Electromagnetic Energy Conversion
ELEC0431

Exercise session 5:
Synchronous machines

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- Three-phase synchronous motors
- Three-phase synchronous generators (alternators)
- Exercise 9

Three-phase synchronous motors

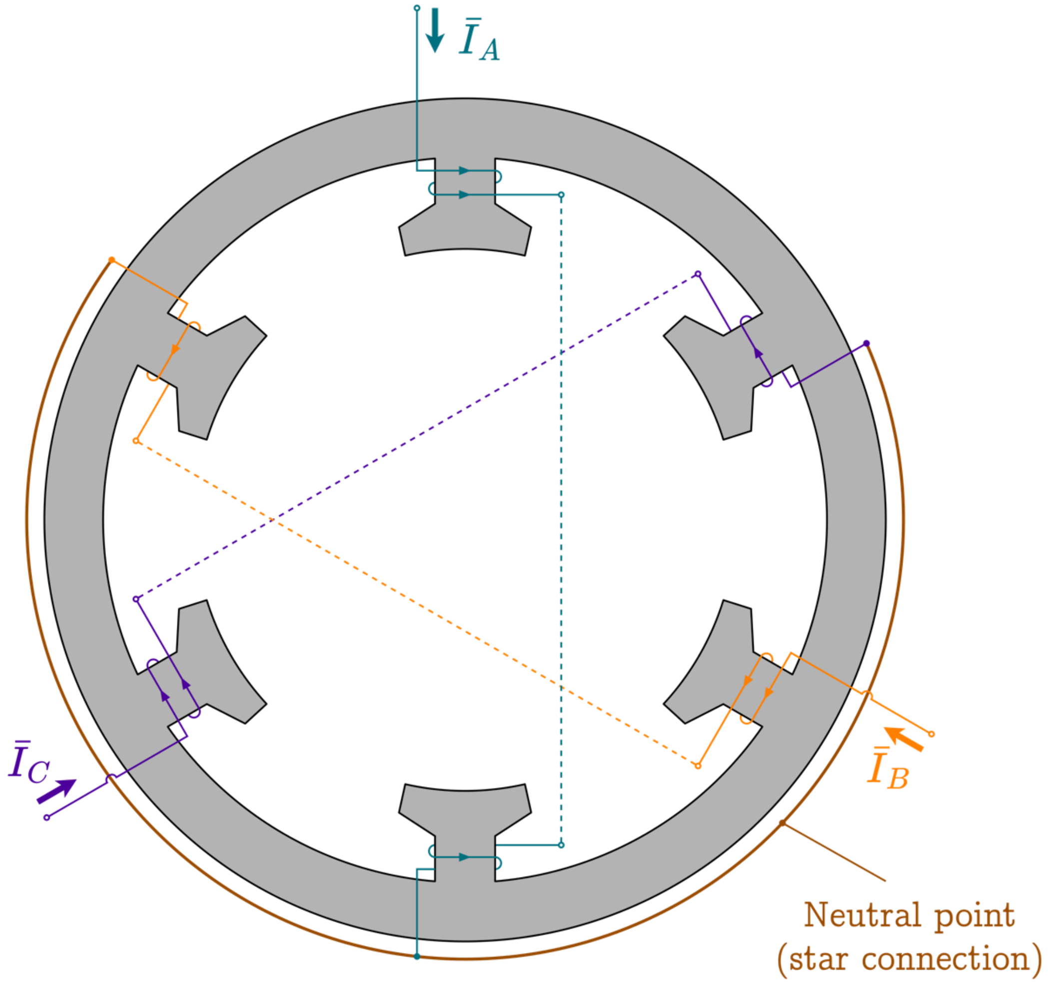
Stators in three-phase motors

Magnetic field in three-phase motors

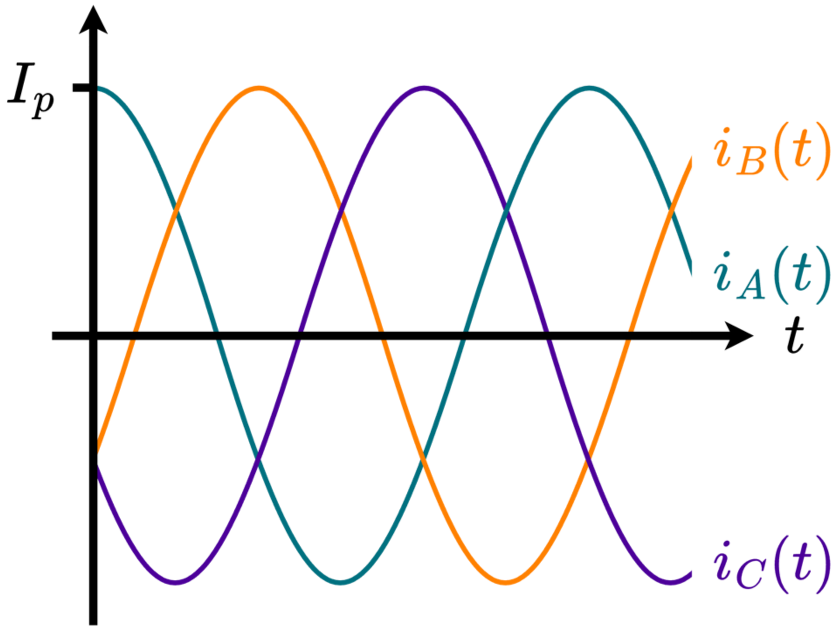
Three-phase synchronous motors

Stators in three-phase motors

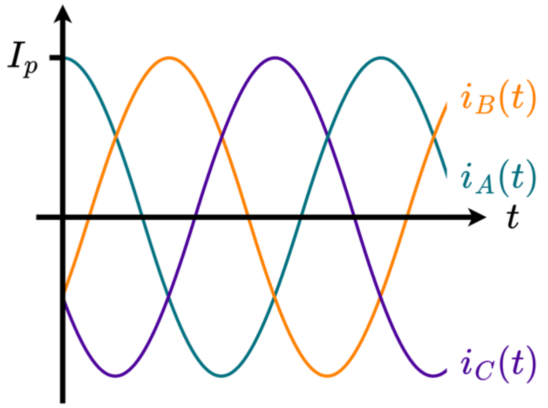
Let's consider a simple stator for a three-phase motor connected in a star configuration:



It is powered by a balanced three-phase electrical grid so that the currents $\bar{I}_A$, $\bar{I}_B$ and $\bar{I}_C$ are out of phase by 120° and have equal peak amplitude I_p.



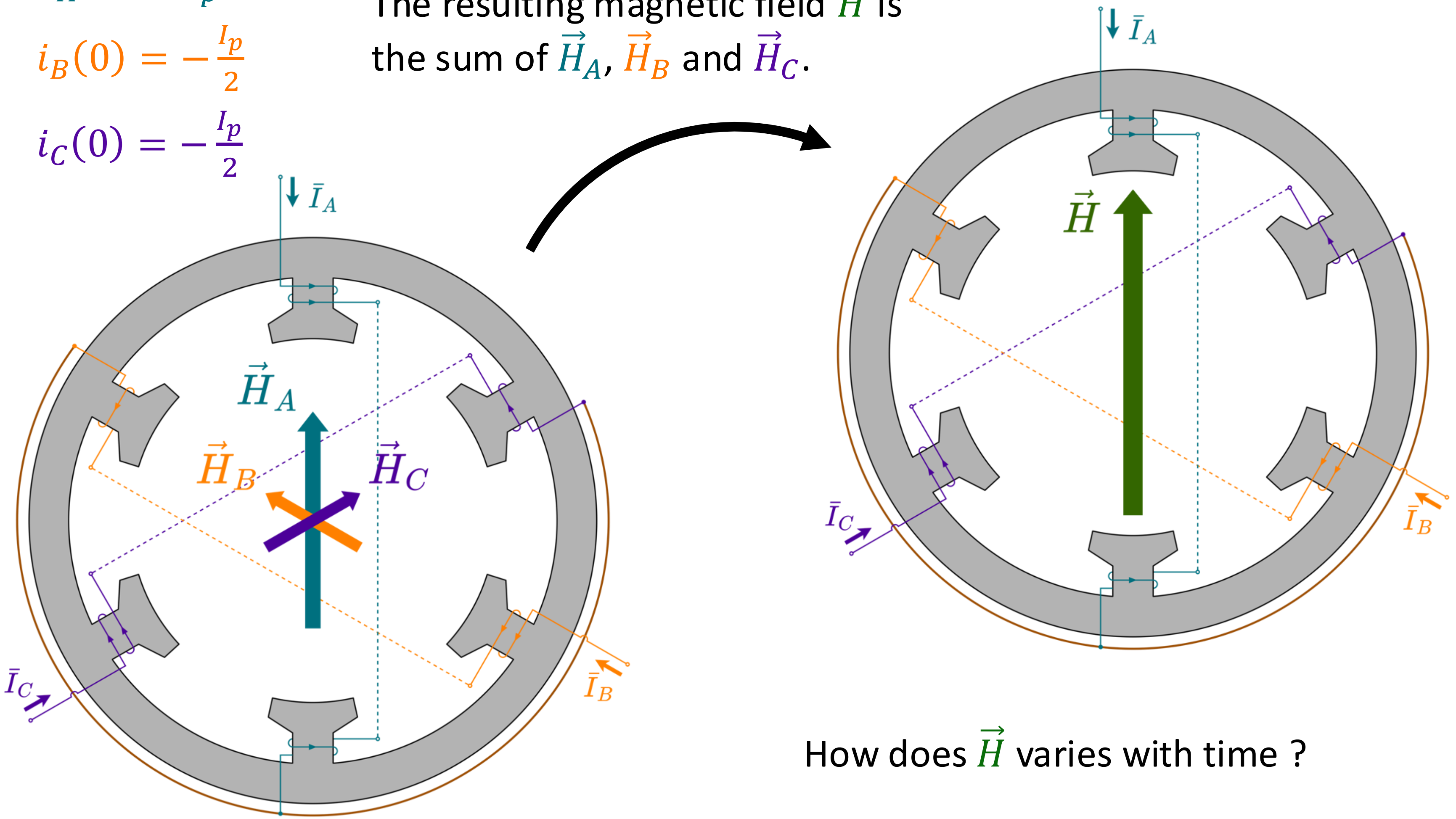
Magnetic field in three-phase motors



At $t = 0$:

- $i_A(0) = I_p$
- $i_B(0) = -\frac{I_p}{2}$
- $i_C(0) = -\frac{I_p}{2}$

The resulting magnetic field $\vec{H}$ is the sum of $\vec{H}_A$, $\vec{H}_B$ and $\vec{H}_C$.

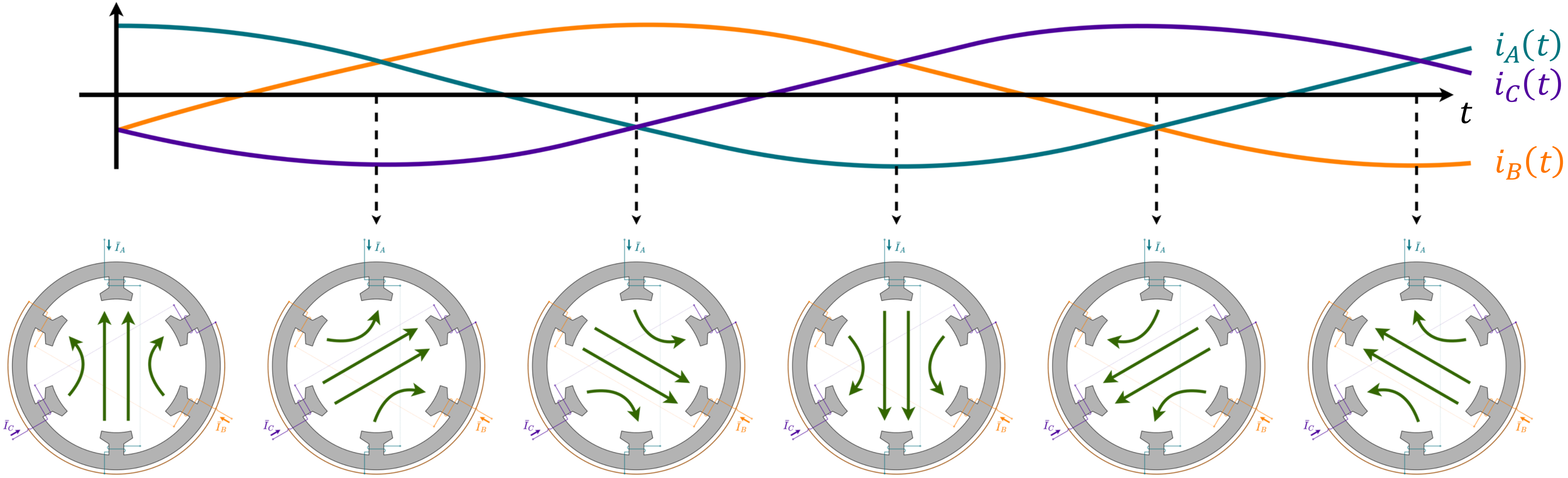


By ampere's law, we know these currents will generate magnetic fields.

As a first approximation, we consider that i_A generates $\vec{H}_A$, i_B generates $\vec{H}_B$ and i_C generates $\vec{H}_C$.

How does $\vec{H}$ varies with time ?

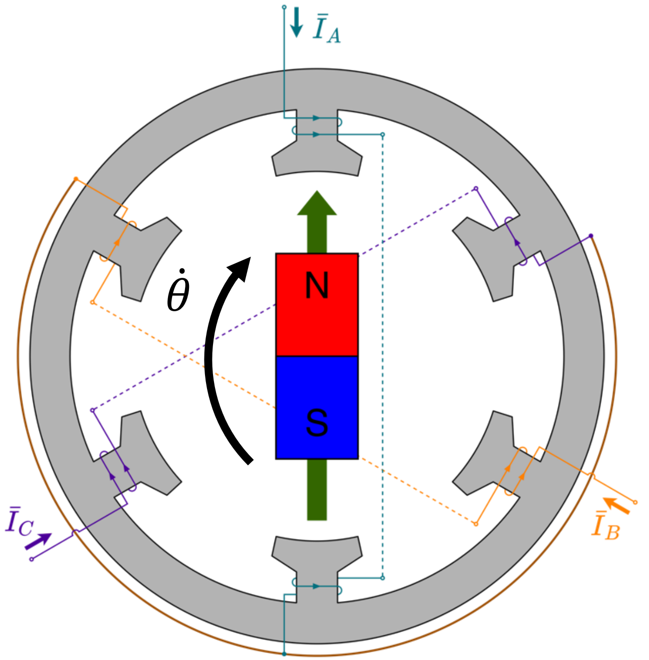
Magnetic field in three-phase motors

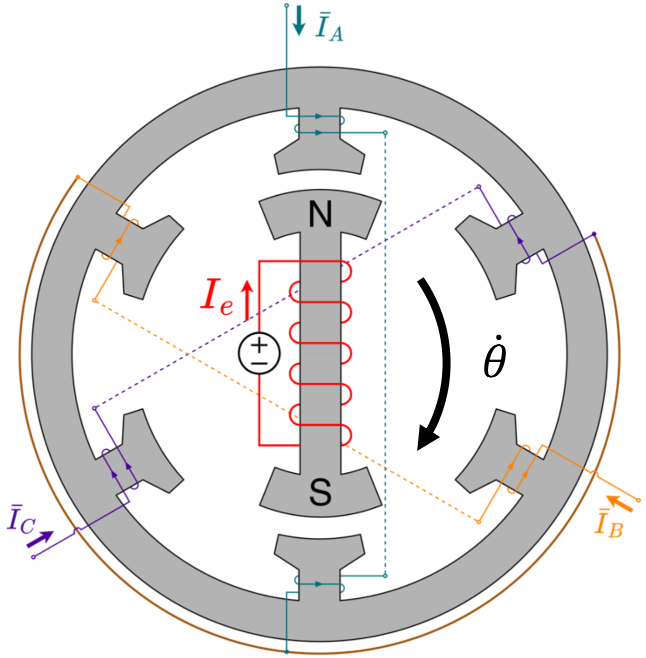


The magnetic field generated in the stator is constant in amplitude and rotates at the frequency of the three-phase power source.

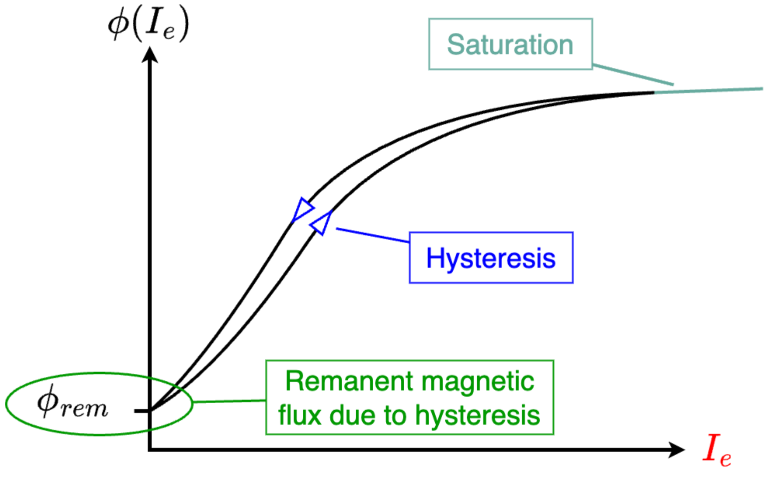
Three-phase synchronous motors

One can put a permanent magnet or an electromagnet in the stator.
In both cases, they will align with the magnetic field and rotate at the same frequency as the three-phase power source
➔ Synchronous motor





Note that electromagnets use ferromagnetic materials exhibiting hysteresis and saturation:



Three-phase synchronous generators (alternators)

Induced emf $\bar{E}_v$

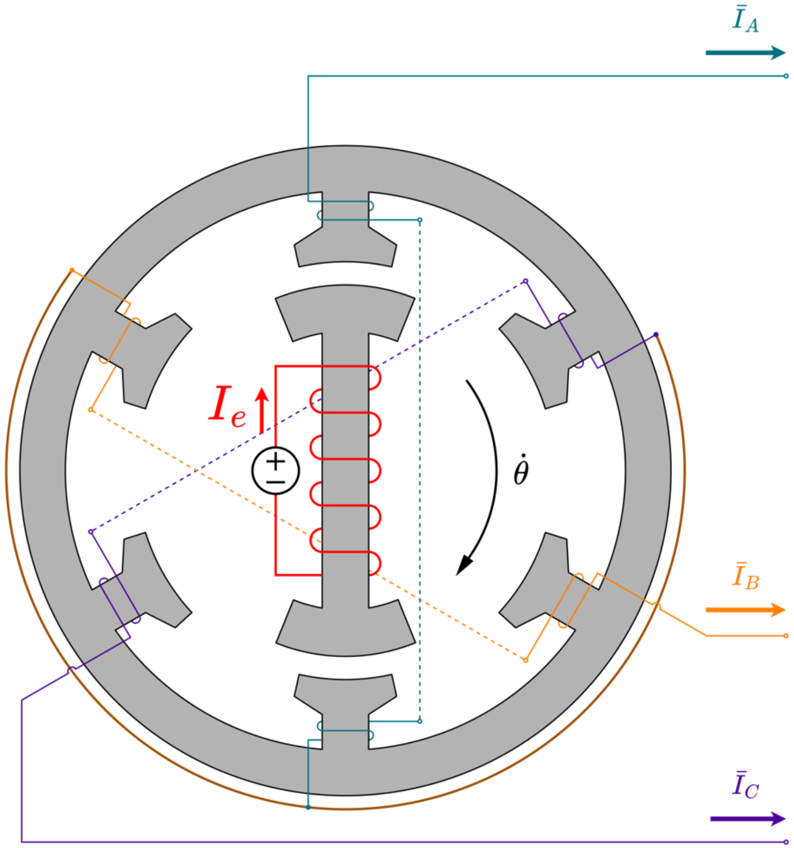
Behn-Eschenburg's model

Number of pairs of poles

Exercise 9

Induced emf $\bar{E}_v$

Three-phase synchronous generators and three-phase synchronous motors are built similarly.



An electromagnet generates a flux $\phi(I_e)$, rotating with the shaft of the machine.

As the magnetic flux perceived by the stator windings varies, it produces an emf, whose amplitude is proportional to $\frac{d\phi(I_e)}{dt}$.

Since it rotates at a speed $\dot{\theta}$, $\frac{d\phi(I_e)}{dt}$ is proportional to $\dot{\theta}\ \phi(I_e)$.

The RMS amplitude E_v of the produced emf is thus given by:

$$E_v = k_e\ \dot{\theta}\ \phi(I_e),$$

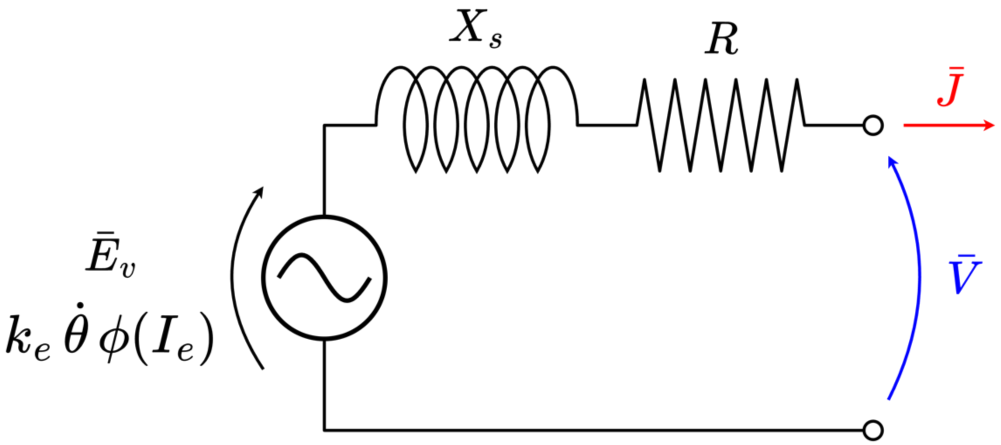
with k_e a scaling factor to determine.

Behn-Eschenburg’s model

The emf $\bar{E}_v$ generated in one phase is not directly equal to the corresponding output phase voltage $\bar{V}$.
This is due to:

- the stator leakage fluxes,
- the armature reaction,
- the wire resistance.

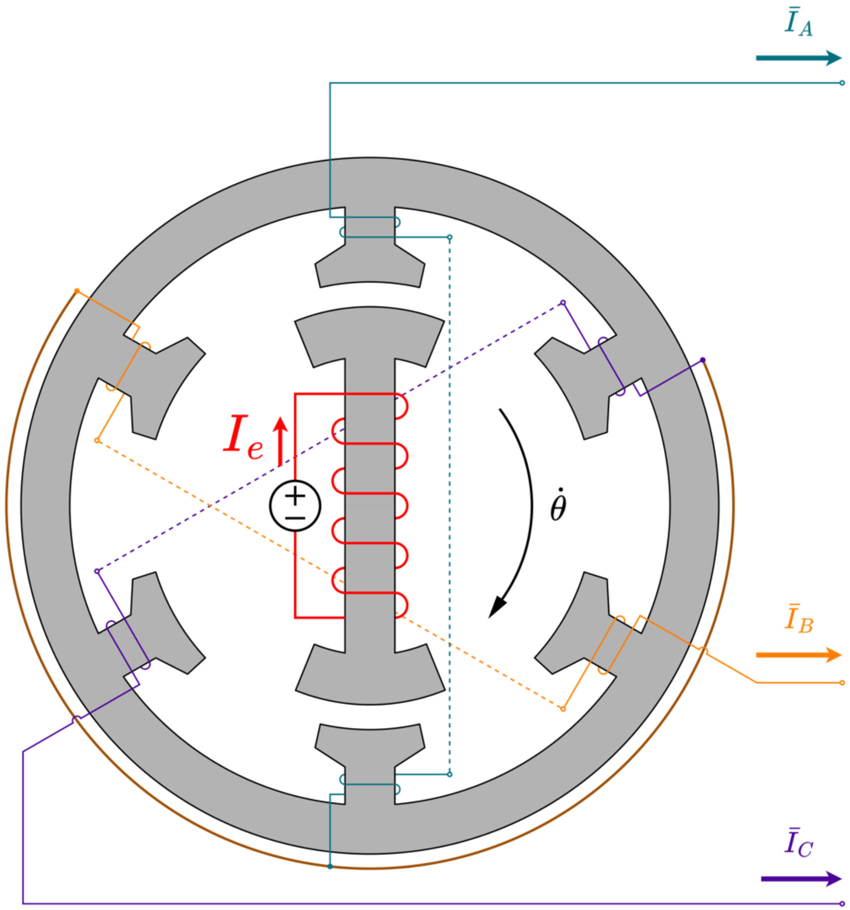
When the ferromagnetic materials are not saturated, we can account for these effects using the Behn-Eschenburg’s model:



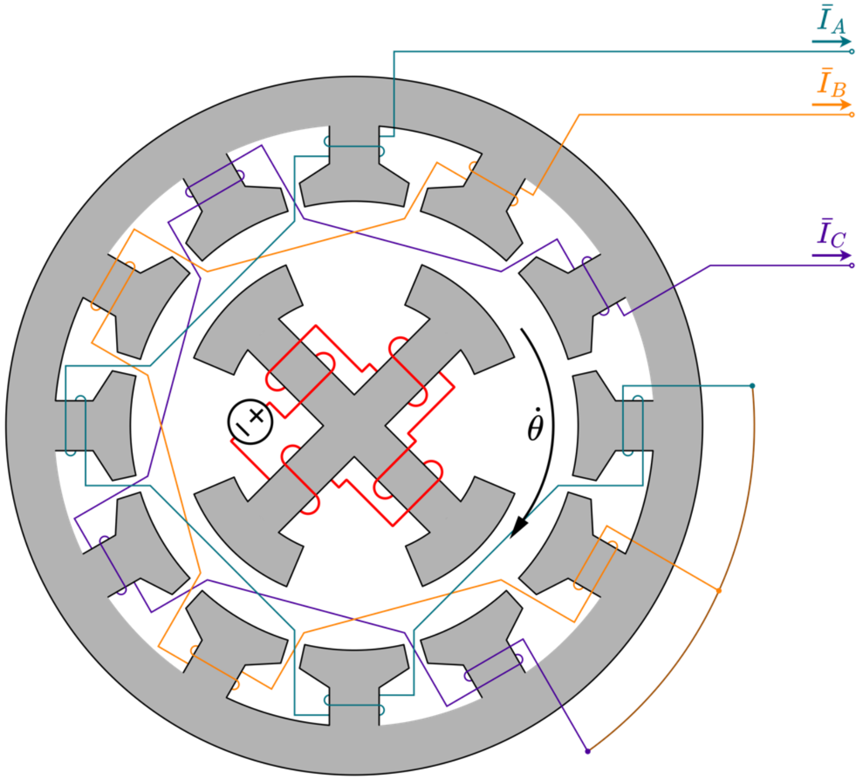
Note:

- Often, $X_s \gg R$.
- Without any load, $\bar{J} = 0$ and $\bar{E}_v = \bar{V}$ ➔ E_v is the **no-load** emf.

Number of pairs of poles



Each phase has two poles
➔ One pair of poles ($p = 1$)



Each phase has four poles
➔ Two pairs of poles ($p = 2$)

The number of pairs of poles p links the speed of rotation $\dot{\theta}$ to the pulsation ω of the currents and voltages:

$$\boxed{\dot{\theta} = \frac{\omega}{p}}$$

Exercise 9: Three-phase turbo-alternator

Turbo-alternators are alternators coupled to turbines allowing to convert the mechanical power of a moving fluid (steam or liquid) to electrical power. In this exercise the turbo-alternator has the following nominal characteristics:

- Power $P_n = 600\ MW$
- Frequency $f_n = 50\ Hz$
- Speed of rotation $\dot{\theta}_n = 3000\ RPM$
- Power factor $\cos\phi_n = 0.9$
- Line voltages $U_n = 20\ kV$
- Ferromagnetic losses $p_f = 543\ kW$
- Mechanical losses $p_m = 1.35\ MW$
- Rotor resistance $R_e = 0.17\ \Omega$
- Excitation system efficiency $\eta_e = 0.92$
- Stator phase resistance $R = 2.3\ m\Omega$.

To characterize the turbo-alternator three tests have been performed:

- Using open stator windings, at the nominal speed of rotation $\dot{\theta}_n$, the RMS direct voltage values have been measured with respect to the RMS current intensity I_e flowing through the inductor (table on the right).
- When turning at the nominal speed of rotation $\dot{\theta}_n$, using short-circuited stator windings and an excitation current I_e of $1.18\ kA$, an RMS current equal to half the nominal RMS value flows in each of the stator windings.
- When turning at the nominal speed of rotation $\dot{\theta}_n$, connecting an inductive load and using an excitation current I_e of $2.085\ kA$, an RMS current equal to half the nominal RMS value flows in each of the stator windings for an RMS line voltage of 10 kV.

I_e [A]	E_v [kV]
400	5.2
700	9.1
963	11.5
1200	13
1450	14
1900	15

Exercise 9: Three-phase turbo-alternator

1. Calculate the nominal RMS intensity I_n of the line currents.
2. Compute the total losses and the turbo-alternator efficiency at the nominal operating point, knowing the RMS excitation current value is $I_e = 3.2\ kA$ and that the alternator is in star configuration.
3. Calculate the mechanical power the turbine must provide for each of the considered test.

Using Behn-Eschenburg’s model with the experimental measurements:

4. Calculate the (unsaturated) synchronous reactance X_s of the turbo-alternator.
5. Draw the phasor diagram corresponding to the Behn-Eschenburg’s model for the nominal operating point, assuming the current lags the voltage.
6. Compute the RMS value E_v of the synchronous electromotive force.
7. Draw the internal angle δ_{int} and give its value.