METU PowerLab Seminar Series

Motor Drive Strategies

‘The Others’

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Presentation Plan

Motivation & Scope

Some Quick Remarks

Inverter Model & Induction Machine Model

Direct Torque Control

Model Predictive Control

An Overview on Motor Drive Research

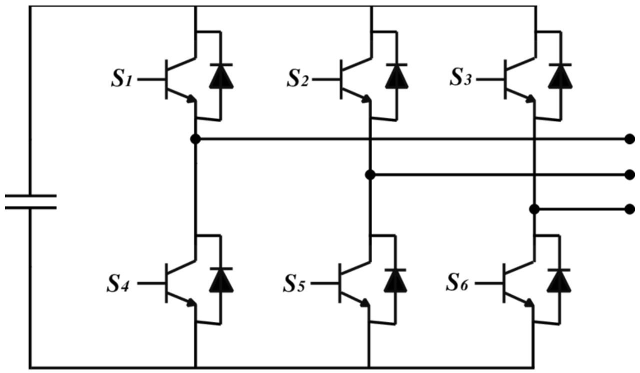
Some Quick Remarks

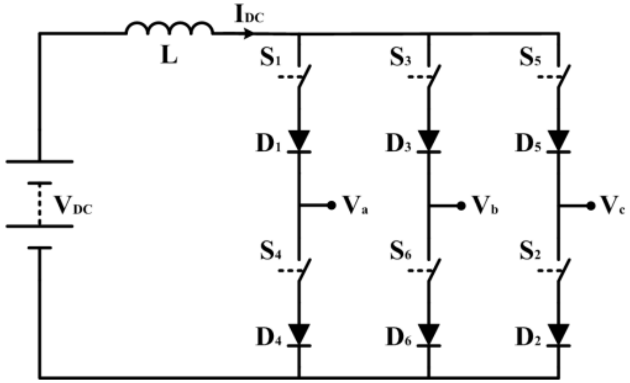
Voltage Source Inverter – Current Source Inverter

‘Current Controlled’ – ‘Voltage Controlled’

The vast majority: **Current Controlled Voltage Source Inverter**

We provide ‘**Volt-seconds**’ to the grid/machine that the VSI is connected to. We measure **currents**.



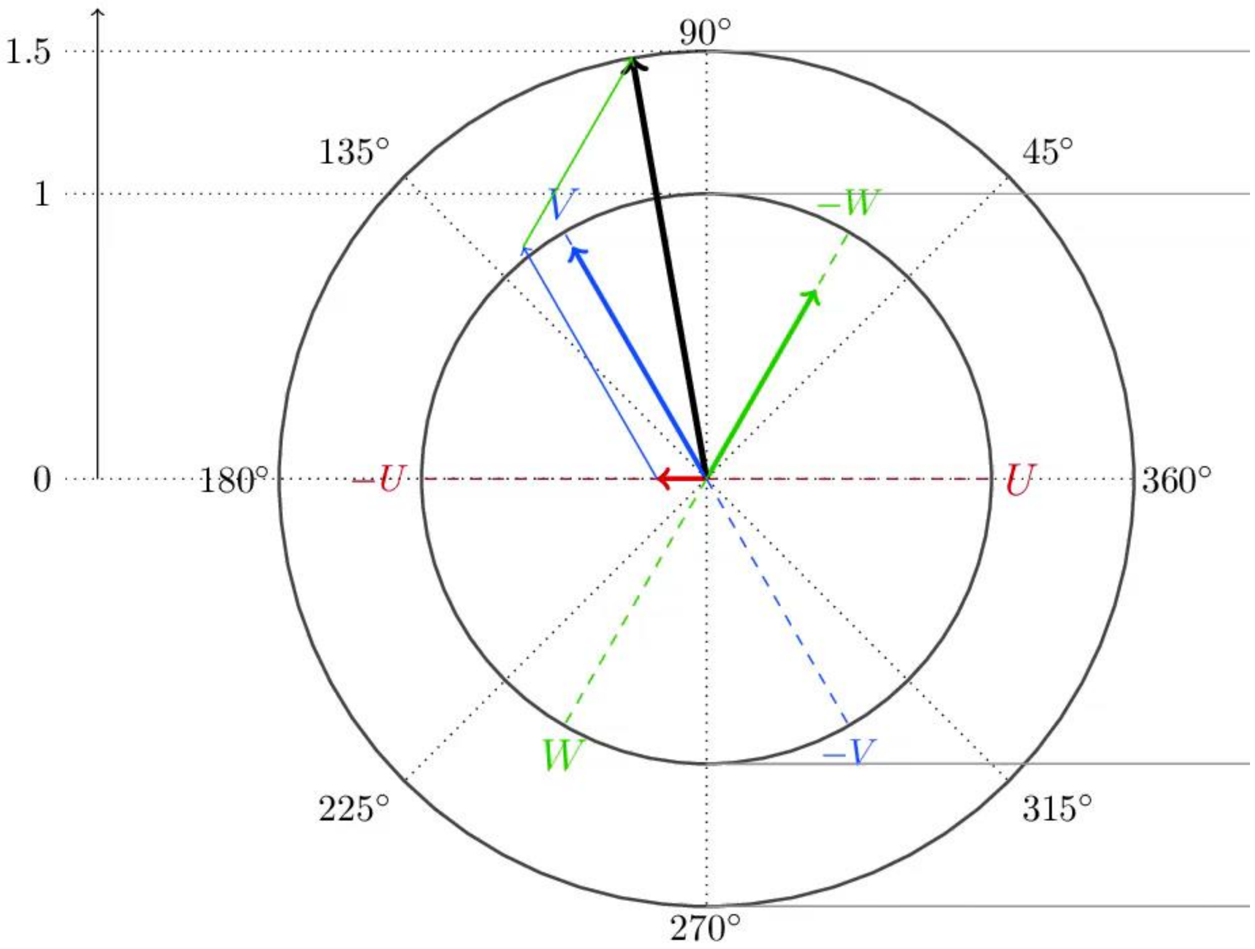


Question #1

Propose a ‘Voltage Controlled – Voltage Source Inverter’ control scheme.

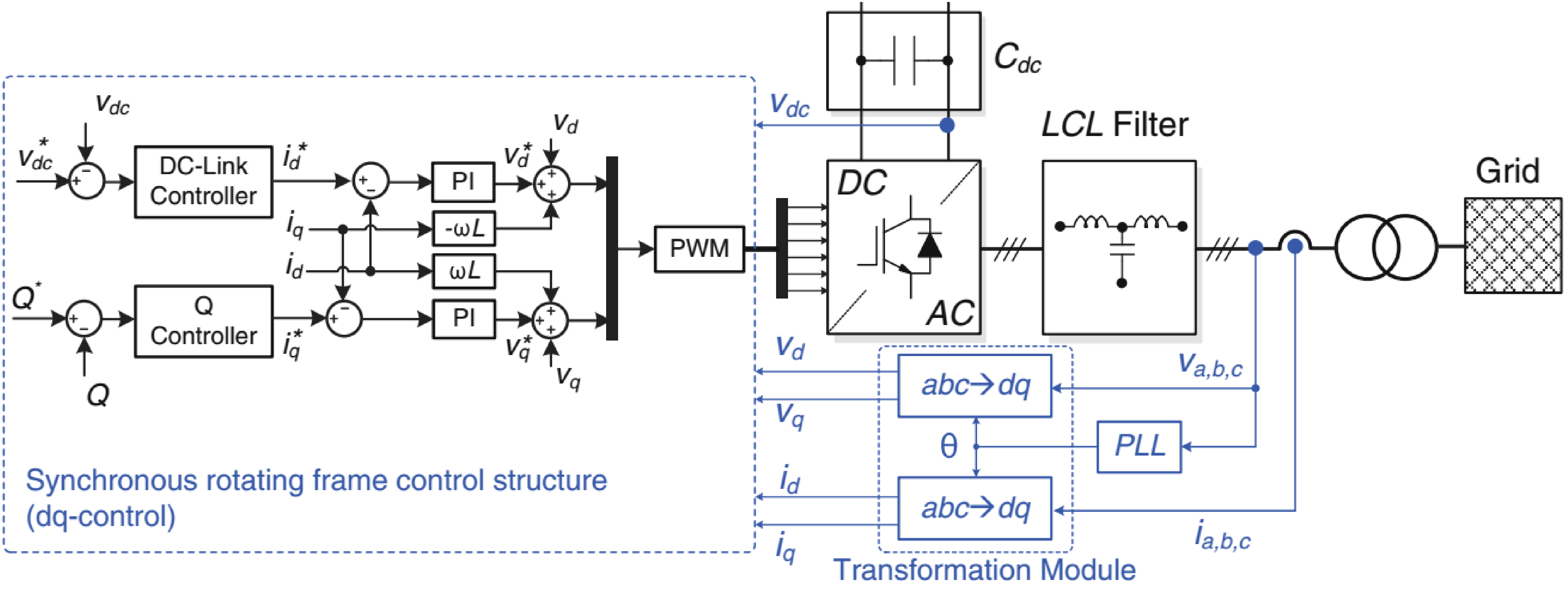
What is wrong / disturbing about it?

Rotating Vectors



Source: https://www.switchcraft.org/

An Off-Topic Example



Ref: Advanced and Intelligent Control in Power Electronics and Drives

Question #2

Suppose that you want an inverter to be connected to a grid. But you do not want it to send or receive any power, i.e. Iabc=0.

What are the voltage references that you should feed into your modulators?

Vabc = 0 ?

Question #3

d-q quantities are DC quantities.

DC quantities are especially suitable for our standart control schemes.

Why?

An Off-Topic Example

Comparison: FOC of PMSM vs Control of Grid Connected VSI

FOC of PMSM	**Grid Connected VSI**
D-axis → magnetic field	D-axis → Voltage Vector
Q-axis → Back EMF	Q-axis → 90° away
D-axis current: Interacts with field	D-axis current: current in phase with V → P
Q-axis current: Produces pure P → Torque	Q-axis current: current with 90° → Q
Control: Id=0, Iq=As much torque needed	Control: Iq=0, Id=As much power available

Question #4

CASE: A near-ideal Induction Machine is driven via FOC.

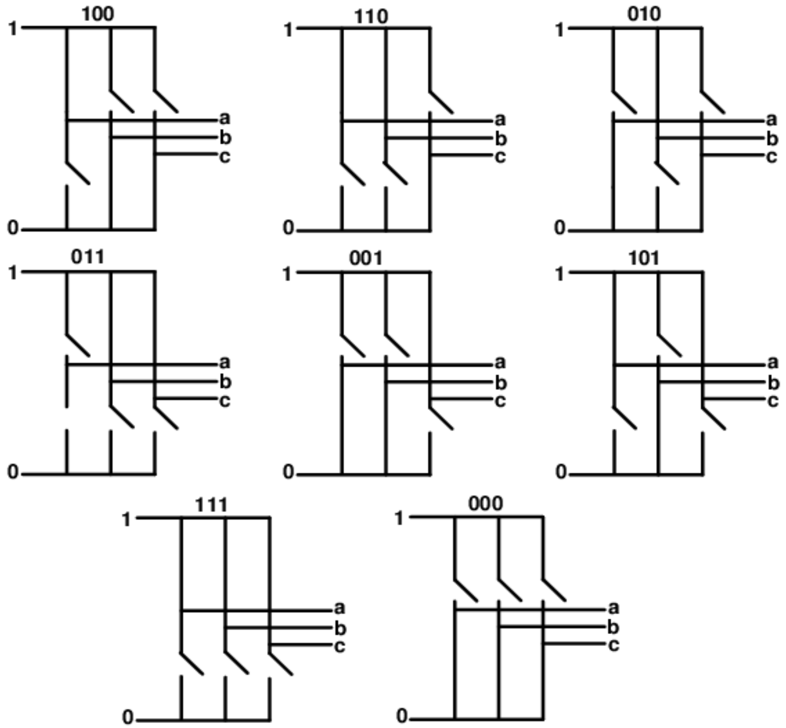
At rated speed & no-load (Load Torque = 0), it draws P=20 W, Q=600 VAR

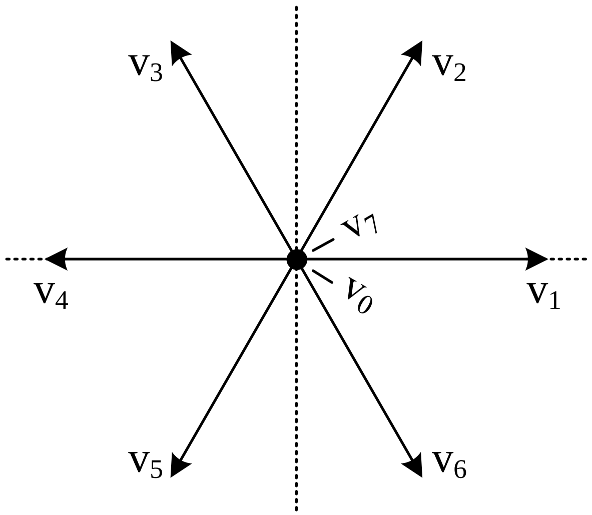
At rated speed & full-load (Load Torque = 1 p.u.), it draws P=800 W, Q=900 VAR

a) It's normal, because…

b) You have a problem, because…

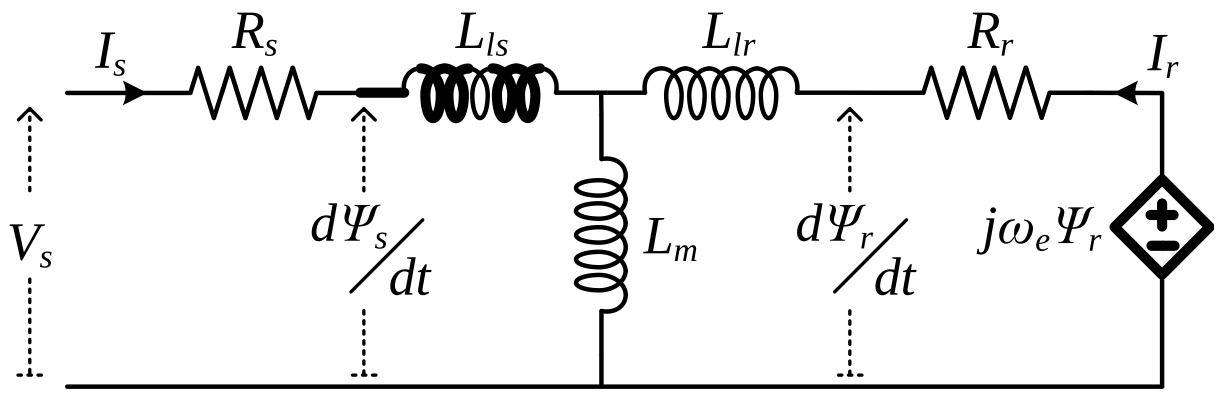
Inverter Model





$\boldsymbol{v}_n$	$s = [s_a s_b s_c]$	$\boldsymbol{v} = v_\alpha + jv_\beta$
$\boldsymbol{v}_0$	0 0 0	0
$\boldsymbol{v}_1$	1 0 0	$2/3V_{dc}$
$\boldsymbol{v}_2$	1 1 0	$1/3V_{dc} + j\sqrt{3}/3V_{dc}$
$\boldsymbol{v}_3$	0 1 0	$-1/3V_{dc} + j\sqrt{3}/3V_{dc}$
$\boldsymbol{v}_4$	0 1 1	$-2/3V_{dc}$
$\boldsymbol{v}_5$	0 0 1	$-1/3V_{dc} - j\sqrt{3}/3V_{dc}$
$\boldsymbol{v}_6$	1 0 1	$1/3V_{dc} - j\sqrt{3}/3V_{dc}$
$\boldsymbol{v}_7$	1 1 1	0

Induction Machine Model



$$V_s = R_s I_s + \frac{d\Psi_s}{dt}$$

$$0 = R_r I_r + \frac{d\Psi_r}{dt} - jw_e\Psi_r$$

$$\Psi_s = L_s I_s + L_m I_r$$

$$\Psi_r = L_m I_s + L_r I_r$$

Question #5

In both DTC and MPC, we do not employ Park’s transform.

No d-q quantities, hence control variables are not represented in DC.

How?

Direct Torque Control

Invention: mid-80s

Two variants: Takahashi – Depenbrock

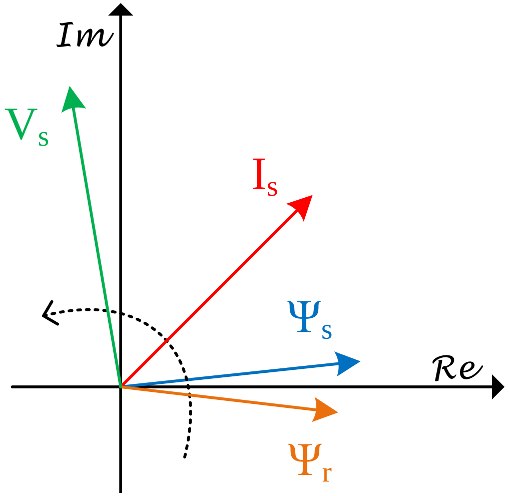
Currently championed by ABB

No current control loop (!?)

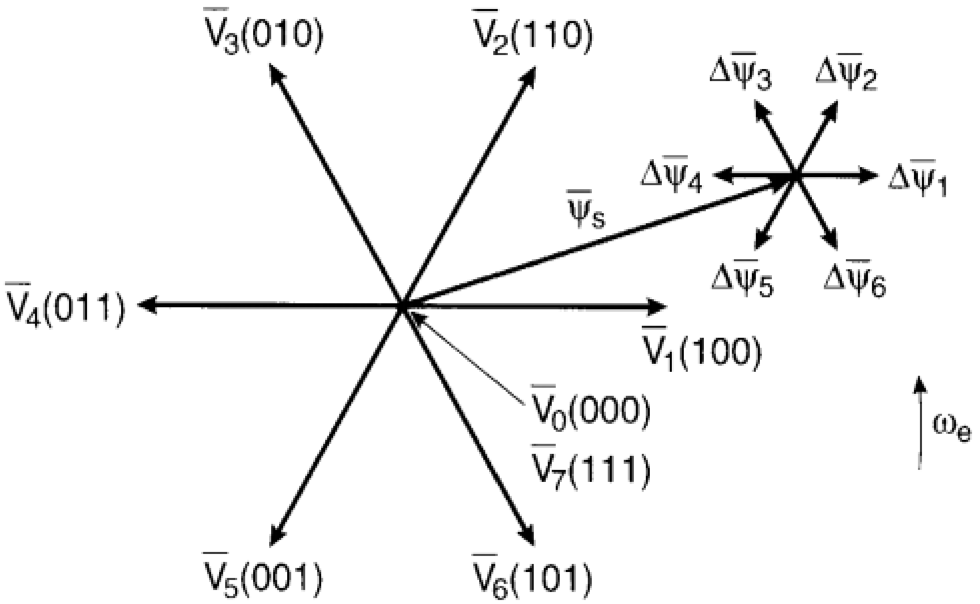
No PWM modulation (!?)

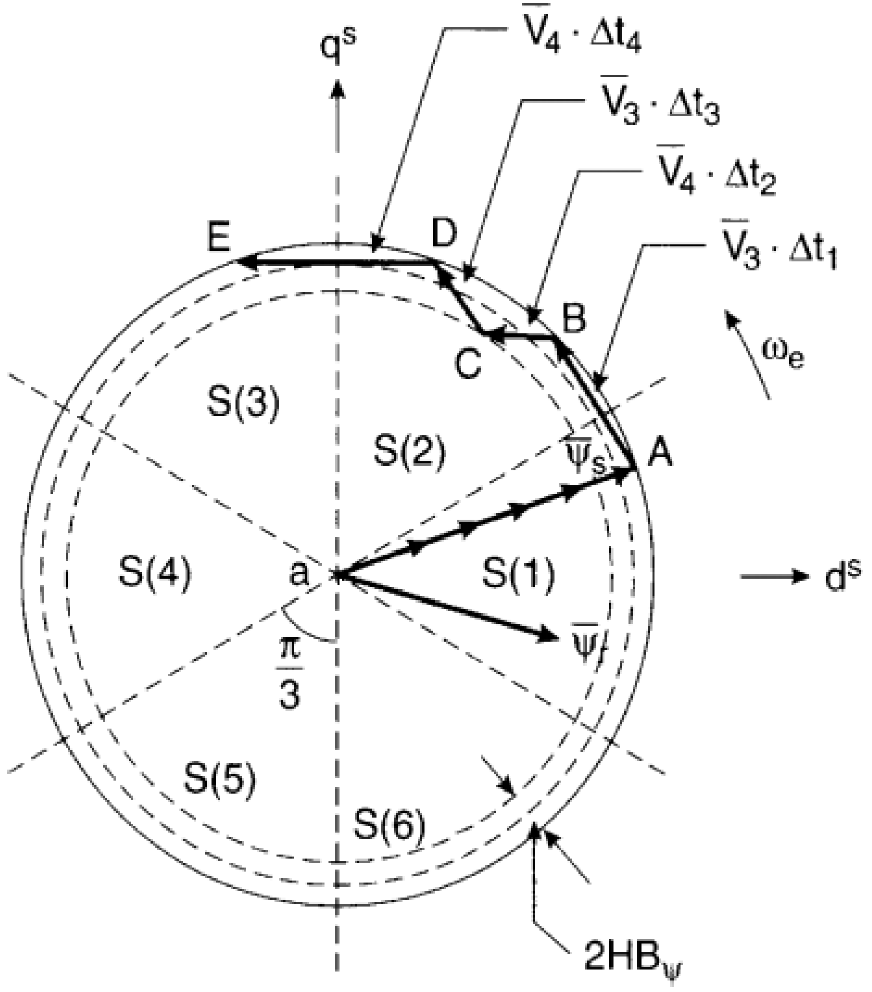
ADVANTAGES	DISADVANTAGES
Faster Dynamics	Variable swithcing frequency
Simple and Robust Structure	Performance is estimator dependent
No dependence on rotor dynamics	Higher ripple

Direct Torque Control



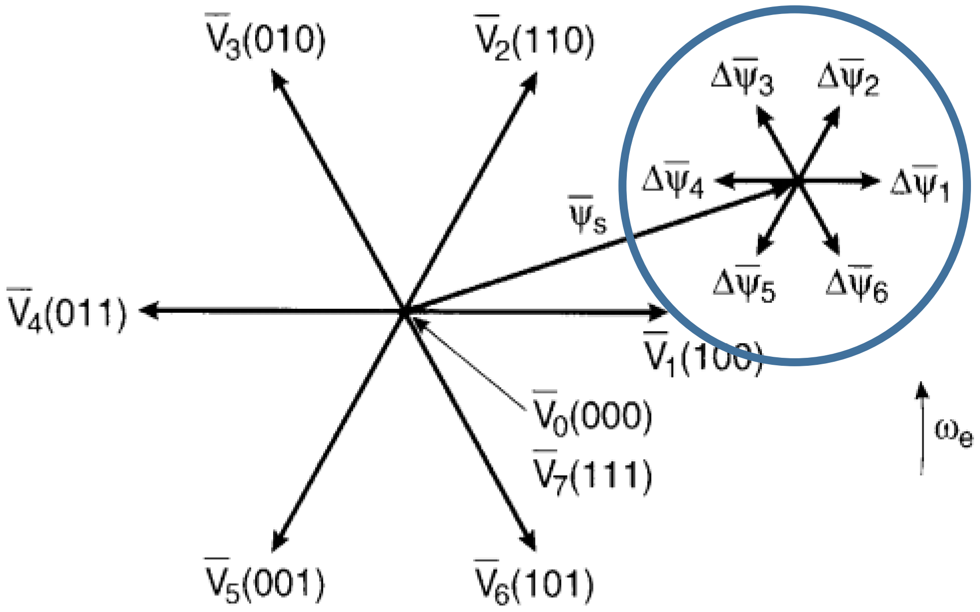
$$\frac{d\Psi_s}{dt} = V_s - R_s I_s$$





Ref: Modern Power Electronics and AC Drives by B. Bose

Direct Torque Control



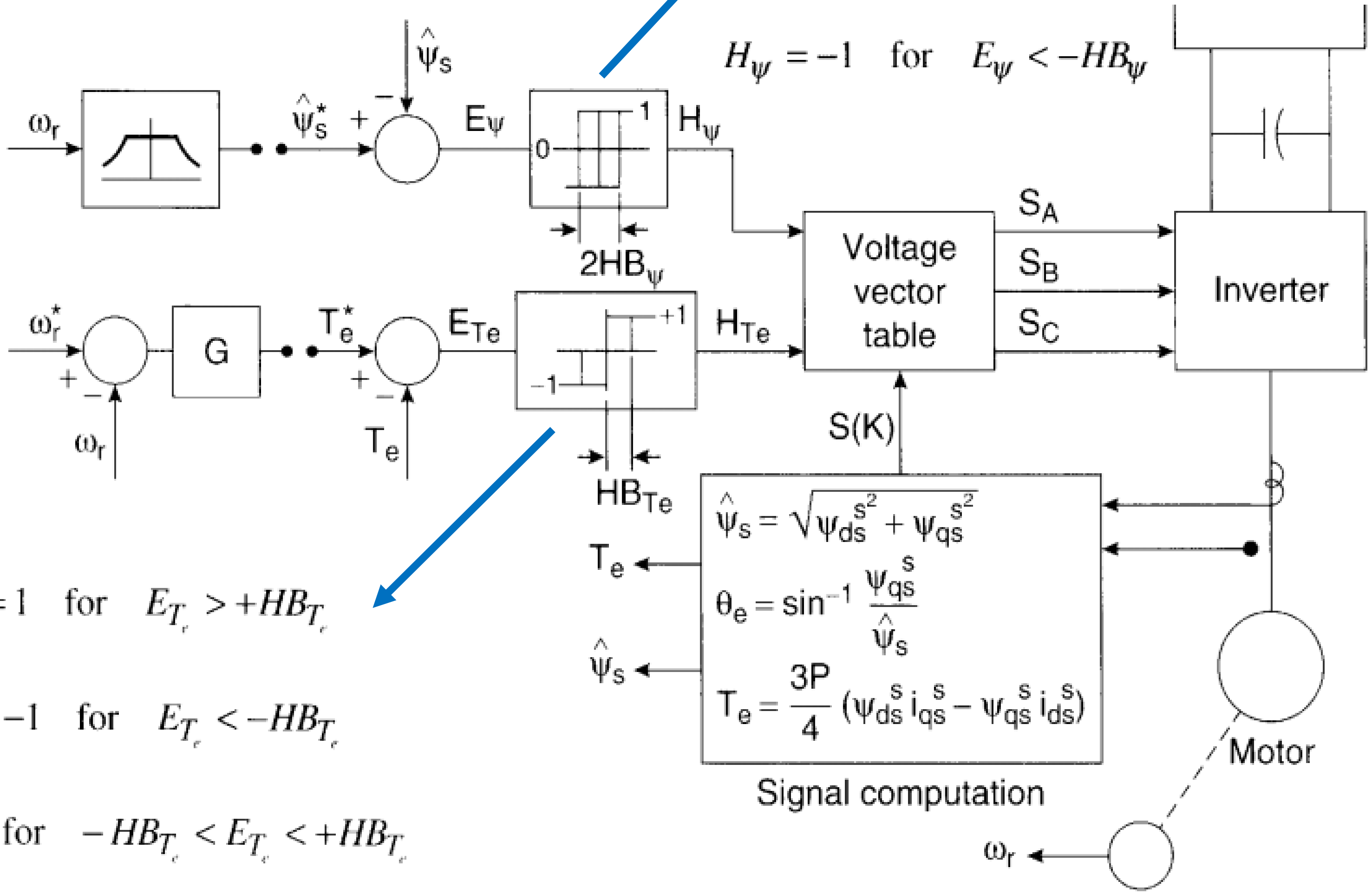
Voltage vector	V_1	V_2	V_3	V_4	V_5	V_6	V_0 or V_7
ψ_s	↑	↑	↓	↓	↓	↑	0
T_e	↓	↑	↑	↑	↓	↓	↓

Ref: Modern Power Electronics and AC Drives by B. Bose

Direct Torque Control

$$H_{\psi} = 1 \quad \text{for} \quad E_{\psi} > +HB_{\psi}$$

$$H_{\psi} = -1 \quad \text{for} \quad E_{\psi} < -HB_{\psi}$$



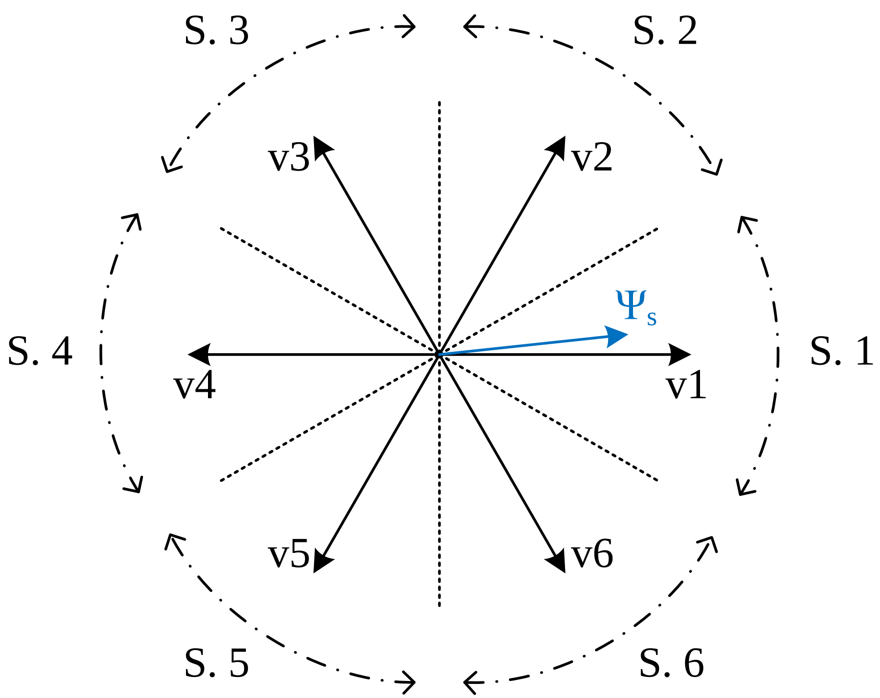
$$H_{Te} = 1 \quad \text{for} \quad E_{T_e} > +HB_{T_e}$$

$$H_{Te} = -1 \quad \text{for} \quad E_{T_e} < -HB_{T_e}$$

$$H_{Te} = 0 \quad \text{for} \quad -HB_{T_e} < E_{T_e} < +HB_{T_e}$$

Ref: Modern Power Electronics and AC Drives by B. Bose

Direct Torque Control



H_ψ	H_{Te}	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_0	V_7	V_0	V_7	V_0	V_7
	−1	V_6	V_1	V_2	V_3	V_4	V_5
−1	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_7	V_0	V_7	V_0	V_7	V_0
	−1	V_5	V_6	V_1	V_2	V_3	V_4

Ref: Modern Power Electronics and AC Drives by B. Bose

Model Predictive Control

Invention: 60s, for power electronics: 2000 and on…

‘Model’ based

A promising alternative for the industry-standard FOC and DTC

Many varieties, our focus is on ‘Finite Control-Set Model Predictive Control’ (FCS-MPC)

ADVANTAGES	DISADVANTAGES
Faster dynamics	Computationally expensive
Simple and intuitive	Performance is model dependent
Flexible	Variable frequency
Good fit for nonlinearities	New (in power electronics)

Model Predictive Control

Measure

ESTIMATION → **PREDICTION** → **OPTIMIZATION**

Apply Vector X

What is the situation now?

What will the situation be in the next step
if I do this and that?

What is the best course of action?

Model Predictive Control - Estimation

$$V_s = R_s I_s + \frac{d\Psi_s}{dt}$$

$$0 = R_r I_r + \frac{d\Psi_r}{dt} - jw_e \Psi_r$$

$$\Psi_s = L_s I_s + L_m I_r$$

$$\Psi_r = L_m I_s + L_r I_r$$

'The Current Model'

$$\frac{d\Psi_r}{dt} = R_r \frac{L_m}{L_r} I_s - \left(\frac{R_r}{L_r} - jw_e\right)\Psi_r$$

$$\Psi_s = \frac{L_m}{L_r}\Psi_r + \sigma L_s I_s$$

Discretized:

$$\Psi_r(k) = \Psi_r(k-1) + \Delta t.\left(R_r \frac{L_m}{L_r} I_s(k) - \left(\frac{R_r}{L_r} - jw_e(k)\right)\Psi_r(k-1)\right)$$

$$\Psi_s(k) = \frac{L_m}{L_r}\Psi_r(k) + \sigma L_s I_s(k)$$

Model Predictive Control – Prediction

The superscript ‘p’ indicates predicted variables.

$$\Psi_s^p(k+1) = \Psi_s(k) + \Delta t.V_i(k) - \Delta t R_s I_s(k)$$

$$I_s^p(k+1) = \left(1 + \frac{\Delta t}{\tau_\sigma}\right) I_s(k) + \frac{\Delta t}{\Delta t + \tau_\sigma} \frac{1}{R_\sigma} \left(\left(\frac{k_r}{\tau_r} - k_r j \omega_e(k) \right) \Psi_r(k) + V_i(k) \right)$$

$$T_e^p(k+1) = 1.5 p \mathfrak{Im}\{\Psi_s^{p*}(k+1) I_s^p(k+1)\}$$

Model Predictive Control – Optimization

The Cost Function:

$$g = \left|T_e^{ref}(k) - T_e^{p}(k+1)\right| + \lambda \left|\left|\Psi_s\right|^{ref} - \left|\Psi_s^{p}(k+1)\right|\right|$$

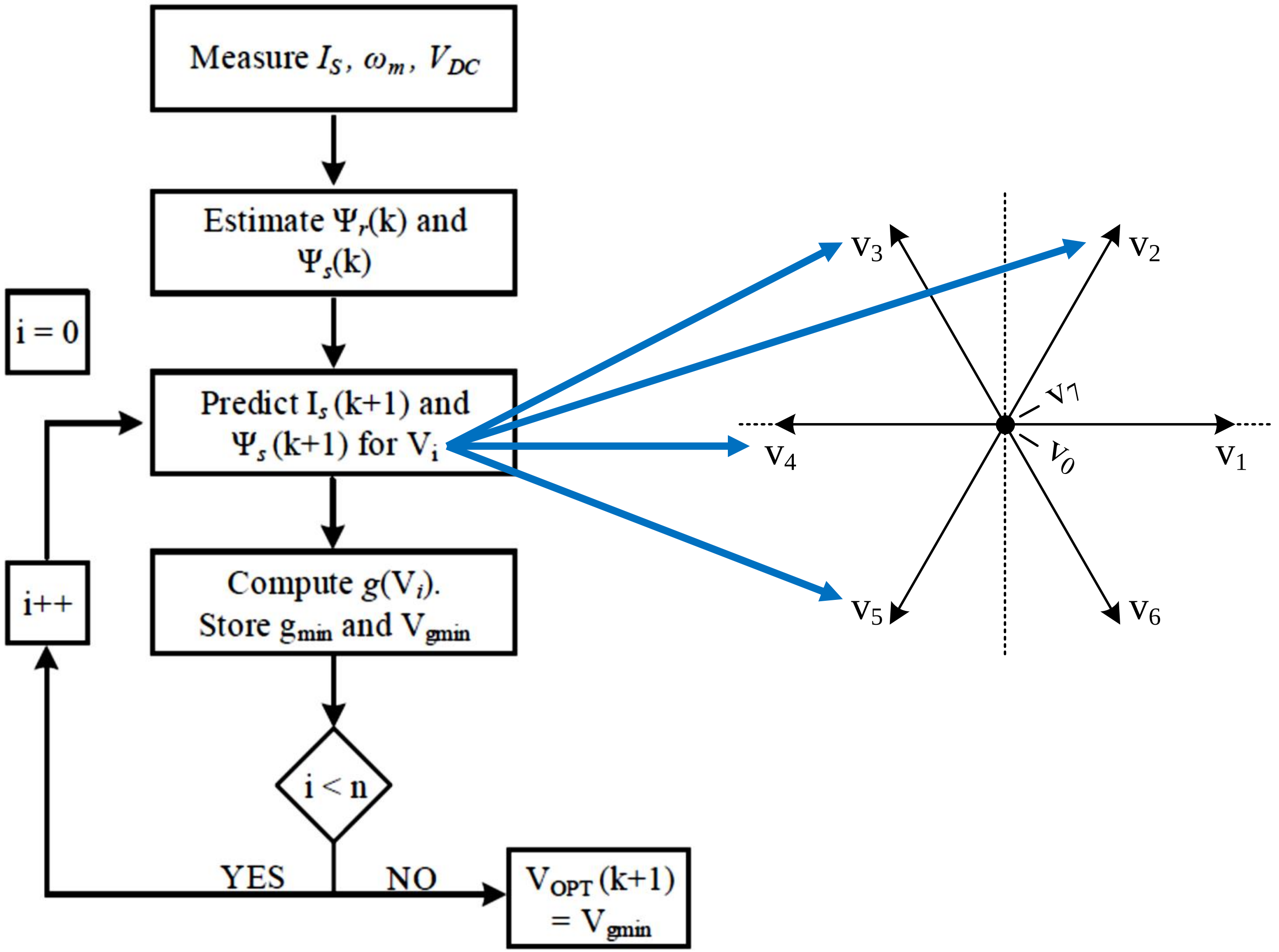
These can also be added:

Switching loss penalty

Capacitor voltage balance

Common mode voltage

Model Predictive Control – Flowchart



A Comparison

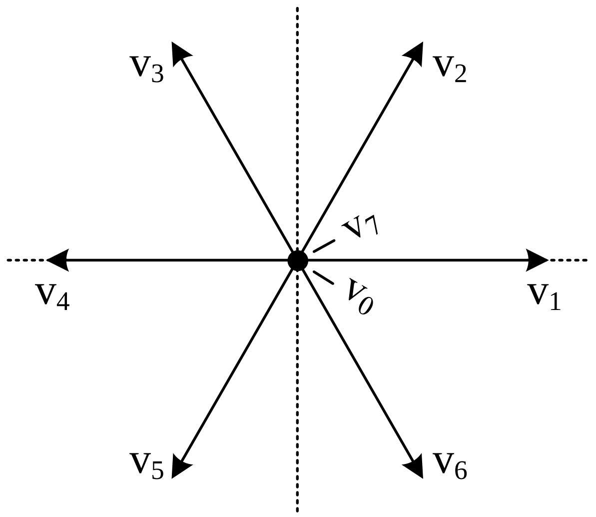
Table 1.1: Comparison among FOC, DTC and PTC

Index	FOC	DTC	PTC
Structural complexity	higher	lower	lower
Axis transformation	yes	no	no
Modulator	yes	no	no
Parameter sensitivity	higher	lower	higher
Position sensor	yes	no	no
Switching frequency	fixed	variable	variable
Inclusion of system nonlinearity	hard	hard	easy
Dynamic response	slower	faster	faster
Torque and flux ripple	lower	higher	lower
Current THD	lower	higher	higher
Computational complexity	lower	lower	higher
Weighting factor	no	no	yes

A Glimpse on Research

- Reduced set
- Dynamic lambda
- Extra vectors and duty cycle feedforward
- High performance observers (for fluxes, machine parameters, etc…)

A Glimpse on Research - 1



Predictions are made for each voltage vector.

Problem: Computational Cost

Propose solution(s)

A Glimpse on Research - 2

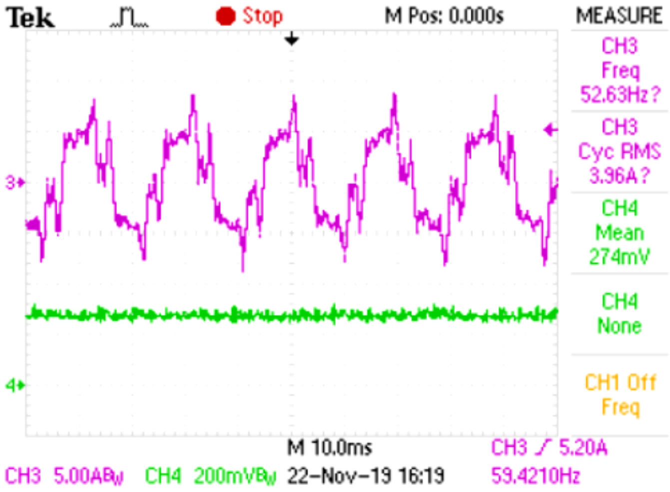
$$g = \left|T_e^{ref}(k) - T_e^{p}(k+1)\right| + \lambda \left| |\Psi_s|^{ref} - \left|\Psi_s^{p}(k+1)\right| \right|$$

How to tune 'Lambda'?

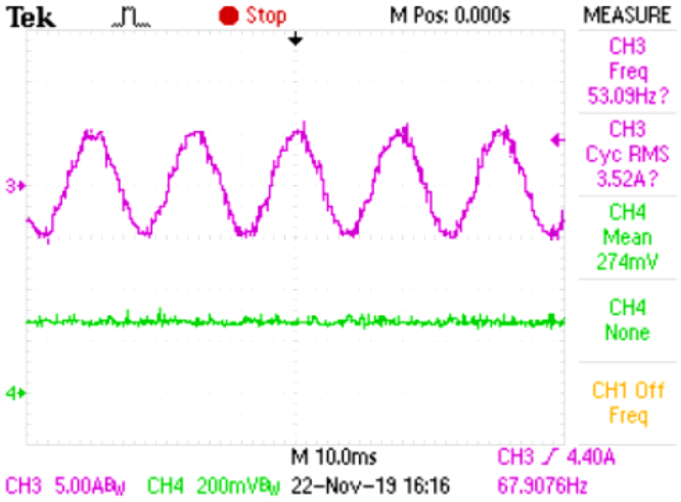
Should 'Lambda' be fixed?

Is it 'one size fits all'?

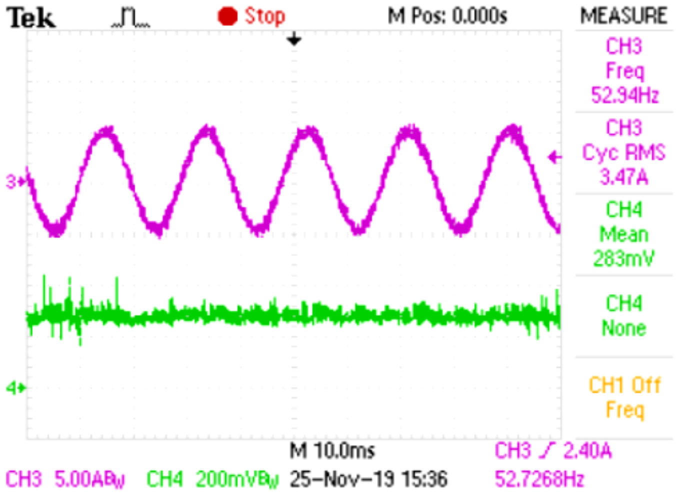
A Glimpse on Research - 2



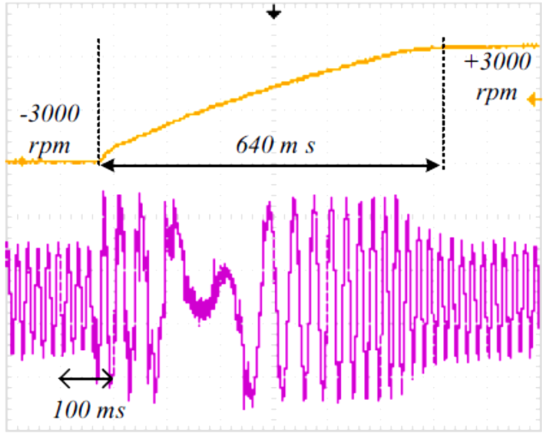
a) $\lambda = 5$



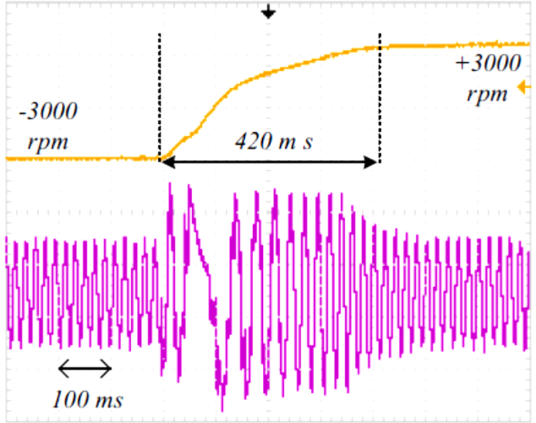
b) $\lambda = 12$



c) $\lambda = 25$

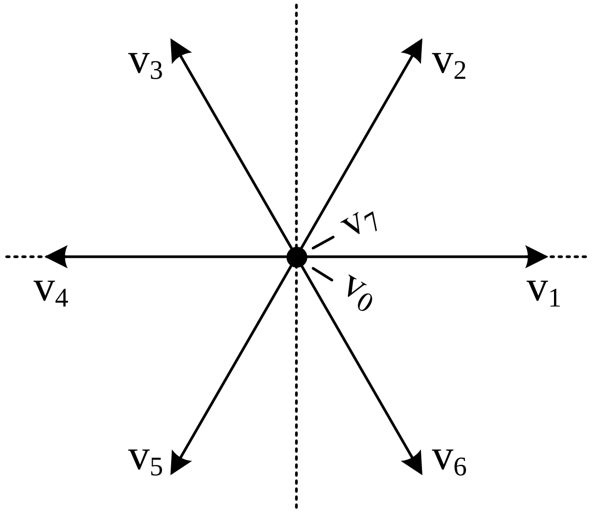


a) $\lambda = 25$



b) $\lambda(\Delta\omega)$ *linear*

A Glimpse on Research - 3

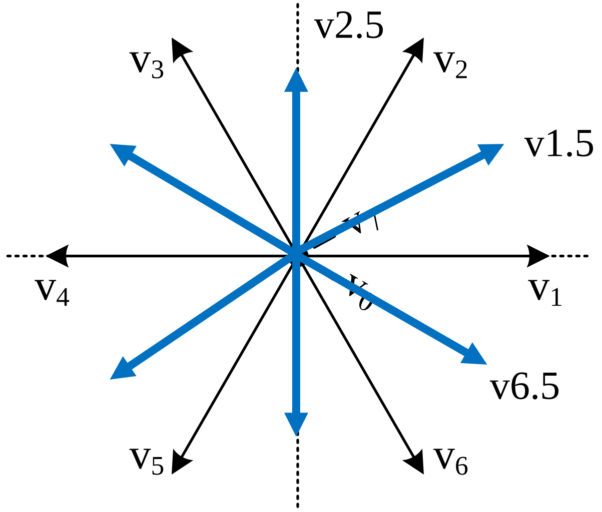


Situation for MPC: v1 – v2 – v1 – v0 – v2 – v3 – v0 - ……

Result: Higher ripple vs FOC

Propose methods to change this.

A Glimpse on Research - 3



Method #1

- Pre-calculate ‘duty cycle’
- Say, d=0.8
- v1 ➞ v1(80%) + v0(20%)
- v2 ➞ v2(80%) + v0(20%)

Method #2

An Overview on Motor Drive Research

- Sensorless Operation
- Drive strategies and their variations for machine types, application types…
- Upgrades for weaknesses (Fixed switching DTC, low ripple MPC, etc…)
- High performance observers (for fluxes, machine parameters, etc…)

The End

Questions?