CITIES Korean International Workshop

MPC APPLICATIONS TO POWER CONVERTERS

22nd October, 2015

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CONTENTS

1. Introduction

Model Predictive Control (MPC)

- Minimize a **cost index** at each time step
- Handle **physical constraints** in a systematic way
- Draw much attention in many application areas

- Require proper **modelling** of target systems
- Require efficient method to solve the **minimization problem**

Power Converters

- AC/DC converter, DC/AC inverter, DC/DC converter
- Used in 'Renewable energy systems', 'Electrical drives', 'Smart grid systems', and etc.
- **Require fast sampling** (> 5KHz)

Key points in MPC derivation

Cost Index Design

- Voltage Regulation, Current Regulation
- Switching Loss etc
- Cost Horizon

⇒ State Tracking Cost Index, Single Horizon

On-line optimization

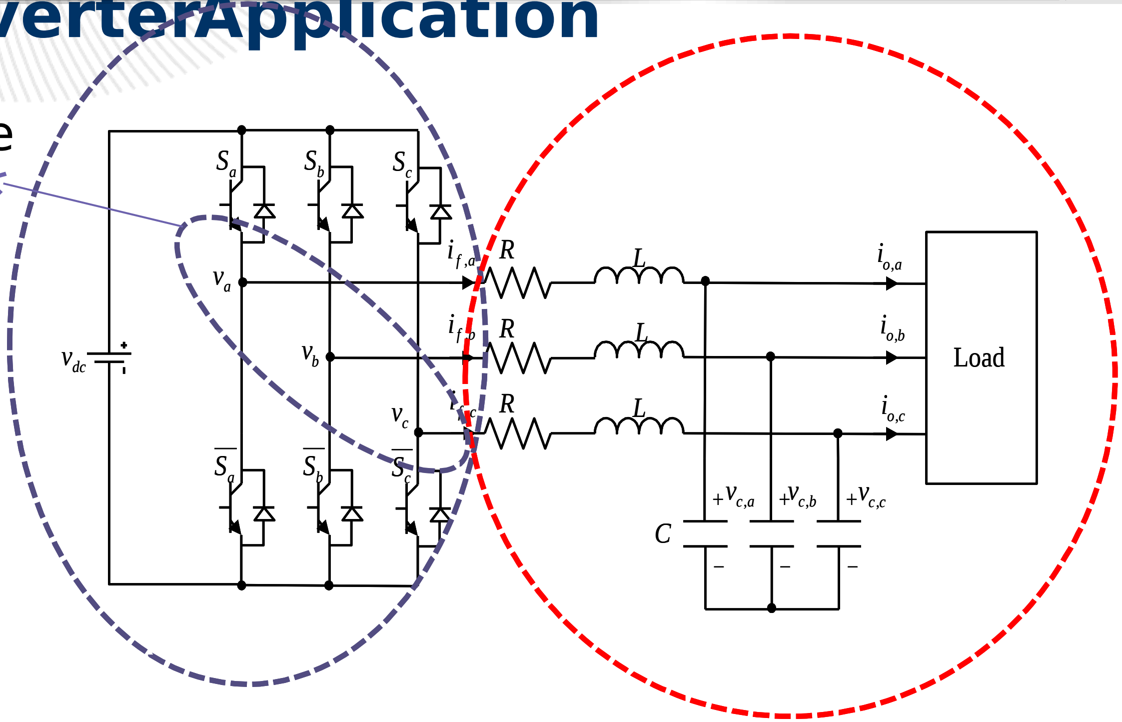
- CCS-MPC
- FCS-MPC

⇒ No numeric algorithm is used

2. The Features of Power Converters

DC/AC Converter – UPS ConverterApplication

Input Voltage
(control)



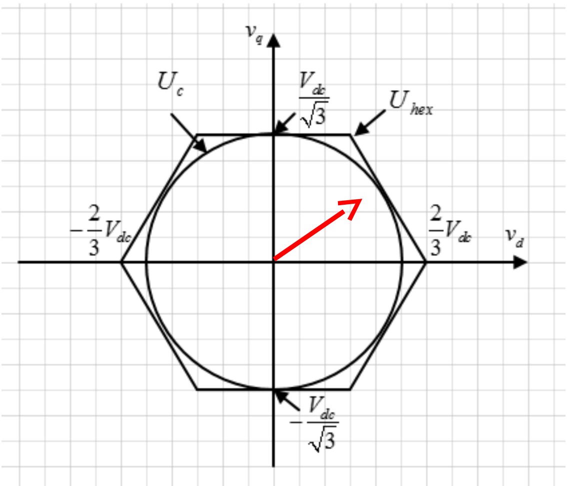
2-Level Inverter
(Actuator)

Output LC Filter & Load
(Plant)

Actuator Setting

VOLTAGE VECTORS OF A TWO-LEVEL INVERTER

State	S_a	S_b	S_c	Voltage Vector
0	OFF	OFF	OFF	$v_0 = 0\angle 0$
1	ON	OFF	OFF	$v_1 = \frac{2}{3}V_{dc}\angle 0$
2	ON	ON	OFF	$v_2 = \frac{2}{3}V_{dc}\angle 60$
3	OFF	ON	OFF	$v_3 = \frac{2}{3}V_{dc}\angle 120$
4	OFF	ON	ON	$v_4 = \frac{2}{3}V_{dc}\angle 180$
5	OFF	OFF	ON	$v_5 = \frac{2}{3}V_{dc}\angle 240$
6	ON	OFF	ON	$v_6 = \frac{2}{3}V_{dc}\angle 300$
7	ON	ON	ON	$v_0 = 0\angle 0$



Finite Control Set Actuation

: The control input is chosen to be one of the available Voltage Vector

: FCS-MPC

Continuous Control Set Actuation

: Synthesize a new vector by adjusting application duration of two adjacent Voltage Vectors

: Space Vector PWM (SV-PWM)

: CCS-MPC

2. The Features of Power Converters

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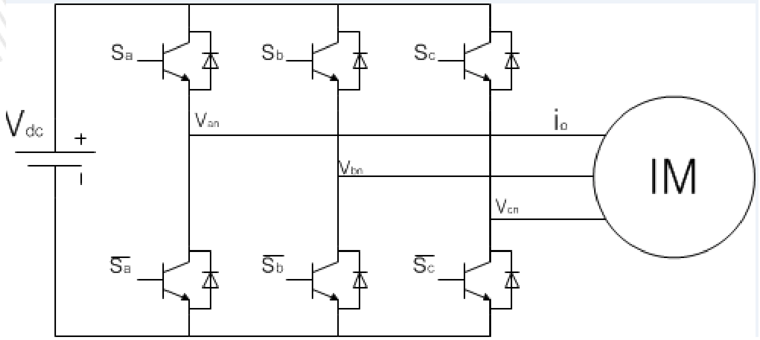
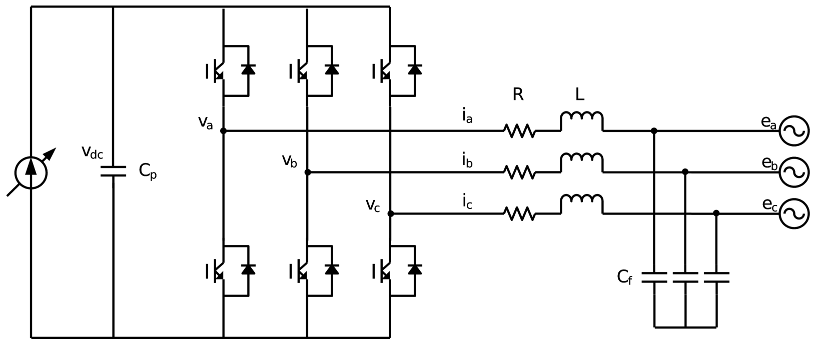
DC/AC Converter – Motor Drive

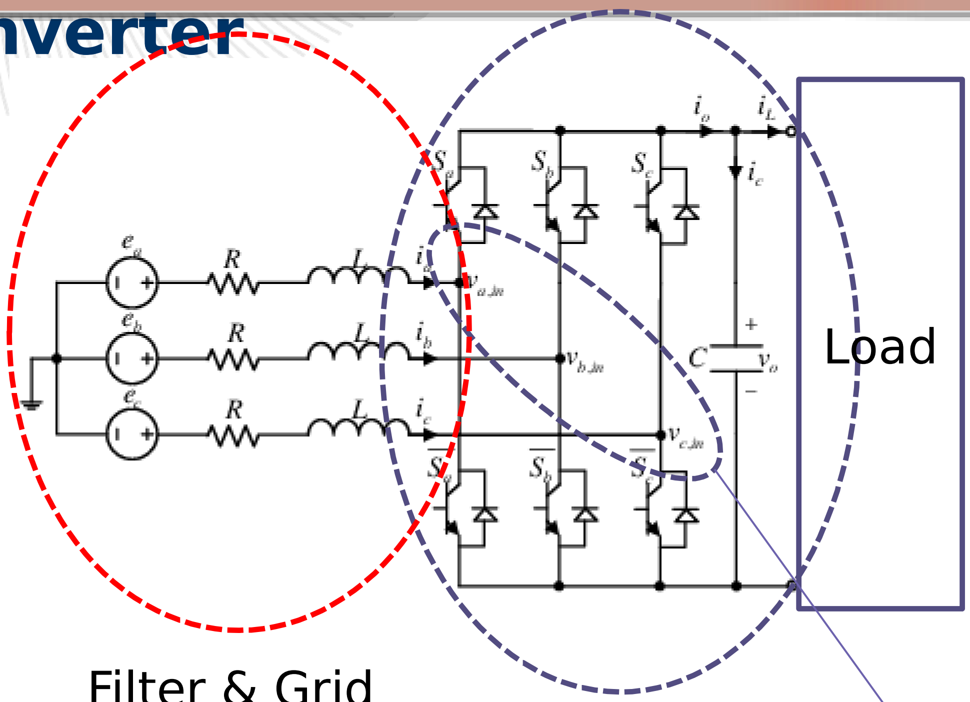


Grid Connected PV Inverter



2. The Features of Power Converters

AC/DC Inverter – Power Control, UPS Converter



Filter & Grid
(Plant)

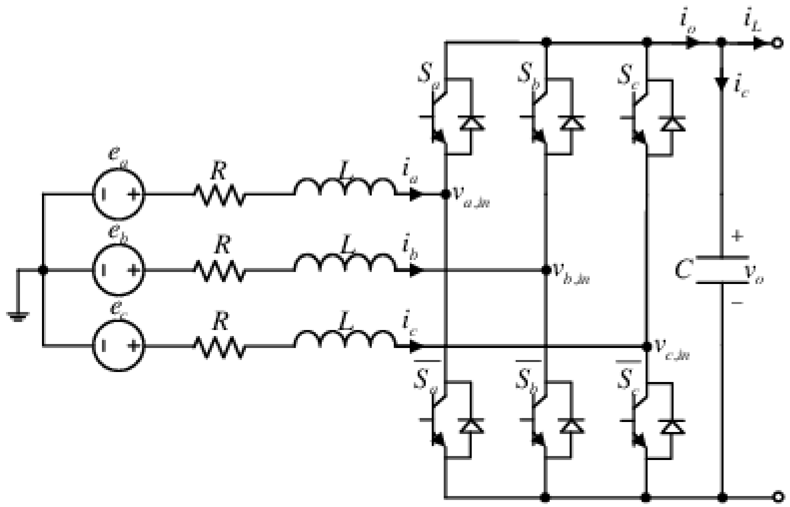
2-Level Inverter
(Actuator)

Input Voltage
(control)

Bilinear Plant Model

3. Power Control using AC/DC Converter

Offset-Free Model Predictive Control for the Power Control of Three-Phase
AC/DC Converters(IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 62, NO. 11, 2015, YI Lee et. al)



$$\frac{d\mathbf{i}_{dq}(t)}{dt} = \mathbf{A}_c \mathbf{i}_{dq}(t) + \mathbf{B}_c v_o(t)\mathbf{u}(t) + \mathbf{d}_c$$

where

$$\mathbf{i}_{dq}(t) := \begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix}, \quad \mathbf{u}(t) := \begin{bmatrix} u_d(t) \\ u_q(t) \end{bmatrix}$$

$$\mathbf{d}_c := \begin{bmatrix} 0 \\ \frac{E_m}{L} \end{bmatrix}, \quad \mathbf{A}_c := \begin{bmatrix} -\frac{R}{L} & -\omega \\ \omega & -\frac{R}{L} \end{bmatrix}$$

$$\mathbf{B}_c := \begin{bmatrix} -\frac{1}{2L} & 0 \\ 0 & -\frac{1}{2L} \end{bmatrix}$$

Active & Reactive Power : $p(t) = \frac{3}{2} E_m i_q(t), \; q(t) = -\frac{3}{2} E_m i_d(t)$

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}v_o\mathbf{u}(k) + \mathbf{d} \quad (9)$$

where

$$\mathbf{x} := \begin{bmatrix} i_d(k) \\ i_q(k) \end{bmatrix} \qquad U_c := \left\{ \mathbf{u} \in \mathbb{R}^2 \mid \|\mathbf{u}\| \le \frac{2}{\sqrt{3}} \right\}$$

A. Desired Steady-State Condition

$$\mathbf{x}^0 = \mathbf{A}\mathbf{x}^0 + \mathbf{B}v_o\mathbf{u}^0 + \mathbf{d}$$

$$\mathbf{x}^0(\mathbf{r}) = \begin{bmatrix} x_1^0(\mathbf{r}) \\ x_2^0(\mathbf{r}) \end{bmatrix} = \begin{bmatrix} -\frac{2r_q}{3E_m} \\ \frac{2r_p}{3E_m} \end{bmatrix}$$

$$\mathbf{u}^0(\mathbf{r}, \mathbf{d}) = \frac{1}{v_o}\mathbf{B}^{-1}\left((\mathbf{I}_{2\times 2} - \mathbf{A})\mathbf{x}^0(\mathbf{r}) - \mathbf{d}\right).$$

B. DOB Design

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}v_o\mathbf{u}(k) + \tilde{\mathbf{d}}(k)$$

$$\tilde{\mathbf{d}}(k+1) = \tilde{\mathbf{d}}(k).$$

$$\mathbf{z}(k+1) = \mathbf{A}_a\mathbf{z}(k) + \mathbf{B}_a v_o\mathbf{u}(k) \qquad (17)$$

$$\mathbf{y}(k) = \mathbf{C}_a\mathbf{z}(k) \qquad (18)$$

where

$$\mathbf{z}(k) := \begin{bmatrix} \mathbf{x}(k) \\ \tilde{\mathbf{d}}(k) \end{bmatrix}, \; \mathbf{A}_a := \begin{bmatrix} \mathbf{A} & \mathbf{I}_{2\times2} \\ \mathbf{0}_{2\times2} & \mathbf{I}_{2\times2} \end{bmatrix} (\in \mathbb{R}^{4\times4})$$

$$\mathbf{B}_a := \begin{bmatrix} \mathbf{B} \\ \mathbf{0}_{2\times2} \end{bmatrix} (\in \mathbb{R}^{4\times2}), \; \mathbf{C}_a := [\mathbf{I}_{2\times2} \quad \mathbf{0}_{2\times2}] (\in \mathbb{R}^{2\times4}).$$

The DOB to estimate $\tilde{\mathbf{d}}(k)$ is constructed as

$$\hat{\mathbf{z}}(k+1) = \mathbf{A}_a\hat{\mathbf{z}}(k) + \mathbf{B}_a v_o\mathbf{u}(k) + \mathbf{L}_{\text{obs}}\mathbf{C}_a\mathbf{e}_z(k)$$

C. MPC Design

$$J\left(\mathbf{x}(k),\mathbf{u}(k)\right) := \|\hat{\mathbf{e}}(k+1|k)\|_{\mathbf{P}}^2 + r_u \left\|\mathbf{u}(k) - \hat{\mathbf{u}}^0(k)\right\|^2$$

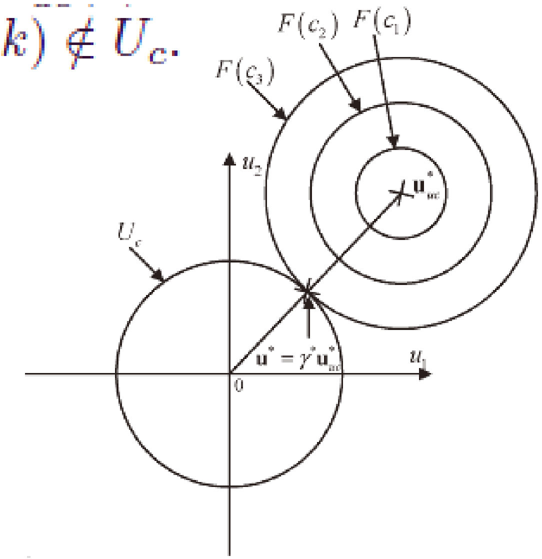
$$\begin{aligned}\hat{\mathbf{e}}(k+1|k) &:= \mathbf{e}(k+1|k)\Big|_{\tilde{\mathbf{d}}=\hat{\mathbf{d}}(k)} \\ &= \mathbf{A}\mathbf{x}(k) + \mathbf{B}v_o\mathbf{u}(k) + \hat{\mathbf{d}}(k) - \mathbf{x}^0(\mathbf{r})\end{aligned}$$

$$\begin{aligned}\hat{\mathbf{u}}^0(k) &:= \mathbf{u}^0(\mathbf{r},\tilde{\mathbf{d}})\Big|_{\tilde{\mathbf{d}}=\hat{\mathbf{d}}(k)} \\ &= \frac{1}{v_o}\mathbf{B}^{-1}\left((\mathbf{I}_{2\times 2} - \mathbf{A})\mathbf{x}^0(\mathbf{r}) - \hat{\mathbf{d}}(k)\right).\end{aligned}$$

$$\min_{\mathbf{u}(k)\in U_c} J\left(\mathbf{x}(k),\mathbf{u}(k)\right).$$

$$\mathbf{u}_{uc}^{*}(k) = -\Phi(v_o)^{-1}\left(v_o \mathbf{B}^T \mathbf{P}\mathbf{w}(k) - r_u \hat{\mathbf{u}}^0(k)\right) \quad \text{if } \mathbf{u}_{uc}^{*}(k) \in U_c.$$

$\mathbf{u}_{uc}^{*}(k) \notin U_c.$

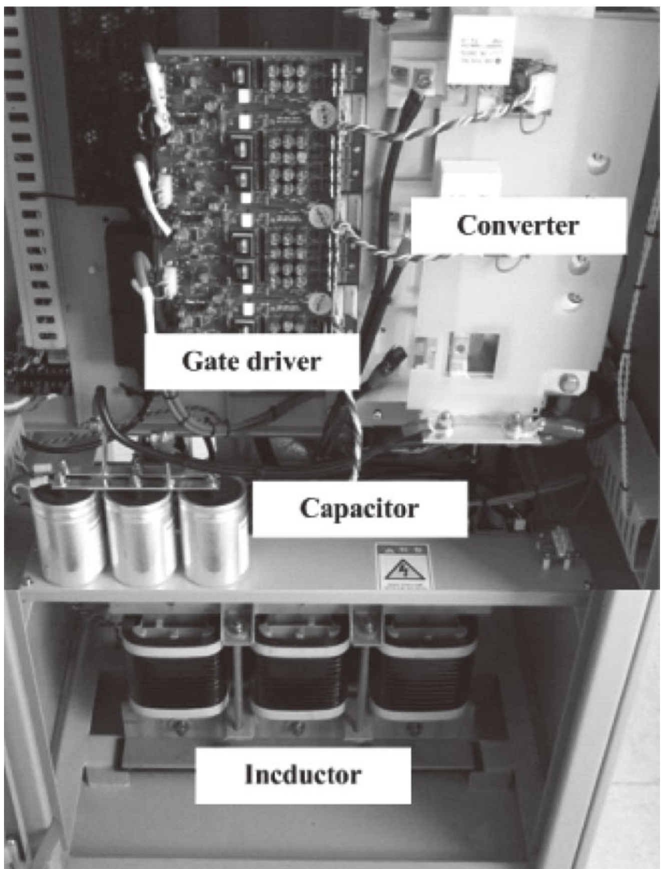


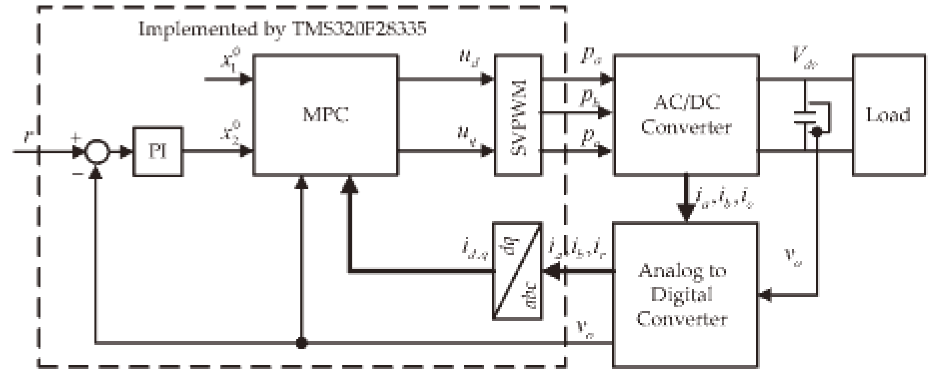
$$\mathbf{B}^T\mathbf{P}\mathbf{B} = \beta \mathbf{I}_{2\times 2}.$$

Stability is guaranteed if P is chosen properly

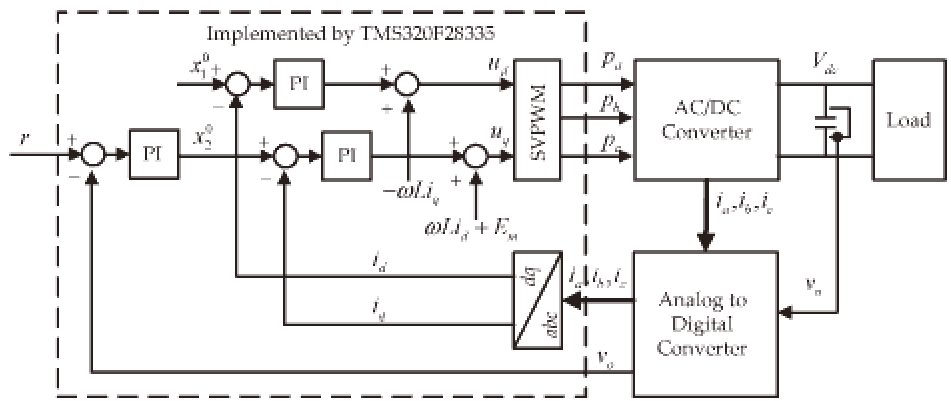
V. EXPERIMENTS

25KW AC/DC Converter with $R = 4\,Ohm$

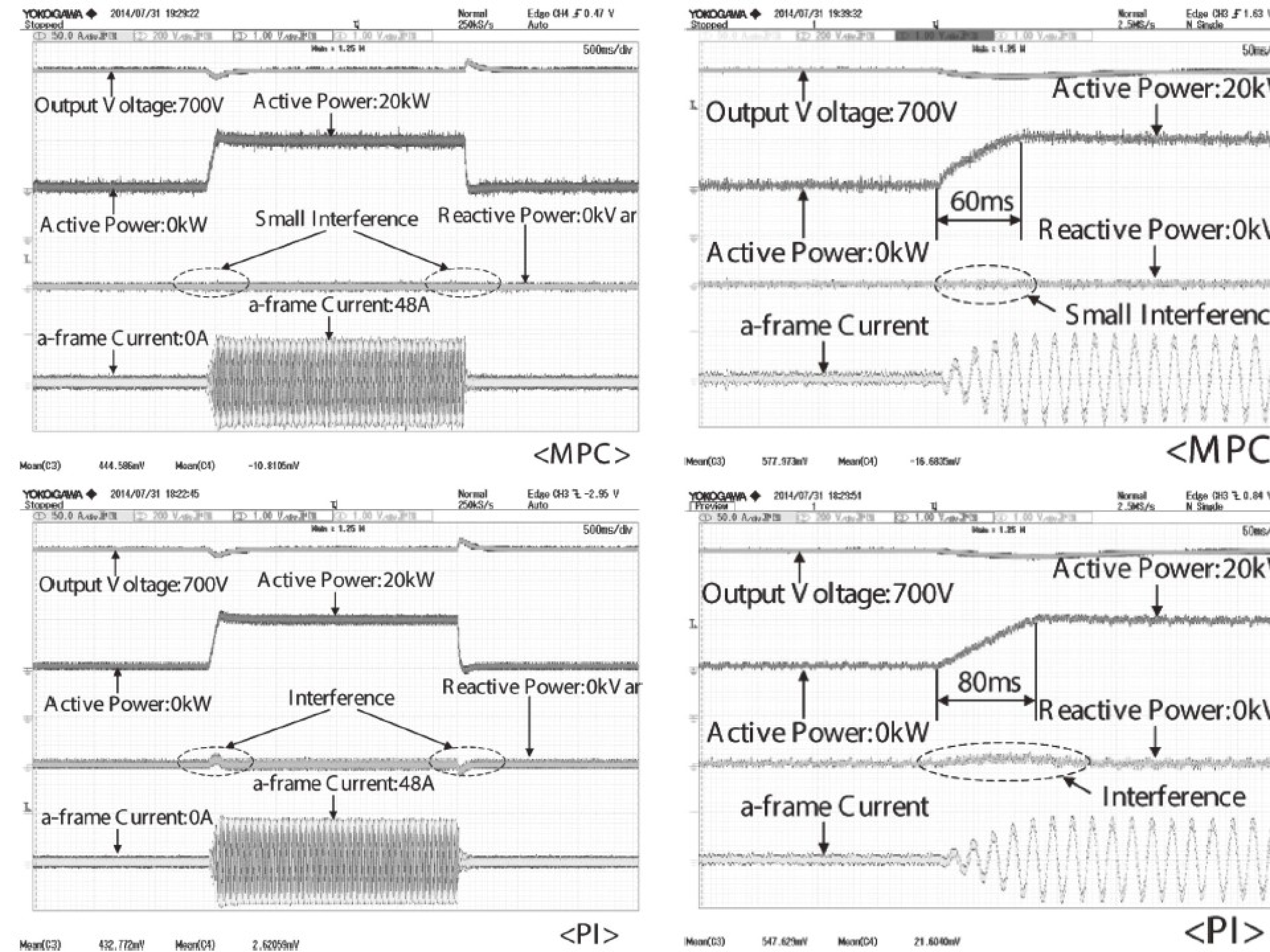




<Implemented Closed-Loop System using the proposed MPC>



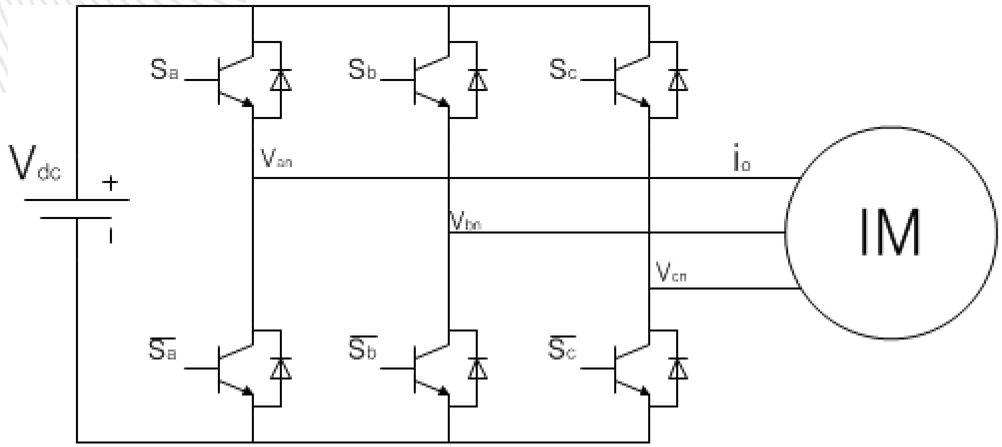
<Implemented Closed-Loop System using the classical PI scheme>



Output Voltage:700V
Active Power:20kW
Active Power:0kW
Small Interference
Reactive Power:0kVar
a-frame Current:48A
a-frame Current:0A
<MPC>
Output Voltage:700V
Active Power:20kW
Active Power:0kW
60ms
Reactive Power:0kV
Small Interferenc
a-frame Current
<MPC
Output Voltage:700V
Active Power:20kW
Active Power:0kW
Interference
Reactive Power:0kVar
a-frame Current:48A
a-frame Current:0A
<PI>
Output Voltage:700V
Active Power:20kW
80ms
Reactive Power:0kV
Active Power:0kW
Interference
a-frame Current
<PI>

4. Torque Control of an Induction Motor

Finite Control Set Model Predictive Control Method for Torque Control of Induction Motors using a State Tracking Cost Index, submitted to IEEE PE



Model :

$$x[k+1] = Ax[k] + Bu[k]$$

$$A = I_{4\times 4} + A_c h, \;\; B = B_c h,$$

$$x[k] = \begin{bmatrix} i_{dqs}[k] \\ \lambda_{dqr}[k] \end{bmatrix}, u[k] = \begin{bmatrix} v_{dq}[k] \\ 0 \end{bmatrix}.$$

Torque :

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}),$$

Reference State computation

The reference torque $T_e^*(k)$ is assumed to be given

A method to provide a proper reference state $x^*(T_e^*(k))$

$$x^*(T_e^*, \lambda^*) = \begin{bmatrix} i_{ds}^* \\ i_{qs}^* \\ \lambda_{dr}^* \\ \lambda_{qr}^* \end{bmatrix} = \begin{bmatrix} \frac{\lambda^*}{L_m} \\ \frac{2}{3}\frac{2}{P}\frac{L_r}{L_m}\frac{T_e^*}{\lambda^*} \\ \lambda^* \\ 0 \end{bmatrix}.$$

MTPA flux reference is:

$$\hat{\lambda}^*(k) = \sqrt{\frac{2}{3}\frac{2}{P}L_r T_e^*(k)}.$$

Definition of a cost function

$$J(k) = (x^*(T_e^*, \lambda^*) - x[k+1|k])^T W (x^*(T_e^*, \lambda^*) - x[k+1|k]),$$

Choice of Weighting : $W - A^T W A > 0$

$$J(k) = \sum_{j=0}^{\infty} e^T[k+j]\Psi e[k+j]$$

$$\Psi := W - A^T W A.$$

Solution of the FCS-MPC

TABLE I

VOLTAGE VECTORS OF A TWO-LEVEL INVERTER

State	S_a	S_b	S_c	Voltage Vector
0	OFF	OFF	OFF	$v_0 = 0\angle 0$
1	ON	OFF	OFF	$v_1 = \frac{2}{3}V_{dc}\angle 0$
2	ON	ON	OFF	$v_2 = \frac{2}{3}V_{dc}\angle 60$
3	OFF	ON	OFF	$v_3 = \frac{2}{3}V_{dc}\angle 120$
4	OFF	ON	ON	$v_4 = \frac{2}{3}V_{dc}\angle 180$
5	OFF	OFF	ON	$v_5 = \frac{2}{3}V_{dc}\angle 240$
6	ON	OFF	ON	$v_6 = \frac{2}{3}V_{dc}\angle 300$
7	ON	ON	ON	$v_0 = 0\angle 0$

Step 1:

- Evaluate the cost index for the voltage vectors
- Choose the optimal voltage vector

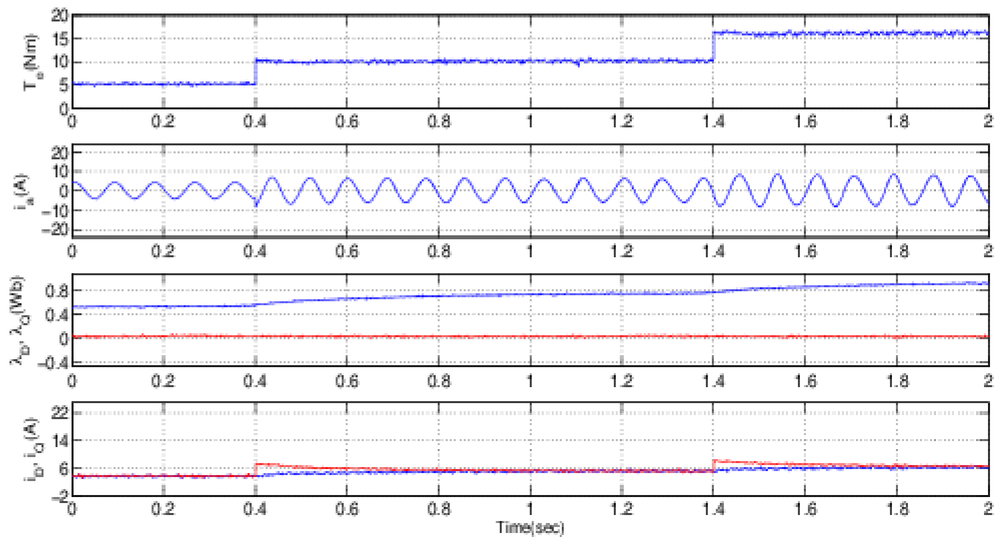
$$v_{sel}(k).$$

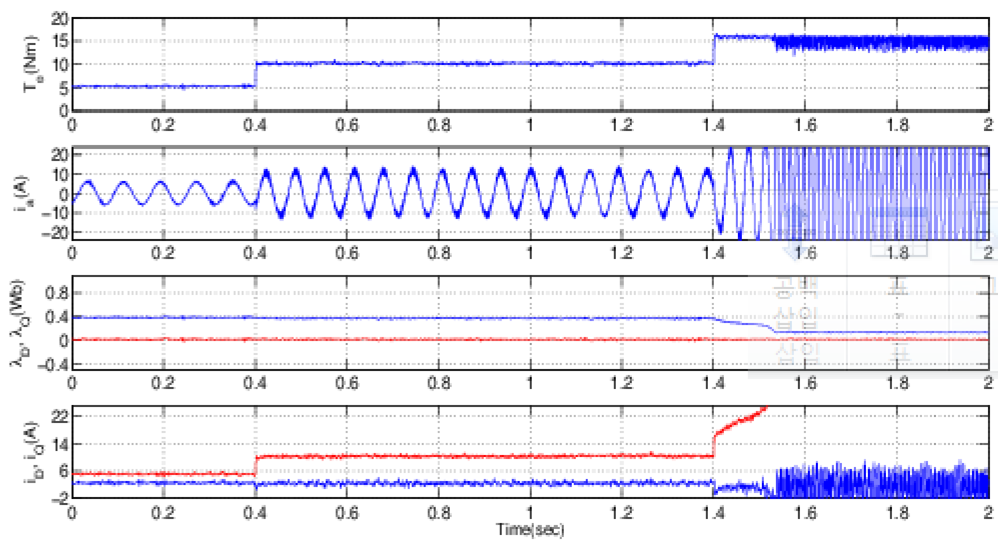
Step 2:

- Compute the optimal modulation factor minimizing the cost index further

$$\mu^* = \frac{v_{sel}^T B^T W (x^*(T_e^*, \lambda^*) - Ax[k])}{2v_{sel}^T B^T W B v_{sel}}$$

Experiments


Te(Nm)
ia(A)
λD, λQ(Wb)
iD, iQ(A)
Time(sec)


Te(Nm)
ia(A)
λD, λQ(Wb)
iD, iQ(A)
Time(sec)

5. Discussion

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How to cooperate ?

- BESS management
- Grid Connection of PV
- EV