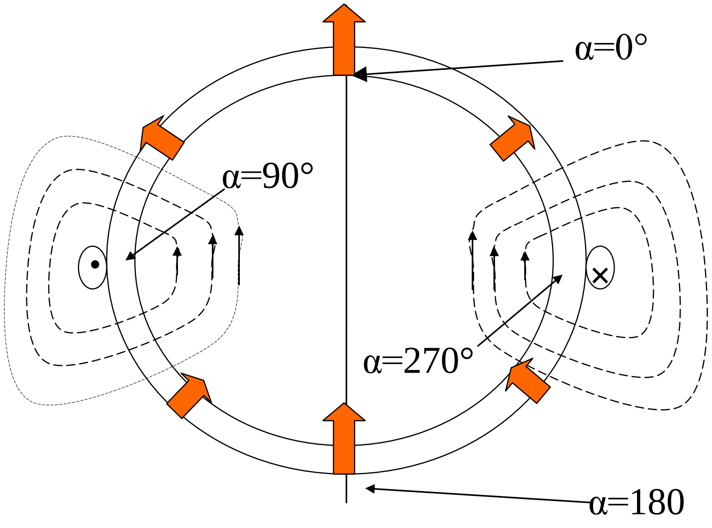




3. Torque Production

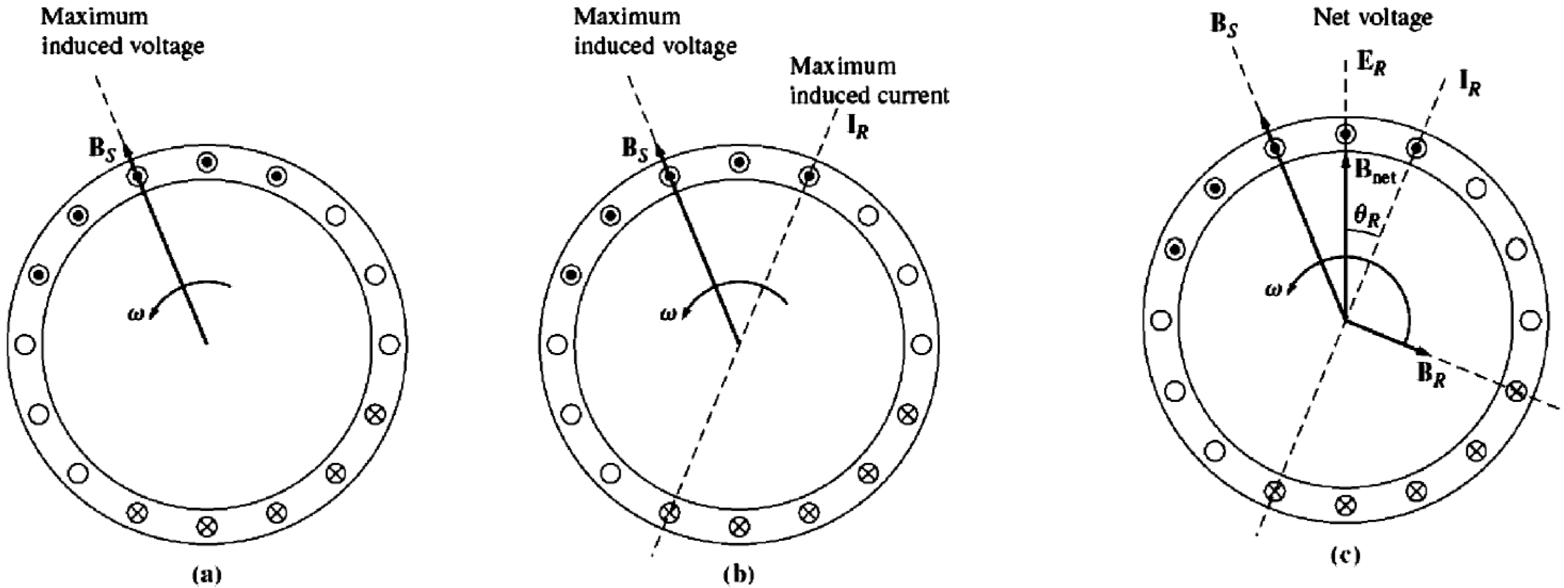
http://engineeringtutorial.com/squirrel-cage-induction-motor-animation/





Radially outward is positive; radially inward is negative.

3. Torque Production



Note:

(a) The rotating stator field **B**S induces a voltage in the rotor bars

(b) The rotor voltage produces a rotor current flow, which lags behind the voltage because of the inductance of the rotor

(c) The rotor current produces a rotor magnetic field **B**R lagging 90 degree behind itself, and **B**R interacts with **B**S to produce a couterclockwise torque in the machine

$$\mathbf{B}_{\text{total}} = \mathbf{B}_s + \mathbf{B}_r \qquad T_{\text{dev}} = K B_r B_{\text{total}} \sin(\delta)$$

3. Torque Production

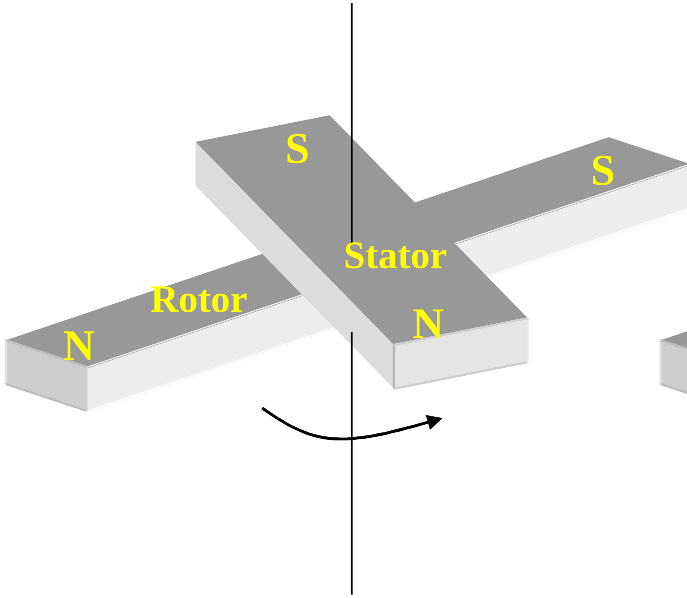


Fig a: generator operation

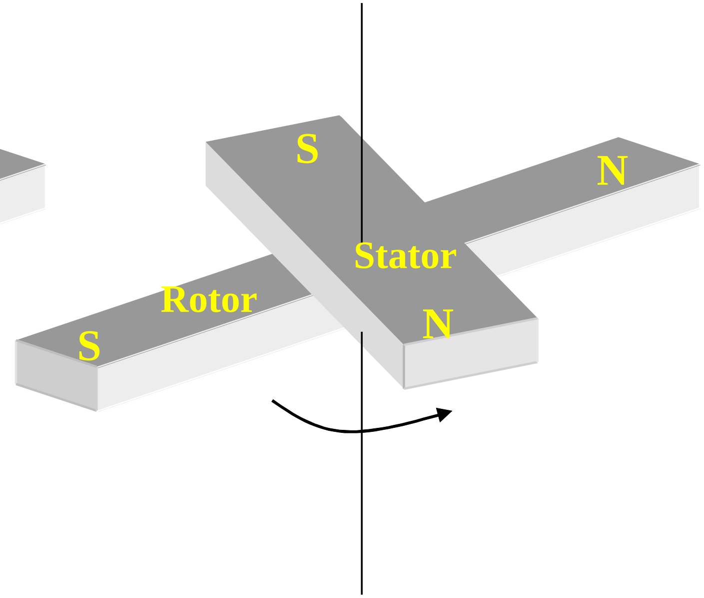


Fig b: Motor operation

In order to produce constant torque, two rotating magnetic fields must have the same rotational velocity.

(a) Rotor bar (rotated by mech. power) pushing Stator bar (P_{elec} Generation)

(b) Stator bar (rotated by elec. power) pulling Rotor bar (P_{mech} Generation)

<u>Q. What's the speed of the rotor's rotating magnetic field in case of constant torque produce?</u>

4. *Speed & Frequency & Slip*

Fact : The rotor must have speed (ω_r) which differs from speed of rotating magnetic field (ω_e) from stator. Otherwise, no voltage is induced in rotor windings.

$\omega_e = \omega_{r\_rmf} = \omega_{s\_rmf}$

Speed of rotating magnetic field (from stator)

$\omega_{sync} = \frac{2}{p}\omega_e$

=

ω_r

Rotor Speed (physical movement)

$\omega_{rm} = \frac{2}{p}\omega_r$

+

$\omega_s = \omega_{slip}$

Speed of rotating magnetic field ***relative to rotor*** (from stator)

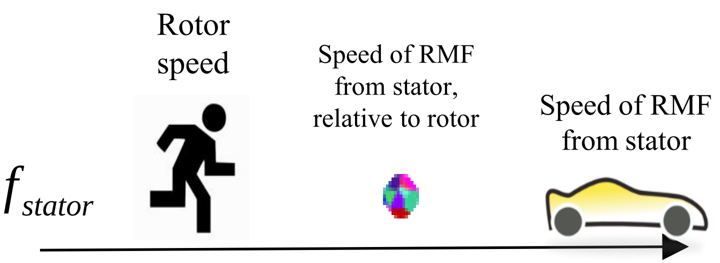
$$\omega_e = \omega_r + \omega_s$$

$$\Rightarrow \omega_s = \omega_e - \omega_r$$

$$\Rightarrow s = \frac{\omega_e - \omega_r}{\omega_e} = \frac{\omega_s}{\omega_e}$$

$$\Rightarrow \omega_{slip} = s\omega_e \Rightarrow f_{rotor} = s \cdot f_{stator}$$

Frequency (rad/sec) of rotor currents.



4. *Speed & Frequency & Slip* **(Summary)**

$$slip\_speed = \frac{n_{syn} - n}{n_{syn}} = \frac{\omega_{syn} - \omega_{rm}}{\omega_{syn}} = \frac{\omega_e - \omega_r}{\omega_e} \qquad \omega_e = 2\pi f_e [rad/\sec];\ f_e = 60Hz$$

$$\Rightarrow n_{sync} = \frac{60}{2\pi}\frac{2}{P}\omega_e = \frac{120}{P} f_e$$

Calculate the mechanical speed first and then convert it to angular frequency!!!

$$n_{syn} = \frac{120}{P} \cdot f_e \ \text{[rpm]} \qquad \omega_{syn} = \frac{2}{P}\omega_e \ \text{[r/s]} \qquad \omega_r = \frac{P}{2}\omega_{rm}$$

Please keep in mind that rotor's physical angular speed can't be compared to the rotor current frequency. ***Rotor current frequency*** solely depends on ***rotor's relative speed*** to the ***stator rotating magnetic field*** which is the same as slip speed.

And finally:

$$s = \frac{\omega_e - \omega_r}{\omega_e} = \frac{\omega_s}{\omega_e} \Rightarrow \omega_s = \omega_e - \omega_r = s \cdot \omega_e$$

$$f_{slip} = f_{rotor} = s \cdot f_e$$

4. *Speed & Frequency & Slip* **(Clarification)**

Slip speed(ω_s): ω_s occurs due to

the motion (speed) of the magnetic field
and
the motion (speed) of the rotor.

$$\omega_s = \omega_e - \omega_r$$

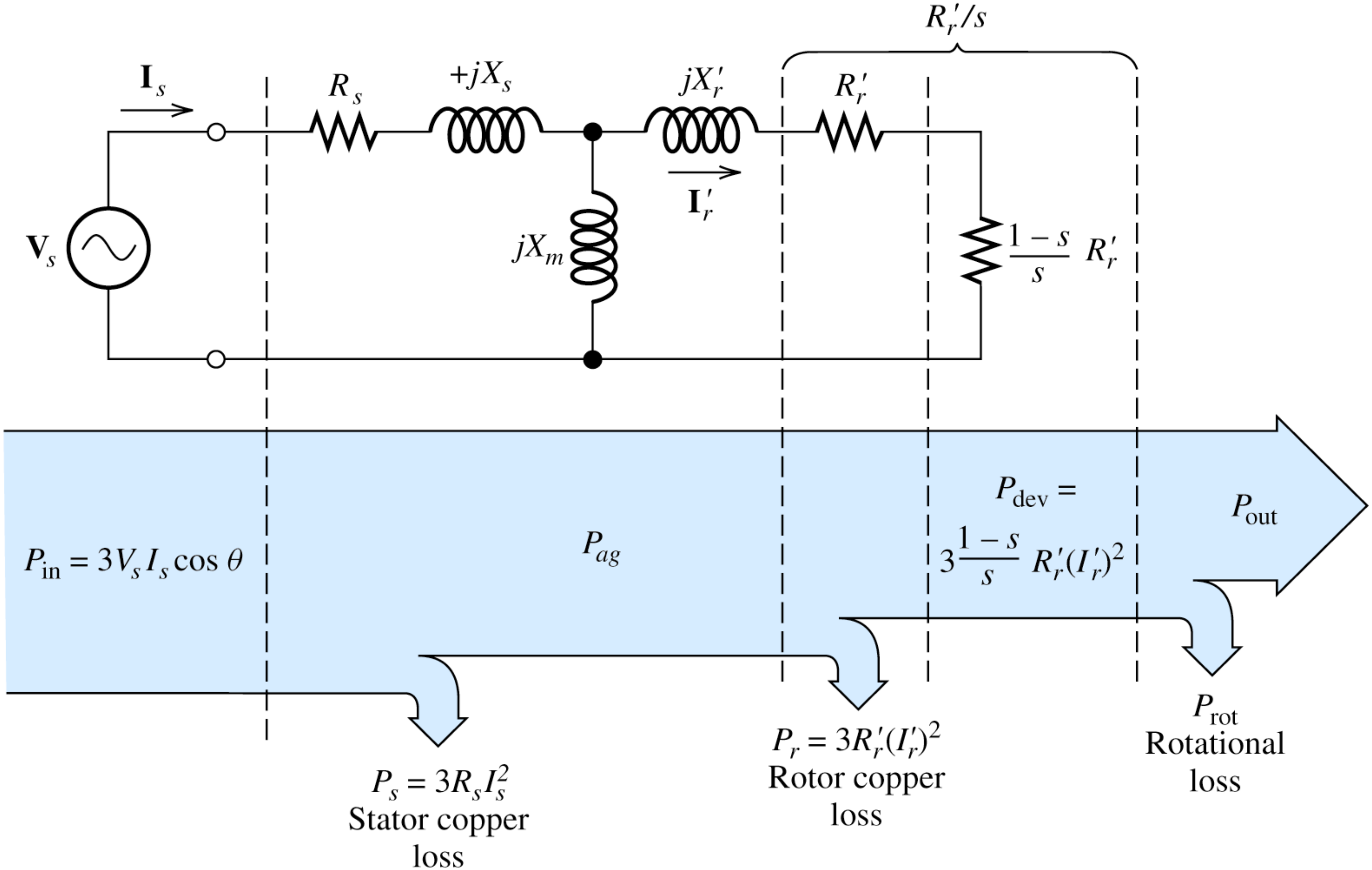
From another view, it is

the speed of the rotating magnetic field from the stator
referenced to
the rotor

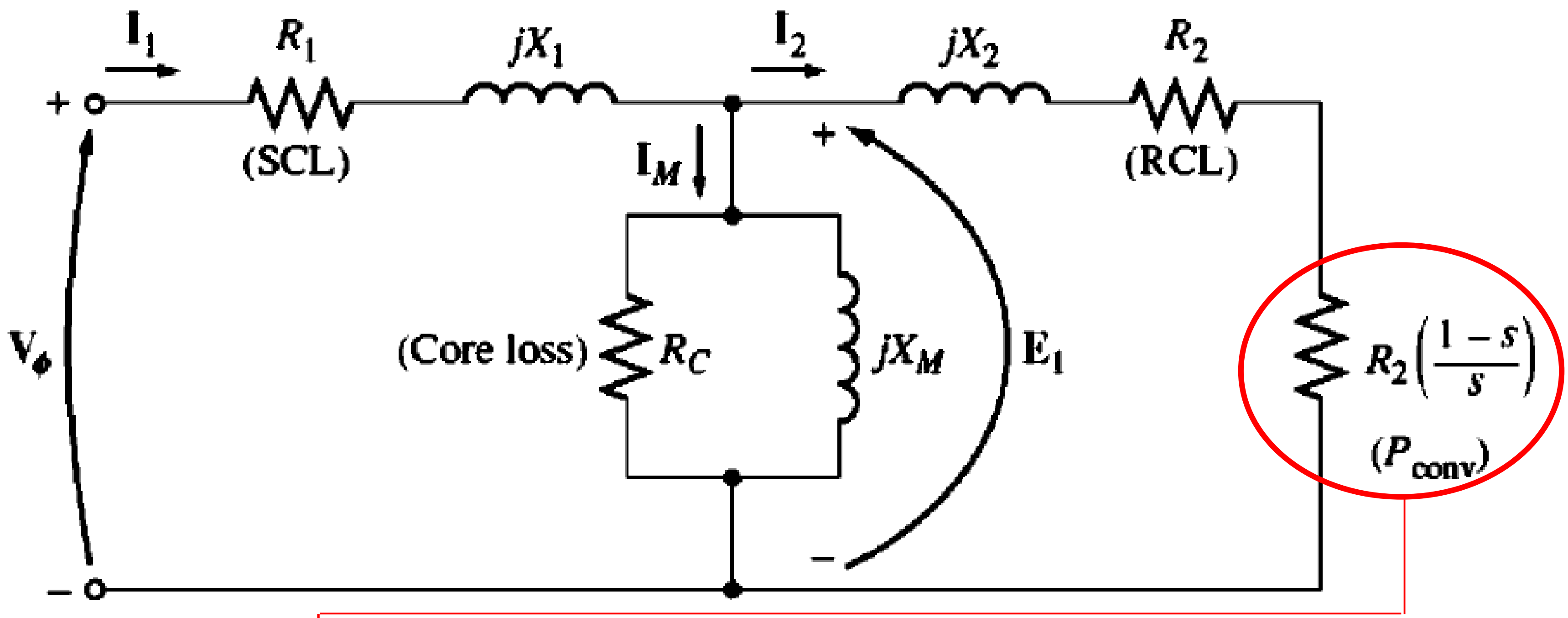
ω_{slip} is eventually the frequency (rad/sec) of the electrical quantities in the rotor winding.

$$f_{slip} = f_{rotor} = s \cdot f_e$$

5. Equivalent Circuit



5. *Equivalent Circuit*



The main difference between the transformer equivalent circuit and the induction machine equivalent circuit is ***the loading***: the transformer load is an actual impedance whereas the induction machine load is a variable resistance that depends on "s".

What does the induction machine load (Varying Resistance) represent?

It represents the ***mechanical power*** provided to the shaft. Thus the induction machine ***load*** is a purely "real" electrical load since energy transfer by mechanical means must be Watt[W] only (this is not the case for the transformer)

5. *Equivalent Circuit*

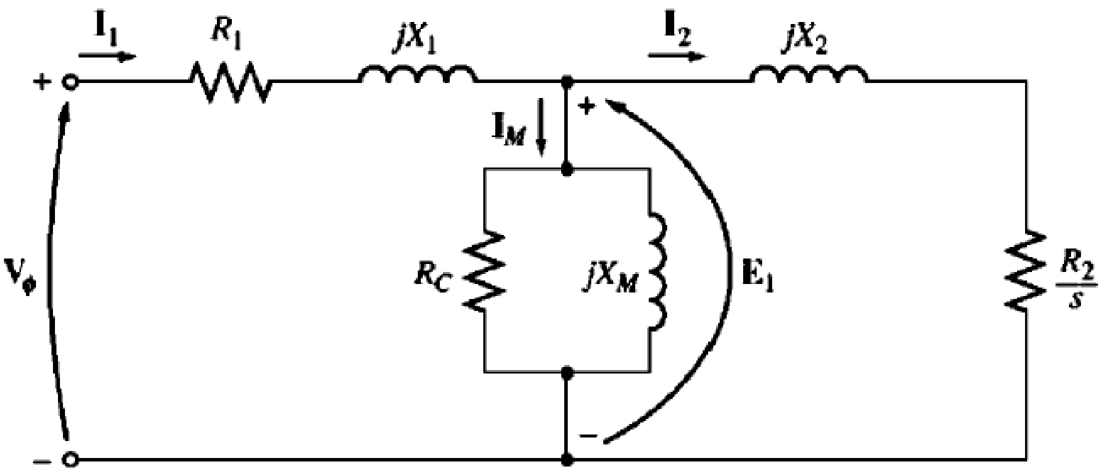
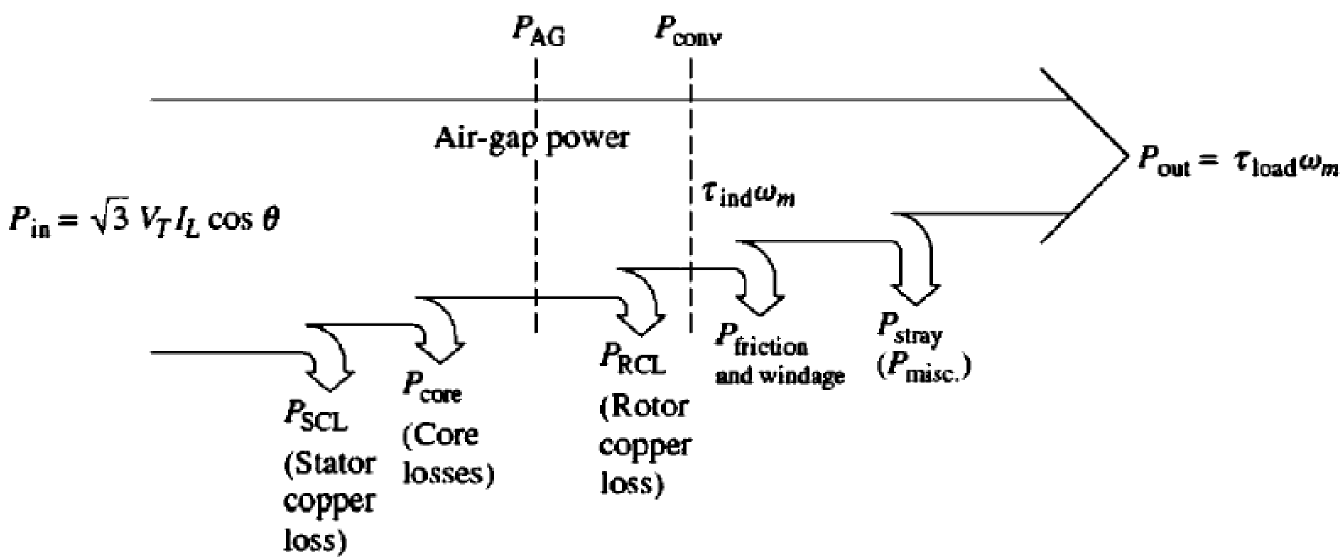
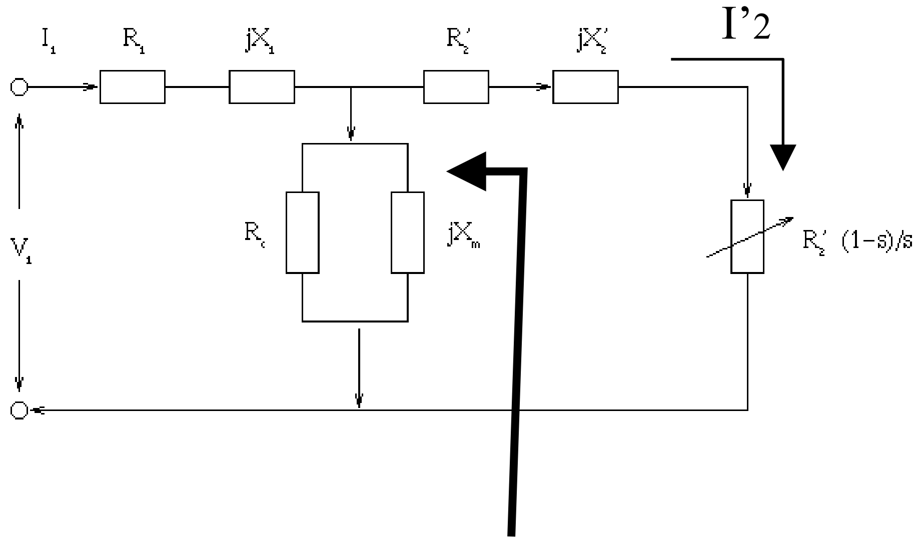


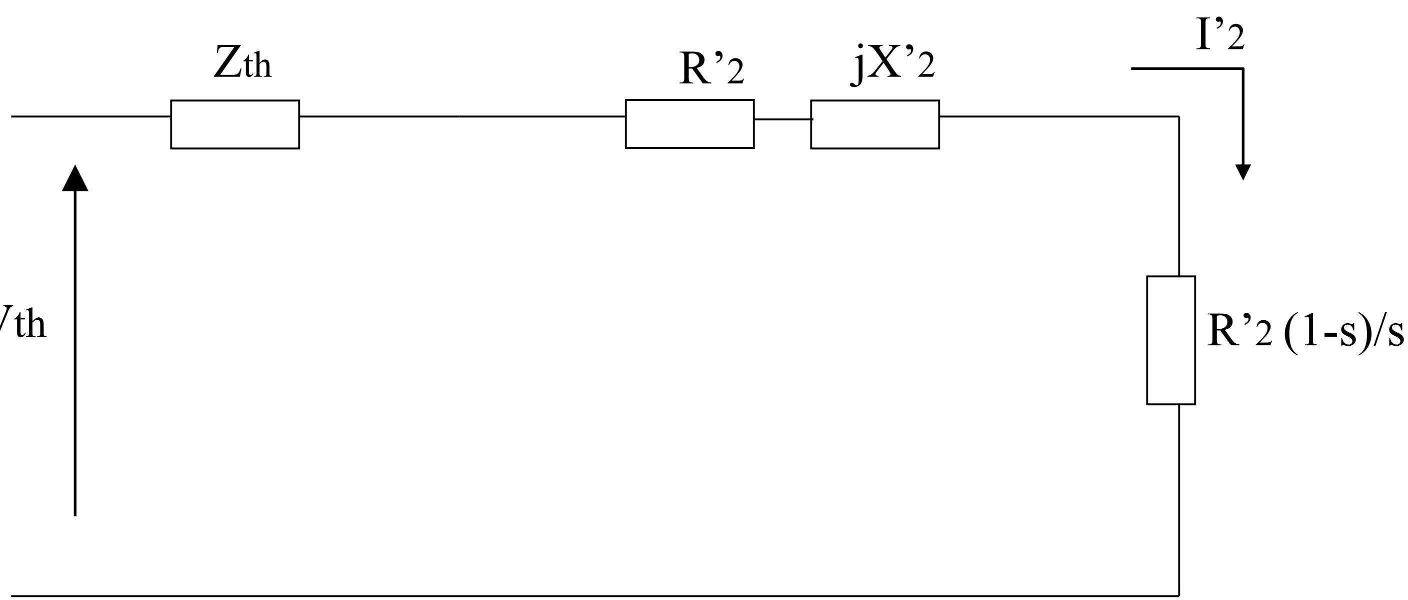
FIGURE 7–12
The per-phase equivalent circuit of an induction motor.



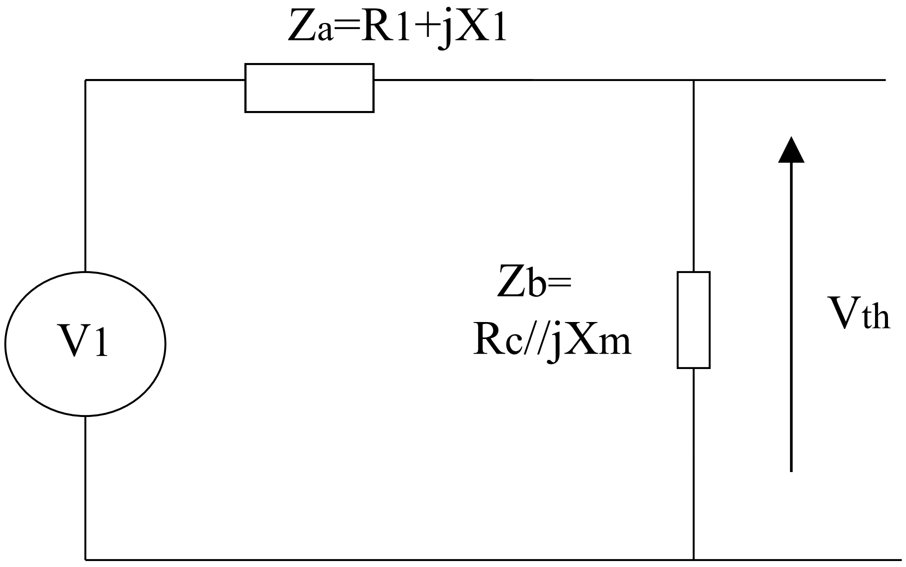
6. Thevenin Equivalent Circuit



An alternative way to obtain I'_2 is by use of Thevenin, looking into the terminals as shown.



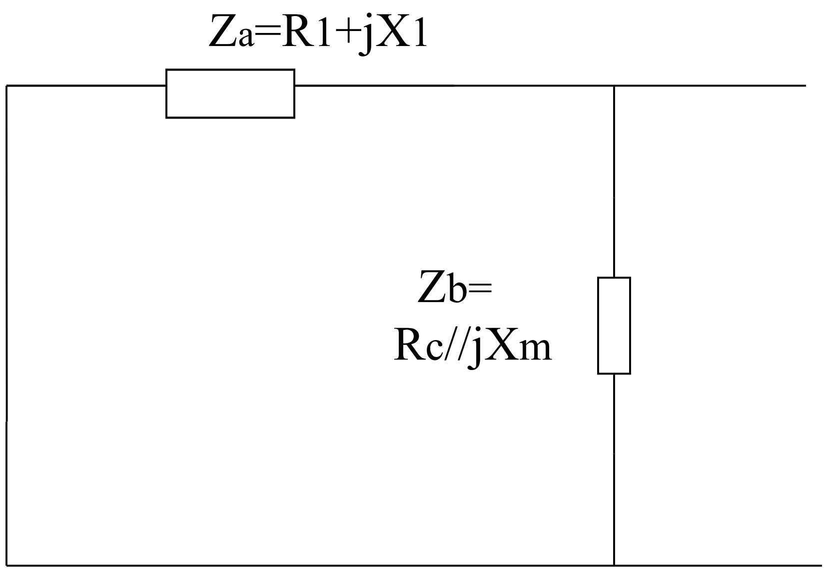
6. Thevenin Equivalent Circuit



By voltage division:

$$V_{th} = V_1 \frac{Z_b}{Z_a + Z_b}$$

Note that V_1 is the line-to-neutral voltage, given by $V_1 = V_{LL}/\text{sqrt}(3)$.



The two impedances are in parallel:

$$Z_{th} = Z_a \,//\, Z_b = \frac{Z_a Z_b}{Z_a + Z_b}$$