Variable frequency converter drives for asynchronous machines

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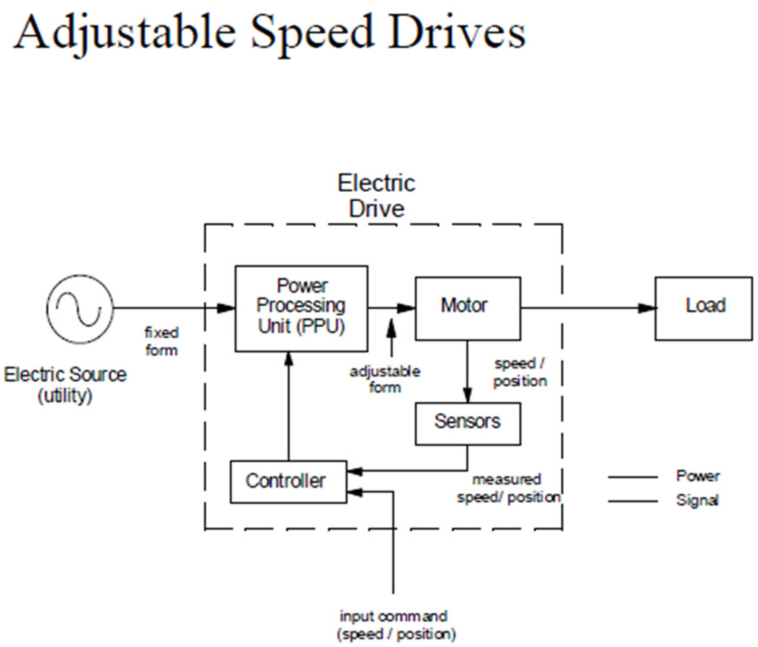
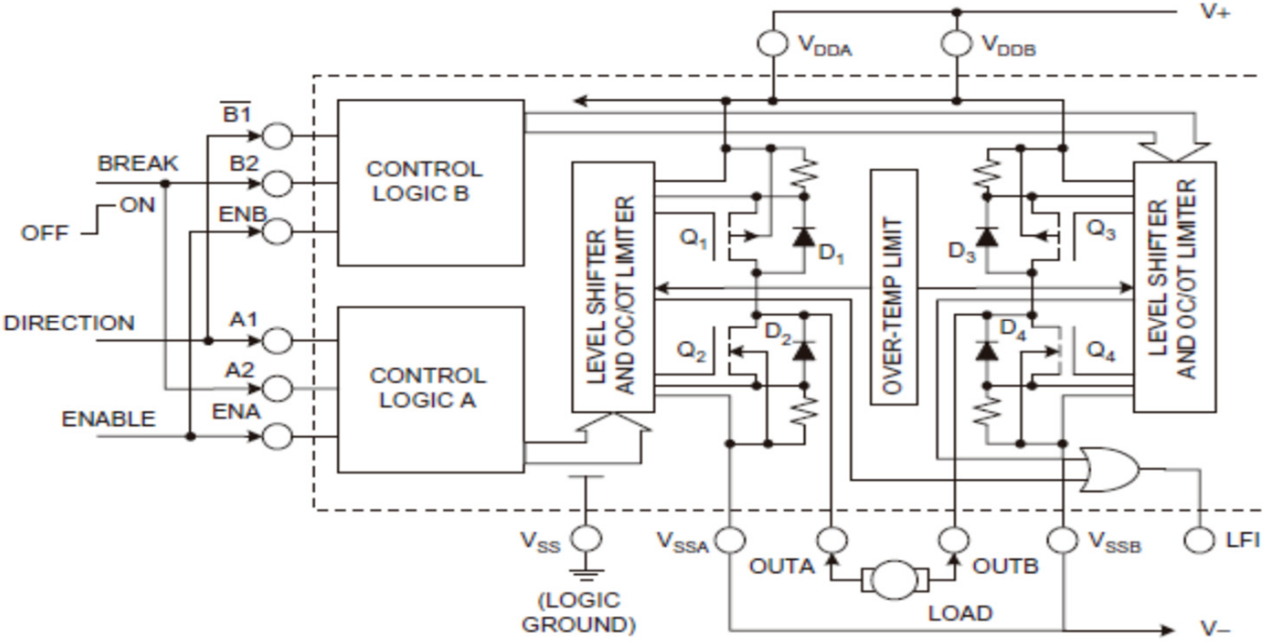
The need for speed control

Speed control is necessary everywhere!

- Industrial processes (control and energy saving)
- Transportations (public means, elevators/escalators)
- Everyday life (HVAC and other appliances control and energy savings)



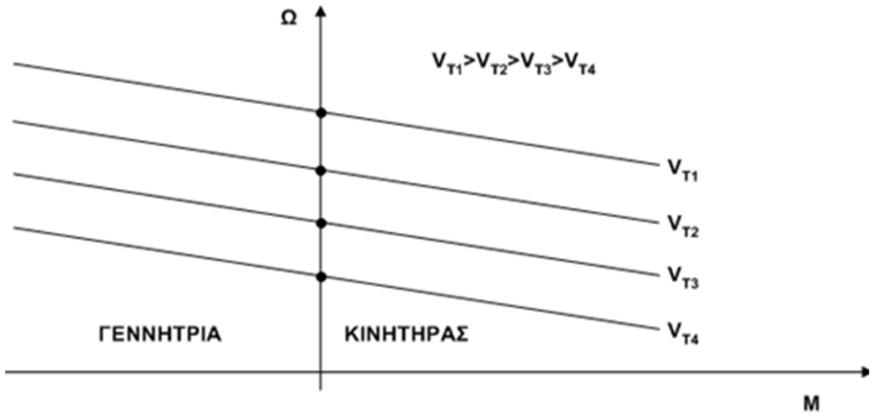
Adjustable speed drive block diagram



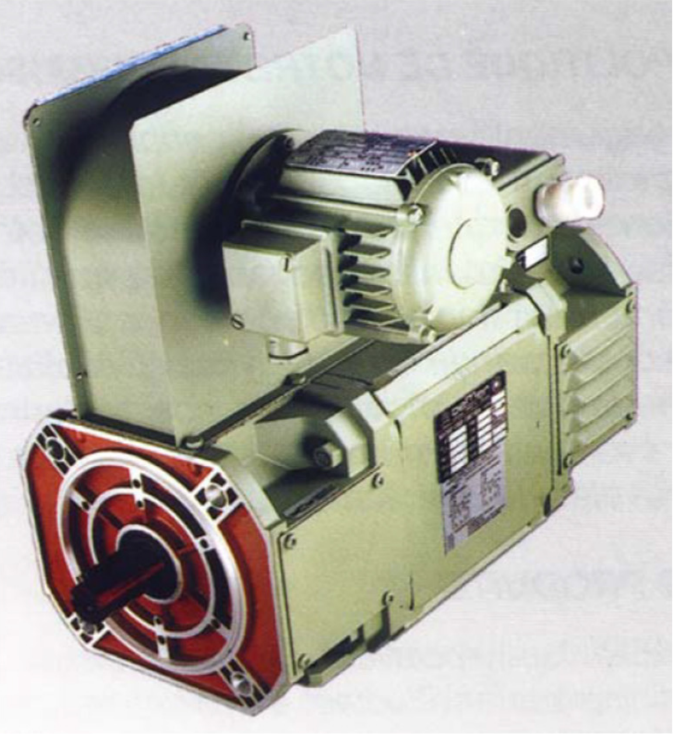
Harris HIP 4011 dc motor drive

Everyone loves dc machines!

- Separate excitation current – natural direct field control
- Linear machines, i.e. rotor voltage regulates rotor speed
- Heavy constructions, high inertia, low efficiency, maintenance costs



Speed control diagrams under constant excitation (separate excitation DC machine)



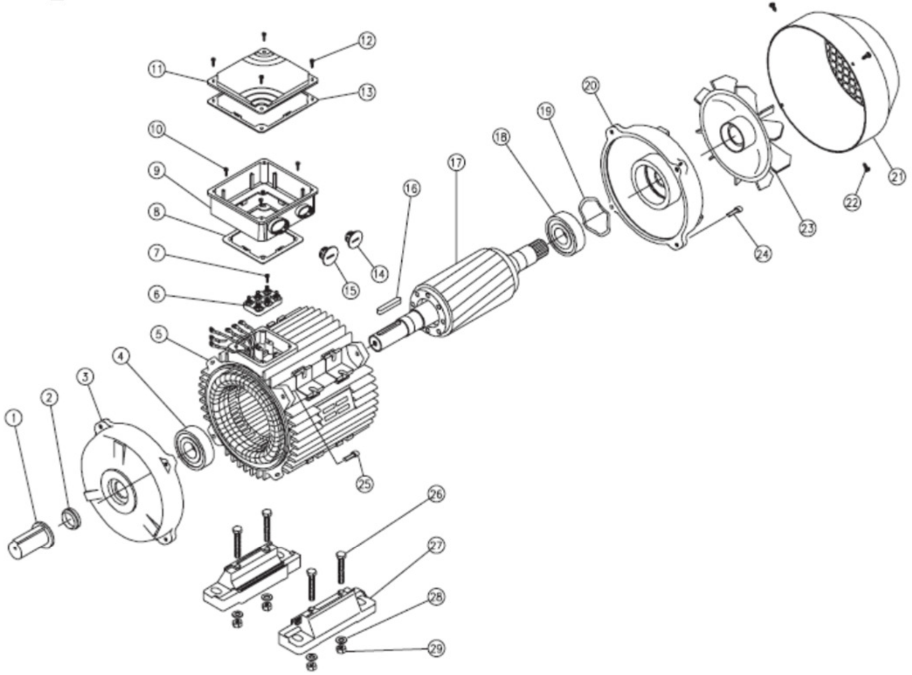
DC Machine (OEMER)

Asynchronous machines improve use of energy

Hereby we refer to 3-phase IMs

- Robust construction, especially the squirrel-cage one
- Lower weight and inertia, comparing to DC Machines
- More efficient, comparing to DC Machines
- Suitable for very high-speeds (e.g. up to tens of thousands of rpm)
- Suitable for harsh operational environments
- Low maintenance costs

How about speed control facilitation???



Part description

1	Shaft protection
2	Dust seal drive end
3	Endshield drive end
4	Bearing drive end
5	Stator frame
6	Terminal board
7	Fixing screw terminal board
8	Gasket terminal box
9	Terminal box
10	Fixing screw terminal box
11	Terminal box lid
12	Fixing screw terminal box lid
13	Gasket terminal box lid
14	Blank gland plug
15	Blank gland plug
16	Key
17	Rotor complete
18	Bearing non-drive end
19	Pre-load washer
20	Endshield non-drive end
21	Fan cover
22	Fixing screw fan cover
23	Fan
24	Fixing bolt endshield non-drive end
25	Fixing bolt endshield drive end
26	Fixing bolt motor feet
27	Motor feet
28	Fixing washer motor feet
29	Fixing nut motor feet

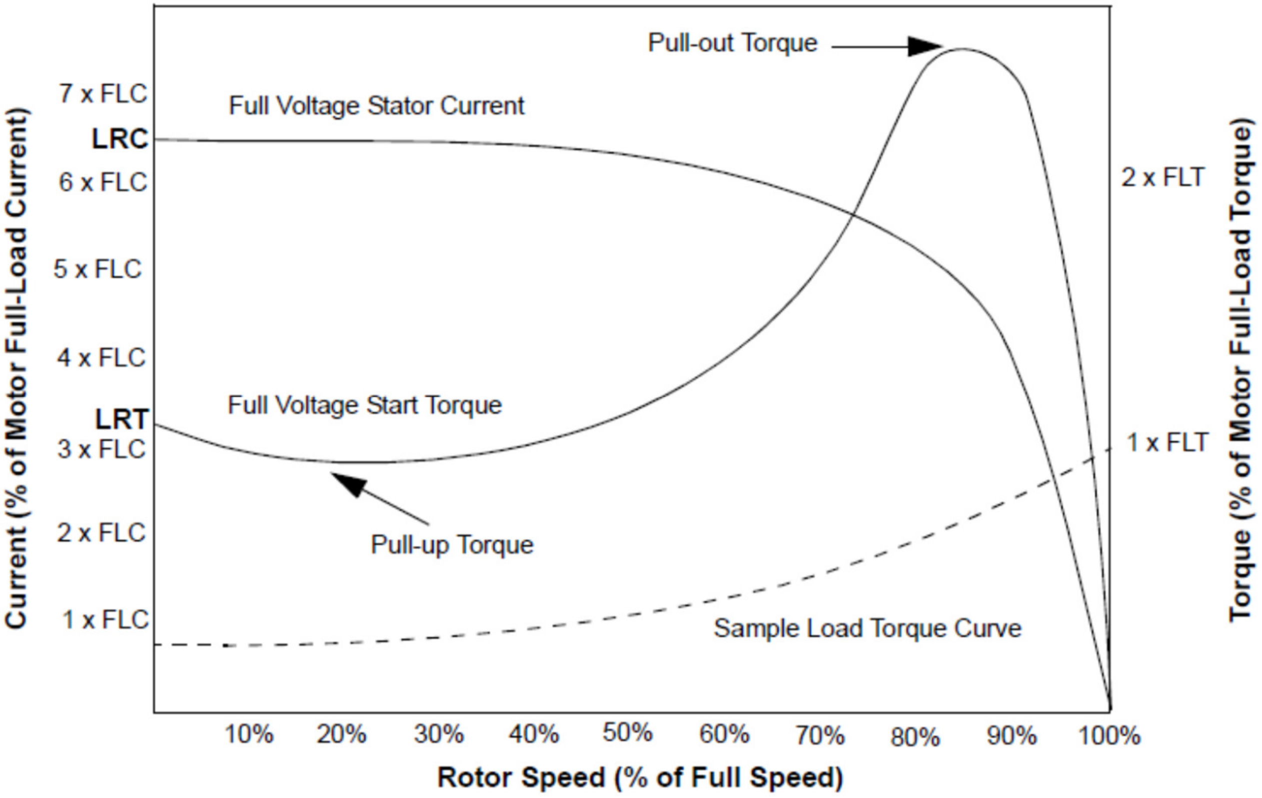
Three-Phase Asynchronous Machine Spare Parts (AEG)

Asynchronous machine torque curves

Highly non-linear behavior

- Single-speed machine: operation close to the synchronous speed, minus slip!
- Stator voltage regulation does not contribute to speed control: only suitable for machine soft start (starting current regulation)
- Excitation and rotor currents are mixed together – difficult to implement torque control

How about speed control facilitation???

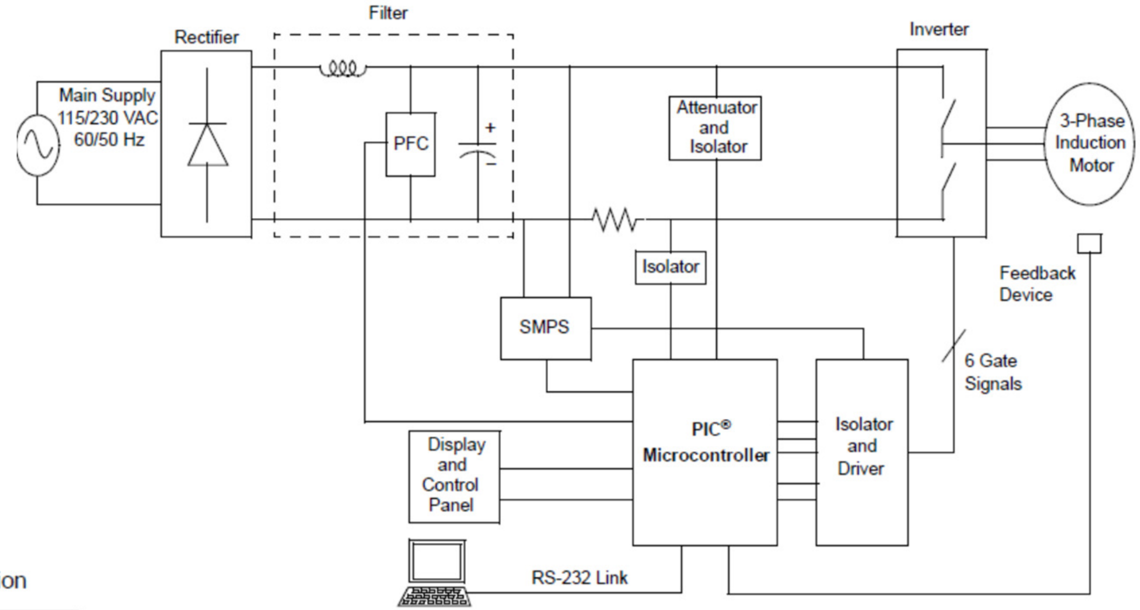


Three-Phase Asynchronous Machine Typical Torque-Speed Curve (MICROCHIP, AN887)

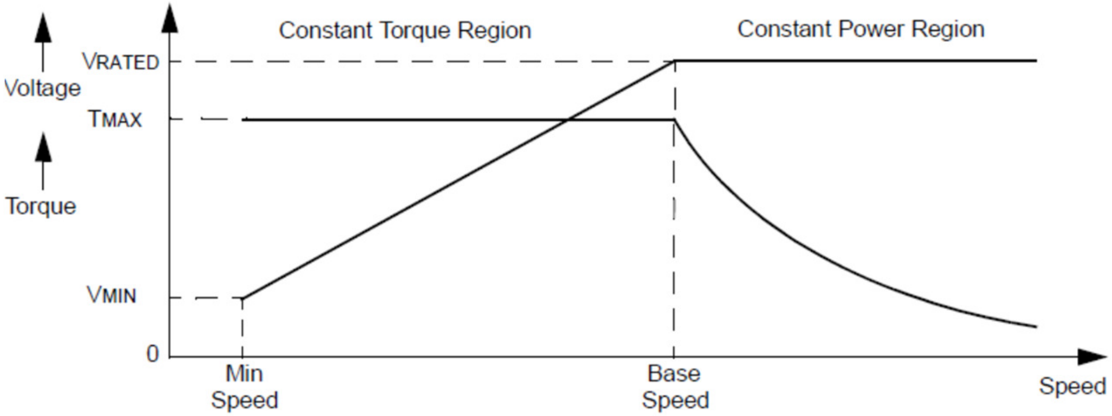
Asynchronous machine Scalar-based control

- **Scalar methods → Machine equivalent circuit in a <u>steady-state</u>!**

- **Proper operation in applications in which fast changes in the machine torque, speed, flux, etc. are not required!**



Inverter block diagram (MICROCHIP, AN887)



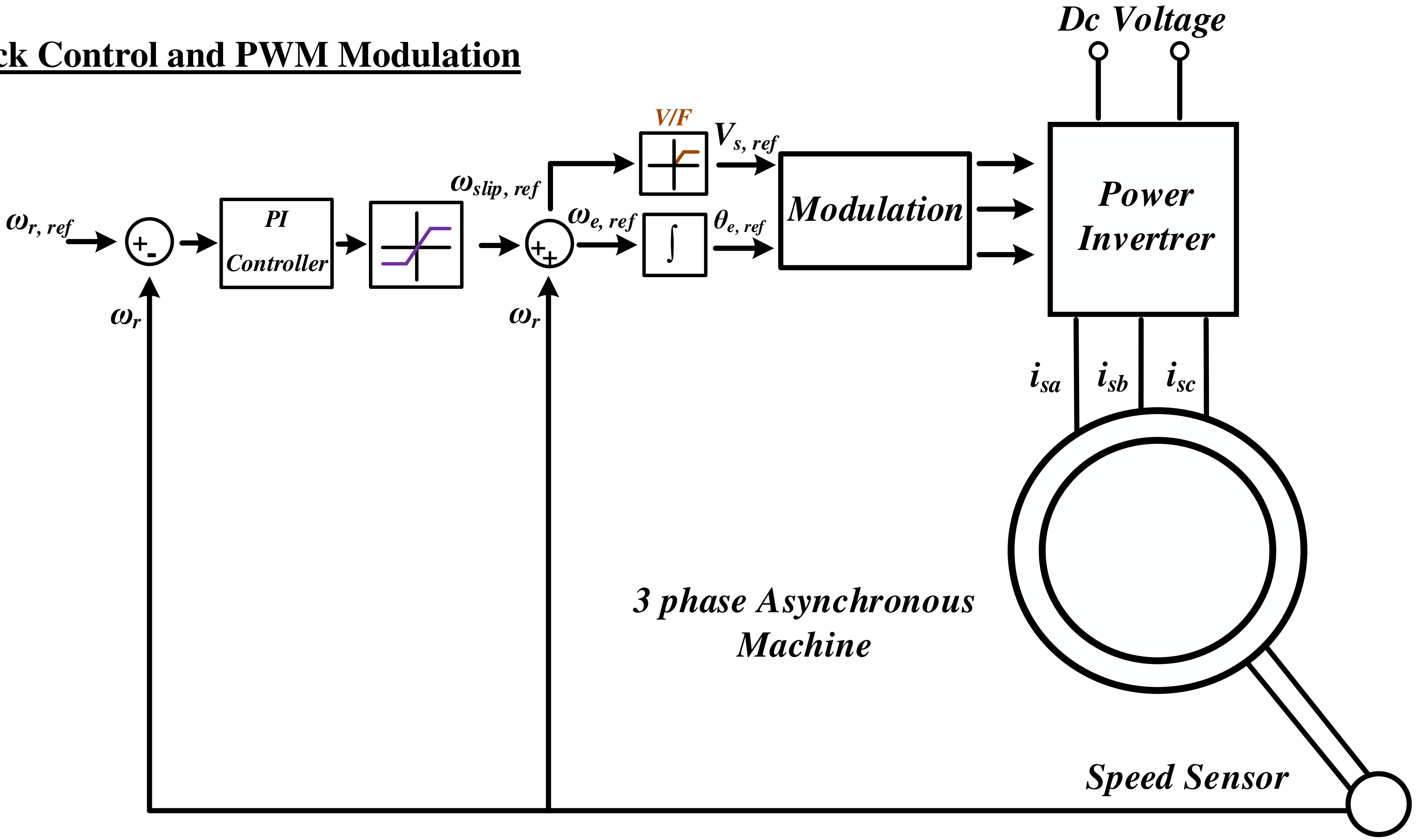
V-f Curve (MICROCHIP, AN887)

Open-loop V-F control

- Simple and efficient control technique for regular applications
- Variable speed is obtained by regulating synchronous speed (i.e. stator frequency)
- Stator voltage is kept proportional to frequency setpoint, providing the so-called Constant Torque Region (Flux remains almost constant)
- For speeds higher than the nominal one, the machine operates in constant power region by keeping stator voltage to its nominal value
- Imprecise control of rotor speed due to slip
- Absence of feedback lead to incorrect estimation of instantaneous machine quantities (i.e. due to drop in the stator resistance, variations of the DC link voltage feeding the inverter, etc.)

Closed-loop Scalar control 1/5

1) V/F with Speed Feedback Control and PWM Modulation



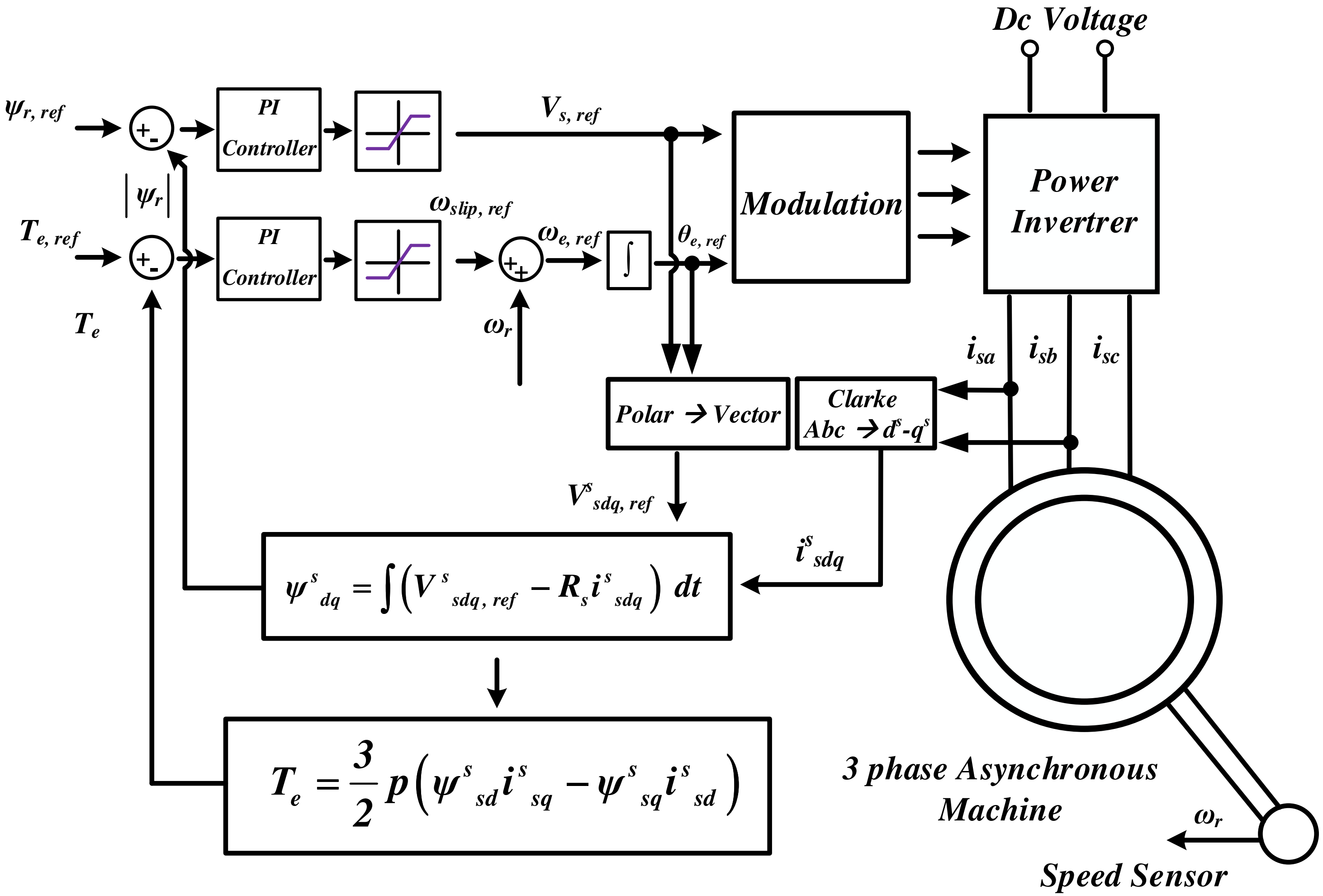
(Source: Control Strategies for Induction Motors in Railway Traction Applications, Review, Energies, MDPI, 2020)

Closed-loop Scalar control 2/5

2) Flux & Torque Control with PWM Modulation

Flux and Torque control loops instead of the V/F ratio, to obtain the desired stator voltage magnitude and angle.

- ✓ Precise control of the machine’s operating point in a steady-state!
- \- Coupling between flux and torque is not considered for the control design, so a very slow dynamic response is required to avoid over currents and torque pulsations!



(Source: Control Strategies for Induction Motors in Railway Traction Applications, Review, Energies, MDPI, 2020)

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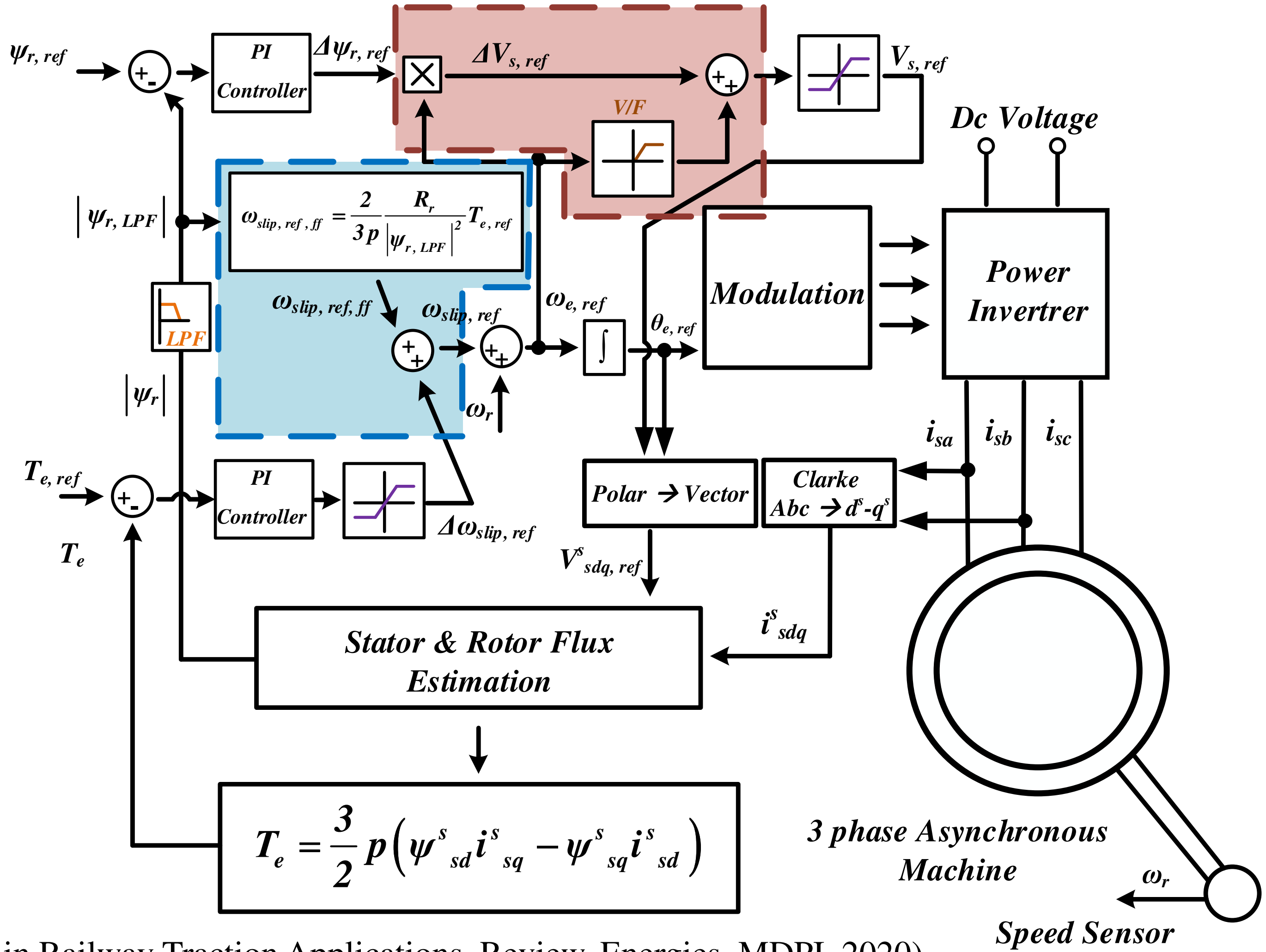
Closed-loop Scalar control 3/5

3) V/F Flux & Torque Control with Feedback & Feedforward

- Two Feedforward terms to enhance the **dynamic response** of the closed-loop V/F control!
- The dynamic response relies on the **accuracy** of the feedforward terms!

✓ **Torque regulator** → The desired torque is followed with no error!

✓ Easy operation in the field-weakening region.



(Source: Control Strategies for Induction Motors in Railway Traction Applications, Review, Energies, MDPI, 2020)

Slide 10

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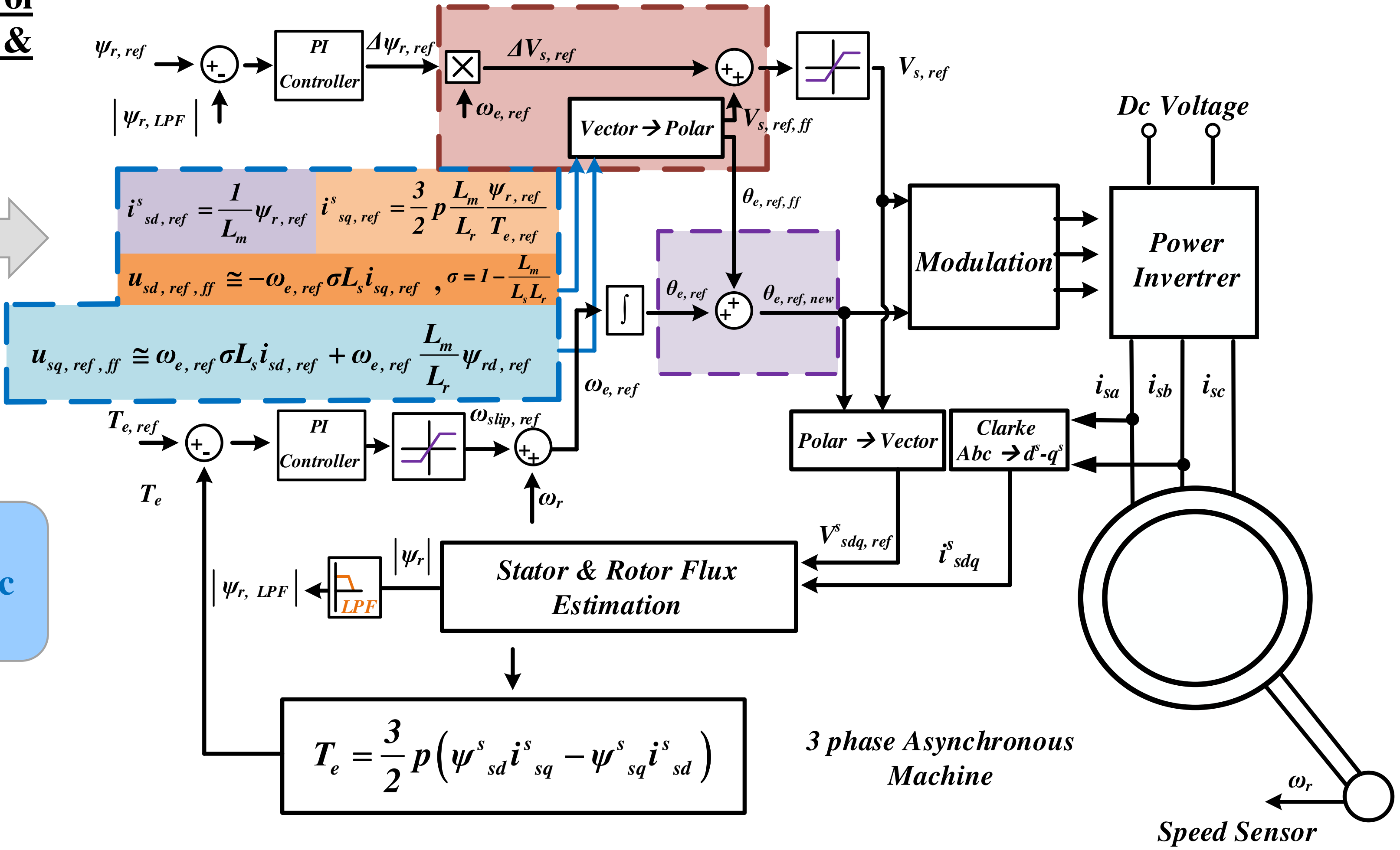
Closed-loop Scalar control 4/5

4) Flux & Torque Control with Feedback & Feedforward

d-q Model Rotor Flux Reference Frame



Control loops based on dynamic machine model

(Source: Control Strategies for Induction Motors in Railway Traction Applications, Review, Energies, MDPI, 2020)

Closed-loop Scalar control 5/5

Flux & Torque Control with Feedback & Feedforward, based on the machine d-q model in the rotor flux reference frame

- Mismatch between model and actual parameters → Errors in the feedforward voltages!

- Derivatives are problematic in practice.

✓ Reduced effect of R_s when the control is intended to operate at a high speed!

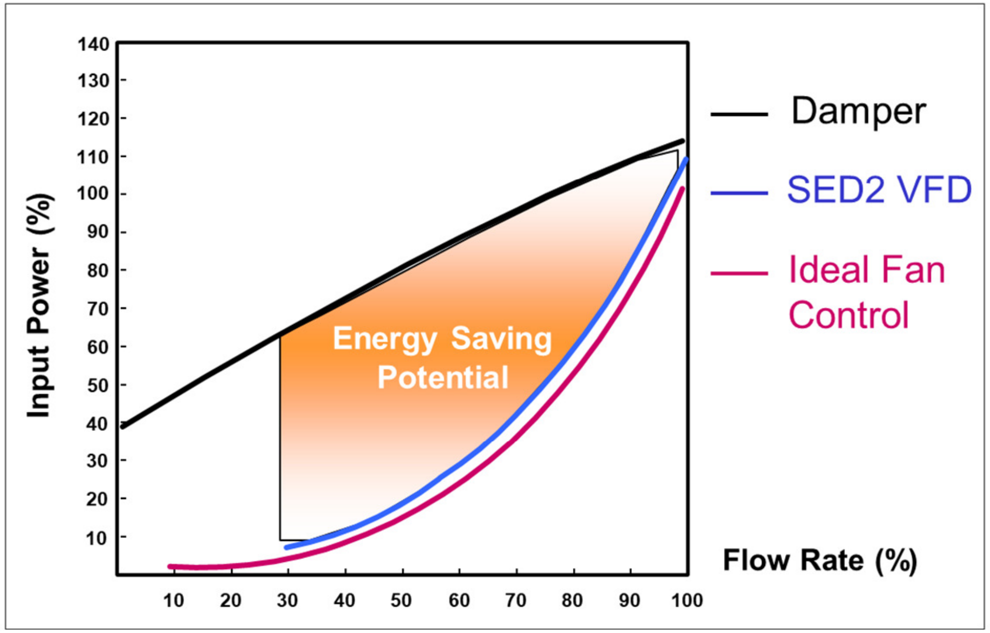
(Source: Control Strategies for Induction Motors in Railway Traction Applications, Review, Energies, MDPI, 2020)

Industrial V-F drive example

Siemens SED2 VFD Advantages

- Low harmonics design
- Small enclosure size
- Many standard features
- Reduces operating cost
- Low power losses/high efficiency
- Minimal effect on customer power
- Wide power range – from ½ to 125 HP

Potential energy savings using a VFD vs. modulating flow with a damper

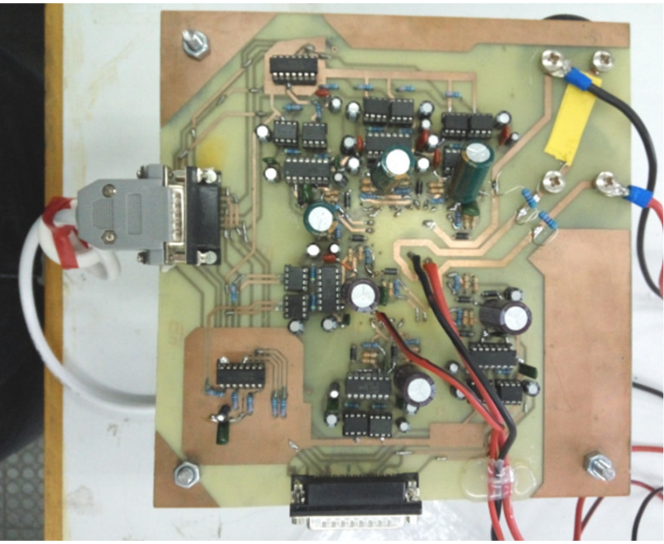


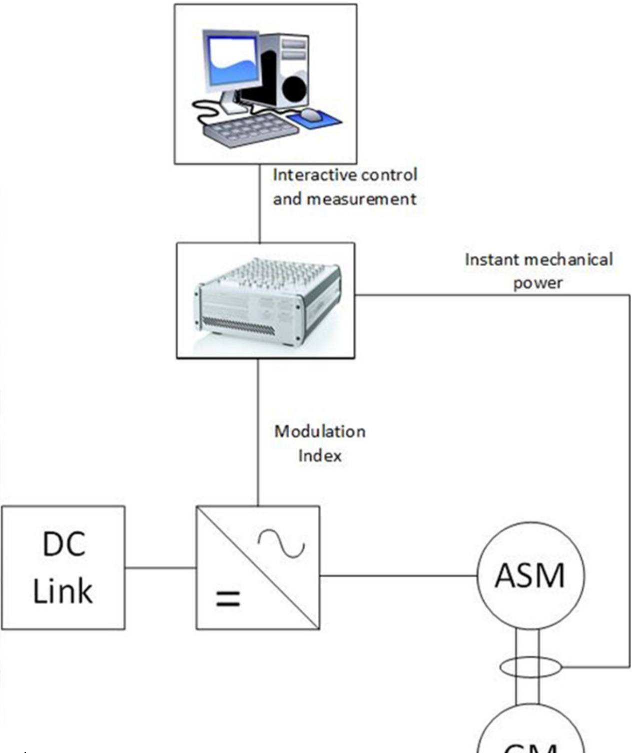
V-f control does not contribute to the separate regulation of the excitation and the rotor currents

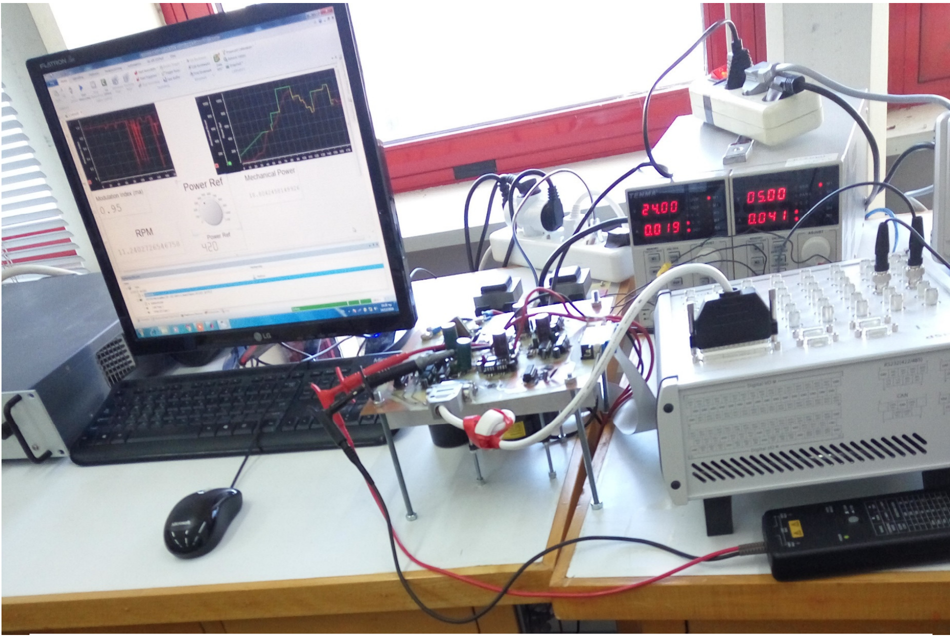
Need for torque control, especially in transportation systems and high-power industrial processes

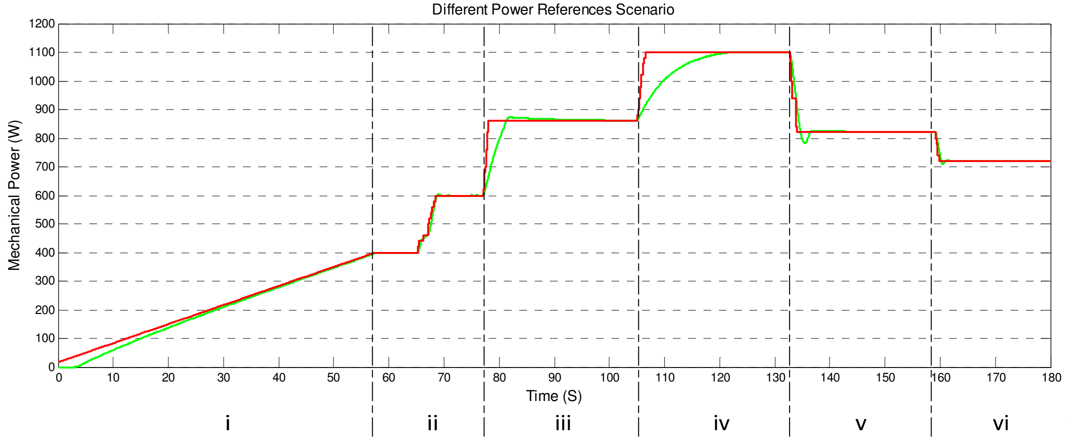
Can we control the asynchronous machine like a separate-excited DC machine???

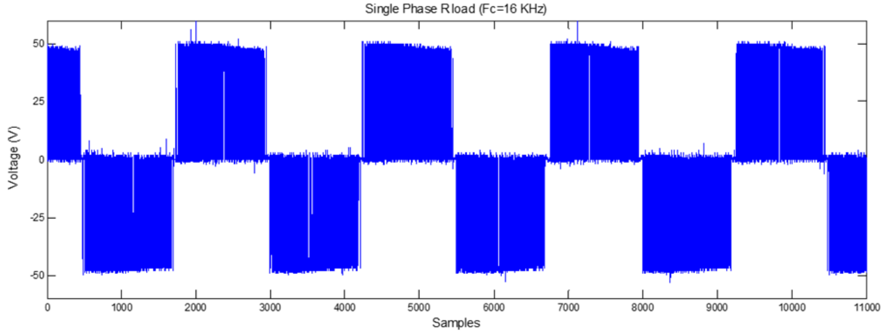
Experimental 3-L inverter example

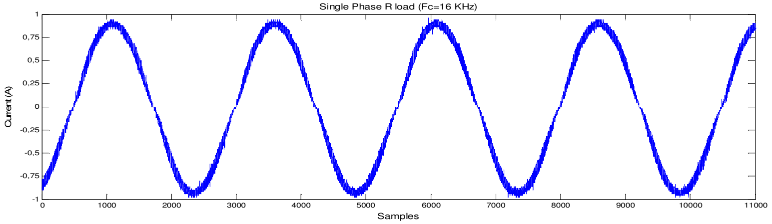






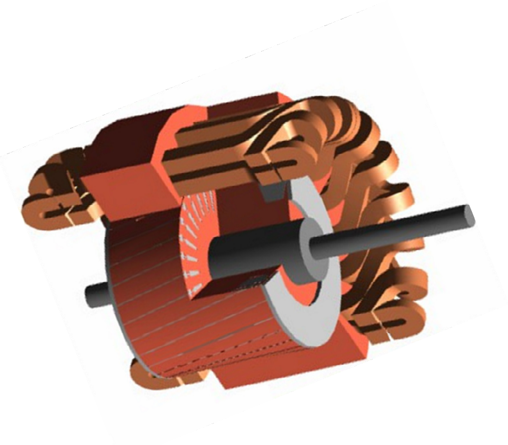






DSPACE control – 97.4% efficiency (A. Babouras, Diploma Thesis, DUTH, 2016

Vector Control of Asynchronous Machines



Vector Control pros:

- ***Independent torque and field (flux) control (via separate stator current components)***
- ***Superior system dynamic response***
- ***Satisfactory torque control at low speed (including zero speed)***

Vector Control cons:

- ***Complicated control, based on rotating vector coordinate transformation system***
- ***Hardware computational burden***

Vector control target:

Independent torque current (I_A) and magnetic flux (ψ_F) control, as in separate excitation DC machines

E/M torque equation: $T_e = c\ \psi_F\ I_A = c\ I_F\ I_A$

Independence of armature voltage (V_A) and excitation voltage (V_F) supply circuits, so I_F , I_A independence

So, E/M torque control via separate current components!!

DC machines E/M torque control pros over AC machines E/M torque control :

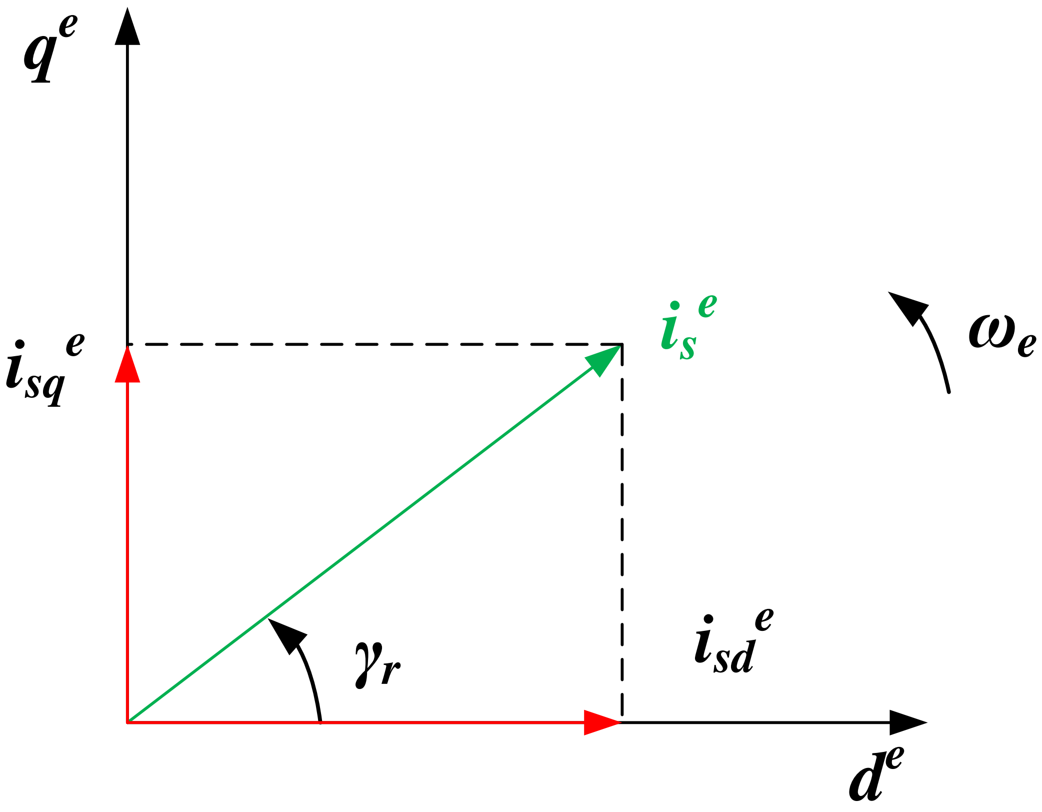
- *Simpler implementation,* I_F, I_A *(time invariant, DC quantities)*
- *Collector-brushes system obtains* 90^0 *constant angle between* I_A *and* ψ_F

Vector Control Basics

- ***Amplitude and phase angle of stator current vector (I_s)***
- ***Two separate components of (I_s), field current (I_F) and torque current (I_A)***

How??

Transformation of AC stator quantities into time invariant ones (that is DC!!!)



- *d-q 2-phase coordinate system*
- *Rotates with synchronous speed* ω_e
- i_{sd}^e *proportional to Flux linkage* (ψ_r), *so* $i_{sd}^e \sim I_F$
- $i_{sq}^e \sim I_A$
- $T_e = c\, i_{sd}^e\, i_{sq}^e = c\, I_F\, I_A$

So, E/M Torque control

from separate stator current components!!

Asynchronous machines vector control Pros over conservative control of DC machines:

- ***Better torque control dynamic response (in terms of speed)***
- ***AC machines have lower electric time constant (τ_e)***
- ***AC machines have lower Inertia***

Cons

- ***More difficult implementation***
- ***Higher cost***

Vector control coordinate systems

- ***Transformation of i_{sA}, i_{sB}, i_{sC} into i_{sd}^{s} , i_{sd}^{s} (stator stationary reference frame)***

- ***Clarke transformation (a-b-c, time variant reference frame into d^s-q^s, space variant reference frame)***

$$\begin{bmatrix} i_{sd}^{s} \\ i_{sq}^{s} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{sA} \\ i_{sB} \\ i_{sC} \end{bmatrix}$$

- ***Both reference frames are stationary (in time and space, respectively), resulting in rotating machine quantities!***

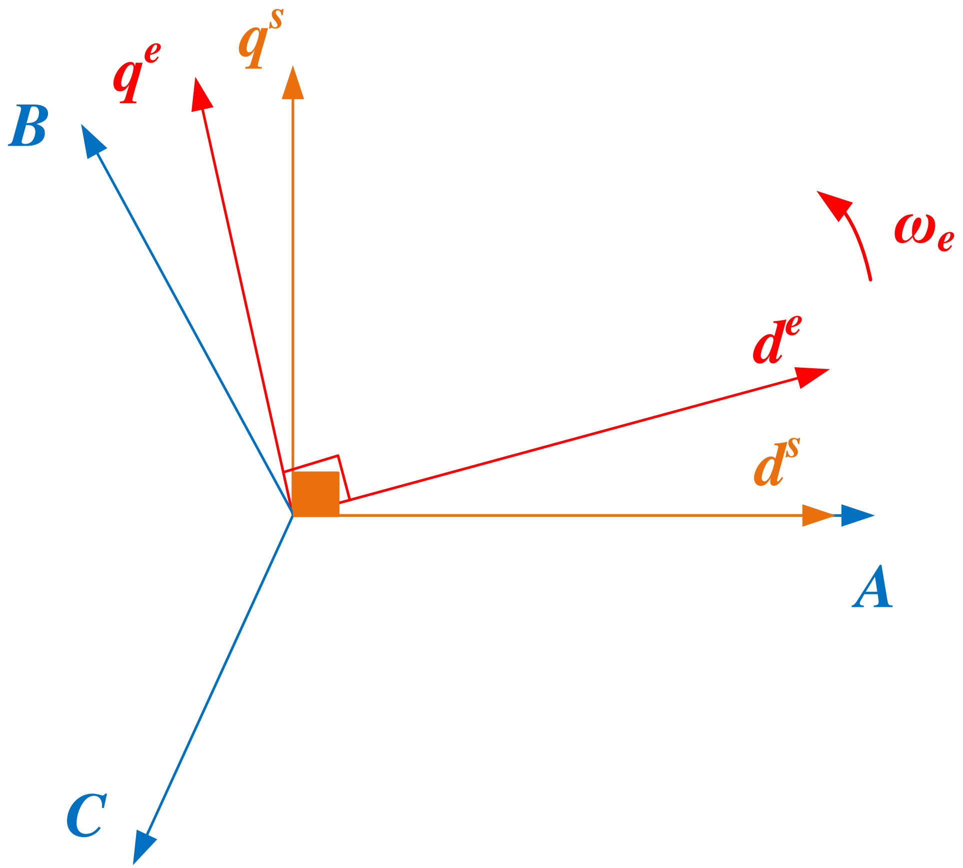
Vector control coordinate systems

- ***Transformation of i_{sd}^{s} , i_{sq}^{s} into i_{sd}^{e} , i_{sq}^{e} (synchronously rotating reference frame, ω_e)***

- ***Park Transformation (a-b-c into d^e-q^e or d^s-q^s into d^e-q^e)***

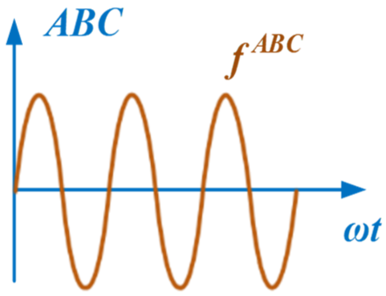
$$\begin{bmatrix} i_{sd}^{e} \\ i_{sq}^{e} \end{bmatrix} = \begin{bmatrix} cos\omega_e t & sin\omega_e t \\ -sin\omega_e t & cos\omega_e t \end{bmatrix} \begin{bmatrix} i_{sd}^{s} \\ i_{sq}^{s} \end{bmatrix}$$

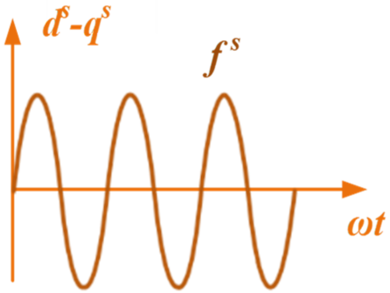
Clarke-Park transformed vectors

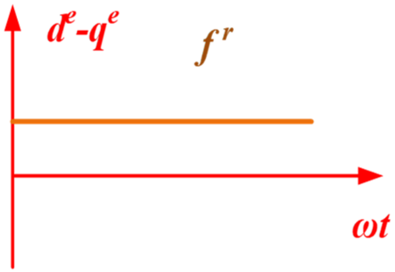


- *A-B-C : stationary axes, rotating vectors (time variant reference frame)*
- *d^s-q^s : stationary axes, rotating vectors (time variant reference frame)*
- *d^e-q^e : rotating axes, static space vectors!*

Clarke-Park in time domain

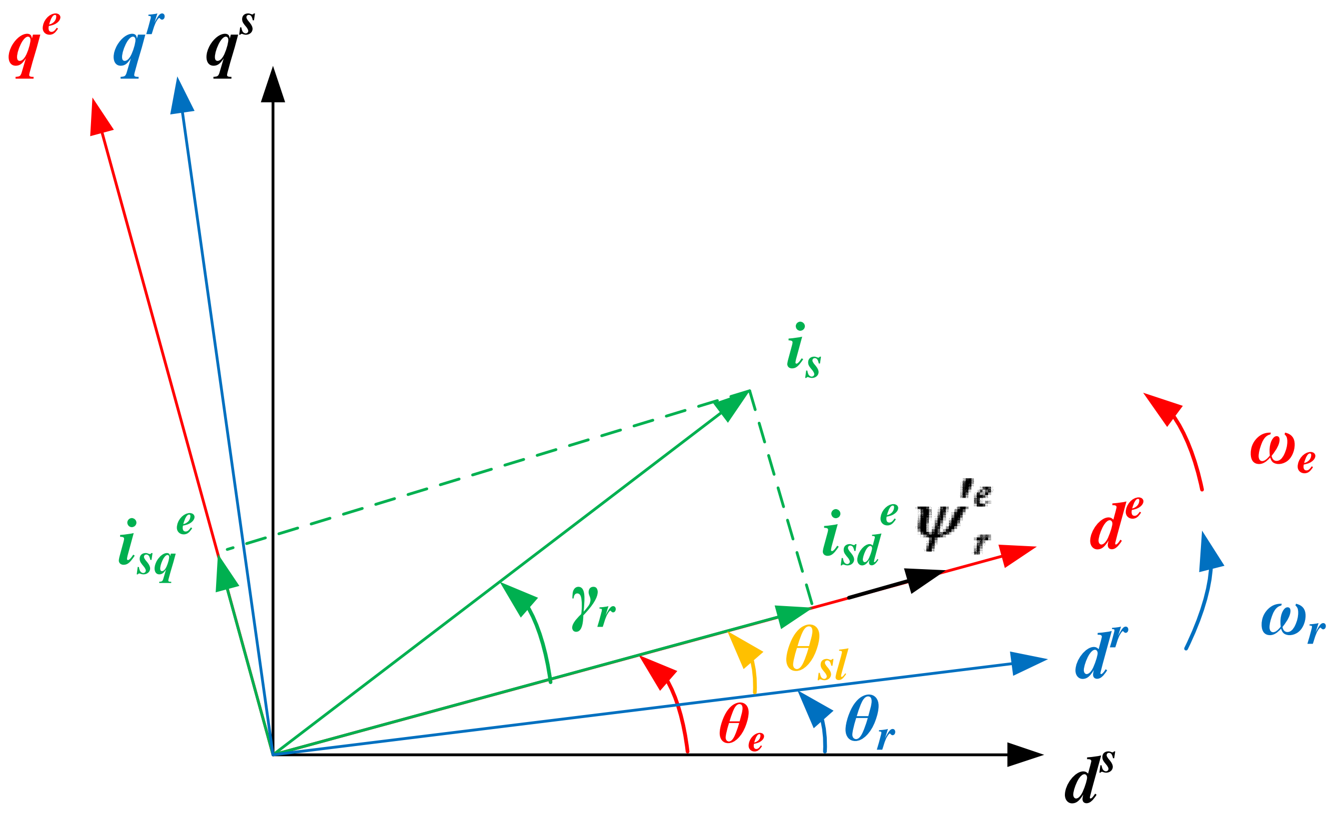






- ***A-B-C : stationary axes, rotating vectors (time variant reference frame)***
- ***d^s-q^s : stationary axes, rotating vectors (time variant reference frame)***
- ***d^e-q^e : rotating axes, static space vectors!***

Clarke-Park in space domain



Clark – Park Transformations of sinusoidal quantities (N. Apostolidou MSc Thesis, DUTH, 2018)

- i_s ***stator current***
- $\psi'^e_r = \psi'^e_{rd}$ ***rotor flux linkage (stator oriented)***
- ω_e ***synchronous speed***
- ω_r ***rotor speed***
- θ_e ***rotating frame – stator angle***
- θ_r ***rotor – stator angle***
- θ_{sl} ***slip angle***
- $\gamma_r = \tan^{-1}(i_{sq}^e / i_{sd}^e)$ ***phase angle in rotating reference frame***

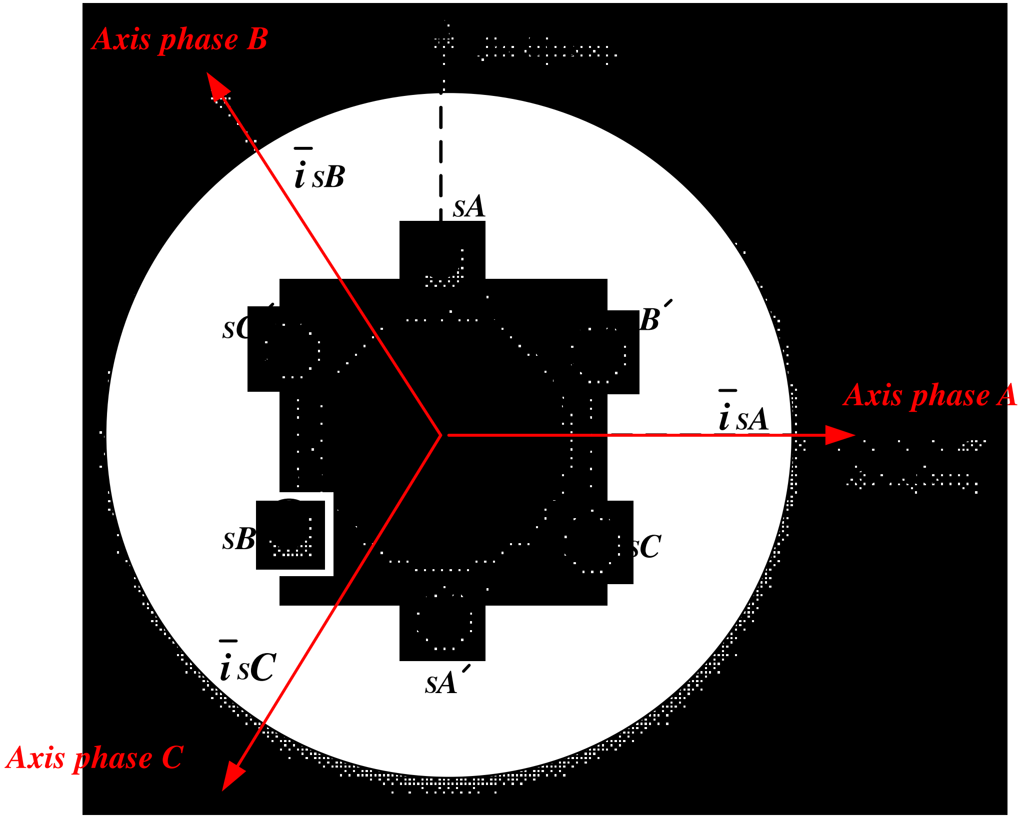
Conclusions:

While i_s^s rotates with respect to stationary d^s-q^s frame,

i_s^e, ψ'^e_r are stationary with respect to rotating d^e-q^e (both rotate with ω_e), so time invariant quantities (that is DC quantities!) → Easier to be used as control variables!!

NOTE : Direct transformation from ABC to d^e-q^e is possible (that is skipping Clarke)

Implementation of Space Vectors in AC Machine



Assumptions:

- *3 Phases, 2 poles*
- *Concentrated windings*
- *Symmetrical phase windings*
- *Reference magnetic axis sA*

Instantaneous Phase Currents

$$i_{sA}(t) = \hat{I}_s cos(\omega_e t + \varphi_s) = \frac{\hat{I}_s}{2}\left[e^{j(\omega_e t+\varphi_s)} + e^{-j(\omega_e t+\varphi_s)}\right]$$

$$i_{sB}(t) = \hat{I}_s cos(\omega_e t + \varphi_s - \frac{2\pi}{3}) = \frac{\hat{I}_s}{2}\left[e^{j\left(\omega_e t+\varphi_s-\frac{2\pi}{3}\right)} + e^{-j\left(\omega_e t+\varphi_s-\frac{2\pi}{3}\right)}\right]$$

$$i_{sC}(t) = \hat{I}_s cos(\omega_e t + \varphi_s - \frac{4\pi}{3}) = \frac{\hat{I}_s}{2}\left[e^{j\left(\omega_e t+\varphi_s-\frac{4\pi}{3}\right)} + e^{-j\left(\omega_e t+\varphi_s-\frac{4\pi}{3}\right)}\right]$$

Phase currents space vectors, s : stationary stator reference frame

$$\bar{\imath}_{sA} = i_{sA}(t)e^{j0}$$

$$\bar{\imath}_{sA} + \bar{\imath}_{sB} + \bar{\imath}_{sC} = \frac{3}{2}\,\bar{\imath}_s^s$$

$$\bar{\imath}_{sB} = i_{sB}(t)e^{j\frac{2\pi}{3}} \quad \Longrightarrow \quad \bar{\imath}_s^s = \frac{2}{3}\left[1 i_{sA}(t) + \overline{a} i_{sB}(t) + \overline{a}^2 i_{sC}(t)\right],\ \overline{\alpha} = e^{j\frac{2\pi}{3}}$$

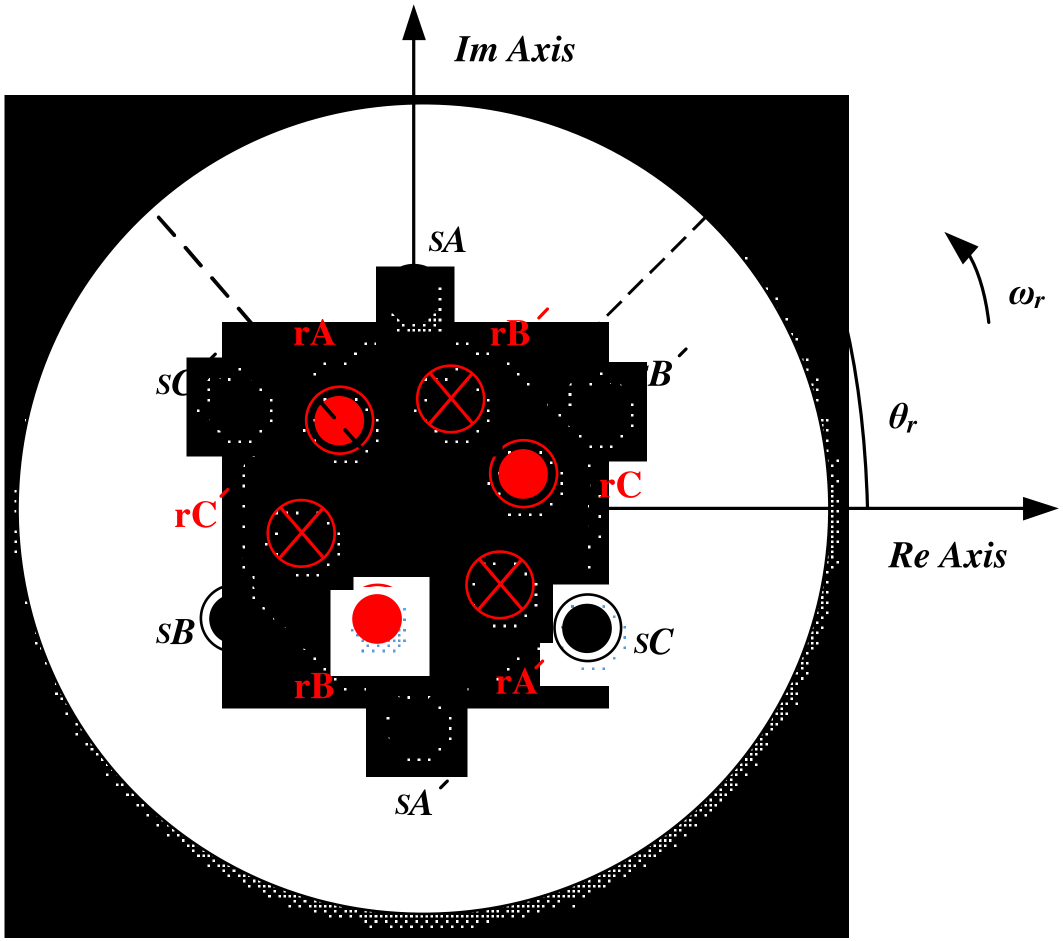
$$\bar{\imath}_{sC} = i_{sC}(t)e^{j\frac{4\pi}{3}}$$

$$\bar{\imath}_s^s = \hat{I}_s e^{j(\omega_e t + \varphi_s)}$$

<u>Notable</u>:

- ***Space vector $\bar{i}_s^s$ rotates with ω_e***
- ***Time vector amplitude equals space vector amplitude ($\hat{I}_s$), so torque equations the same in time and space domain συνεπώς ίδιες***
- ***Machine Electrical and Magnetic quantities presented as space rotating vectors***

Distributed stator and rotor windings



r : rotor reference frame (stationary with respect to rotor)

$$\bar{i}_r^r = \frac{2}{3}\left[1 i_{rA}(t) + \bar{a} i_{rB}(t) + \bar{a}^2 i_{rC}(t)\right]$$

BUT

Rotor rotates!!

So, transformation from rotor reference frame to stator reference frame inevitable!

θ_r ***: rotor speed angle***

ω_r***: rotor speed***

Rotor vectors into Stator reference frame

- ***Rotor current vector:*** $i_r^{\prime} = i_r/a$, $a = N_{seq}/N_{req}$ ***, a transformer ratio***

- ***Stator flux linkage :*** $\bar{\psi}_s^s = L_s \bar{i}_s^s + L_m \bar{i'}_r^r e^{j\theta_r}$

, where $\bar{i'}_r^s = \bar{i'}_r^r e^{j\theta_r}$ ***rotor current into stator reference frame***

Subsequently,

Rotor space vectors multiplied by $e^{j\theta r}$ ***refer to stator reference frame***

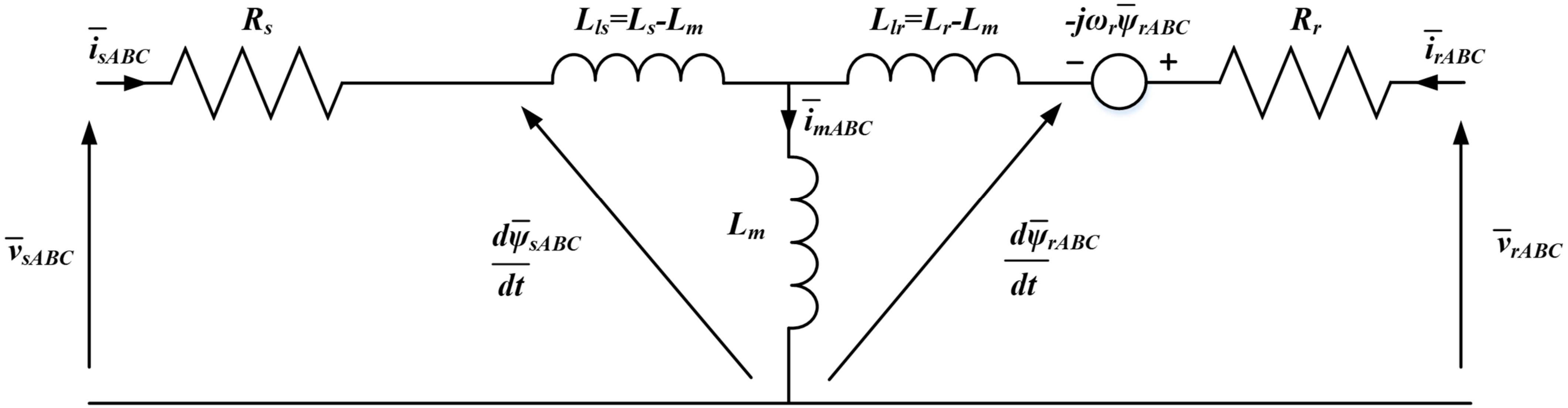
while

Stator space vectors multiplied by $e^{-j\theta r}$ ***refer to rotor reference frame!***

i.e. $\bar{\imath}_s^r = \bar{\imath}_s^s e^{-j\theta_r}$

Asynchronous Machine dynamic electrical equivalent circuits

- ***3-phase, stationary reference frame ABC:***



Equations:

Rotor quantities into stator reference frame:

$$u_{sABC} = R_s i_{sABC} + \frac{d\psi_{sABC}}{dt}$$

$$u'_{rABC} = R'_r i'_{rABC} + \frac{d\psi'_{rABC}}{dt}$$

where $-j\overline{\omega_r}\psi_{rABC}$ *: rotational induced voltage*

$$i'_{rA} = \frac{i_{rA}}{\alpha}$$

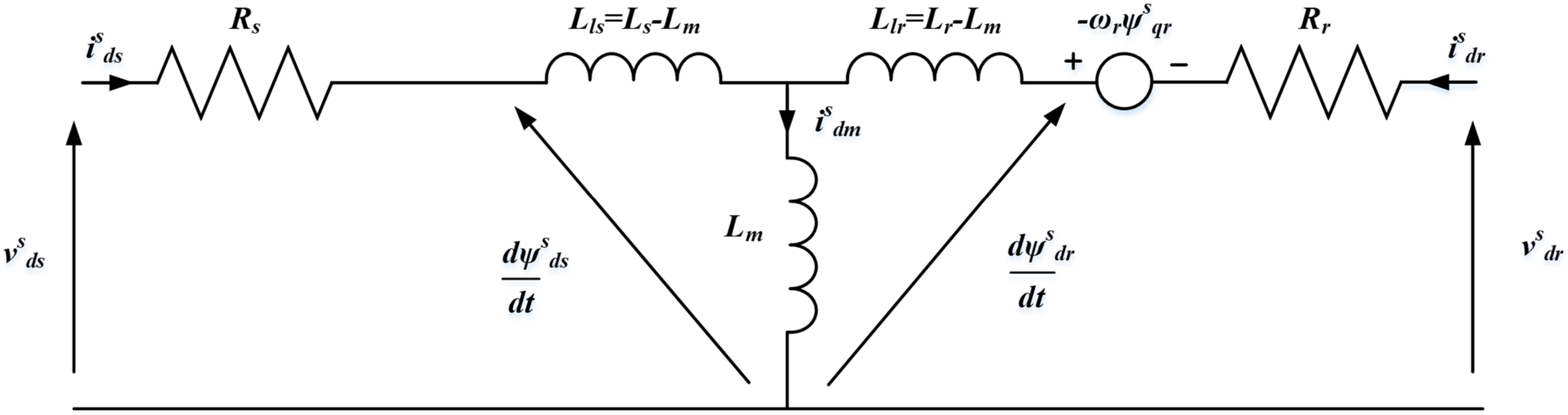
$$\psi'_{rA} = \frac{\psi_{rA}}{\alpha}$$

$$R'_r = a^2 R_r$$

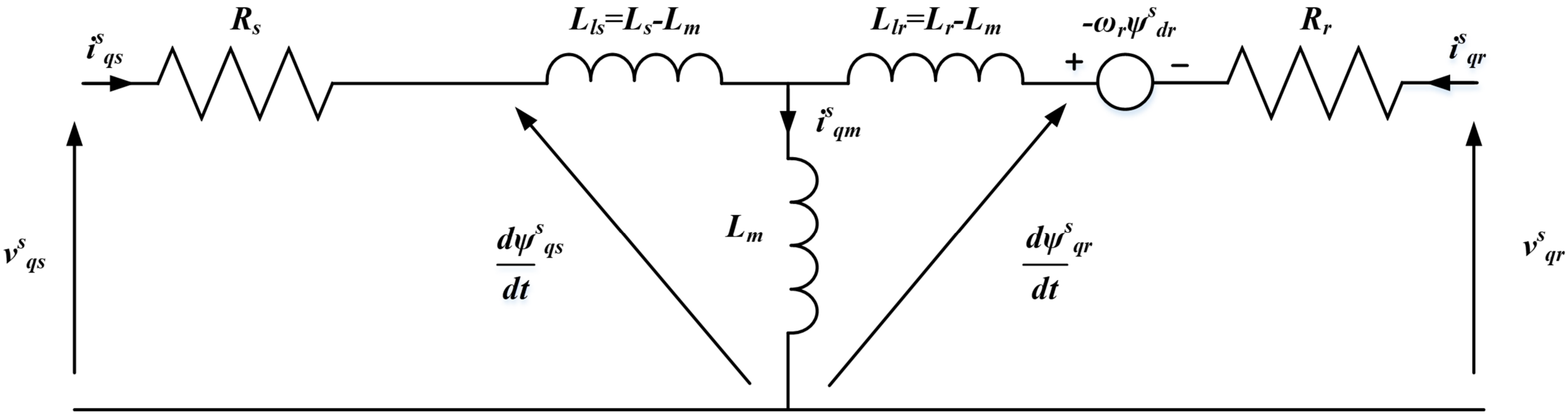
Asynchronous Machine dynamic electrical equivalent circuits

- ***2-phase, stationary reference frame dq (Stator):***

d Axis:



q Axis:


R_s
$L_{ls}=L_s-L_m$
$L_{lr}=L_r-L_m$
$-\omega_r\psi^s_{dr}$
R_r
i^s_{qs}
+
−
i^s_{qr}
i^s_{qm}
v^s_{qs}
$\frac{d\psi^s_{qs}}{dt}$
L_m
$\frac{d\psi^s_{qr}}{dt}$
v^s_{qr}

Equations in Matrix form:

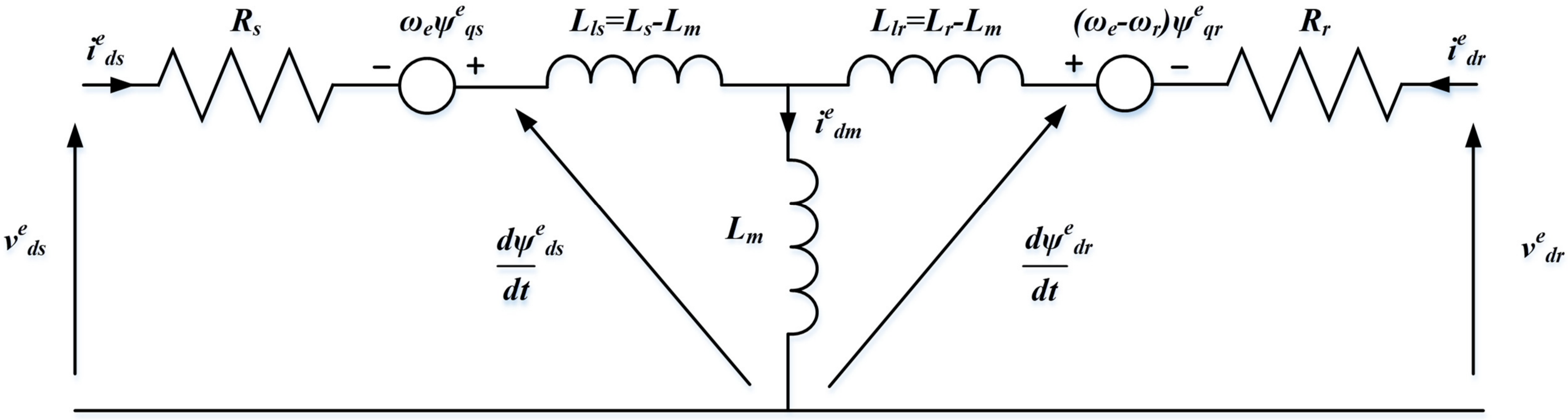
$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{qr}^s \\ v_{dr}^s \end{bmatrix} = \begin{bmatrix} R_s + L_s \frac{d}{dt} & 0 & L_m \frac{d}{dt} & 0 \\ 0 & R_s + L_s \frac{d}{dt} & 0 & L_m \frac{d}{dt} \\ L_m \frac{d}{dt} & -\omega_r L_m & R_r + L_r \frac{d}{dt} & -\omega_r L_r \\ \omega_r L_m & L_m \frac{d}{dt} & \omega_r L_r & R_r + L_r \frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{qs}^s \\ i_{ds}^s \\ i_{qr}^s \\ i_{dr}^s \end{bmatrix}$$

Squirrel cage asynchronous machine: $v_{qr}^s = 0 \; \kappa\alpha\iota \; v_{dr}^s = 0$

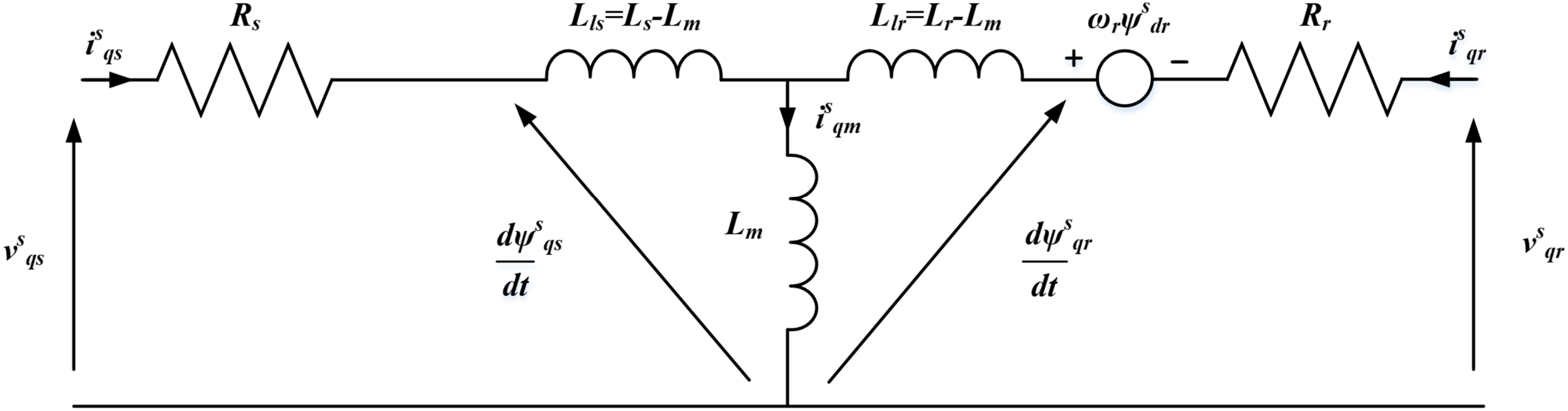
Asynchronous Machine dynamic electrical equivalent circuits

- ***2-phase, synchronously rotating (ω_e) reference frame:***

d Axis:



q Axis :


R_s
$L_{ls}=L_s-L_m$
$L_{lr}=L_r-L_m$
$\omega_r\psi^s_{dr}$
R_r
i^s_{qs}
+
−
i^s_{qr}
i^s_{qm}
v^s_{qs}
$\frac{d\psi^s_{qs}}{dt}$
L_m
$\frac{d\psi^s_{qr}}{dt}$
v^s_{qr}

Equations in Matrix form:

$$\begin{bmatrix} v_{qs}^{e} \\ v_{ds}^{e} \\ v_{qr}^{e} \\ v_{dr}^{e} \end{bmatrix} = \begin{bmatrix} R_s + L_s \frac{d}{dt} & \omega_e L_s & L_m \frac{d}{dt} & \omega_e L_m \\ -\omega_e L_s & R_s + L_s \frac{d}{dt} & -\omega_e L_m & L_m \frac{d}{dt} \\ L_m \frac{d}{dt} & (\omega_e - \omega_r) L_m & R_r + L_r \frac{d}{dt} & (\omega_e - \omega_r) L_r \\ -(\omega_e - \omega_r) L_m & L_m \frac{d}{dt} & -(\omega_e - \omega_r) & R_r + L_r \frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{qs}^{e} \\ i_{ds}^{e} \\ i_{qr}^{e} \\ i_{dr}^{e} \end{bmatrix}$$

Squirrel cage asynchronous machine : $v_{qr}^{e} = 0 \; \kappa\alpha\iota \; v_{dr}^{e} = 0$

Flux oriented Asynchronous Machine control

3 alternatives:

Stator Flux oriented:

$$\bar{\psi}_s^x = L_s\bar{\iota}_s^x + L_m\bar{\iota}'^x_r = L_{sl}\bar{\iota}_s^x + L_m\left(\bar{\iota}_s^x + \bar{\iota}'^x_r\right)\ \acute{\eta}\ \bar{\psi}_s^x = L_{sl}\bar{\iota}_s^x + L_m\bar{\iota}_m^x$$

Rotor Flux oriented:

$$\bar{\psi}'^x_r = L'_r\bar{\iota}'^x_r + L_m\bar{\iota}_s^x = L_{rl}\bar{\iota}'^x_r + L_m\left(\bar{\iota}_s^x + \bar{\iota}'^x_r\right)\ \acute{\eta}\ \bar{\psi}'^x_r = L'_{rl}\bar{\iota}'^x_r + L_m\bar{\iota}_m^x$$

Magnatizing Flux oriented:

$$\bar{\psi}_m^x = L_m\bar{\iota}_m^x$$

3 alternative torque (T_e) equations for 3 alternative control approaches:

- ***Stator flux oriented control:***

$$T_e = c_s|\bar{\psi}_s^x||\bar{i}_s^x|sin\gamma_s = c_s|\bar{\psi}_s^x|i_{s\beta}^x$$

- ***Rotor flux oriented control :***

$$T_e = c_r|\bar{\psi}'^x_r||\bar{i}_s^x|sin\gamma_r = c_r|\bar{\psi}'^x_r|i_{s\beta}^x$$

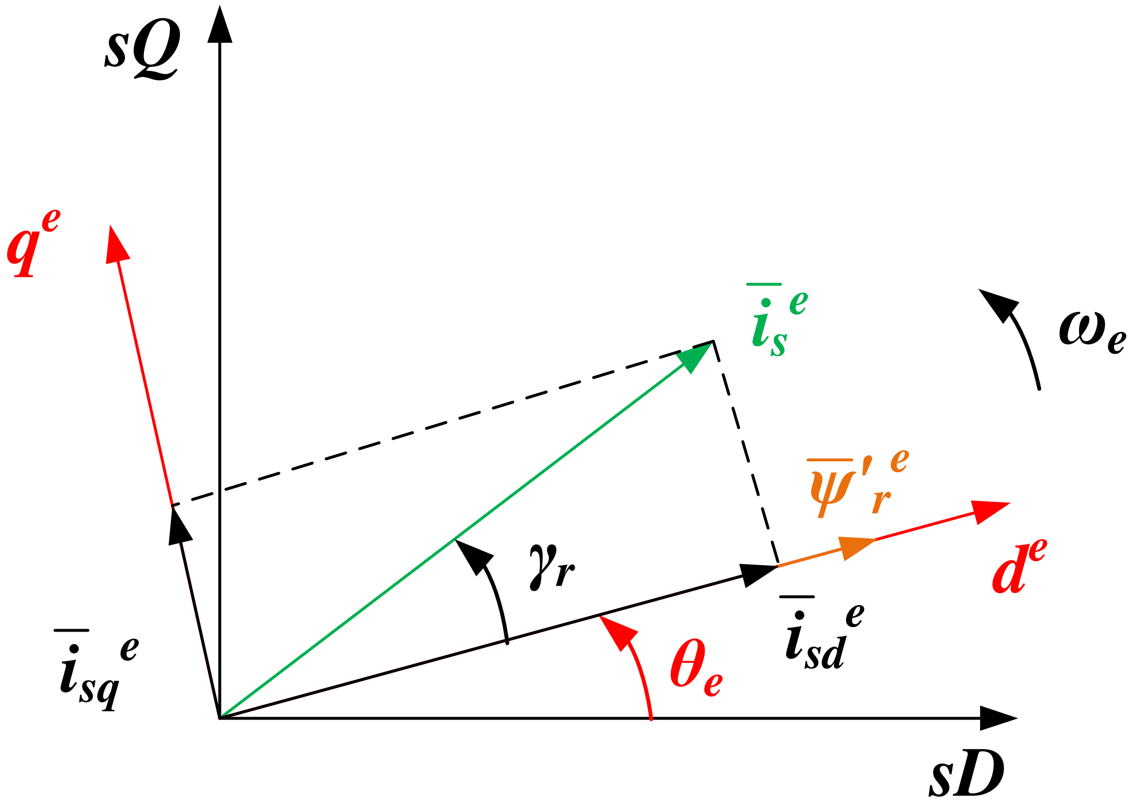
- ***Magnetizing flux oriented control :***

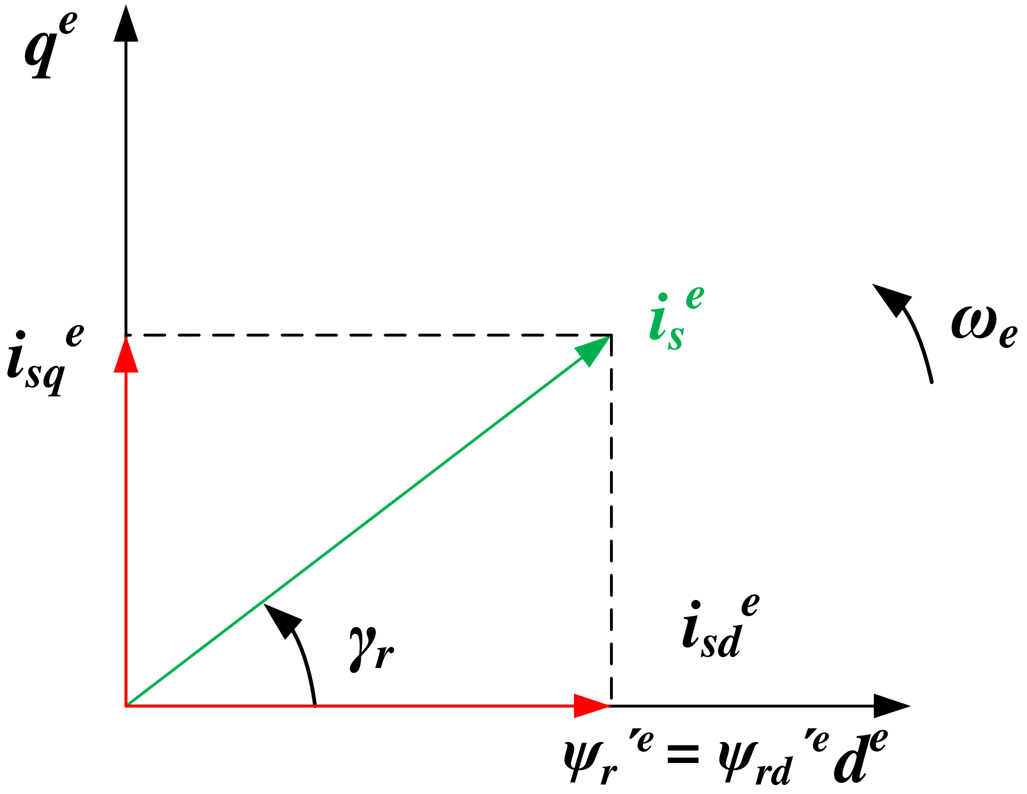
$$T_e = c_e|\bar{\psi}_m^x||\bar{i}_s^x|sin\gamma_m = c_e|\bar{\psi}_m^x|i_{s\beta}^x$$

- *Flux linkage vector determines the $\bar{i}_s$ reference axis, in other words sets the reference frame orientation! That why it's called "field oriented control"!!*

- $\bar{\imath}_{sq}^{x}$, *the vertical stator component of* $\bar{\imath}_{s}^{x}$ *is the torque current and the* $\bar{\imath}_{sd}^{x}$, *the horizontal component of* $\bar{\imath}_{s}^{x}$ *is the field current and is coincident with flux linkage vector, in flux linkage oriented reference frame. (x:general reference frame)*

In most cases, the rotor flux linkage oriented control is adopted, thanks to rotor flux linkage synchronous reference frame orientation (ψ_r rotates with ω_e!!)





$$T_e = c_r \, |\overline{\psi}_r'^e| \, i_{sq}^e = c_r \, \psi_{rd}'^e \, i_{sq}^e$$

$$\psi_{rd}'^e \sim i_{sd}^e$$

$$T_e = c_{r1} \, i_{sd}^e \, i_{sq}^e$$

Independent control of 2 separate stator current components!!

Vector Control Techniques

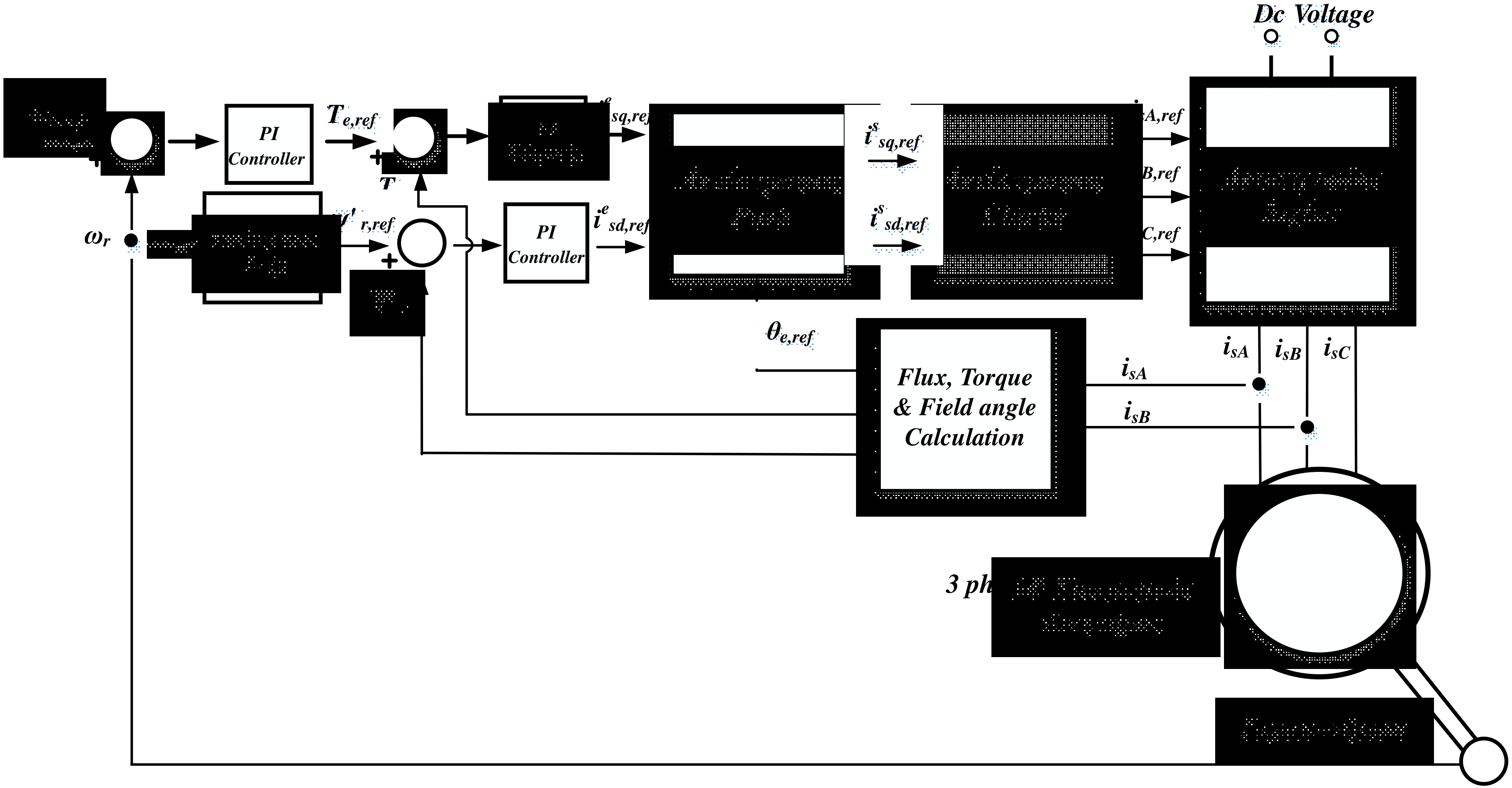
Direct

Field angle θ_e directly from i_s or v_s or ω_r or E_s -BEMF (Flux sensor)

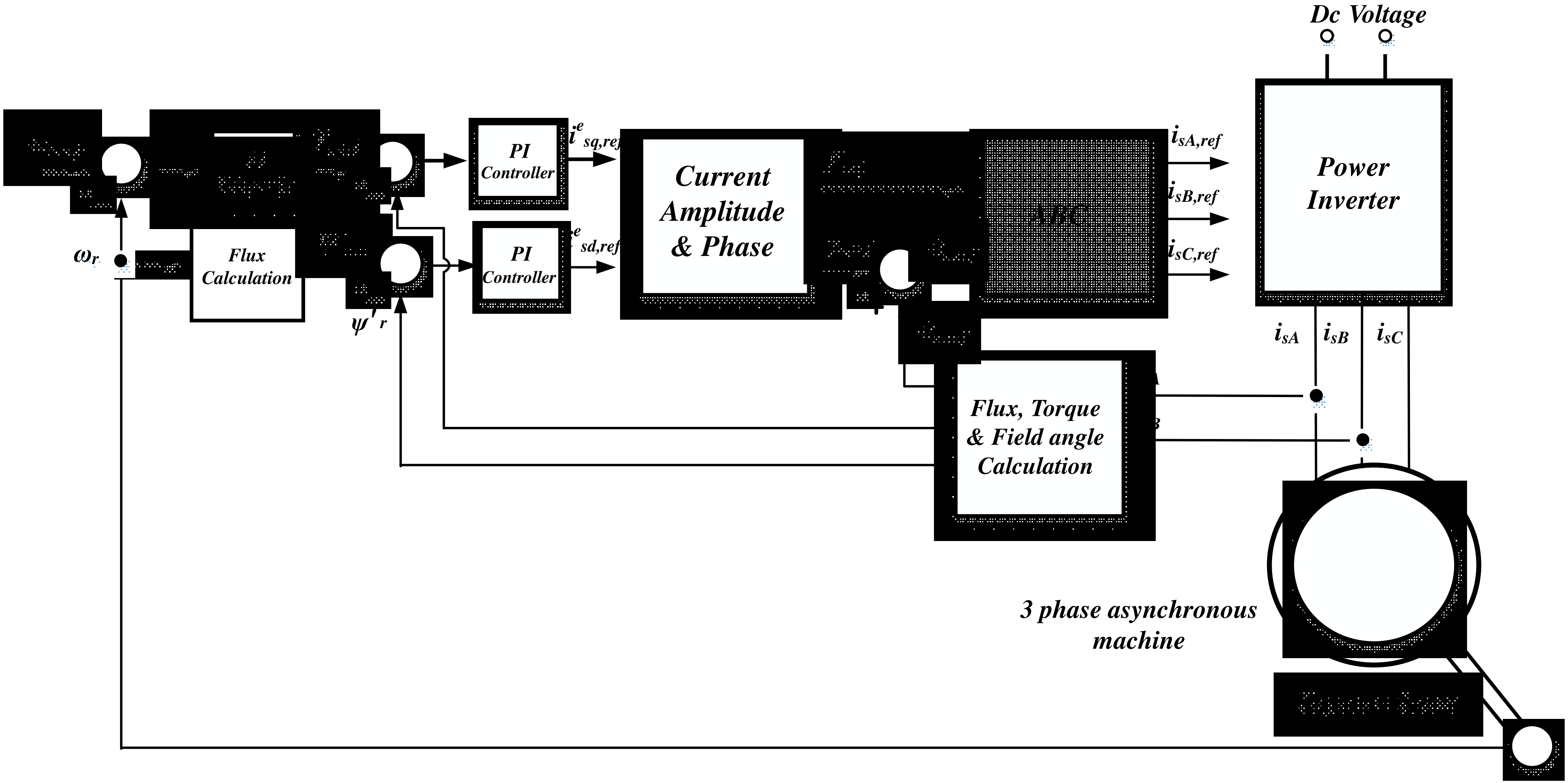
Indirect

Field angle θ_e from ω_r and machine dynamic model

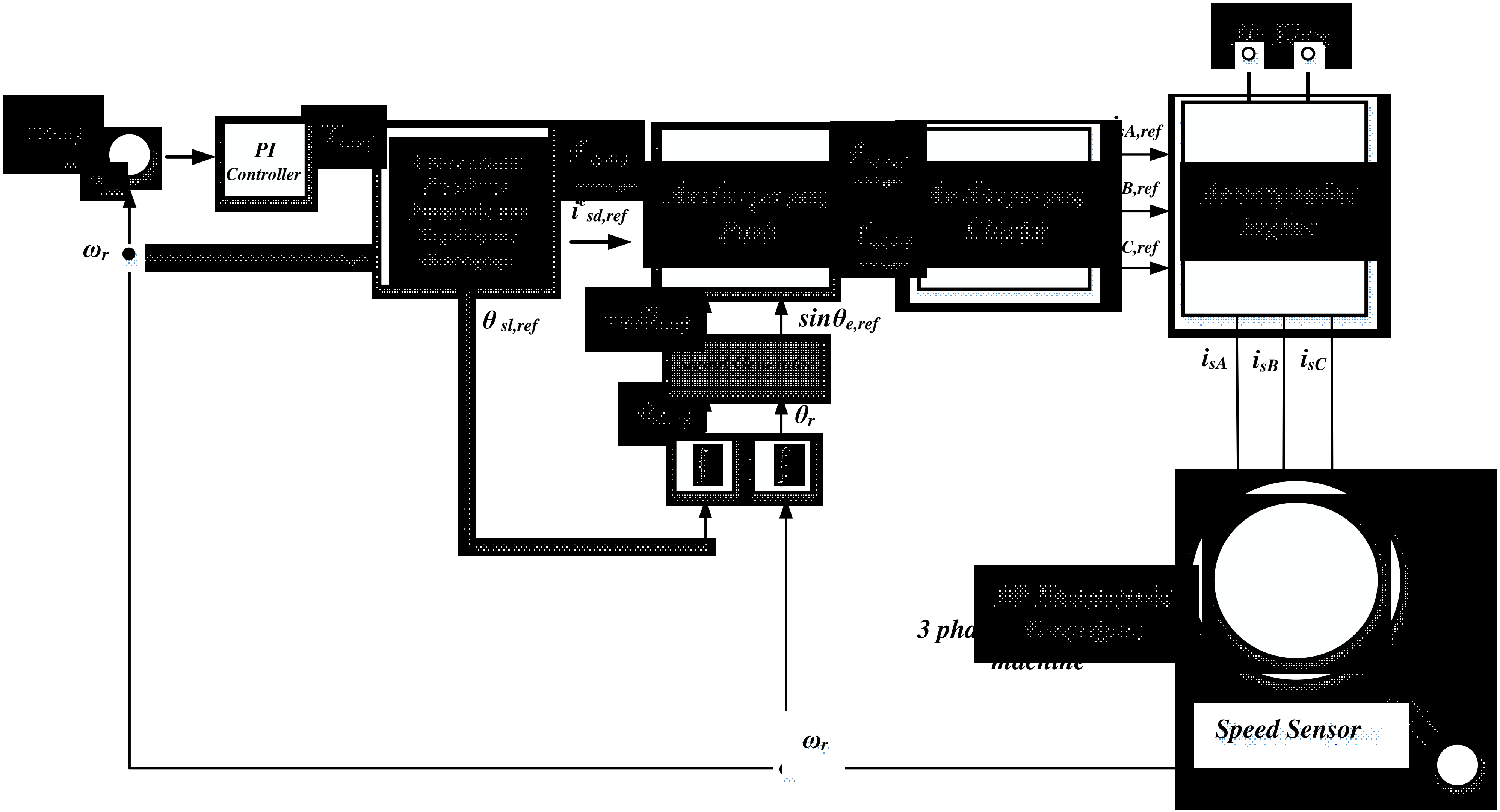
Schematic of direct vector control (reverse Park-Clarke)



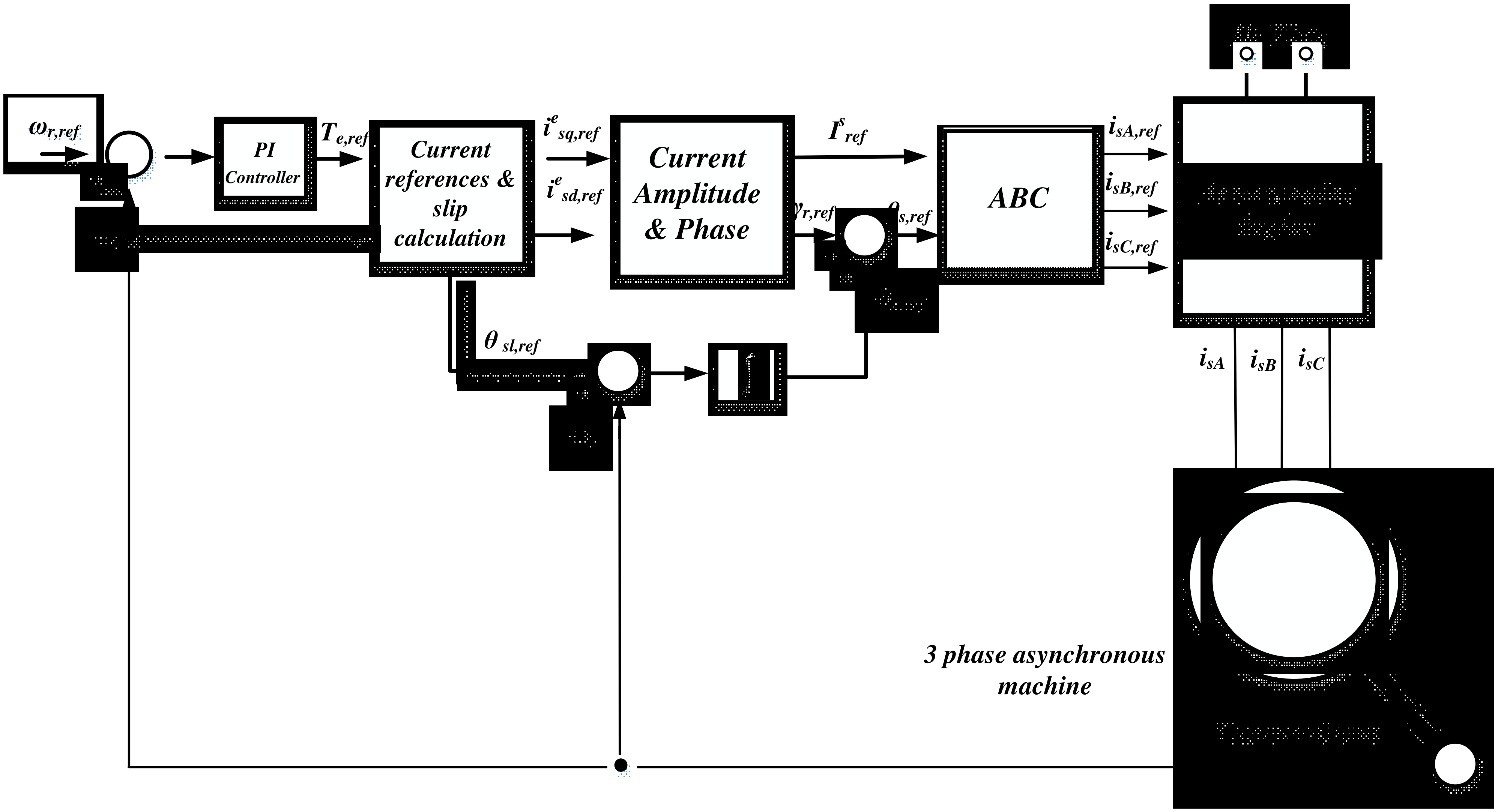
Schematic of direct vector control (reverse Park)



Schematic of indirect vector control (reverse Park-Clarke)



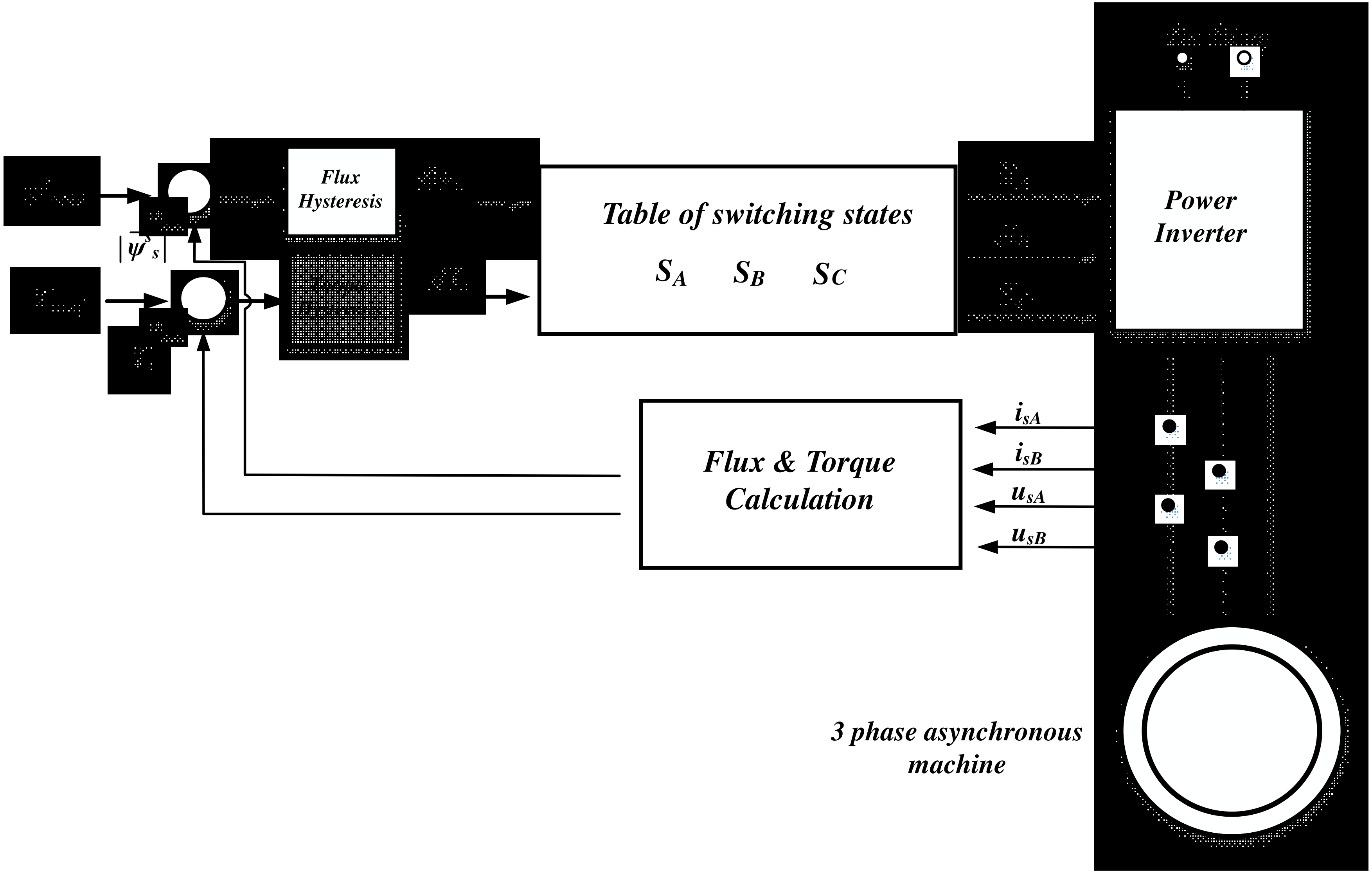
Schematic of indirect vector control (reverse Park)



Direct Torque (DTC) of asynchronous machine

- ***Direct** and **independent** control of T_e and ψ^s_s*
- ***Direct application of appropriate inverter switching states (switching vectors)***
- ***Stator flux oriented control!!***

Schematic of DTC



Flux Hysteresis

$|\psi^s_s|$

Table of switching states

S_A S_B S_C

Power Inverter

Flux & Torque Calculation

i_{sA}

i_{sB}

u_{sA}

u_{sB}

3 phase asynchronous machine

- ***Phase or Line voltages***

$$u_{sd}^{s} = -\frac{u_{sA} + 2u_{sB}}{\sqrt{3}} \qquad u_{sd}^{s} = \frac{u_{sAB} + u_{sCA}}{\sqrt{3}}$$

$$u_{sq}^{s} = u_{sA} \qquad u_{sq}^{s} = \frac{u_{sAB} - u_{sCA}}{3}$$

- ***Phase or Line currents***

$$i_{sq}^{s} = i_{sA}$$

$$i_{sd}^{s} = -\frac{i_{sA} + 2i_{sB}}{\sqrt{3}}$$

- ***Flux linkage components estimation***

$$\psi_{sd}^{s} = \int (u_{sd}^{s} - R \cdot i_{sd}^{s})dt$$

$$\psi_{sq}^{s} = \int (u_{sq}^{s} - R \cdot i_{sq}^{s})dt$$

- ***Synchronous angle*** $\theta_s = tan^{-1}(\psi_{sq}^{s}/\psi_{sd}^{s})$

- ***E/M torque*** $T_e = \frac{3}{2}p(\psi_{sd}^{s} i_{sq}^{s} - \psi_{sq}^{s} i_{sd}^{s})$

Flux linkage comparator

$$d\psi_s = 1 \quad if\ |\bar{\psi}_s^s| \leq |\bar{\psi}_{s,ref}^s| - |\Delta\psi_s|$$

$$d\psi_s = -1 \quad if\ |\bar{\psi}_s^s| \geq |\bar{\psi}_{s,ref}^s| - |\Delta\psi_s|$$

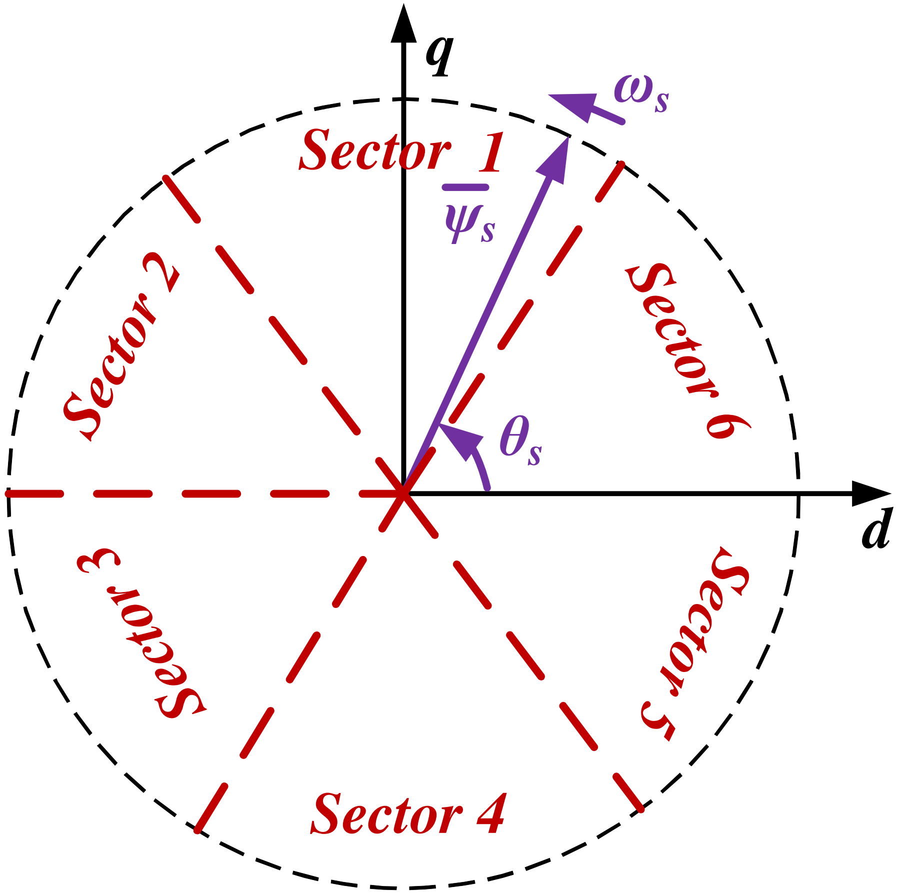
Torque comparator

$$dT_e = 1 \quad if\ |T_e| < |T_{e,ref}| - |\Delta T_e|$$

$$dT_e = 0 \quad if\ |T_{e,ref}| - |\Delta T_e| \leq |T_e| \leq |T_{e,ref}| + |\Delta T_e|$$

$$dT_e = -1 \quad if\ |T_e| > |T_{e,ref}| - |\Delta T_e|$$

Flux vector – Sector estimation



θ_s determines sector!!

Inverter voltage vectors array

$d\psi$	dT_e	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6
1	1	$\bar{u}_2$	$\bar{u}_3$	$\bar{u}_4$	$\bar{u}_5$	$\bar{u}_6$	$\bar{u}_1$
	0	$\bar{u}_7$	$\bar{u}_0$	$\bar{u}_7$	$\bar{u}_0$	$\bar{u}_7$	$\bar{u}_0$
	-1	$\bar{u}_1$	$\bar{u}_2$	$\bar{u}_3$	$\bar{u}_4$	$\bar{u}_5$	$\bar{u}_6$
-1	1	$\bar{u}_3$	$\bar{u}_4$	$\bar{u}_5$	$\bar{u}_6$	$\bar{u}_1$	$\bar{u}_2$
	0	$\bar{u}_0$	$\bar{u}_7$	$\bar{u}_0$	$\bar{u}_7$	$\bar{u}_0$	$\bar{u}_7$
	-1	$\bar{u}_5$	$\bar{u}_6$	$\bar{u}_1$	$\bar{u}_2$	$\bar{u}_3$	$\bar{u}_4$

Inverter switching states

$$\bar{u} = [S_A S_B S_C]$$

$\bar{u}_0 = [000]$

$\bar{u}_1 = [100]$

$\bar{u}_2 = [110]$

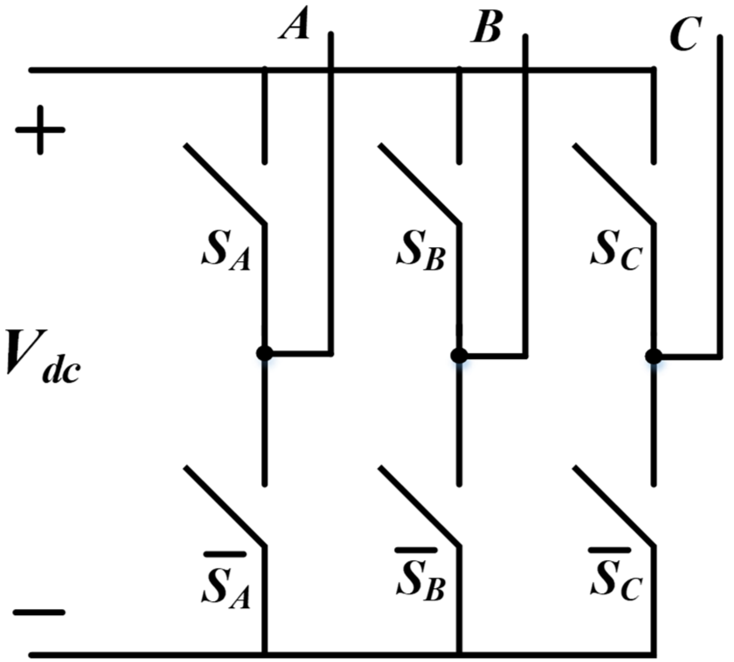
$\bar{u}_3 = [010]$

$\bar{u}_4 = [011]$

$\bar{u}_5 = [001]$

$\bar{u}_6 = [101]$

$\bar{u}_7 = [111]$



Pros:

- ✓*Fast torque response due to its direct control*
- ✓*No need for Park Transformations and PI controllers*
- ✓*Lower inverter switching frequency (f_s), less harmonic losses!*
- ✓*Absence of speed feedback, fewer controllers*
- ✓*Reduced number of controllers, comparing to indirect torque control*
- ✓*Simple implementation, comparing to indirect torque control*

Cons:

- Implementation difficulties in machine start-up, as well as under low speeds

- Very sensitive to machine parameters' deviations - Inevitable flux linkage estimation via mathematical integration of voltage and current → Model accuracy highly depends on T^0C (R_s) & measurement noise

- Torque and flux fluctuations (due to hysteresis control)

- Variable switching frequency – difficulties in filter design – EMI issues

Sensorless Technique – Speed and position control without sensors!

DTC example:

Torque control, no speed control → Electric vehicle!

Acceleration/deceleration via torque command.

No closed speed control necessary

Alternative to DTC → Direct-Self Control (DSC), proposed for high-power drives (Depenbrock, 1987)

- ***3 flux hysteresis controllers determine the voltage applied to the machine by comparing a flux magnitude command with the estimated flux for each phase.***
- ***1 two-level hysteresis torque controller determines the amount of zero voltage.***

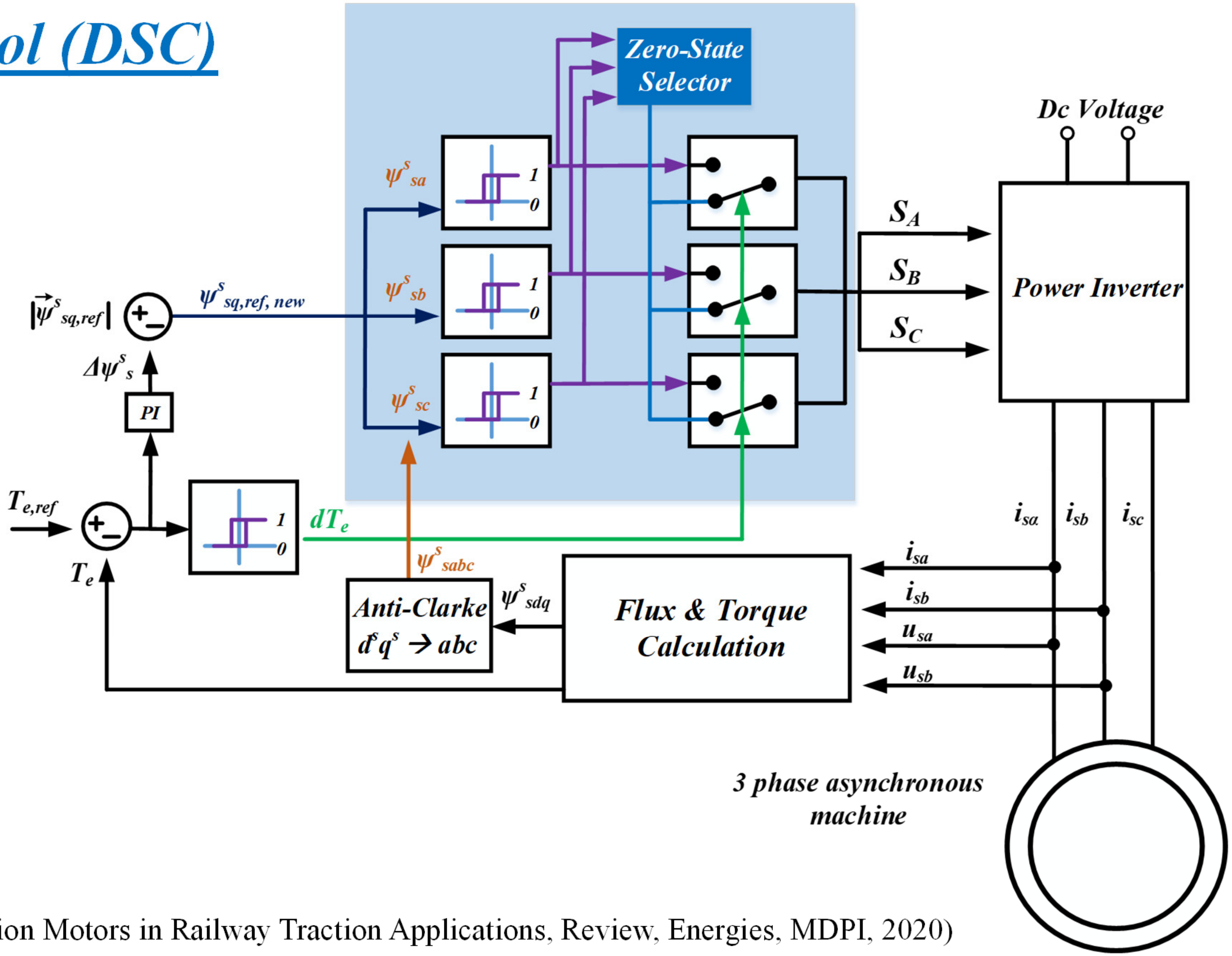
- ***DSC produces Hexagonal stator flux trajectory:***

✓Smooth transition into overmodulation

- Problematic below approximately 30% of the base speed

(Source: Control Strategies for Induction Motors in Railway Traction Applications, Review, Energies, MDPI, 2020)

Direct-Self Control (DSC)



(Source: Control Strategies for Induction Motors in Railway Traction Applications, Review, Energies, MDPI, 2020)

DTC Space Vector Modulation (SVM):

- ***Constant switching frequency!***

The required stator voltage vector is calculated over a sampling period to achieve the desired torque and stator flux. The voltage vector is synthesized using SVM.

✓ ***Fast dynamics of DTC if the inverter operates in the linear region***

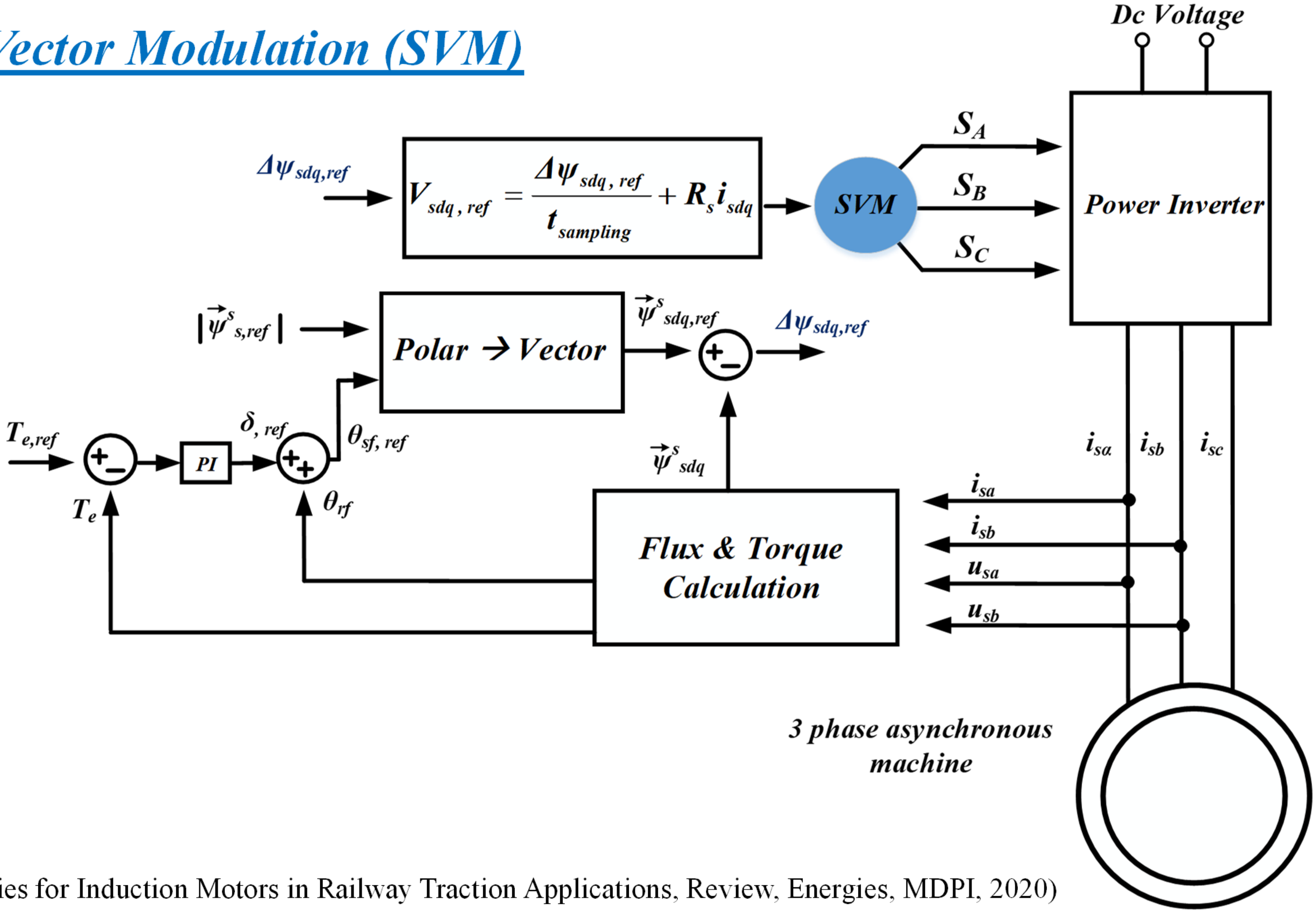
✓ ***Effectively cancels the flux error for relatively small values of*** $t_{sampling}$

-Voltage distortions intrinsic to overmodulation can result in magnitude and phase deviations of the actual stator flux vector, leading to instability problems

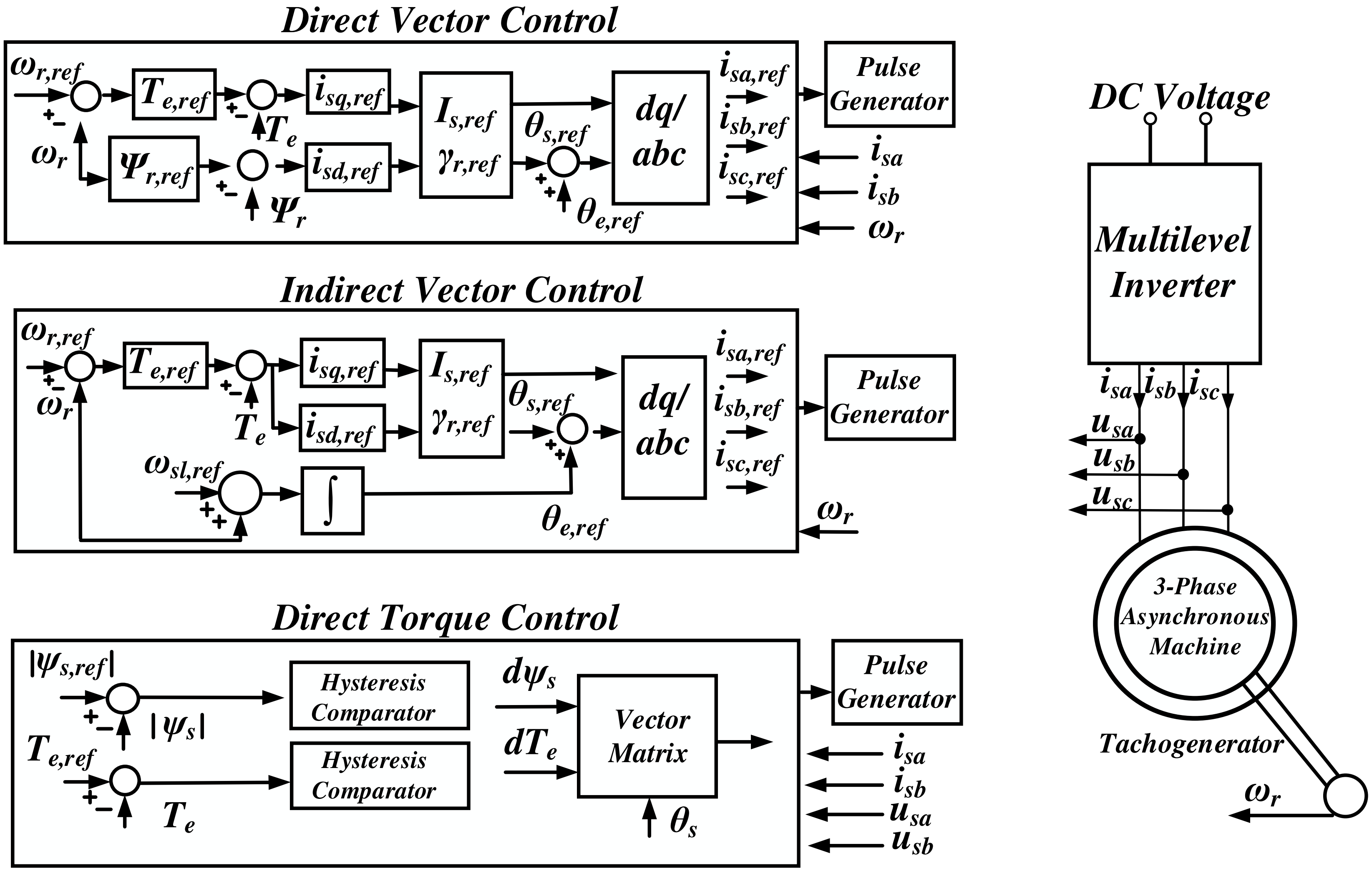
-Large steady-state errors in case of low switching frequencies

(Source: Control Strategies for Induction Motors in Railway Traction Applications, Review, Energies, MDPI, 2020)

DTC Space Vector Modulation (SVM)

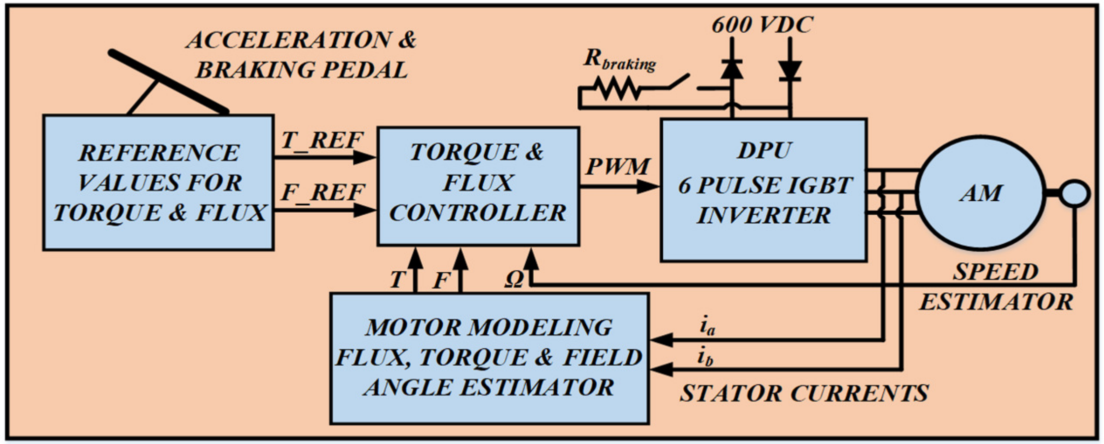


(Source: Control Strategies for Induction Motors in Railway Traction Applications, Review, Energies, MDPI, 2020)



Block diagrams of Direct and Indirect Vector Control as well as Direct Torque Control of induction machines, where pointer -s refers to stator reference frame and -r to rotor reference frame (N. Apostolidou, N. Papanikolaou et al. PACET 2017 Conference)

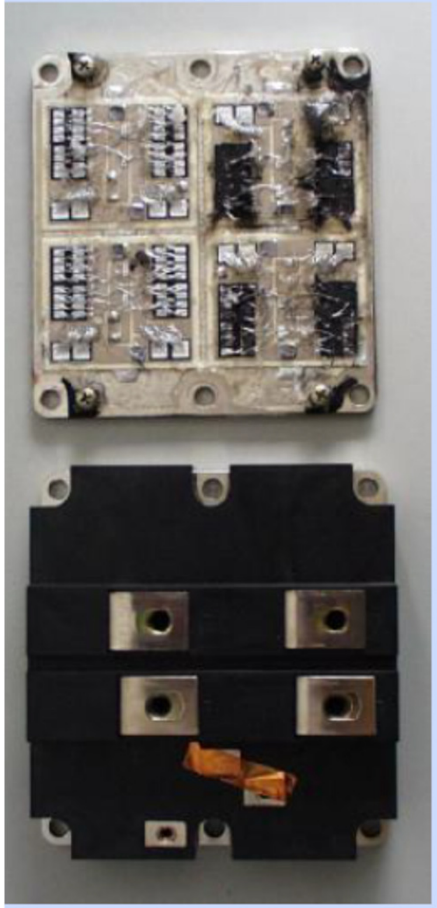
Industrial example – Vector control of Athens trolley-buses

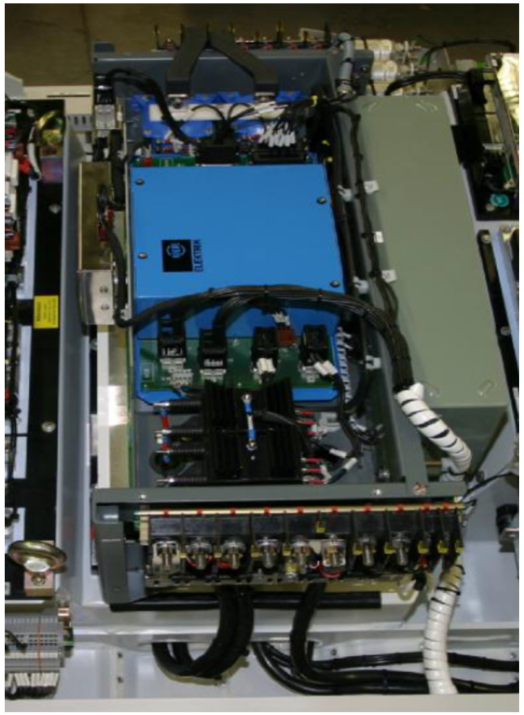


- Direct Vector Control (DVC) scheme is used for the 240 kW asynchronous machine

- 1700 V / 1800 A IGBT Modules are used as the 2-Level inverter main switches

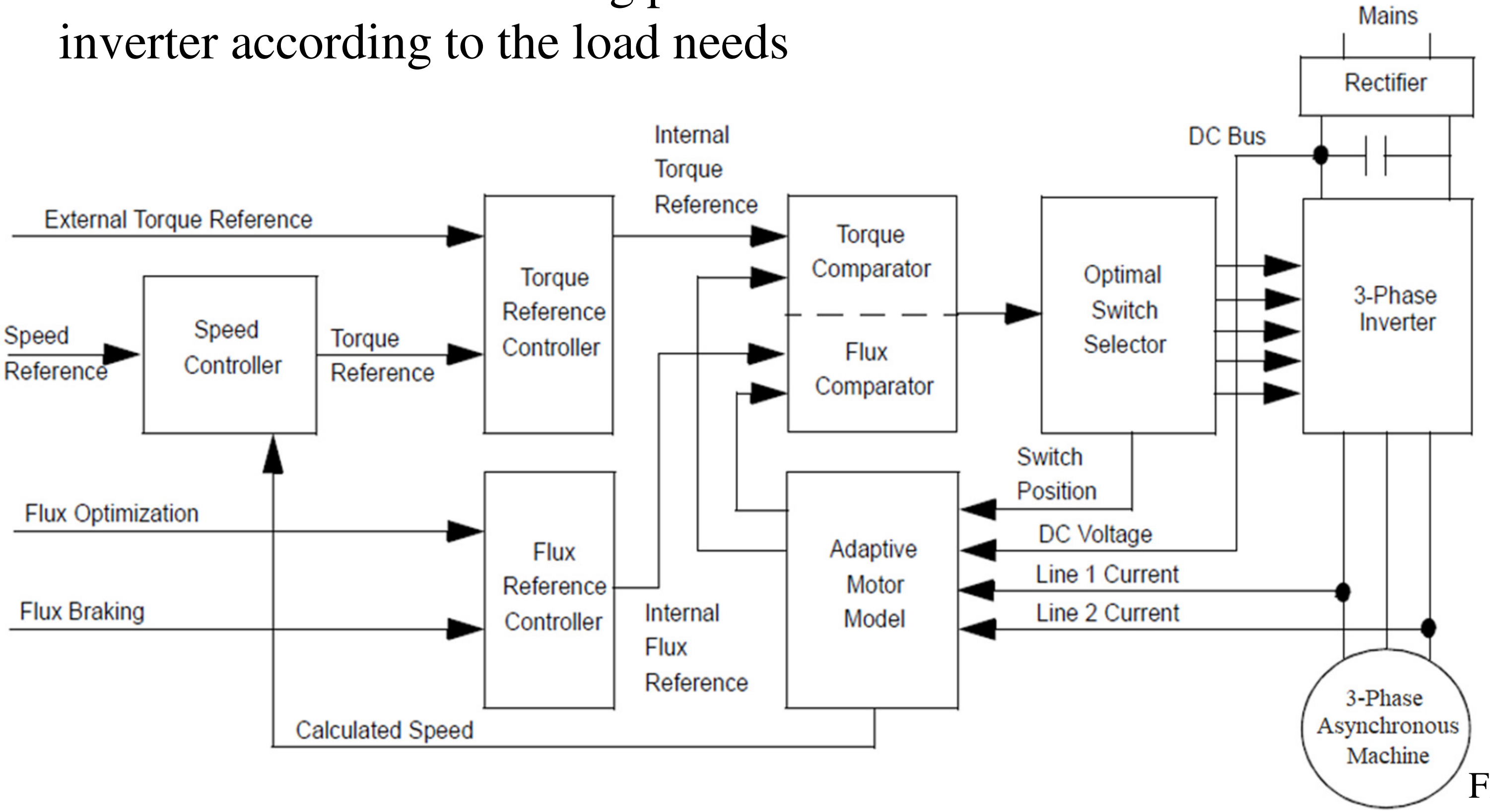
example: Typ FZ 1800 R



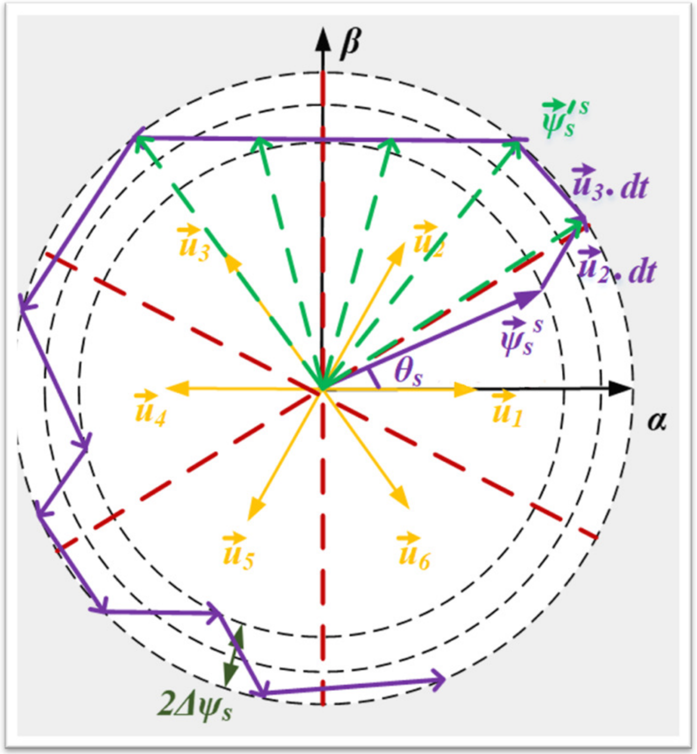


Implementation of Direct Torque Control at Athens trolley-buses 2-L inverter module

DTC has no fixed switching pattern – it switches the inverter according to the load needs



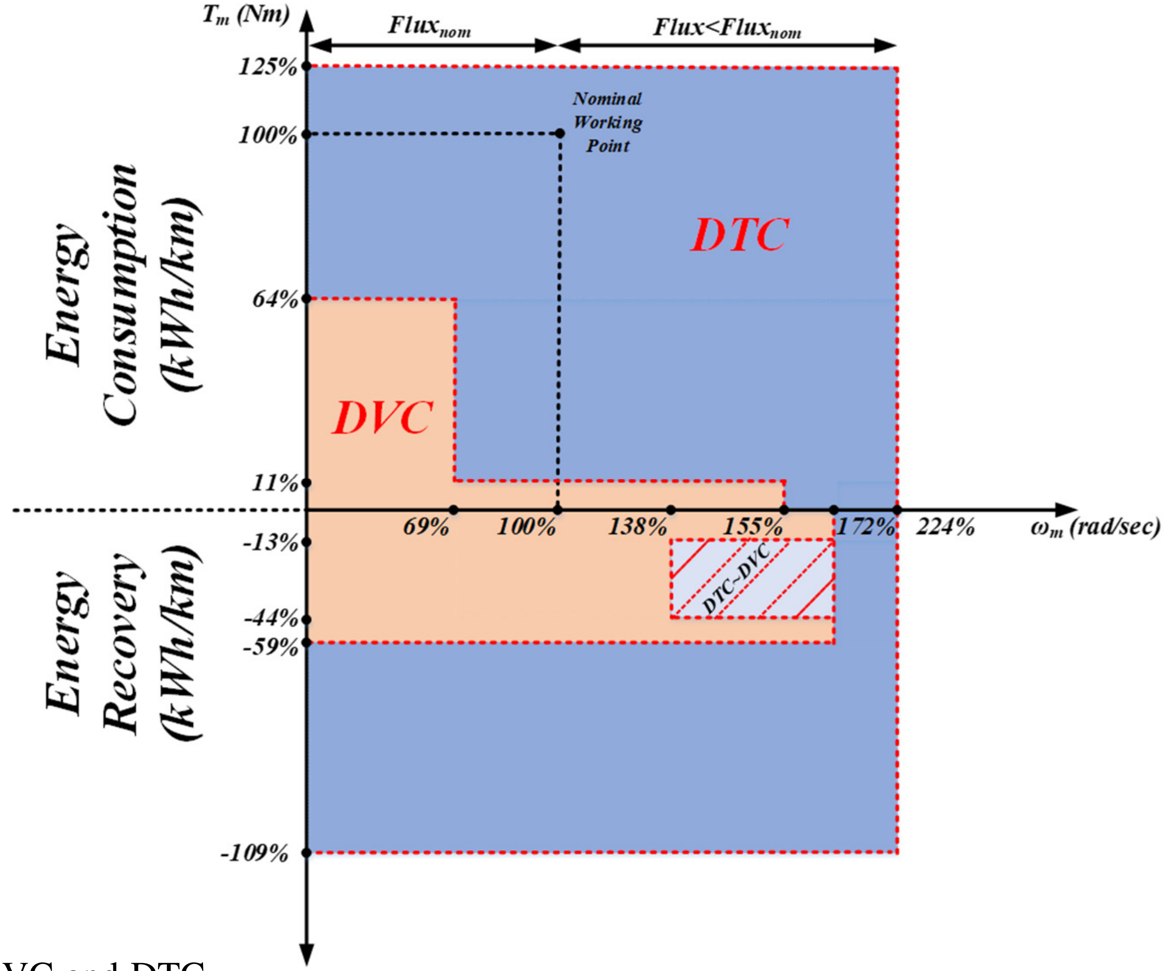
DTC block diagram (MICROCHIP, AN887)



Flux control under DTC, implemented at a 2-L inverter (N. Apostolidou, MSc Thesis, DUTH, 2018)

Study on the performance of DTC & DVC techniques for the case of Athens trolley-buses

- **DTC is more efficient under high-torque operation (i.e. trolley-bus acceleration / braking)**
- **DVC is more efficient under low-torque conditions (i.e. during constant speed operation)**



Energy consumption performance for Athens Trolley-buses under DVC and DTC control schemes (N. Apostolidou, MSc Thesis, DUTH, 2018)

Conclusions

- **Asynchronous machines is a significant machine type for all kinds of human activities (Industry, Transportations, Appliances etc.)**
- **Its efficient operation under various speeds leads to significant energy savings, contributing to a greener footprint**
- **Modern switch-mode inverters and the sophisticated control techniques that they incorporate are the key component for the effective control of asynchronous machines**