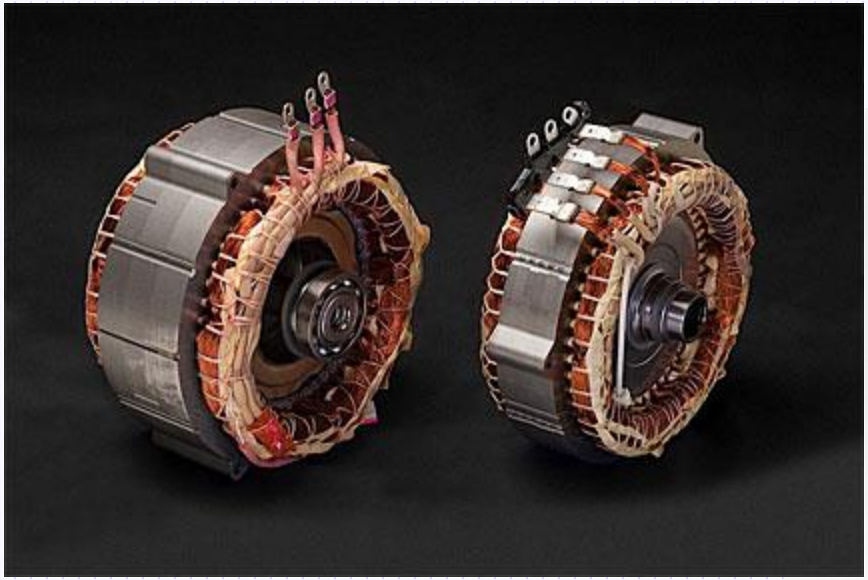
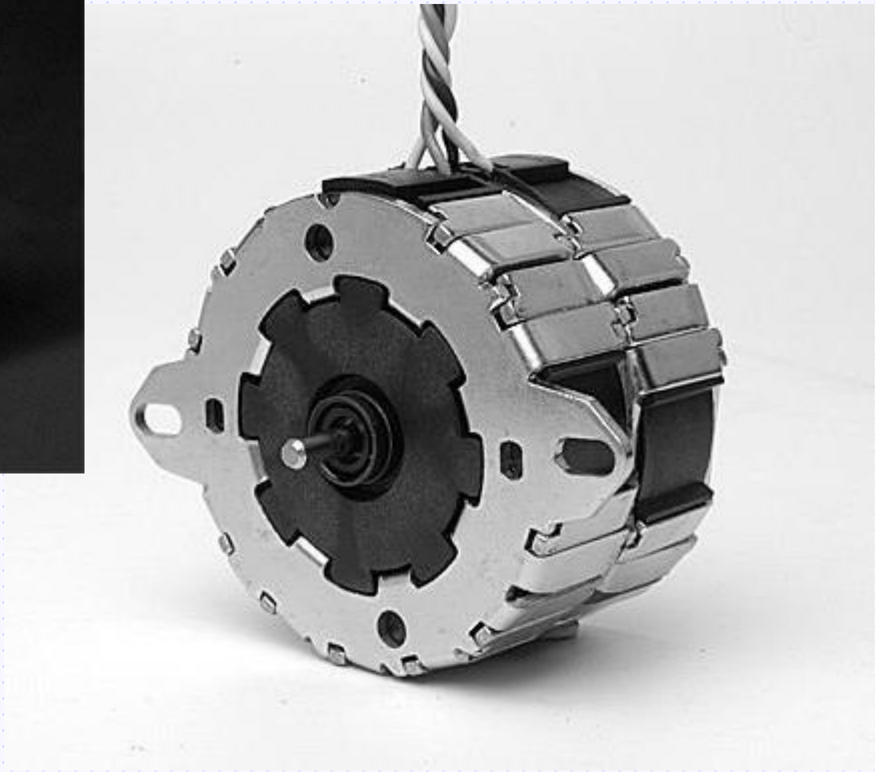
Permanent Magnet Synchronous Motors





Permanent Magnet Technology

The use of permanent magnets (PMs) in construction of electrical machines

brings the following benefits:

- *no electrical energy is absorbed by the field excitation system and thus there are no excitation losses which means substantial increase in the efficiency,*
- *higher torque and/or output power per volume than when using electromagnetic excitation,*
- *better dynamic performance than motors with electromagnetic excitation (higher magnetic flux density in the air gap),*
- *simplification of construction and maintenance,*
- *reduction of prices for some types of machines.*

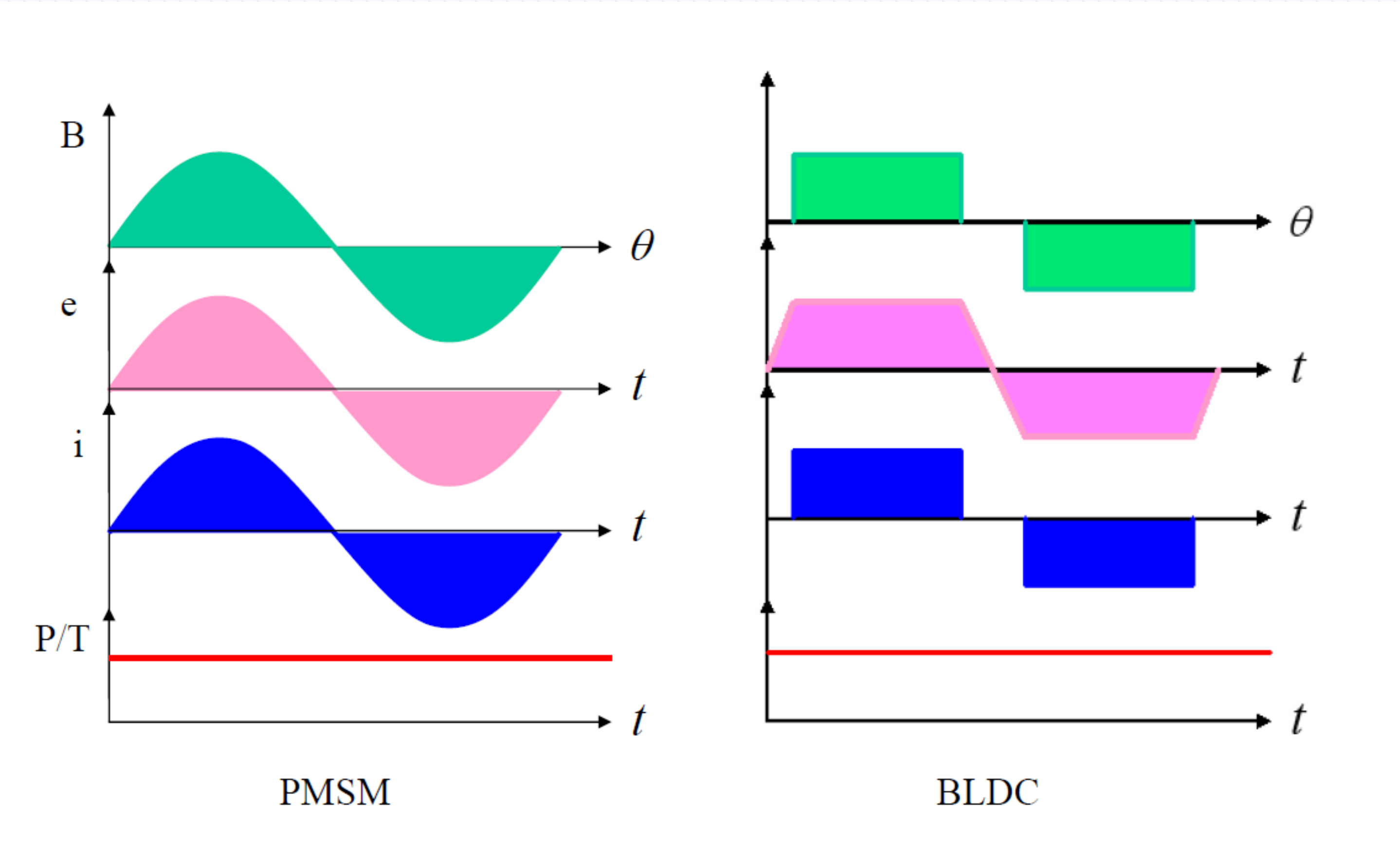
Permanent Magnet Classification

PM Motor → PM Synchronous Motor (PMSM)

PM Motor → PM Brushless Motor (BLDC)

	PMSM	BLDC
Flux Density (in space)	Sinusoidal Distribution	Square Distribution
Back-EMF	Sinusoidal Wave	Trapezoidal Wave
Stator Current	Sinusoidal Wave	Square Wave
Total Power	Constant	Constant
Electromagnetic Torque	Constant	Constant

Permanent Magnet Classification

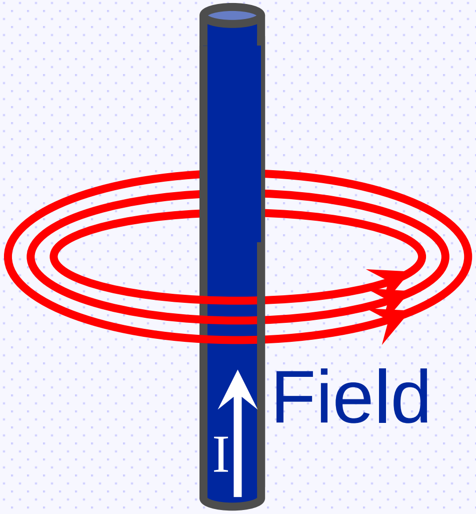


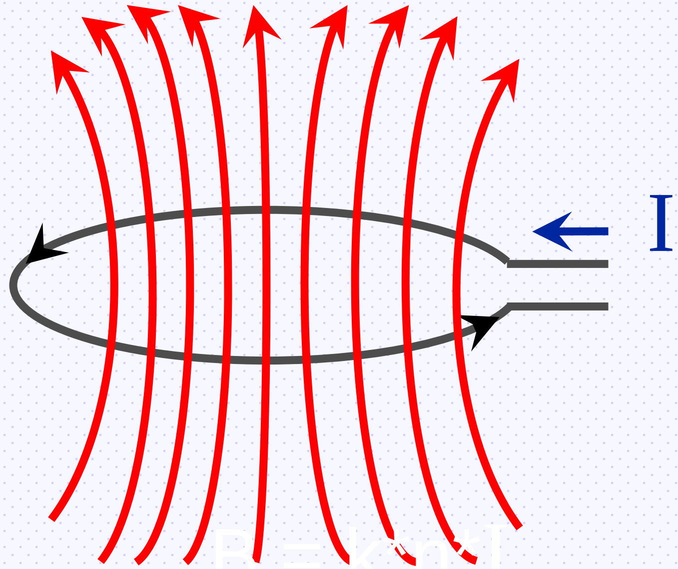
Sensored Field Oriented Control of a Permanent Magnet Synchronous Motor (PMSM)

Learning objectives

- Review of Electromagnetic laws
- Rotating magnetic fields
- Structure of synchronous motors
- Features of synchronous motors
- BLDC and PMSM synchronous motor types
- BLDC and PMSM control overview
- Electro-mechanical parameters for a synchronous motor

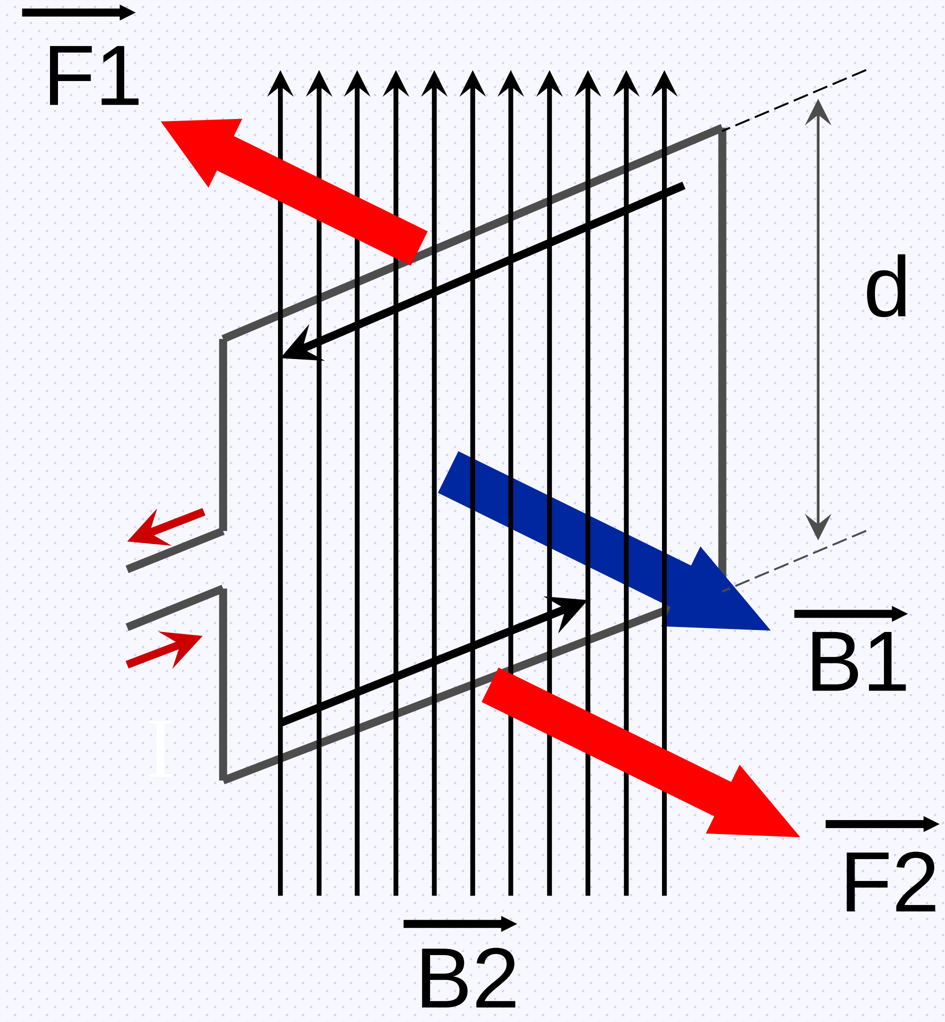
Field generated by a current





- A conductor carrying a current produces a magnetic field around it.
- A conductor that is wound into a coil produces a magnetic field along the axis of the coil.
- The flux produced is proportional to the current through the coil and the number of turns in the coil.

The Current in a Coil

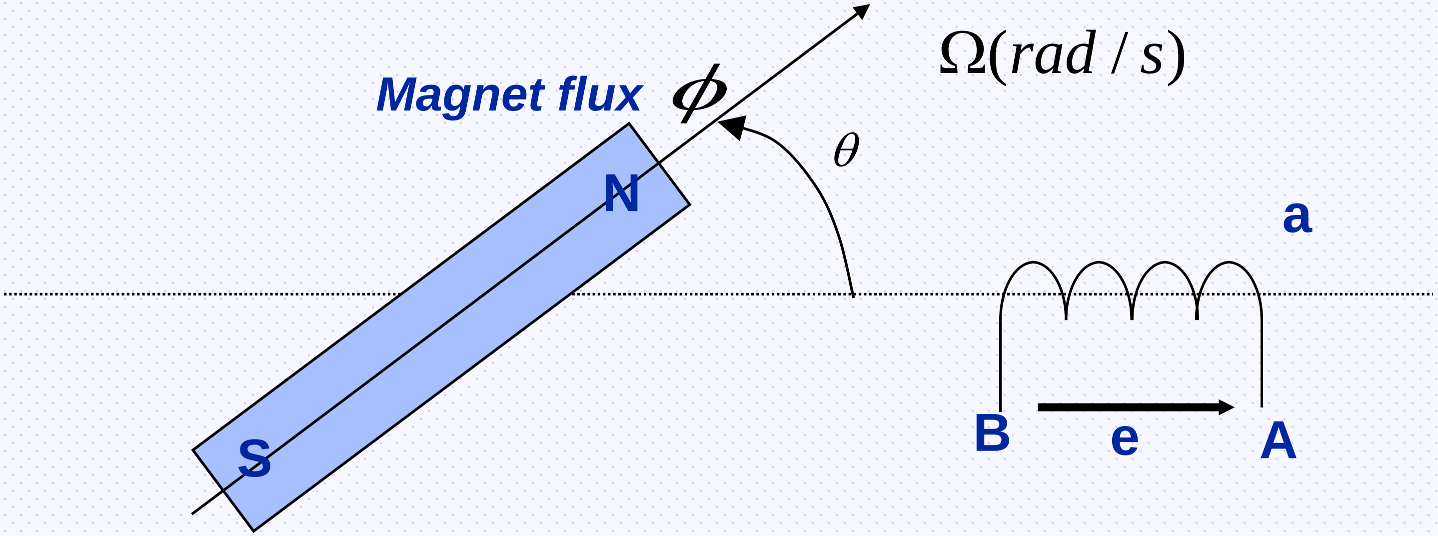


- A coil carrying a current, placed in a magnetic field experiences a force that will cause it to rotate.
- This force is given as the vector cross product of the flux produced by the coil and the flux that is impressed by the external magnetic field.

$$F1 = F2 = B1 \; x \; B2$$

$$T = \left(B1 \bullet B2\right) \bullet d$$

Back EMF generation

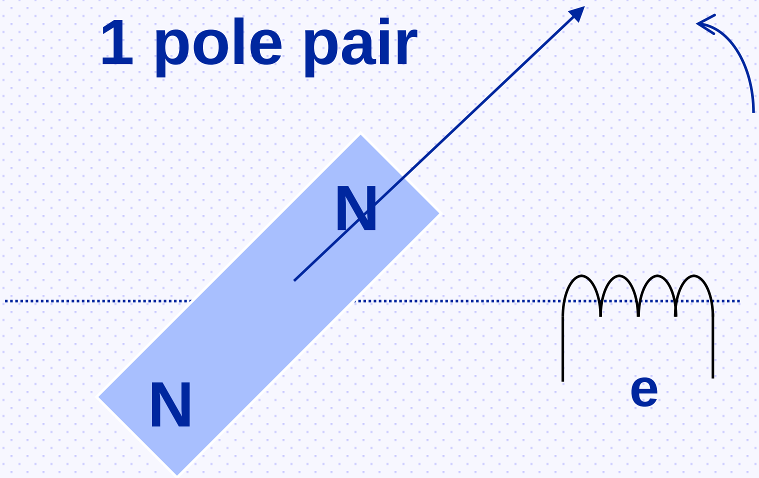


- Magnet rotating in front of winding “a” create an inductive voltage between A and B, e = V_A-V_B called Bemf (Back electromotive force)
- Magnetic flux seen by the winding is given by: $\varphi = \phi\sqrt{2}\cos\Omega t$
- Bemf is then equal to:

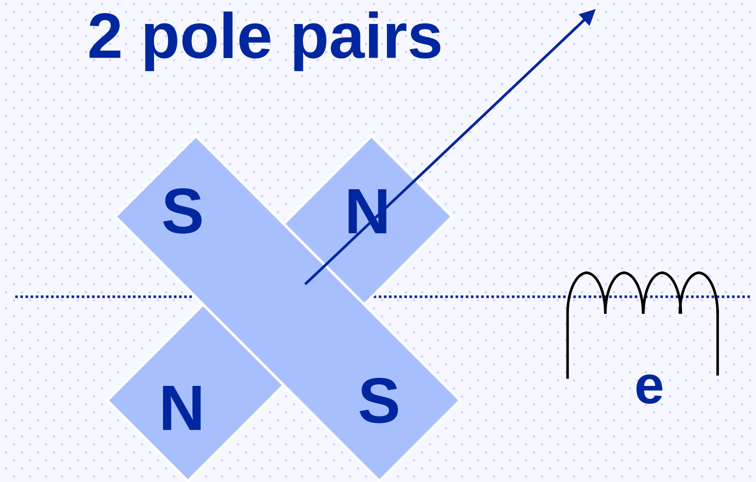
$$\begin{cases} e(t) = -\dfrac{d\varphi}{dt} = \phi\sqrt{2}\Omega\sin(\Omega t) = E\sin(\Omega t) \\ E = \phi\sqrt{2}\Omega \end{cases}$$

Pole pairs

1 pole pair



2 pole pairs



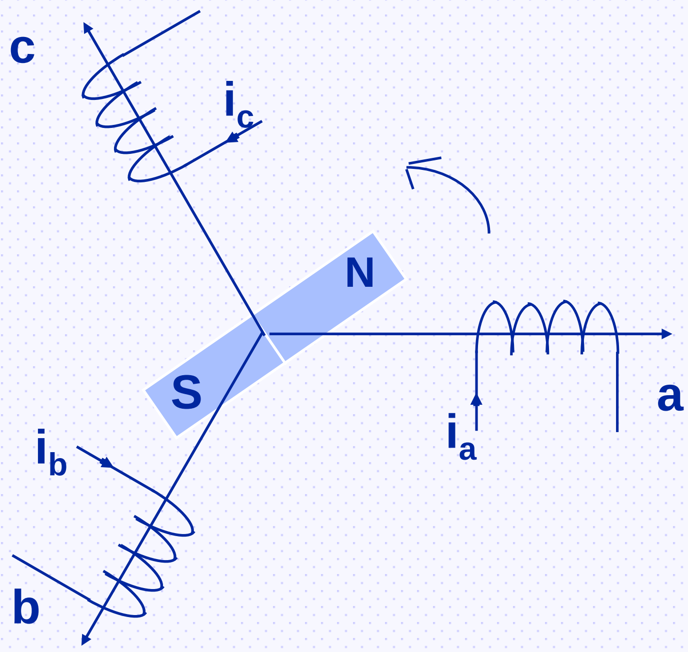
$$e(t) = E\sin(\omega t) \text{ with } \omega = \Omega \qquad e(t) = E\sin(\omega t) \text{ with } \omega = 2\Omega$$

- **For a motor with p poles pairs we have** $\omega = p\Omega$

  ω **is the electrical frequency (rad/s)**

  Ω **is the mechanical frequency (rad/s) or simply the speed of the machine.**

Three phases winding



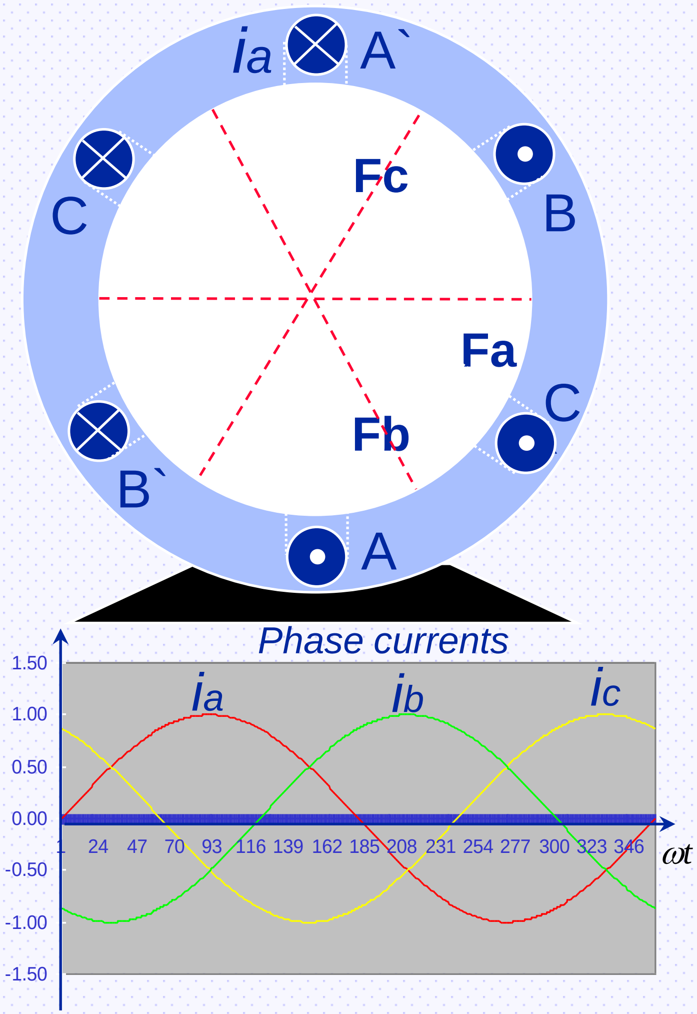
$$\begin{cases} i_a = I_s.e^{j\omega t} \\ i_b = I_S.e^{j\omega t-\frac{2\pi}{3}} \\ i_c = I_S.e^{j\omega t-\frac{4\pi}{3}} \end{cases}$$

$$\begin{cases} e_a = E.e^{jp\Omega t} \\ e_b = E.e^{jp\Omega t-\frac{2\pi}{3}} \\ e_c = E.e^{jp\Omega t-\frac{4\pi}{3}} \end{cases}$$

- For most three phase machines, the winding is stationery, and magnetic field is rotating
- Three phase machines have three stator windings, separated 120° apart physically
- Three phase stator windings produce three magnetic fields, which are spaced 120°in time

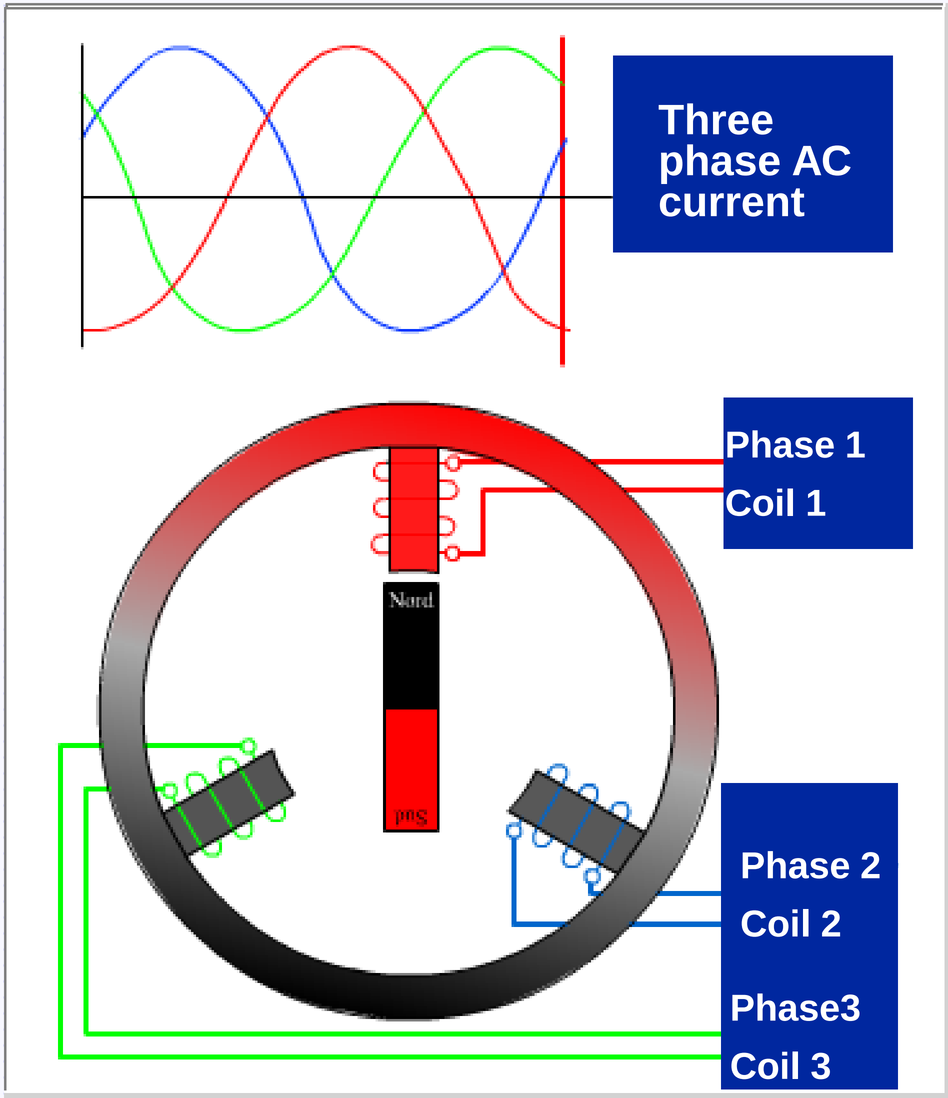
Application to Three Phases Machine Operation Fundamentals

Three stationary pulsating magnetic fields

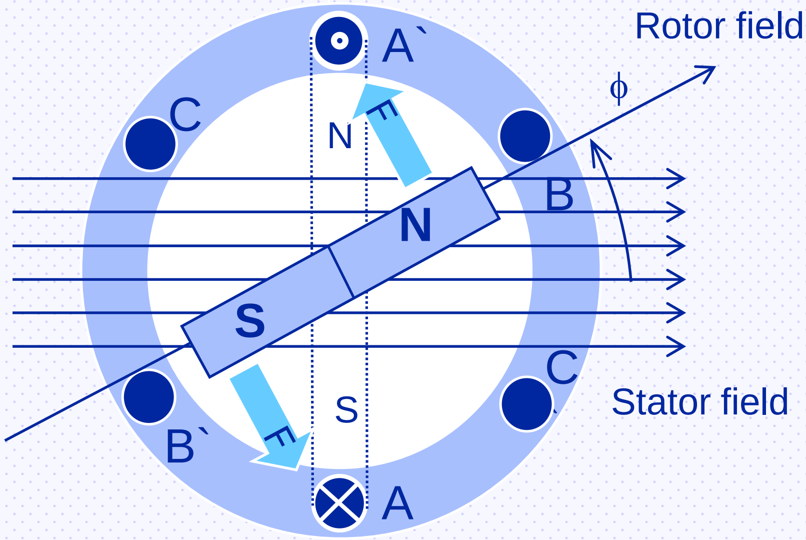


- **The three phase winding produces three magnetic fields, which are spaced 120° apart physically.**
- **When excited with three sine waves that are a 120° apart in phase, there are three pulsating magnetic fields.**
- **The resultant of the three magnetic fields is a *rotating magnetic field.***

Synchronous operation



Theory of operation:



- **Rotor is carrying a constant magnetic field created either by permanent magnets or current fed coils**
- **The interaction between the rotating stator flux, and the rotor flux produces a torque which will cause the motor to rotate.**

- **The rotation of the rotor in this case will be at the same exact frequency as the applied excitation to the rotor.**
- **This is *synchronous* operation.**

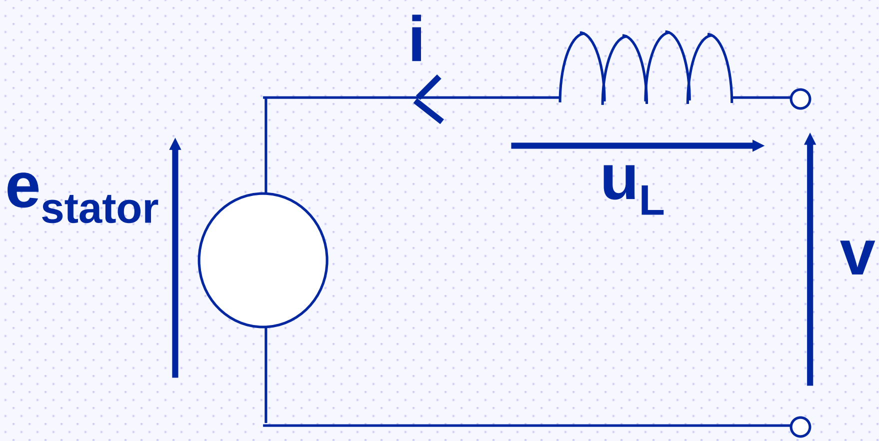
$$\text{Rotor speed (rad/s)}: \Omega = \frac{\omega}{p} \ gives \ \frac{60.f}{p} \ \text{(r.pm)}$$

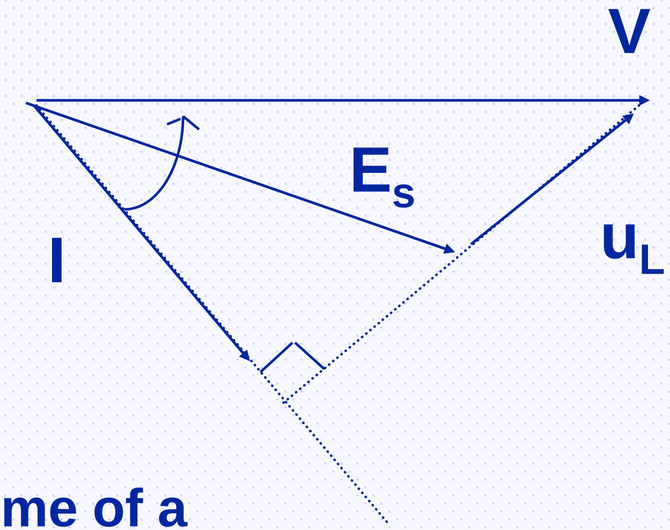
f : AC supply frequency (Hz)

p : motor poles pair per phase

- **Example: a 2 poles pair synchronous motor will run at 1500 r.pm for a 50Hz AC supply frequency**

Electromechanical Parameters





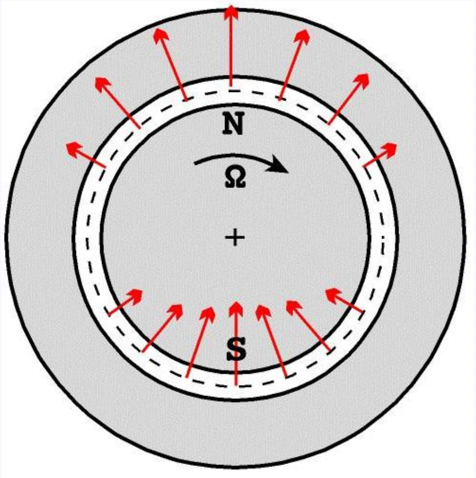
- **Simplified equivalent electrical scheme of a winding of a three phases synchronous motor**

Note: stator resistance neglected

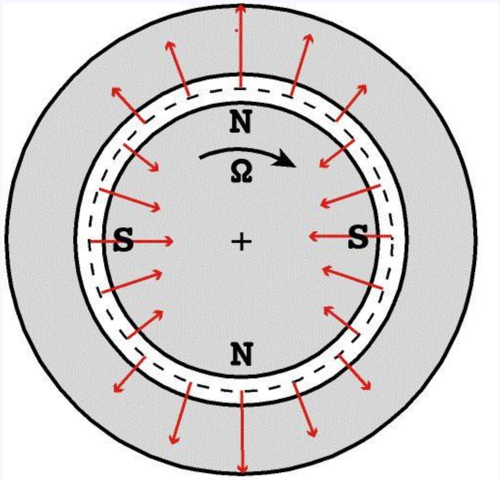
$$\boxed{T_{em} = \frac{3VI\cos\varphi}{\Omega}}$$

$$\begin{cases} T_{em} & : \text{electromechanical torque } (N.m) \\ V & : \text{phase voltage } (V) \\ I & : \text{phase current } (I) \\ \Omega & : \text{motor rotation speed } (rad/s) \end{cases}$$

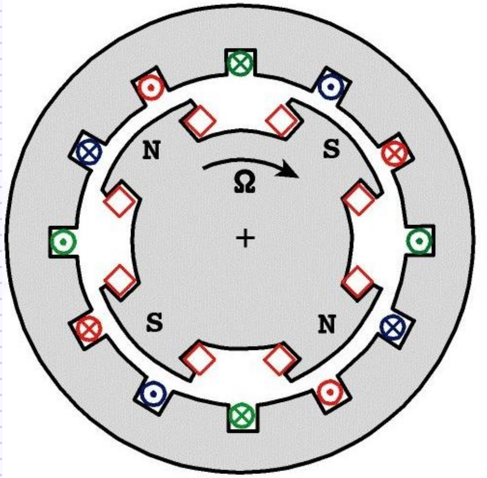
Synchronous Motor Rotor Construction



non-salient rotor pole (p=1)

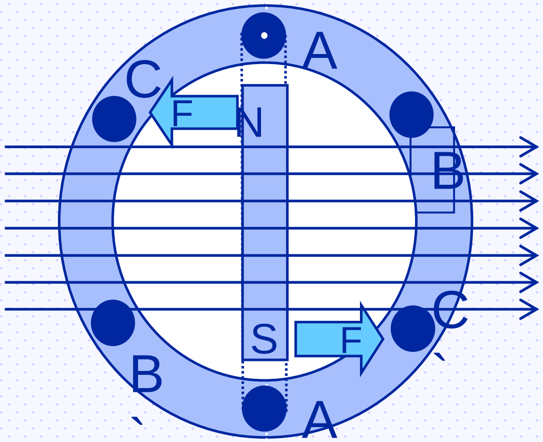


non-salient rotor pole (p=2)



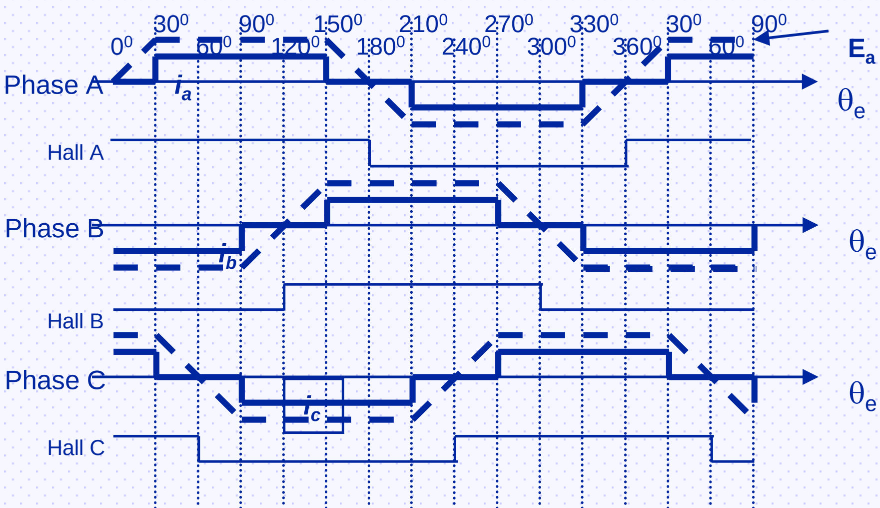
salient rotor pole (p=2)

Synchronous machine classification: BLDC and PMSM

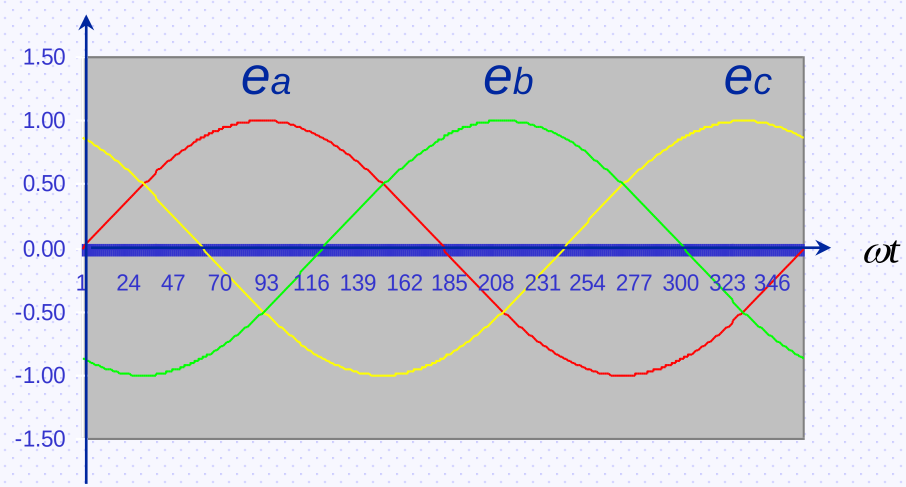


- **Both (typically) have permanent-magnet rotor and a wound stator**
- **BLDC (Brushless DC) motor is a permanent-magnet brushless motor with trapezoidal back EMF**
- **PMSM (Permanent-magnet synchronous motor) is a permanent-magnet brushless motor with sinusoidal back EMF**

Back EMF of BLDC Motor



Back EMF of PMSM



BLDC vs. PMSM

BLDC	PMSM
Synchronous machine	Synchronous machine
Fed with direct currents	Fed with sinusoidal currents
Trapezoidal BEMF	Sinusoidal BEMF
Stator Flux position commutation each 60 degrees	Continuous stator flux position variation
Only two phases ON at the same time	Possible to have three phases ON at the same time
Torque ripple at commutations	No torque ripple at commutations

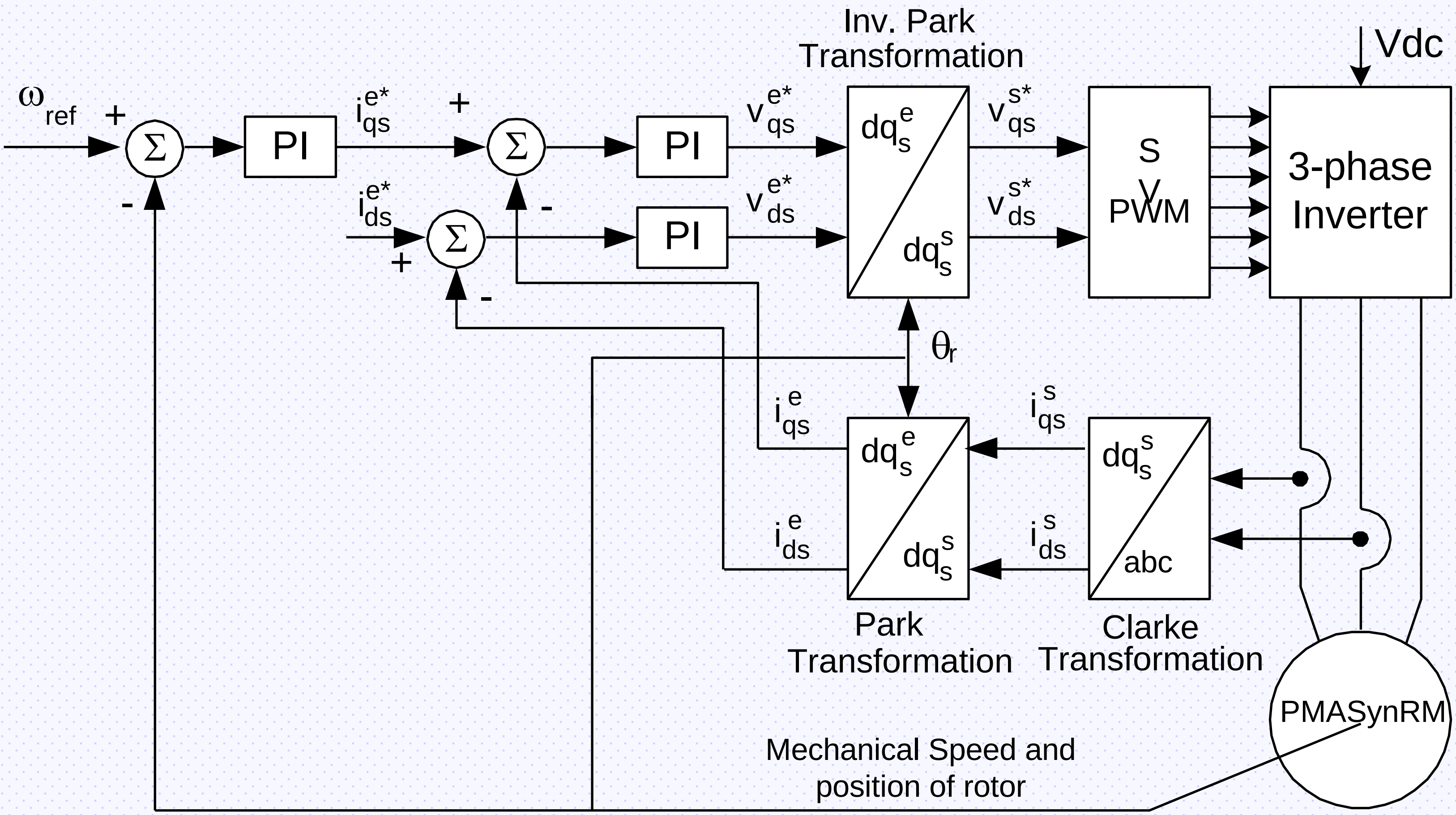
Conclusion

- Synchronous motors use magnetic interaction to convert electrical energy to mechanical.
- Rotor must be synchronized with the rotating stator magnetic field in order to produce torque
- Pole pair numbers and excitation frequency determine the mechanical rotation speed
- Synchronous motors are classified in two categories: BLDC and PMSM
- Each type require an appropriate control

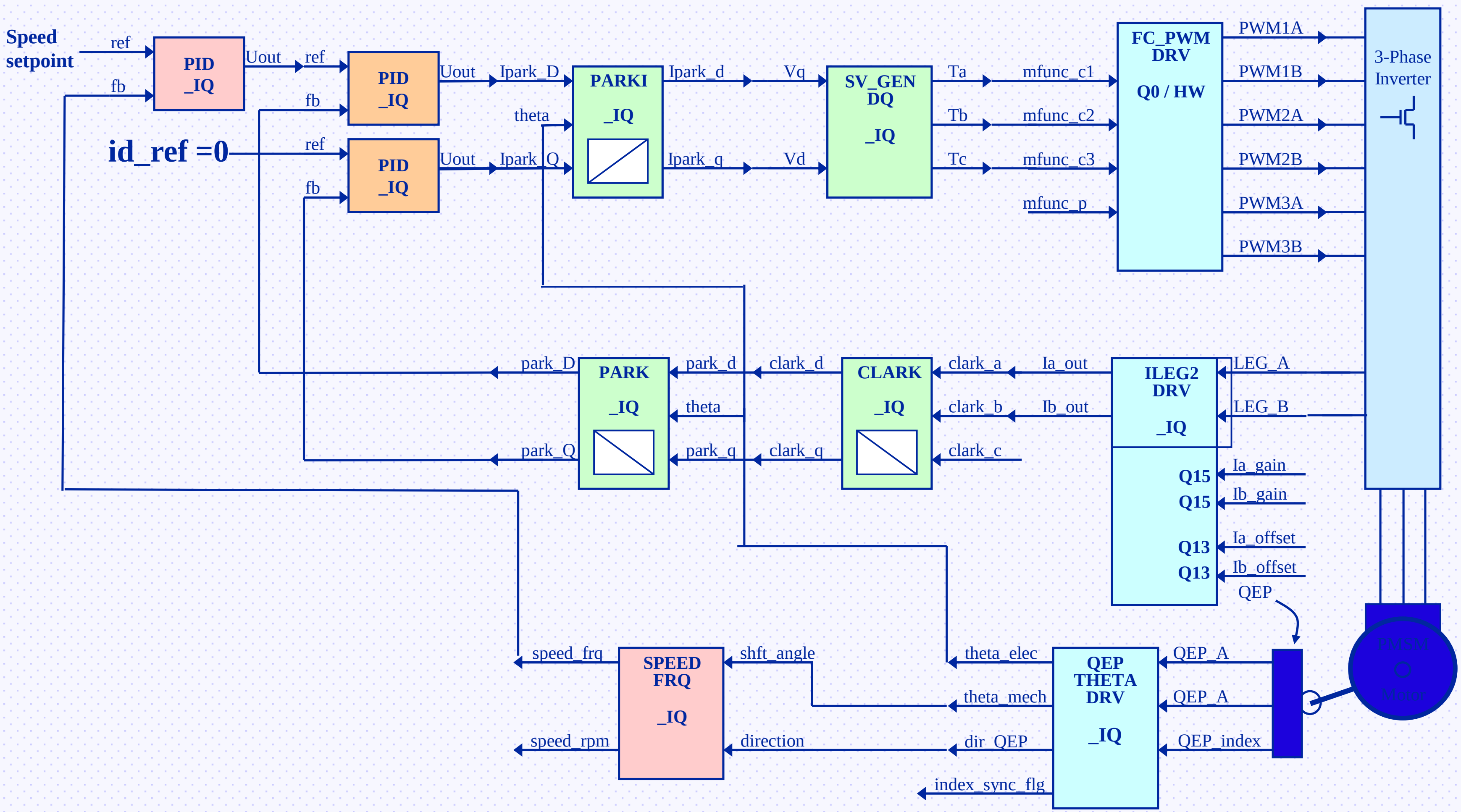
PMSM Control

- Synchronous Motors such as PM motors and SynRMs are getting more popular because of their high power density and high efficiency
- PM Assisted SynRM uses advantages of both PM and Reluctance motor
- The vector control strategy is far more complicated than control of a DC motor requiring use of multiple control loops

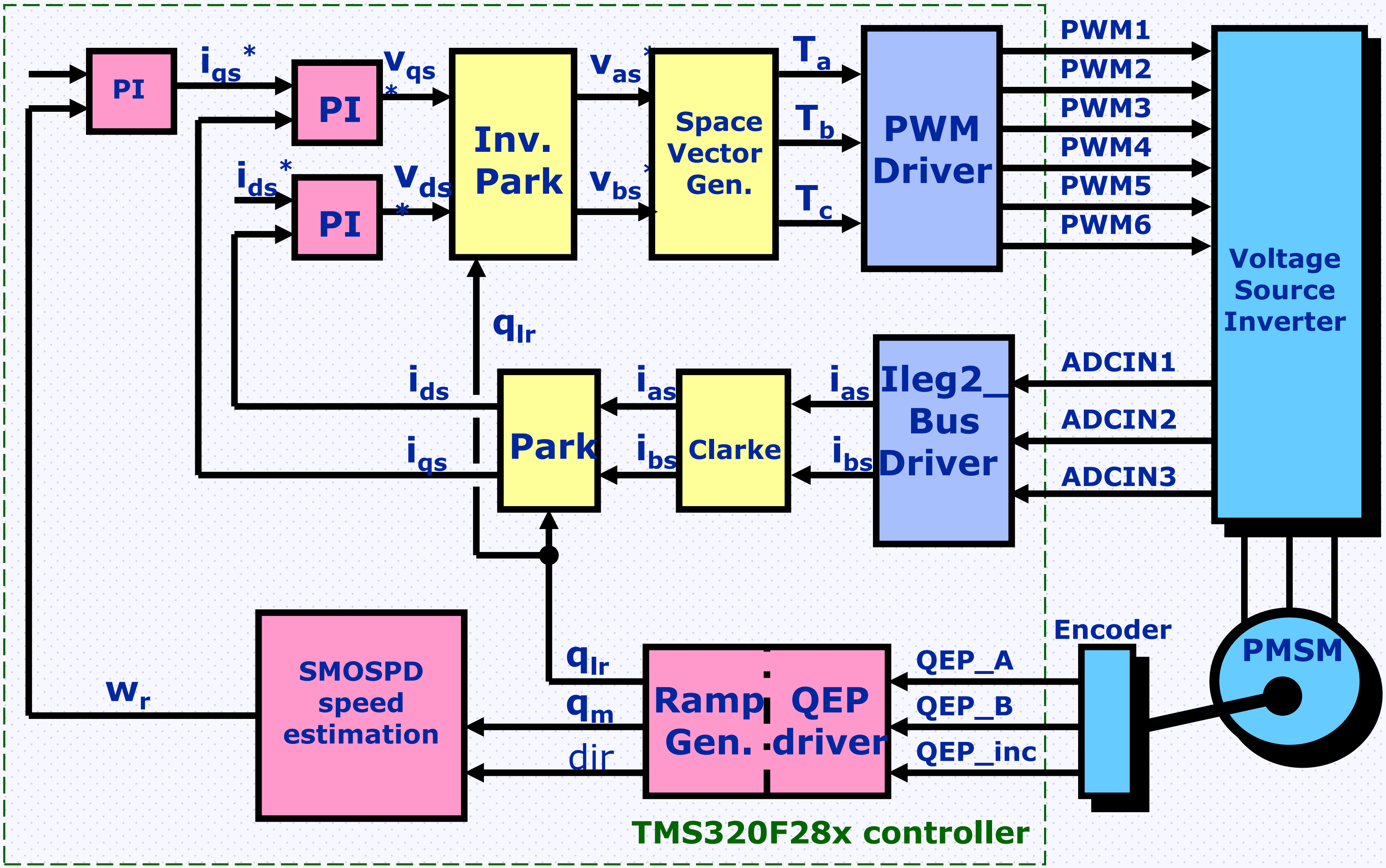
Control System Block-Diagram



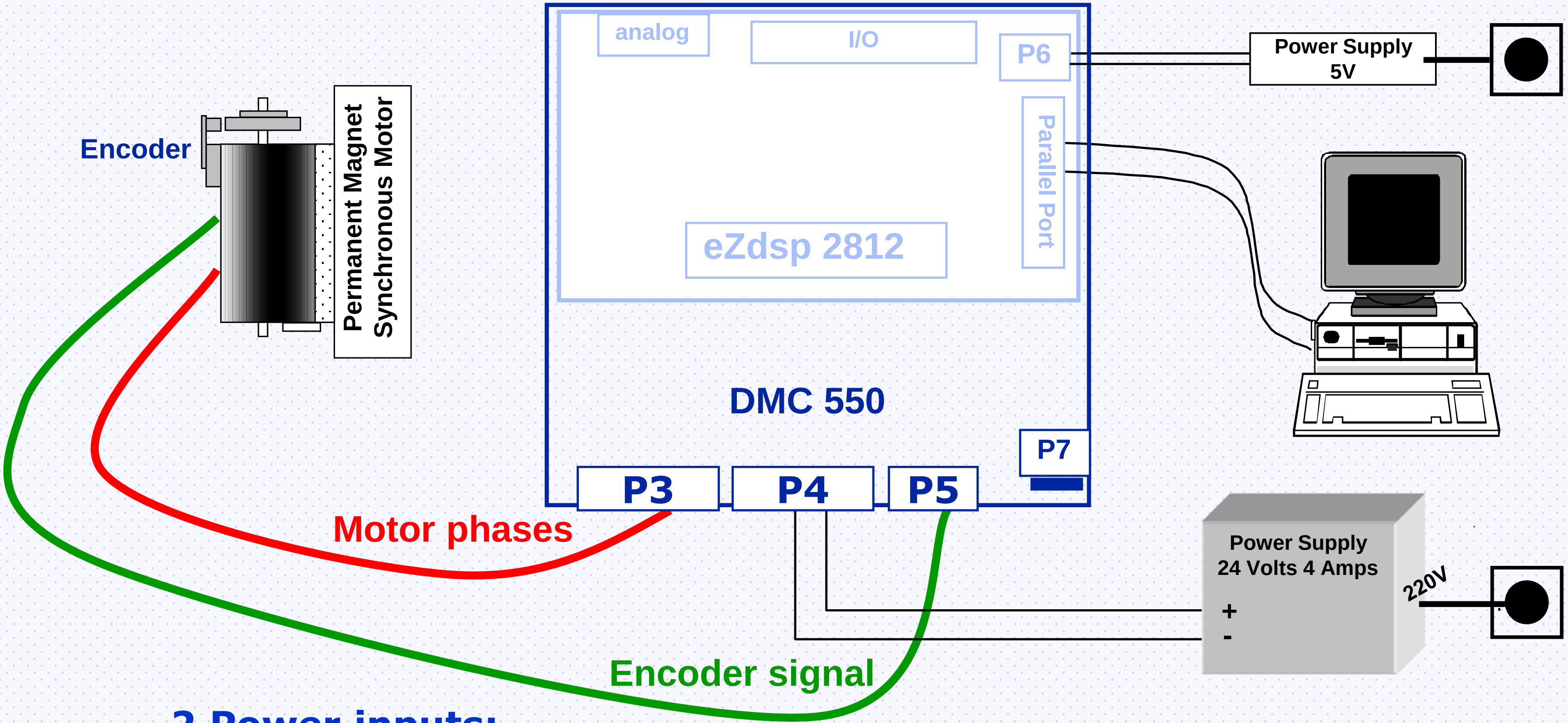
Using the DMC Library



The Equivalent Simulink® Model



Hardware Setup



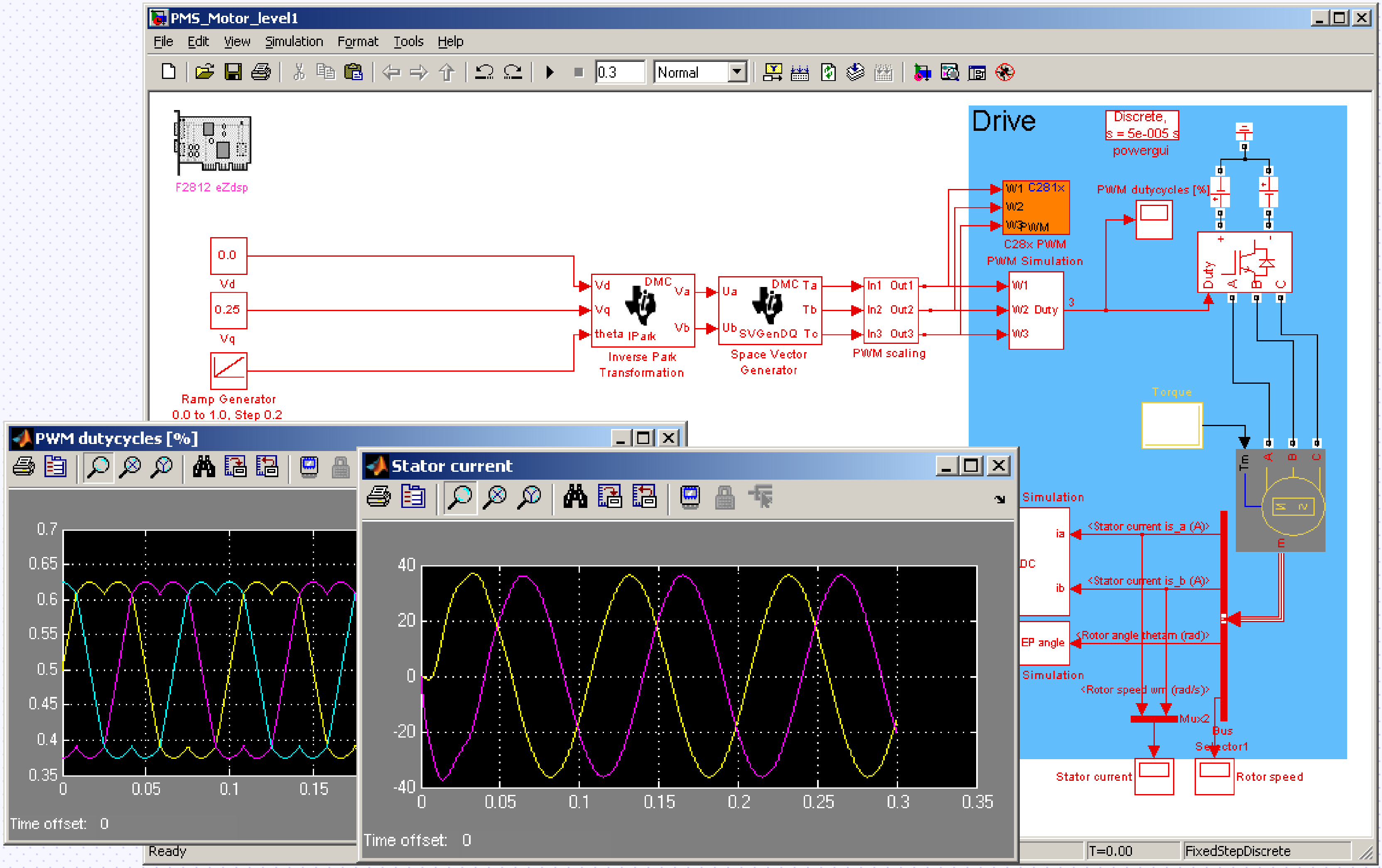
2 Power inputs:

- **5V PSU for the DSP board only (software debug)**
- **0 - 24V PSU for the power stage**

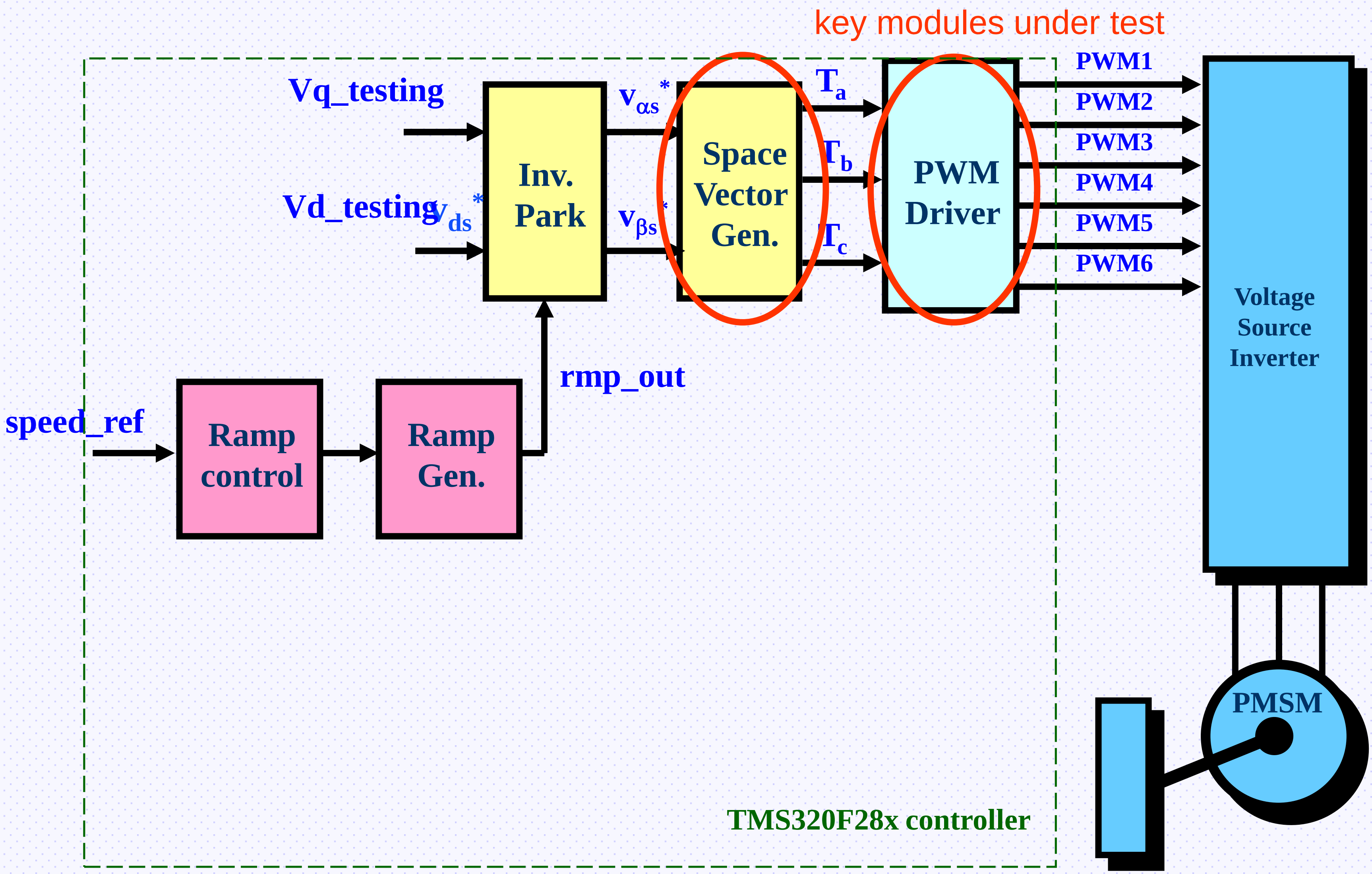
Model-Based Design of a PMSM

- Build Level 1 – Space vector generation
- Build Level 2 - Currents/DC-bus voltage measurement verification
- Build Level 3 - Tuning of dq-axis current closed loops
- Build Level 4 – Encoder verification
- Build Level 5 – Speed closed loop

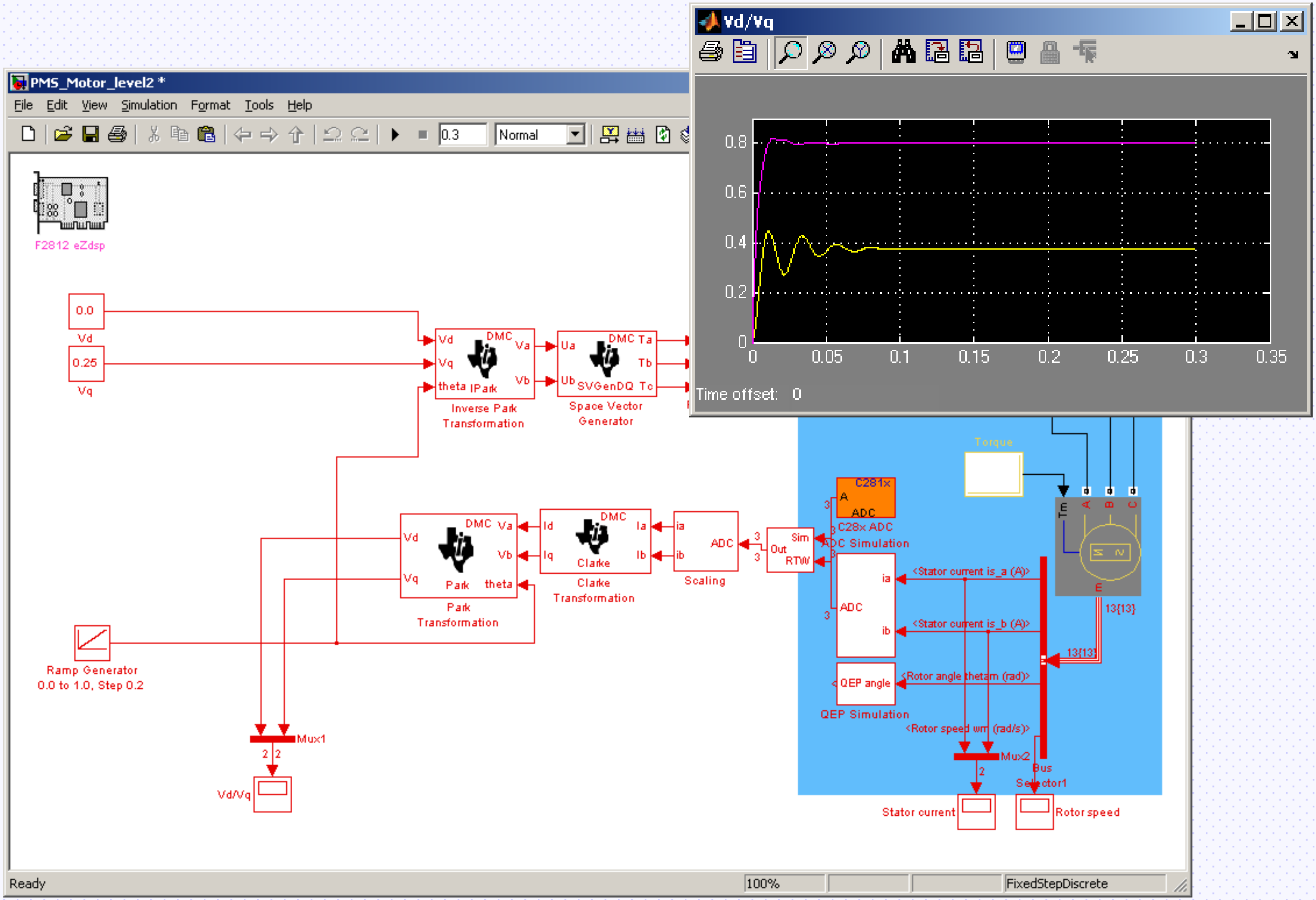
Space vector generation - Simulation



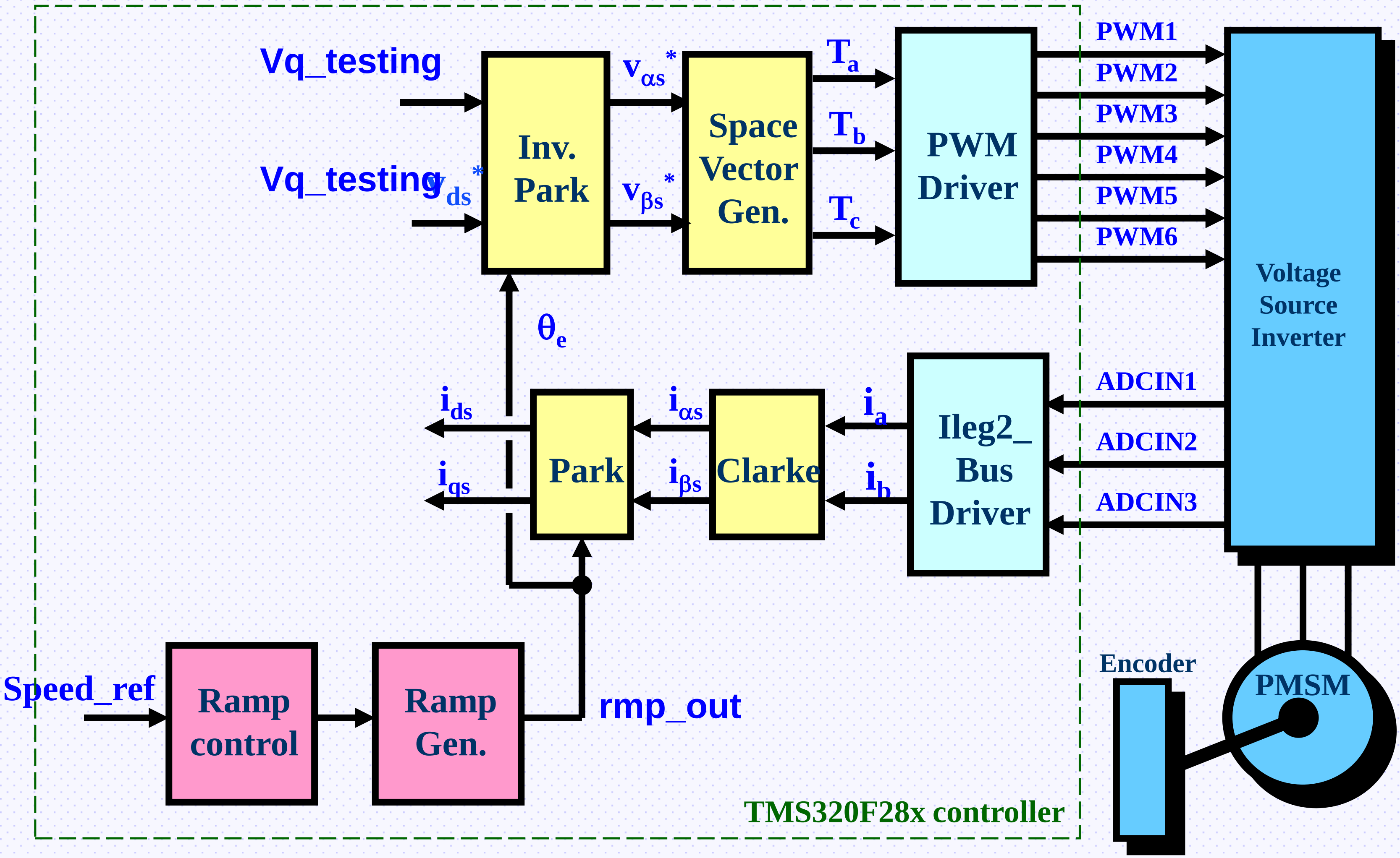
Space vector generation – Real Time



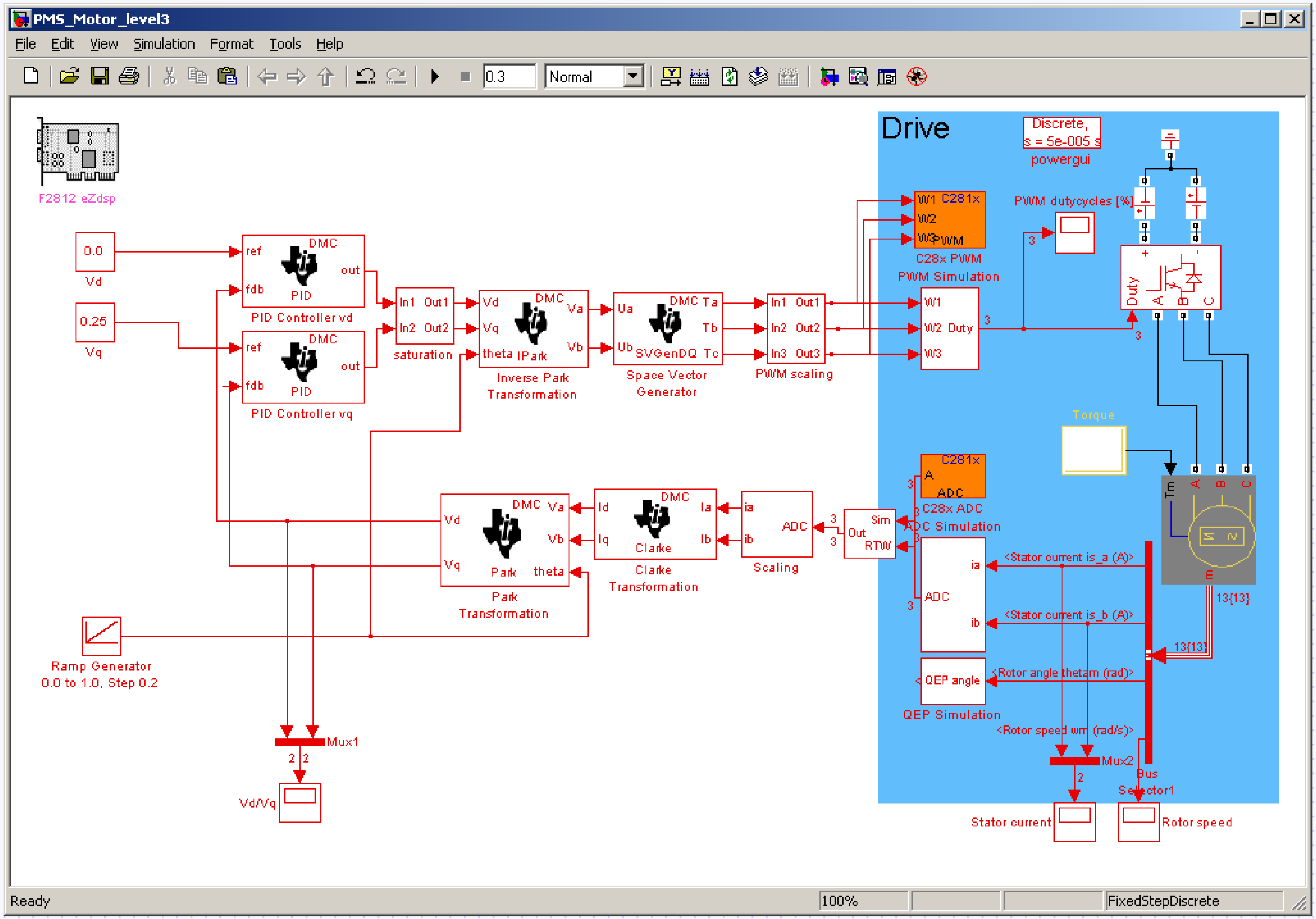
Currents/DC-bus voltage measurement verification - Simulation



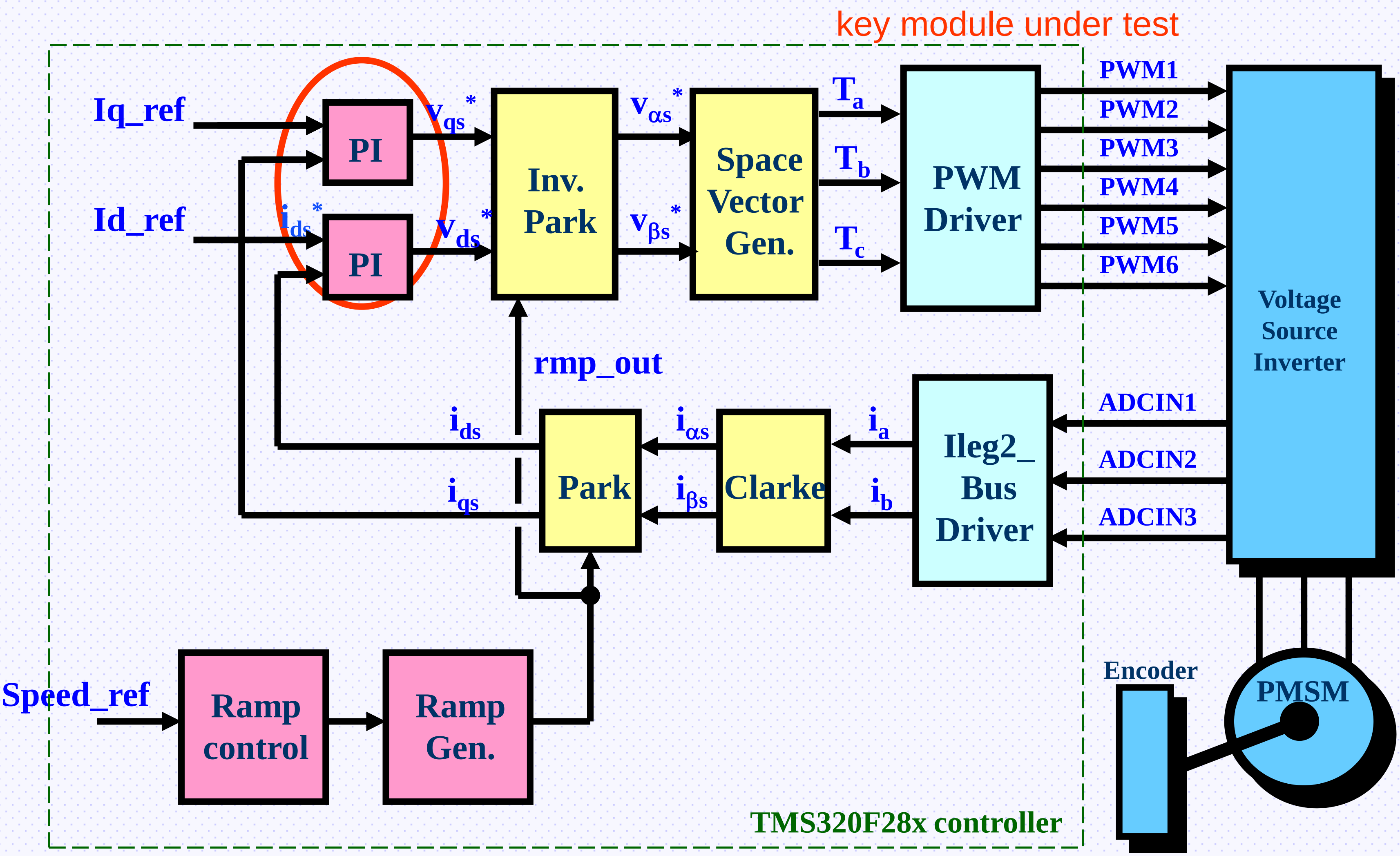
Currents/DC-bus voltage measurement verification – Real Time



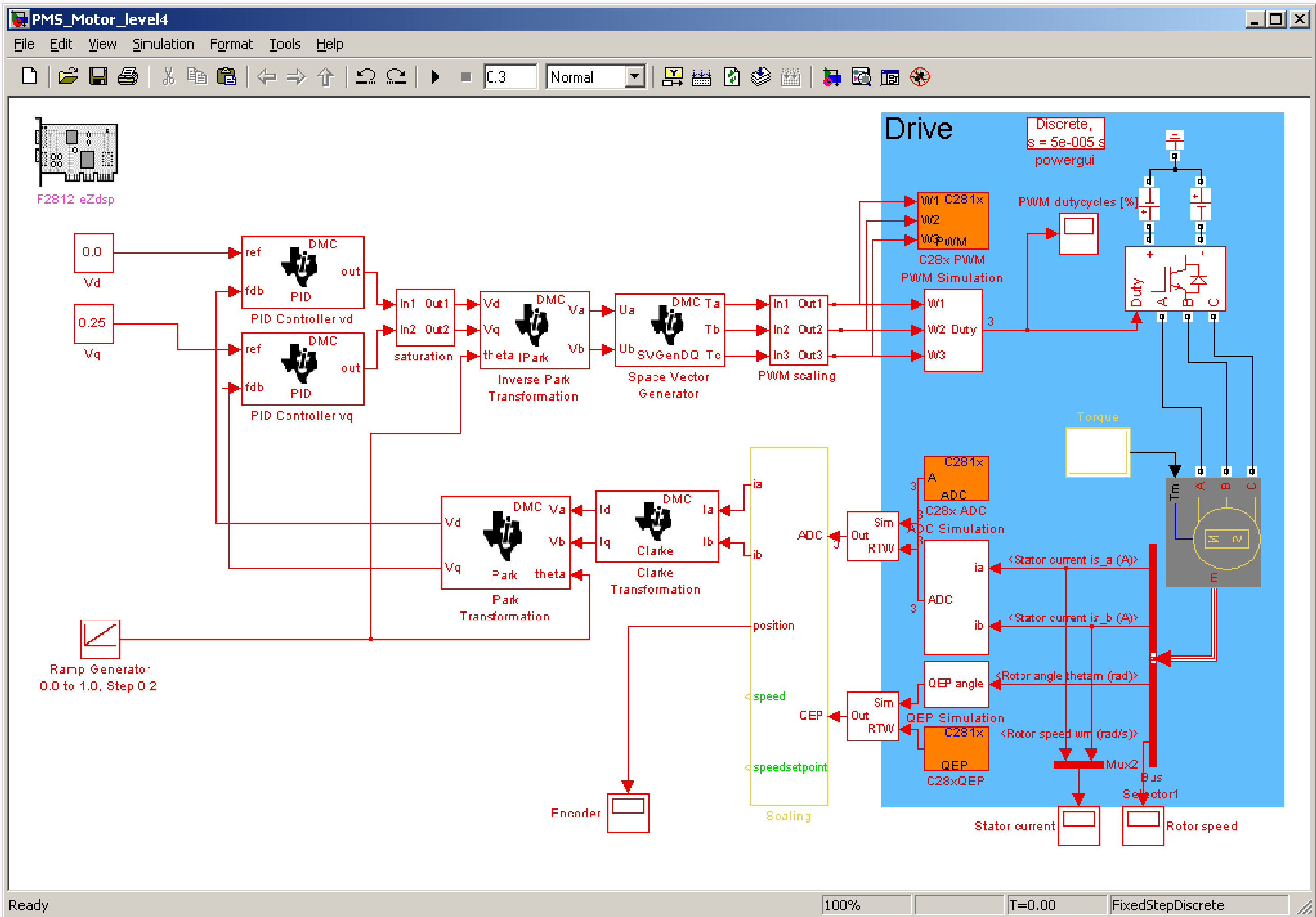
Tuning of dq-axis current closed loops - Simulation



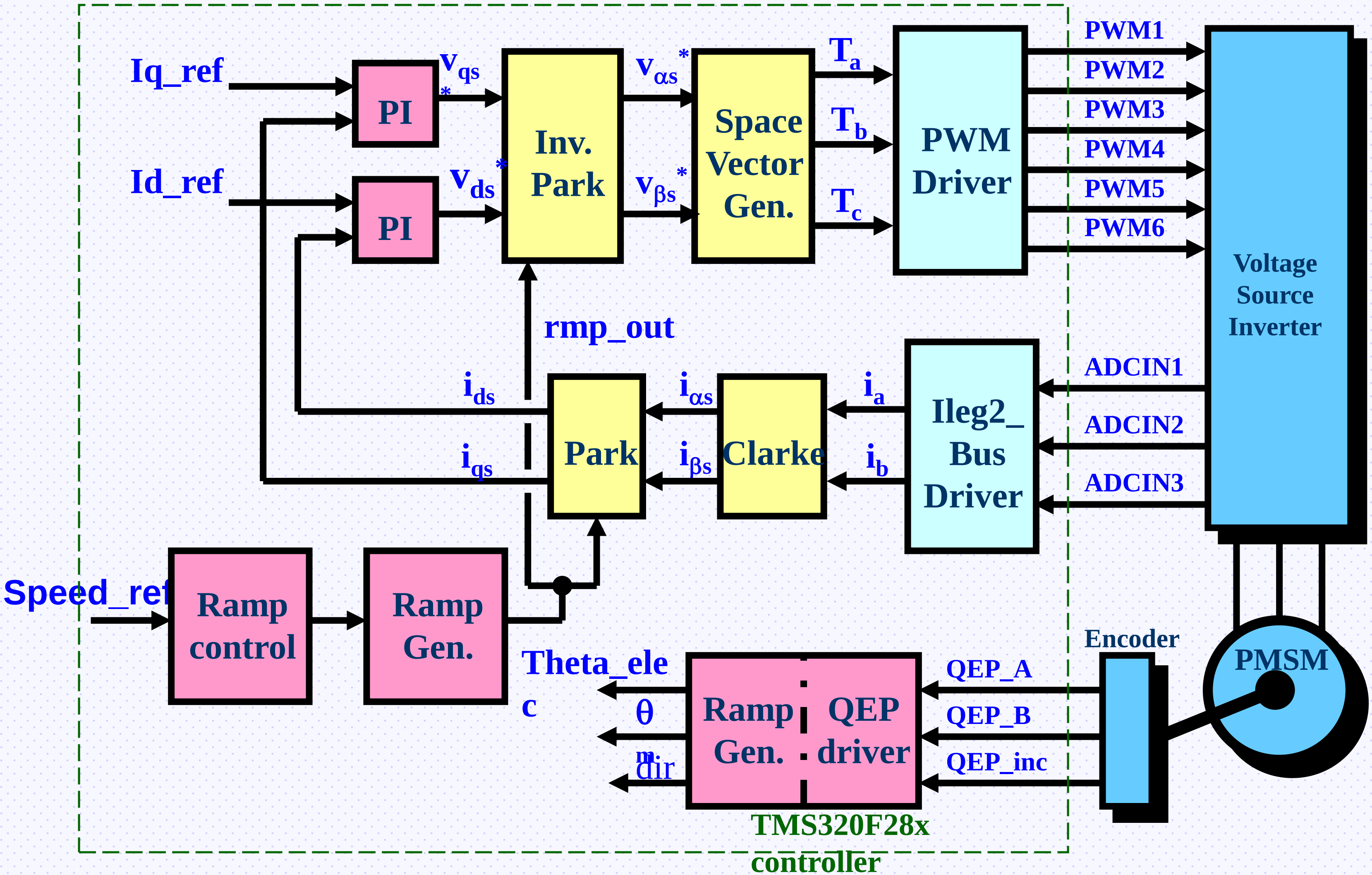
Tuning of dq-axis current closed loops – Real Time



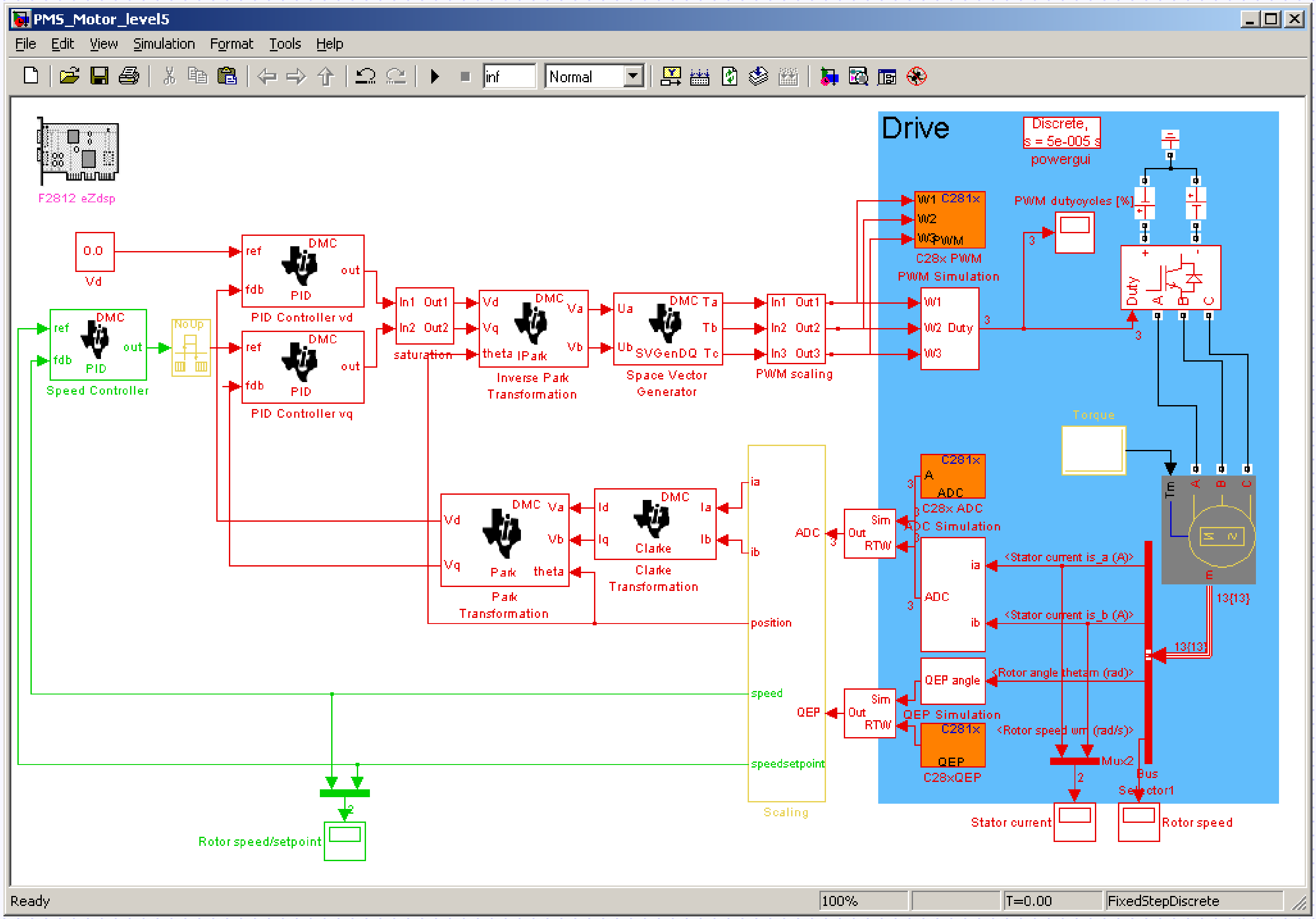
Encoder verification - Simulation



Encoder verification – Real Time



Speed closed loop - Simulation



Speed closed loop – Real Time