Intelligent Fault Tolerant Control of Six-Phase Permanent Magnet Synchronous Motor Drive System for Light Electric Vehicle

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Outline

Abstract

- Due to the greenhouse effect and fossil energy shortage, the concept of carbon reduction and energy saving has been valued highly. Thus, light electric vehicles (LEVs) with high energy efficiency and low emissions are believed to be the best choice of transportation in the future.
- Fault tolerant control for a motor drive system enables a motor to continue operating properly in the event of the failure.
- The purpose of this dissertation is to develop a digital signal processor (DSP)-based intelligent fault tolerant control of six-phase permanent magnet synchronous motor (PMSM) drive system.
- The developed intelligent fault tolerant control motor drive system will be applied to an in-wheel motor drive system in LEV to fulfill the requirements of the safety and system stability in LEV applications.

Outline

- Abstract
- Introduction
- DSP-Based Control System and Six-Phase PMSM Drive System
  - DSP-Based Control System
  - Six-Phase PMSM Drive System and Experimental Setup
- Dynamic Modeling Analysis of Six-Phase PMSM Drive System and Fault Tolerant Control
  - Dynamics of Six-Phase PMSM
  - Fault Tolerant Control
  - Applications: Modeling of LEV and In-Wheel Motor Drive System
- Fault Tolerant Control of Six-Phase PMSM Drive System
  - Using TSKFNN-AMF Control
  - Using Intelligent Complementary Sliding Mode Control
- Fault Tolerant Control of In-Wheel Motor Drive System Using Six-Phase PMSM via Probabilistic Fuzzy Neural Network Control
- Discussions, Conclusions, and Suggestions for Future Works

Introduction

- The technologies of electric vehicles (EVs), including the fuel-cell electric vehicles (FCEVs), hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs), have been developed very rapidly as a solution to energy and environmental problems.

- EVs become popular in some applications, including short-range transportations and motorized wheelchairs. Moreover, to consider the possible change of the habit of driver and the development of the public transportation in the future, LEVs are developed and believed to be the best choice of transportation in the future.

- As an LEV is driven by electric motors, it has the advantages of fast and accurate motor torque generation. Moreover, motors can be installed in two or four wheels with individual control as in-wheel motors.

Introduction

- Products of various kinds of EVs [2]:


Smart EV


Mitsubishi iMiEV


Nissan LEAF


Luxgen EV+


Honda Fit EV


Mini E


Chevrolet Spark EV


Ford Focus Electric

EV


Toyota Prius


Toyota Camry Hybrid


Lexus GS450h


Honda Civic Hybrid


Porsche Cayenne S Hybrid

HEV


Porsche Panamera S E Hybrid


Volvo XC60 Plug-In Hybrid


Mitsubishi Outlander PHEV


Toyota Prius Plug-In


Chevrolet Volt


Honda Accord Plug-In


Cadillac ELR

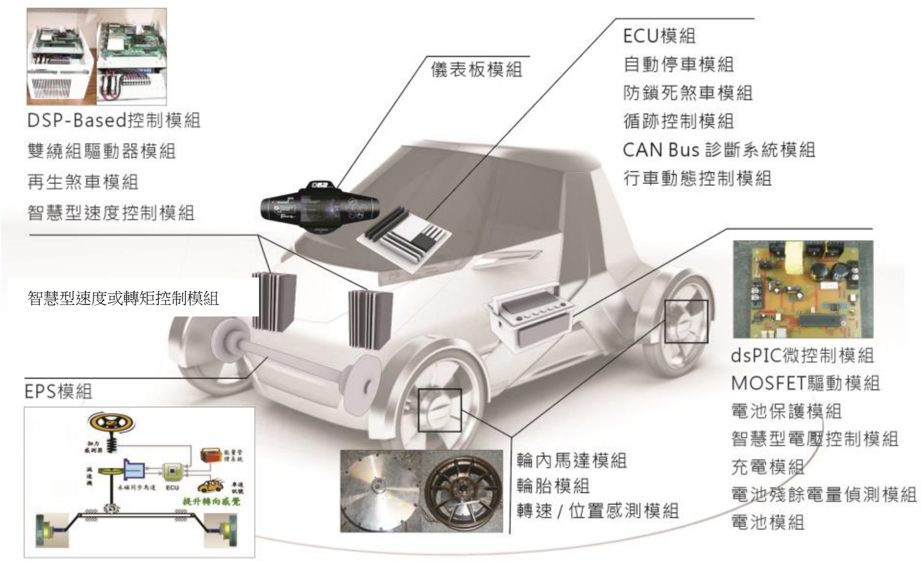
PHEV

主機板式輕量化移動載具前瞻技術

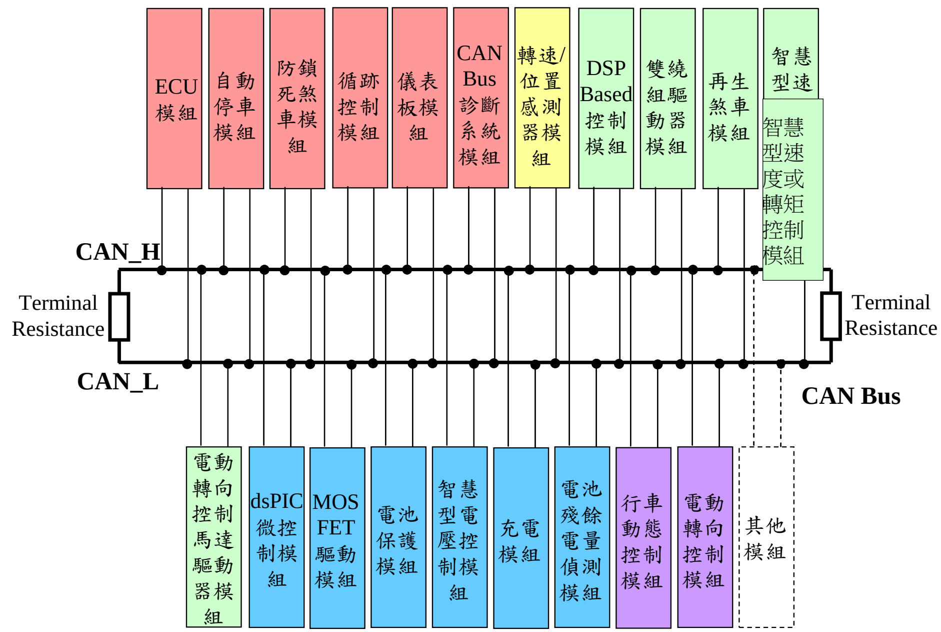
各分項計畫之研究目標與提供之專長

計畫項目	目標	專長
總計畫	主機板式智慧型輕量化移動載具前瞻技術	電機控制、系統整合
子計畫一	行車控制器主機板模組之研發與自動診斷系統設計	車用電子通訊設備
子計畫二	輪內永磁式同步馬達分析及設計	馬達設計與分析
子計畫三	輪內永磁式同步馬達驅動系統	馬達驅動與控制
子計畫四	智能型電池能量管理系統	電池能量管理
子計畫五	載具創意概念設計	車體創意設計
子計畫六	輕量化移動載具動態控制系統之研究	車輛動態系統分析
子計畫七	智慧型輕量化移動載具規格之研究－以主機板式智慧型移動載具前瞻技術研究專案為例	標準規範之訂定

各子計畫之模組利用摩特動力公司之Bug Racer 500為實驗平台進行測試。



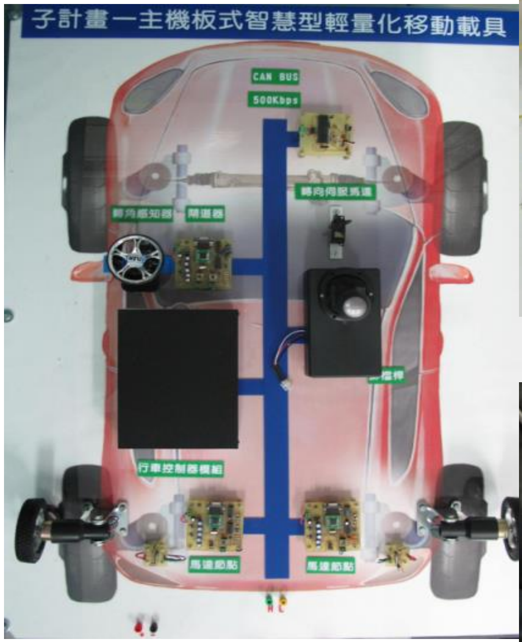
主機板式智慧型輕量移動載具之全車模組圖



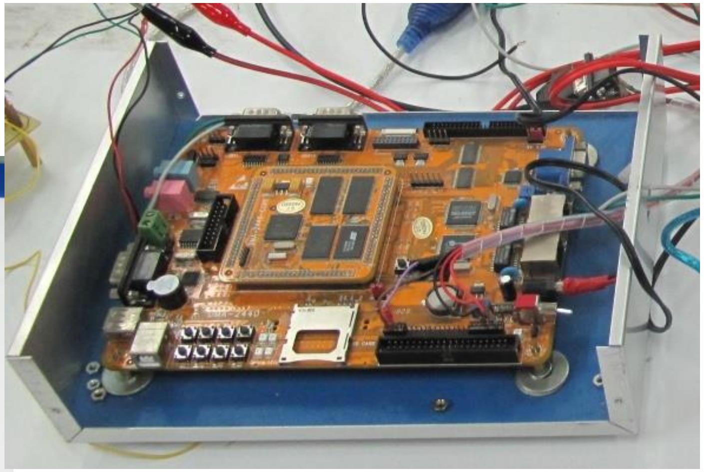
主機板式智慧型輕量移動載具之全車模組CAN Bus網路圖

關鍵模組研究成果

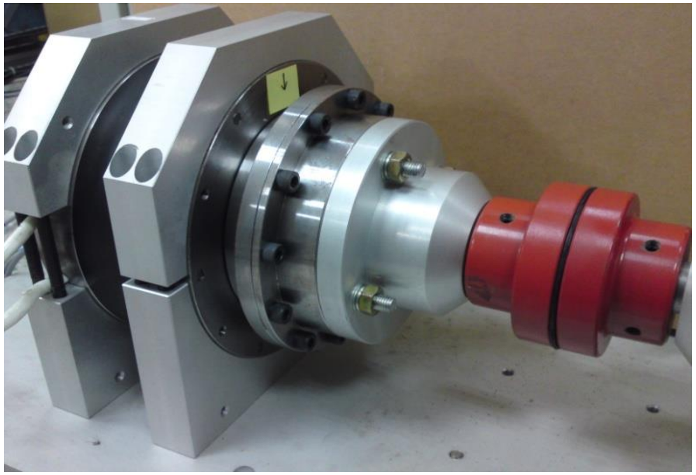
- 關鍵模組實品



CAN Bus連線Demo板



行車控制器主機板模組



六相永磁同步輪內齒輪馬達

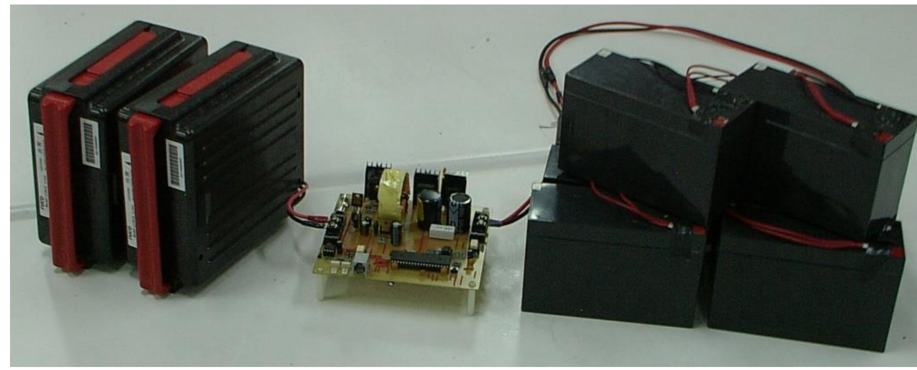
儀表板及診斷模組

六相永磁同步輪內齒輪馬達驅動與控制模組

關鍵模組研究成果

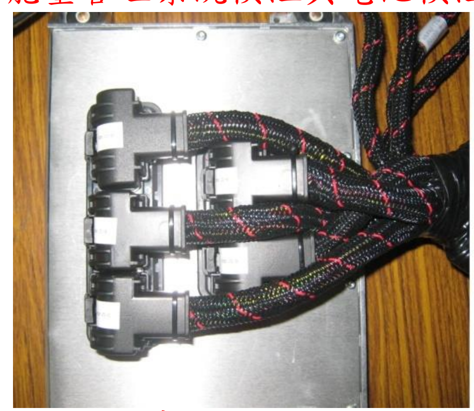
- 關鍵模組實品

電動轉向馬達



能量管理系統模組與電池模組

電動轉向馬達驅動與控制模組

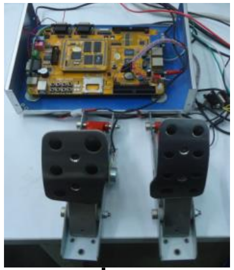


行車動態控制模組

關鍵模組研究成果

- CAN Bus連線整合測試

子計畫一 行車控制器模組



子計畫一 儀表模組

油門、煞車踏板訊號

車速訊號

鋰電池、
鉛酸電池SOC訊號

馬達命令
輪速訊號

子計畫六 行車動態模組 子計畫三 馬達控制器模組 子計畫四 電能管理模組

CAN Bus連線整合測試架構圖

CAN Bus連線整合測試實測影片

子計畫一

傳送油門煞
車踏板訊號

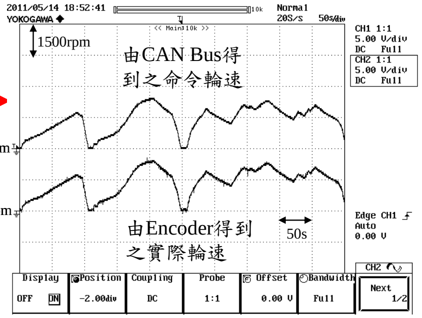
子計畫六

傳送命令
輪速訊號

子計畫三

傳送實際
輪速訊號

馬達輪速
訊號波形



CAN Bus連線測試(輪內馬達驅動)架構與結果圖

Number	Direction	CAN	TimeIdentifier	FrameID	Format	Type	DataLength	Data
00001338	Receive	0	0x00c98080	0x0c000100	Data	Extend	0x08	50 2e 01 00 00 00 00 00
00001339	Receive	0	0x00c980b5	0x0c000300	Data	Extend	0x08	32 5a 32 5a 00 00 00 00
00001340	Receive	0	0x00c980c5	0x0c000700	Data	Extend	0x08	00 00 00 00 00 00 00 00
00001341	Receive	0	0x00c9811c	0x0c000300	Data	Extend	0x08	32 5a 32 5a 00 00 00 00
00001342	Receive	0	0x00c9812c	0x0c000700	Data	Extend	0x08	00 00 00 00 00 00 00 00
00001343	Receive	0	0x00c9813d	0x0c000000	Data	Extend	0x08	00 00 00 00 00 00 00 00
00001344	Receive	0	0x00c9814d	0x0c000100	Data	Extend	0x08	50 2e 01 00 00 00 00 00
00001345	Receive	0	0x00c98183	0x0c000300	Data	Extend	0x08	32 5a 32 5a 00 00 00 00
00001346	Receive	0	0x00c98193	0x0c000700	Data	Extend	0x08	00 00 00 00 00 00 00 00
00001347	Receive	0	0x00c981ea	0x0c000300	Data	Extend	0x08	32 5a 32 5a 00 00 00 00

命令輪速
訊號

踏板訊號

CAN Bus分析儀之訊號分析結果

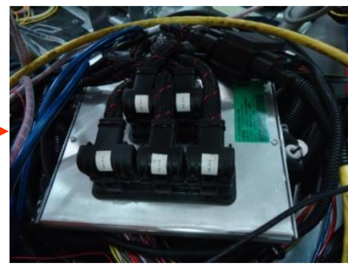
關鍵模組研究成果

- 能量管理系統提供輪內馬達運轉之電能供應測試

子計畫一行車控制器模組

傳送油門及
煞車踏板訊號

子計畫六行車動態模組



傳送命令
輪速訊號

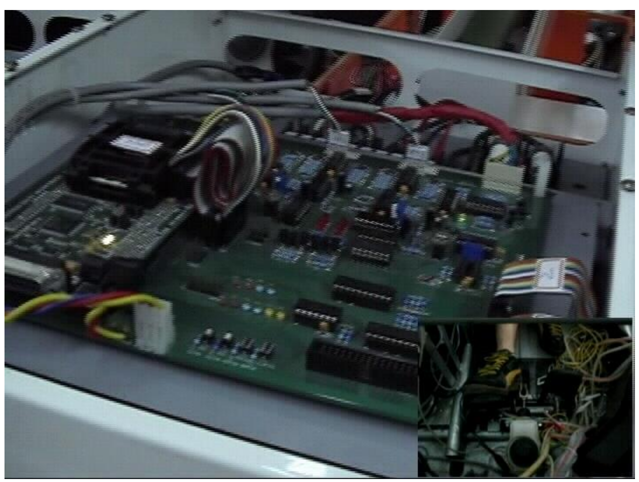
子計畫三輪內馬達驅動器

驅動

子計畫二輪內馬達

電能供應

子計畫四能量管理系統



能量管理系統提供輪內馬達運
轉之電能供應測試實測影片

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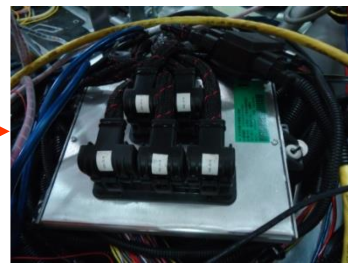
關鍵模組研究成果

- EPS轉向系統測試

子計畫一行車控制器模組

傳送方向盤
轉角訊號

子計畫六行車動態模組

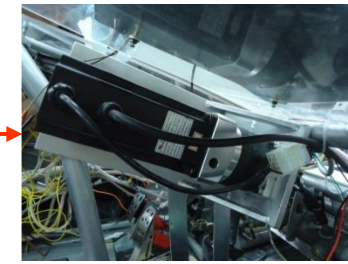


傳送命令
轉角訊號

子計畫三EPS馬達驅動器

驅動

EPS馬達



電能供應

子計畫四能量管理系統

EPS轉向系統測試實測影片

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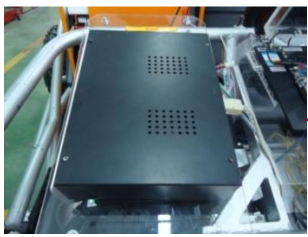
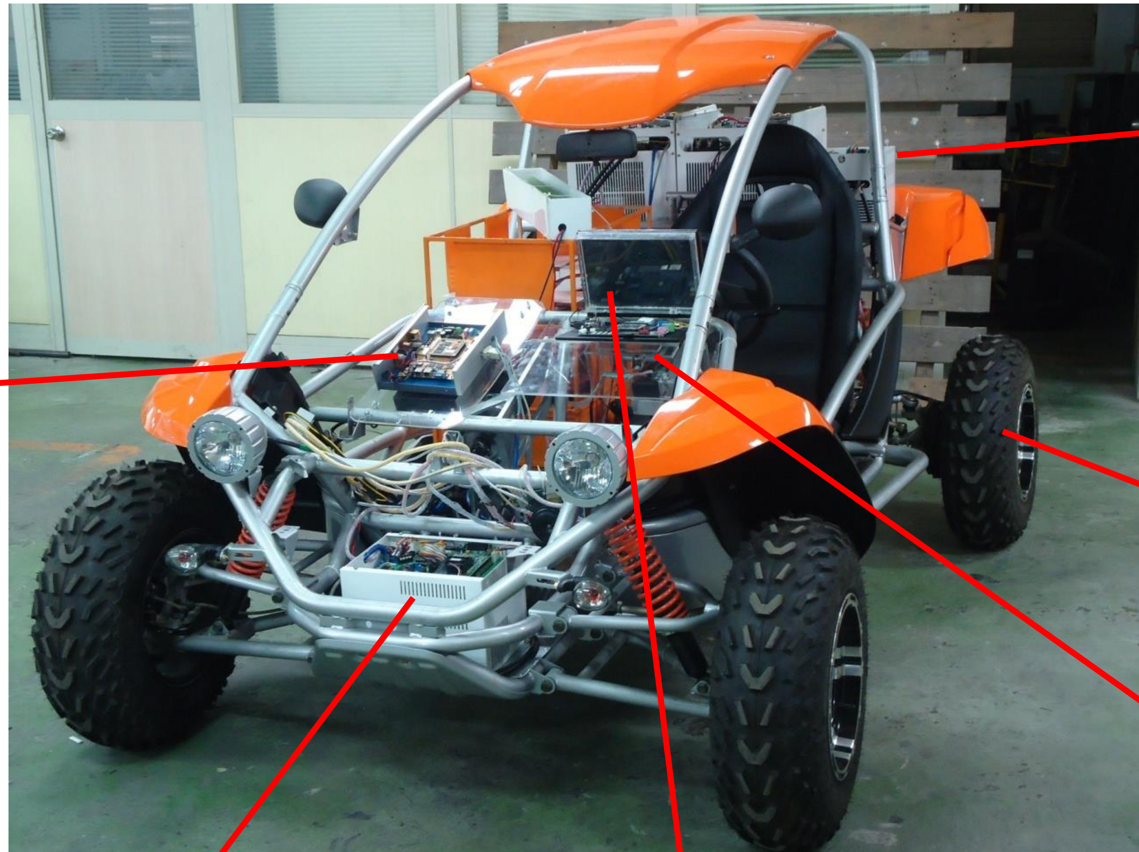
全車整合測試成果



行車控制器主機板模組



EPS馬達驅動器模組(後)

六相永磁同步輪
內齒輪馬達(左)

方向盤轉角感知器

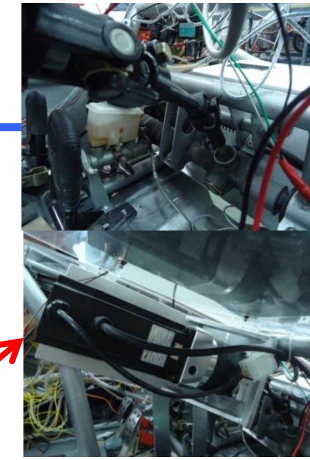
EPS馬達驅動器模組(前)

儀表板與自動診斷系統模組

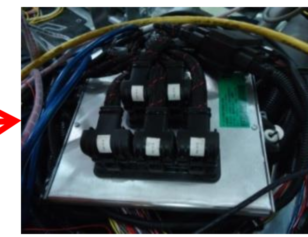
全車整合測試成果

輪內馬達驅動器模組

六相永磁同步輪
內齒輪馬達(右)



EPS馬達 (前)



行車動態控制模組

高功率電池模組

EPS馬達 (後)

能量管理系統模組與高能量電池模組

全車整合測試成果

- 全車架空運轉測試與落地測試

全車架空運轉測試與落地測試

Introduction

- The features of the PMSM are:
  - Compact structure
  - High air-gap flux density
  - High power density
  - High torque capability

- The advantages of multiphase AC motors are:
  - Reduce the single static switches current stress
  - Smooth the electromagnetic torque pulsation
  - Increase the efficiency
  - Decrease the total losses
  - Reduce magnetic flux harmonic
  - Improve reliability

Introduction

- The multiphase AC motors can enhance the system performance and output power via the multiphase inverter drive system technologies.

- Six-phase PMSM with dual three-phase connection can reduce the current rating of winding and disperse the load capacity of the driving inverter.

- When the motor winding or respective inverter is broken, the unbalanced current will cause torque fluctuation so that the motor may be operated under non-smooth situation and lead to a seriously damage. Thus, the fault tolerant control for motor and inverter should be considered.

Introduction

- Fuzzy neural networks (FNNs) possess both advantages including the capability of fuzzy reasoning in handling uncertain information and the capability of artificial NNs in learning from processes.

- Since the TSKFNN provides more powerful representation than the Mamdani type FNN does, the TSKFNN is one of most used FNN schemes.

- Since the dimensions of the standard Gaussian or triangular MF are directly extended in asymmetric membership functions (AMFs), not only the learning capability of the networks can be upgraded but also the number of fuzzy rules can be optimized.

Introduction

- The probabilistic fuzzy neural network (PFNN) combines the advantages of FNN (degree of truth) and PNN (probability of truth).
- Corresponding to each primary membership, there is a secondary membership, which is also a subset in [0, 1], that defines the possibilities for the primary membership.
- The PFNN can enhance the universal applicability of fuzzy systems by bridging the gap between fuzziness and probability and possess the advantages of both the probabilistic fuzzy systems and the NN.

Introduction

- The major advantage of sliding mode control (SMC) system is its insensitivity to system parameter variations and external force disturbance once the system trajectory reaches and stays on the sliding surface.

- Due to the switching action is used in the sliding mode to switch between different structures, the chattering phenomenon appears unavoidably and becomes the most important disadvantage of SMC systems.

- The complementary SMC (CSMC), which not only alleviates the chattering phenomena but also possesses the control accuracy, has been proposed.

- The CSMC can efficiently reduce the guaranteed ultimate bound of the tracking error at least by 50% while using the saturation function as compared with the SMC.

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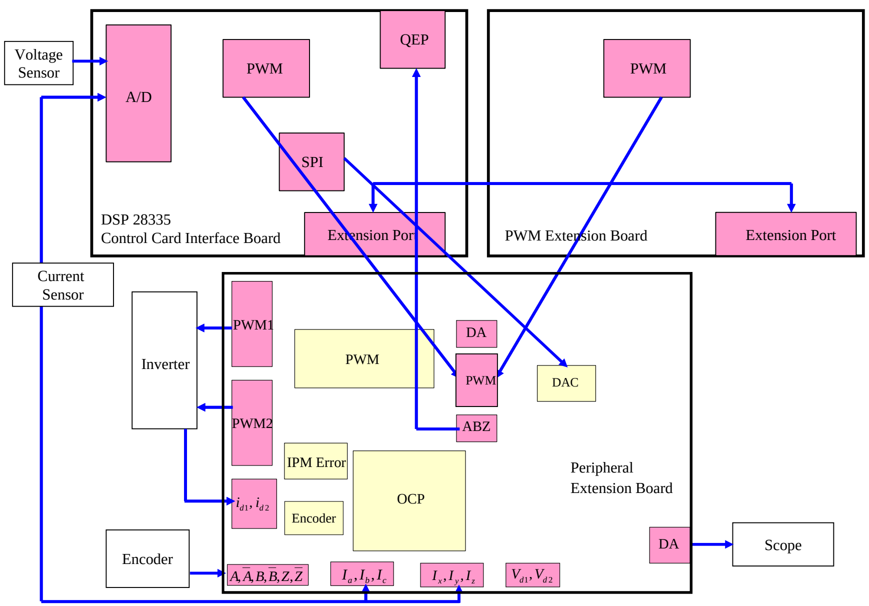
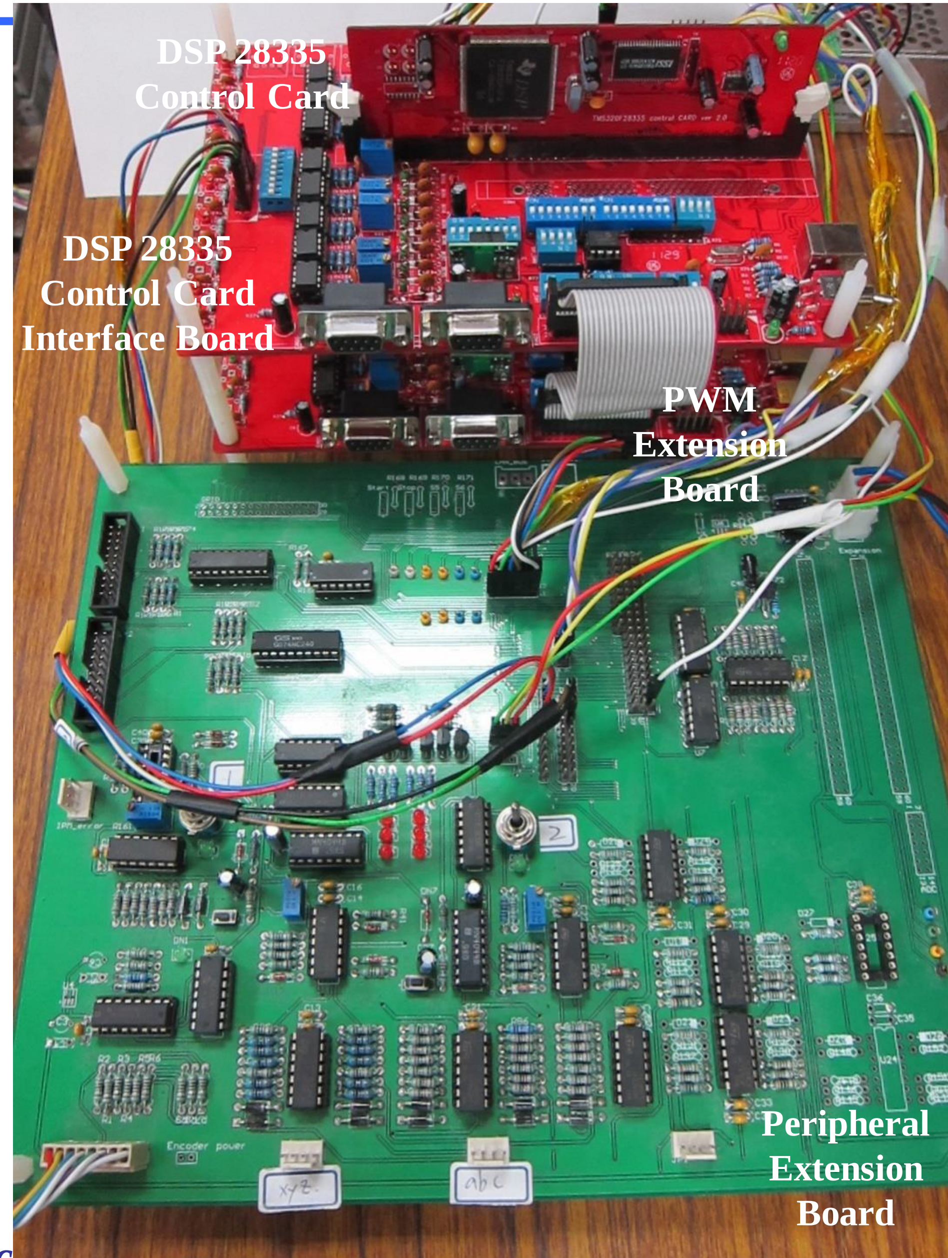
DSP-Based Control System

- The 32-bit floating-point DSP, TMS320F28335, manufactured by TI Inc. is the core of the DSP-based control system. The features of DSP TMS320F28335 are:
  - High performance static CMOS technology with up to 150MHz (6.67ns cycle time)
  - High performance 32-bit floating-point CPU with Harvard bus architecture
  - Fast interrupt response and processing
  - 256K x 16 Flash ROM
  - On-chip oscillator
  - Enhanced control peripherals: twelve PWM outputs and two quadrature encoder interfaces
  - Serial port peripherals: two CAN modules, three SCI modules and one SPI module
  - Sixteen channels 12-bit A/D converter with 80ns conversion rate

DSP-Based Control System

- The DSP-based control system includes the DSP 28335 control card, the DSP 28335 control card interface board, the PWM extension board and the peripheral extension board.





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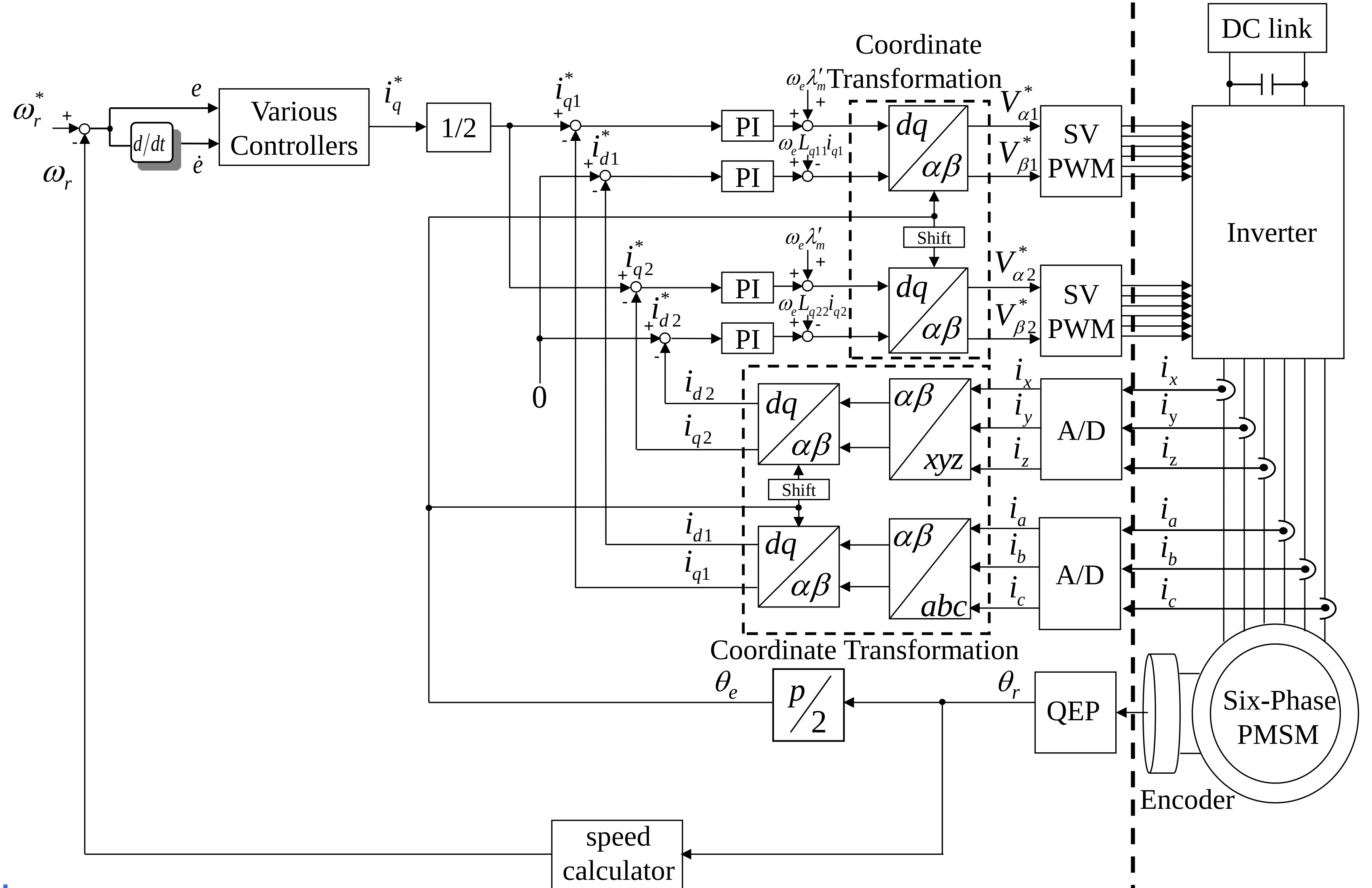
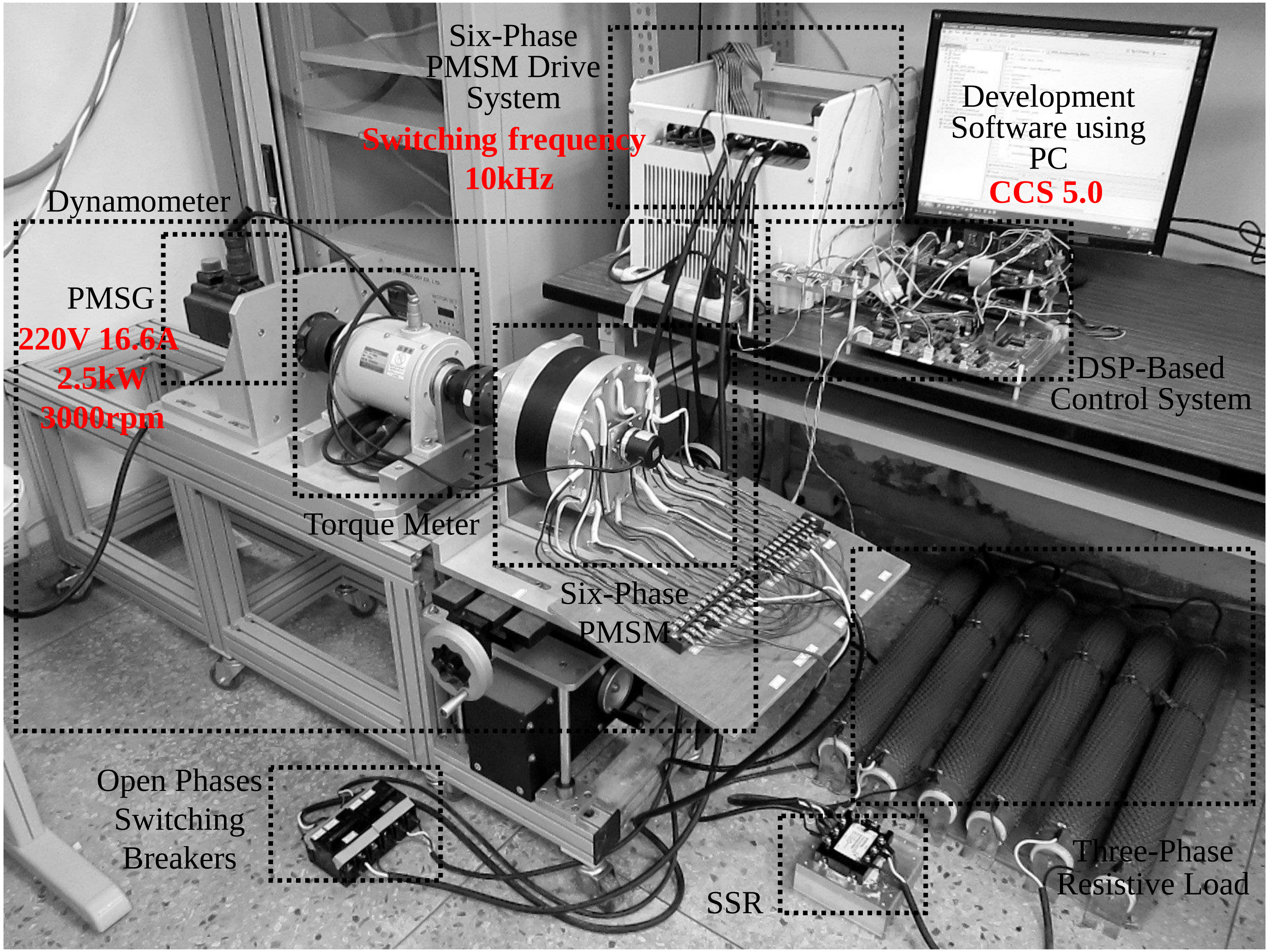
Six-Phase PMSM Drive System and Experimental Setup

- Six-phase PMSM drive system



Six-Phase PMSM Drive System and Experimental Setup

- Experimental setup for six-phase PMSM drive system



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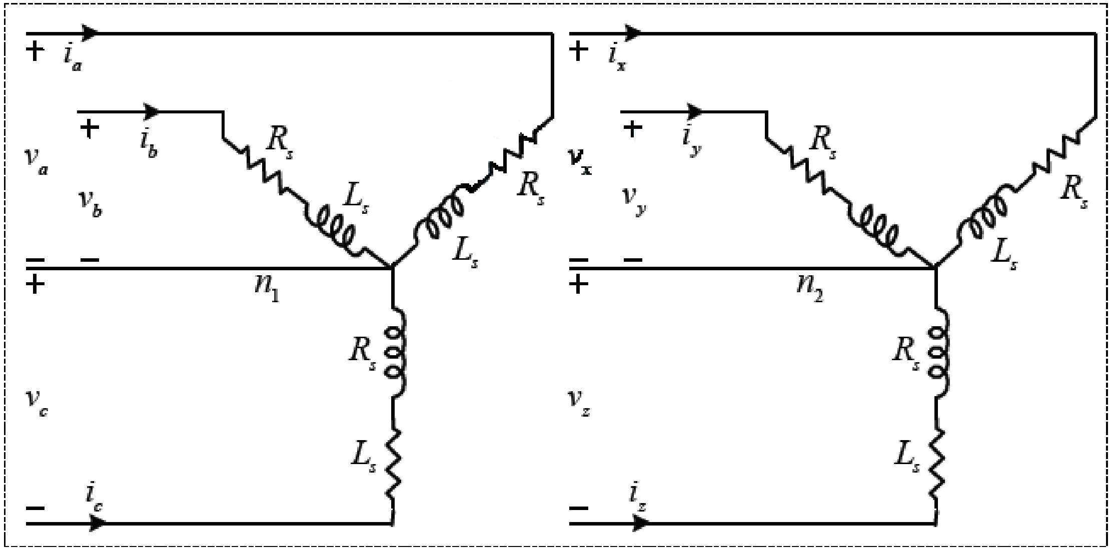
Dynamics of Six-Phase PMSM

- In the particular application of the six-phase PMSM, if one of the three-phase winding or the respective inverter is broken, the power rating of the PMSM is reduced to half and still can be operated safely using the remaining three-phase winding, so that the operating safety of the system can be increased.
- The six-phase PMSM with two three-phase windings is adopted where *abc* winding is spatially 30 electrical degrees phase led to *xyz* winding.



Equivalent circuit of dual three-phase winding of six-phase PMSM

Dynamics of Six-Phase PMSM

- The detail parameters of the six-phase PMSM and its drive system

Parameter	Quantity
Rated Power	2kW
Rated Torque	8.4Nm
Rated Speed	2250rpm
Rated Voltage	220V
Rated Current	11.4A
Pole Pair	14
Motor Inertia	0.0124Nm/(rad/sec^2)
Damping Coefficient	0.016Nm/(rad/sec)
Torque Coefficient	0.49245Nm/A
Permanent Magnet Flux Linkage	0.0469V/(rad/sec)
Inverter	Fuji Electric IPM: 7MBR75SB060 600V/75A IGBT Turn-On Time: 1.2μs IGBT Turn-Off Time: 1μs
DC Link	189V
Switching Frequency	10kHz
Current Sensor	1V=6.8A
Encoder	HONTKO Incremental Encoder: HTR-HB-6-1000-4-L 1000 Pulse/Revolution

Dynamics of Six-Phase PMSM

- The phase voltage and flux linkage equations in the stationary reference frame for *abc* winding and *xyz* winding of six-phase PMSM are shown as:

$$\mathbf{v}_{abc} = \tilde{\mathbf{R}}_s \mathbf{i}_{abc} + \frac{d}{dt}\boldsymbol{\lambda}_{abc} \tag{3.1}$$

$$\boldsymbol{\lambda}_{abc} = \tilde{\mathbf{L}}_{11}\mathbf{i}_{abc} + \tilde{\mathbf{L}}_{12}\mathbf{i}_{xyz} + \boldsymbol{\lambda}'_{mabc} \tag{3.2}$$

$$\mathbf{v}_{xyz} = \tilde{\mathbf{R}}_s \mathbf{i}_{xyz} + \frac{d}{dt}\boldsymbol{\lambda}_{xyz} \tag{3.3}$$

$$\boldsymbol{\lambda}_{xyz} = \tilde{\mathbf{L}}_{22}\mathbf{i}_{xyz} + \tilde{\mathbf{L}}_{21}\mathbf{i}_{abc} + \boldsymbol{\lambda}'_{mxyz} \tag{3.4}$$

- The following transformation matrixes have been used to transfer the above equations into the synchronous rotating reference frame:

$$\mathbf{T}_{qd1} = \frac{2}{3}\begin{bmatrix} \cos\theta_e & \cos(\theta_e - 120^\circ) & \cos(\theta_e + 120^\circ) \\ \sin\theta_e & \sin(\theta_e - 120^\circ) & \sin(\theta_e + 120^\circ) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad \text{for } abc \text{ winding} \tag{3.19}$$

$$\mathbf{T}_{qd2} = \frac{2}{3}\begin{bmatrix} \cos(\theta_e - 30^\circ) & \cos(\theta_e - 150^\circ) & \cos(\theta_e + 90^\circ) \\ \sin(\theta_e - 30^\circ) & \sin(\theta_e - 150^\circ) & \sin(\theta_e + 90^\circ) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad \text{for } xyz \text{ winding} \tag{3.20}$$

Dynamics of Six-Phase PMSM

- The machine model of six-phase PMSM can be described in synchronous rotating reference frame as follows:

$$v_{d1} = R_s i_{d1} + L_{d11}\dot{i}_{d1} - \omega_e L_{q11} i_{q1} \tag{3.21}$$

$$v_{q1} = R_s i_{q1} + L_{q11}\dot{i}_{q1} + \omega_e (L_{d11} i_{d1} + \lambda'_m) \tag{3.22}$$

$$v_{d2} = R_s i_{d2} + L_{d22}\dot{i}_{d2} - \omega_e L_{q22} i_{q2} \tag{3.23}$$

$$v_{q2} = R_s i_{q2} + L_{q22}\dot{i}_{q2} + \omega_e (L_{d22} i_{d2} + \lambda'_m) \tag{3.24}$$

$$\omega_e = \frac{p}{2}\omega_r \tag{3.25}$$

- The developed electric torque can be represented by the following equation:

$$\begin{aligned} T_e = \frac{3}{2}\frac{p}{2}\Big(& [(L_{d11} i_{d1} + \lambda'_m) i_{q1} + (L_{d11} - L_{q11}) i_{d1} i_{q1}] \\ & + [(L_{d22} i_{d2} + \lambda'_m) i_{q2} + (L_{d22} - L_{q22}) i_{d2} i_{q2}]\Big) \end{aligned} \tag{3.26}$$

Dynamics of Six-Phase PMSM

- With the implementation of field-oriented control, the electric torque can be simplified as follows:

$$T_e = K_t(i_{q1}^* + i_{q2}^*) = K_t i_q^* \tag{3.27}$$

$$K_t = \frac{3}{2}\frac{p}{2}\lambda'_m \tag{3.28}$$

where K_t is the torque coefficient; i_{q1}^* and i_{q2}^* are the q-axis torque current commands of the dual three-phase; i_q^* is the q-axis torque current command.

- The developed electric torque can be represented by the following equation:

$$T_e = J\dot{\omega}_r + B\omega_r + T_L \tag{3.29}$$

where J is the inertia of six-phase PMSM; B is the damping coefficient; T_L is the load torque.

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Fault Tolerant Control

- The open phase fault of the six-phase PMSM can be detected according to the feedback of six-phase currents. The six-phase currents detection equation can be described as:

$$I_g^{\text{detect}} = \frac{1}{nT_s}\left[\int_{t_1}^{t_2} i_g^2 dt\right]^{\frac{1}{2}} \tag{3.37}$$

- The open phase fault of the six-phase PMSM can be detected according to whether the detection equation (3.37) equal to zero or not. If the motor operated under nominal condition and the speed command is nonzero, the six-phase currents detection values according to (3.37) are nonzero simultaneously. Thus, the fault detection can be defined as follows:

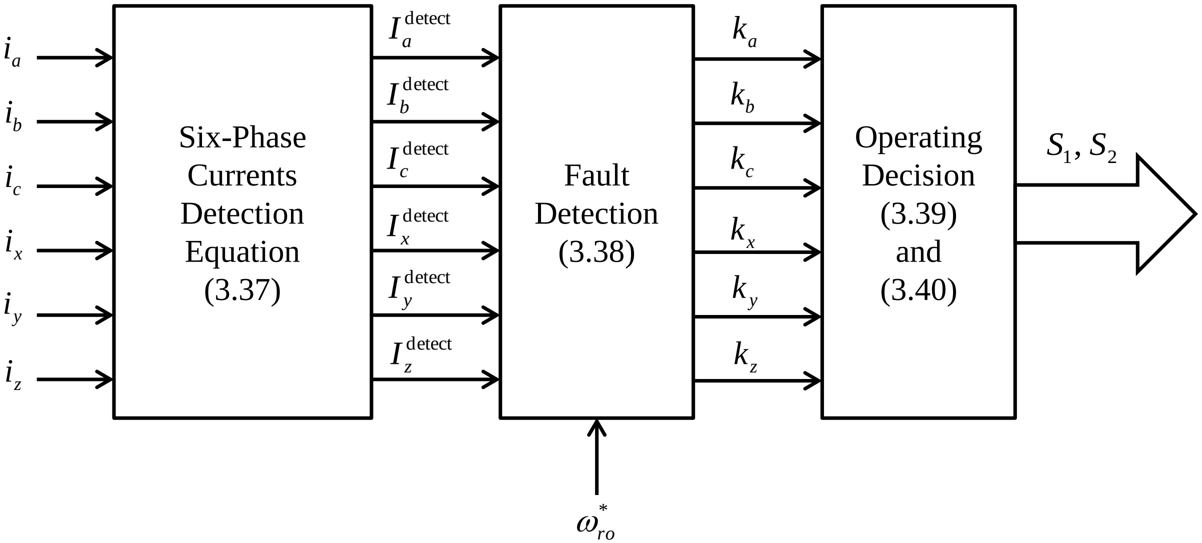
$$k_g = \begin{cases} 0 & if\ \ I_g^{\text{detect}} = 0\ and\ \omega_{ro}^* \neq 0 \\ 1 & otherwise \end{cases} \tag{3.38}$$

Fault Tolerant Control

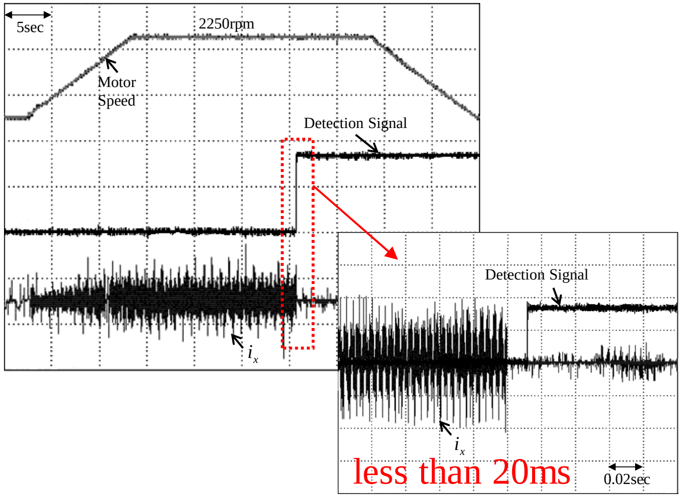
- By using (3.37) and (3.38), the operating decision method is proposed in the following:

$$S_1 = \begin{cases} 0 & if\ \ k_a = 0\ or\ k_b = 0\ or\ k_c = 0 \\ 1 & otherwise \end{cases} \qquad (3.39)$$

$$S_2 = \begin{cases} 0 & if\ \ k_x = 0\ or\ k_y = 0\ or\ k_z = 0 \\ 1 & otherwise \end{cases} \qquad (3.40)$$



Fault detection and operating decision method

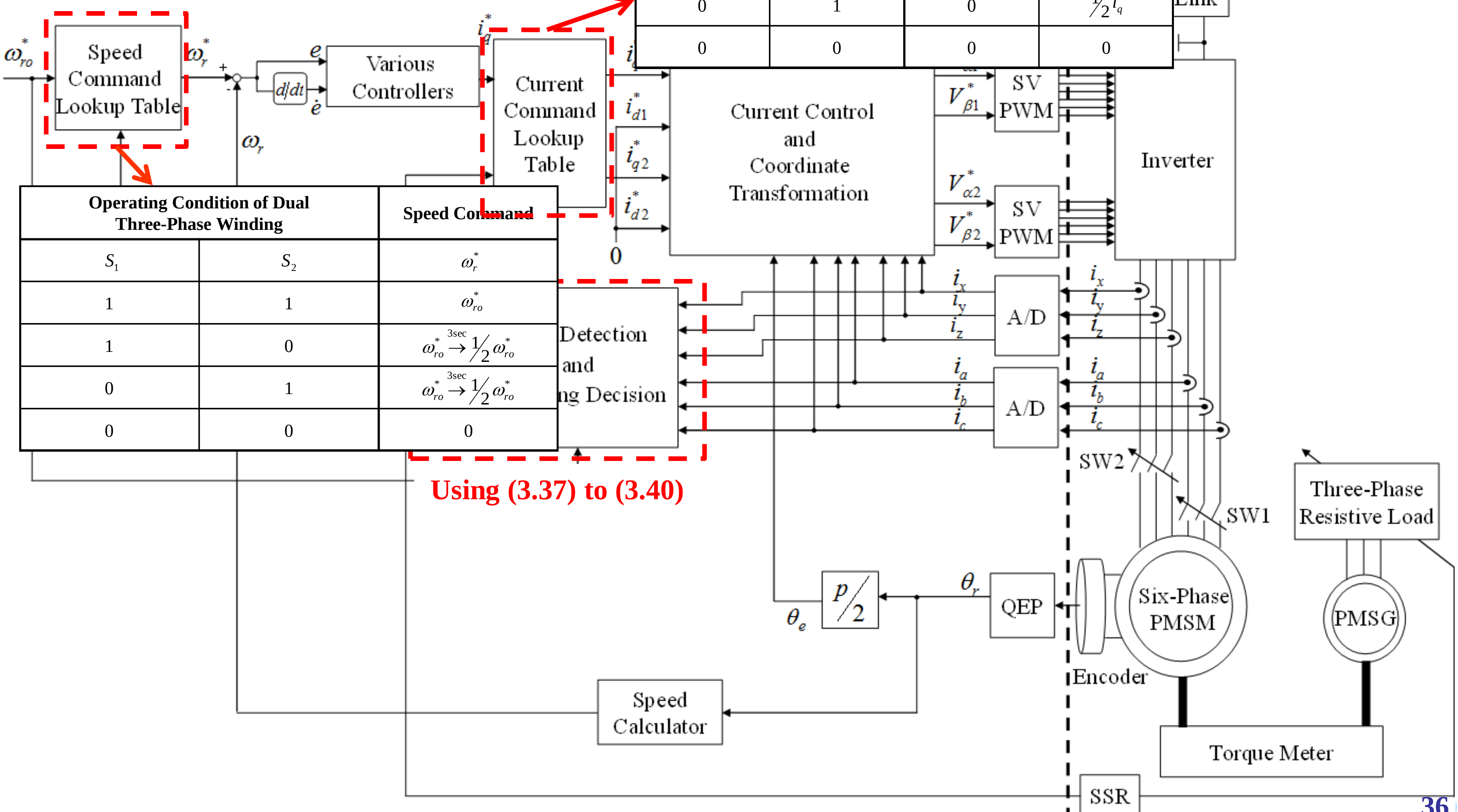


Experimental results of fault detection under faulty condition

Fault Tolerant Control

- Fault tolerant control of six-

Operating Condition of Dual Three-Phase Winding		Current Command	
S_1	S_2	i_{q1}^*	i_{q2}^*
1	1	$\frac{1}{2} i_q^*$	$\frac{1}{2} i_q^*$
1	0	$\frac{1}{2} i_q^*$	0
0	1	0	$\frac{1}{2} i_q^*$
0	0	0	0



Operating Condition of Dual Three-Phase Winding		Speed Command
S_1	S_2	ω_r^*
1	1	ω_{ro}^*
1	0	$\omega_{ro}^* \xrightarrow{3sec} \frac{1}{2} \omega_{ro}^*$
0	1	$\omega_{ro}^* \xrightarrow{3sec} \frac{1}{2} \omega_{ro}^*$
0	0	0

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Applications: Modeling of LEV and In-Wheel Motor Drive System

- The major factors that should be considered are the road condition, aerodynamic drag, hill climbing and acceleration etc., and a vehicle dynamic model can be given as [3, 75]:

$$F_{LEV} = \mu_{rr} mg + \frac{1}{2}\rho A C_d v^2 + mg\sin\phi + m\dot{v} + F_L \tag{3.41}$$

$$T = \frac{F_{LEV}\, r}{G} \tag{3.42}$$

$$\omega_r = \frac{v}{r} \tag{3.43}$$

- The required torque of a single in-wheel motor and the torque equation of an in-wheel motor can be shown as:

$$\frac{T}{n} = T_{motor} = K_t i^* \tag{3.44}$$

$$\begin{aligned} T_e &= J_w\dot{\omega}_r + B_w\omega_r + T_{motor} \\ &= J_w\dot{\omega}_r + B_w\omega_r + \frac{T}{n} \end{aligned} \tag{3.45}$$

Applications: Modeling of LEV and In-Wheel Motor Drive System

- Assuming the system parameter variations of the PMSM are absent, then the overall vehicle dynamic model of LEV system including the torque equation of the PMSM can be written as:

$$
\begin{aligned}
T_e &= (\bar{J}_w + m\frac{r^2}{nG^2})\dot{\omega}_r + \bar{B}_w\omega_r + \frac{r}{nG}(\mu_{rr}mg + \frac{1}{2}\rho A C_d v^2 + mg\sin\phi + F_L) \\
&= (\bar{J}_w + m\frac{r^2}{nG^2})\dot{\omega}_r + \bar{B}_w\omega_r + T_{wL}
\end{aligned}
\tag{3.46}
$$

- Photographs of the six-phase PMSM, the gearbox, the in-wheel motor, the rim and the wheel are shown as:

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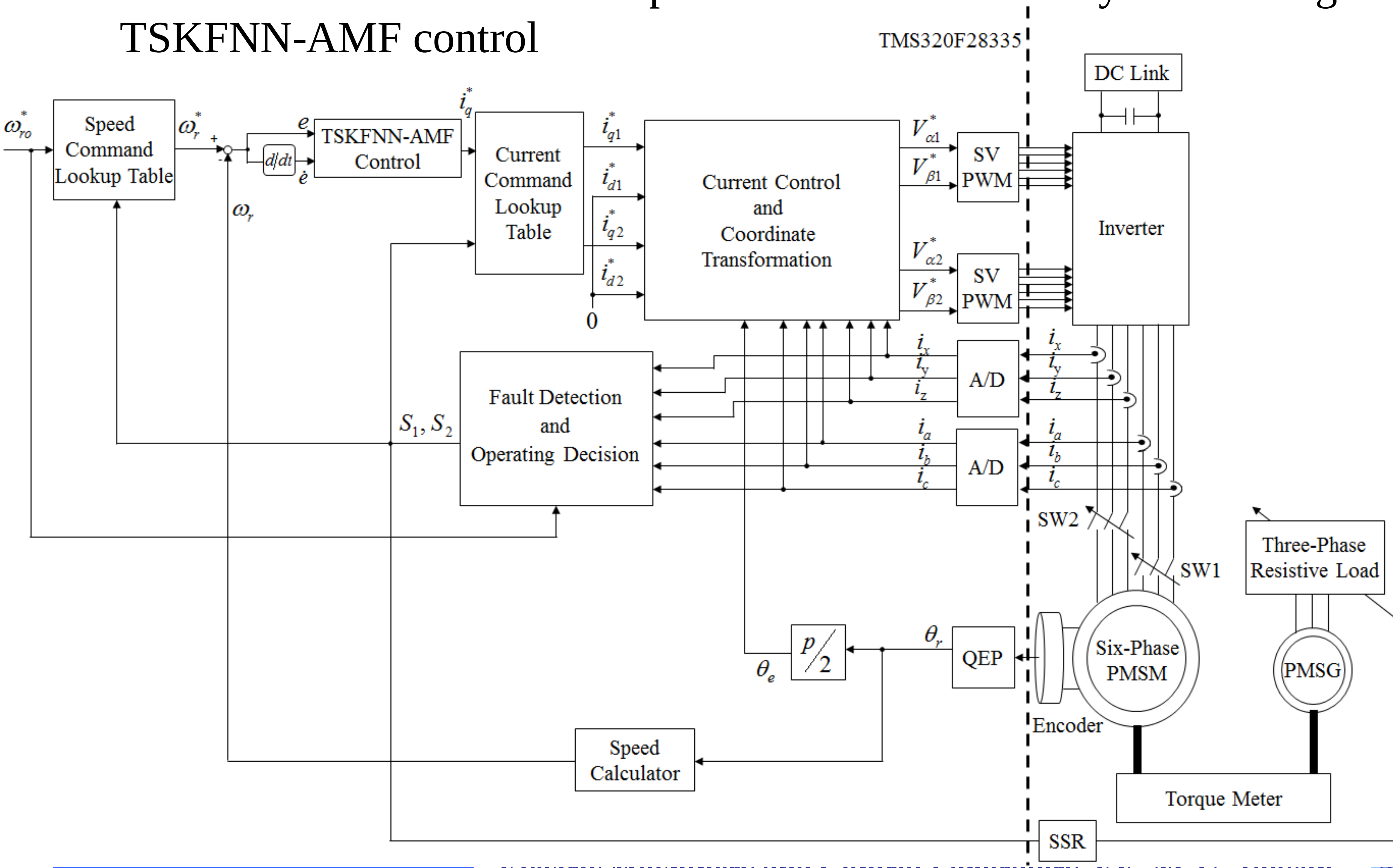
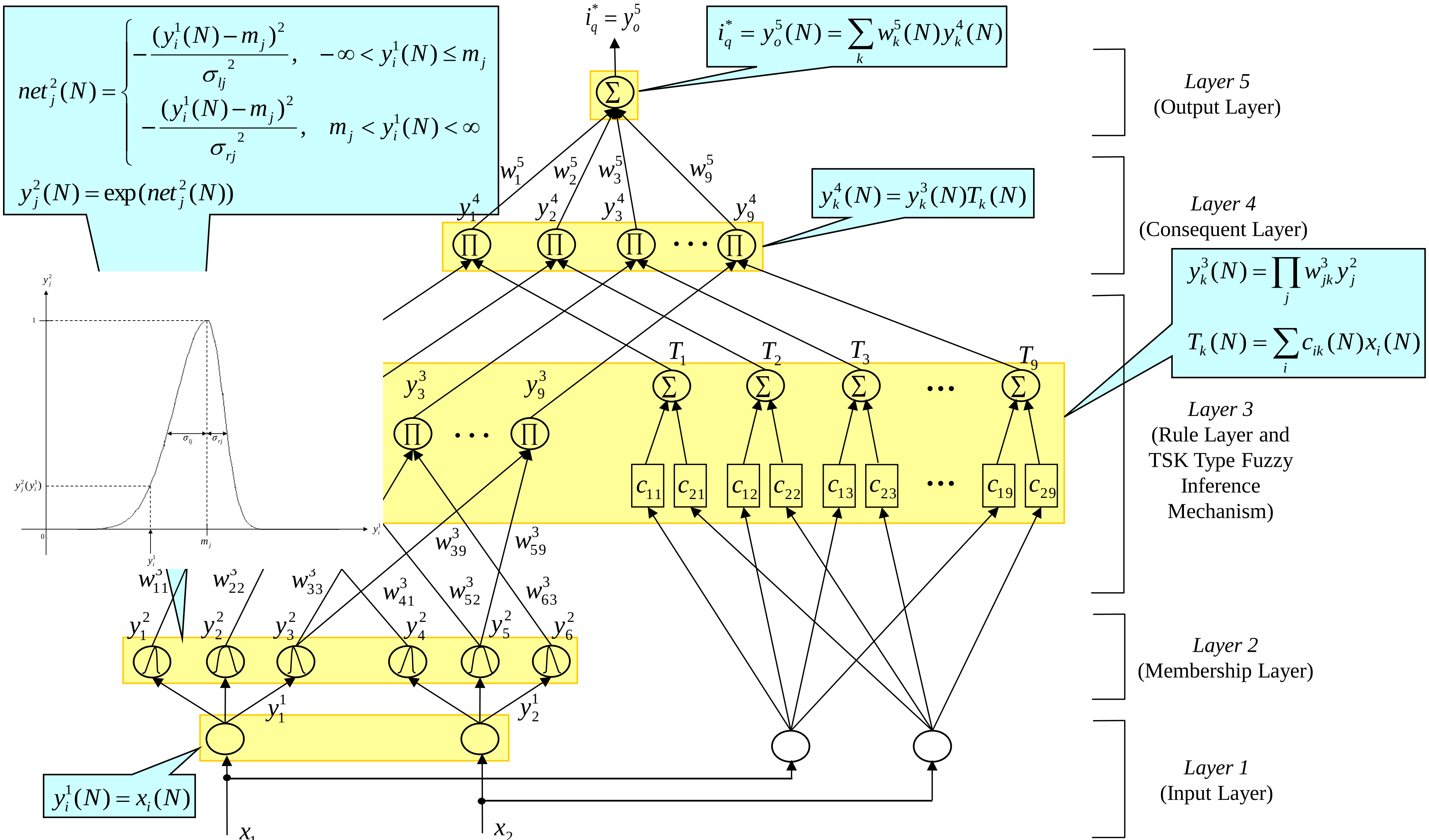
Fault Tolerant Control of Six-Phase PMSM Drive System—Using TSKFNN-AMF Control

- Fault tolerant control six-phase PMSM drive system using TSKFNN-AMF control



Fault Tolerant Control of Six-Phase PMSM Drive System—Using TSKFNN-AMF Control

- TSK type FNN with asymmetric membership function



- To obtain the leaning algorithm for the TSKFNN-AMF, the BP learning rule is adopted here. First, the energy function is defined as:

$$E = \frac{1}{2}(\omega_r^* - \omega_r)^2 = \frac{1}{2}e^2 \qquad (4.9)$$

- Then, the update laws are:

$$\Delta w_k^5 = -\eta_w \frac{\partial E}{\partial w_k^5} = -\eta_w \frac{\partial E}{\partial y_o^5(N)} \frac{\partial y_o^5(N)}{\partial w_k^5} = \eta_w \delta_o^5 y_k^4 \qquad (4.11)$$

$$\Delta c_{ik} = -\eta_c \frac{\partial E}{\partial c_{ik}} = -\eta_c \frac{\partial E}{\partial y_o^5(N)} \frac{\partial y_o^5(N)}{\partial y_k^4(N)} \frac{\partial y_k^4(N)}{\partial T_k(N)} \frac{\partial T_k(N)}{\partial c_{ik}(N)} = \eta_c \delta_k^4 y_k^3 x_i \qquad (4.15)$$

$$\begin{aligned}
\Delta m_j &= -\eta_m \frac{\partial E}{\partial m_j(N)} \\
&= -\eta_m \frac{\partial E}{\partial y_o^5(N)} \frac{\partial y_o^5(N)}{\partial y_k^4(N)} \frac{\partial y_k^4(N)}{\partial y_k^3(N)} \frac{\partial y_k^3(N)}{\partial y_j^2(N)} \frac{\partial y_j^2(N)}{\partial net_j^2(N)} \frac{\partial net_j^2(N)}{\partial m_j(N)} \\
&= \begin{cases} \eta_m \delta_j^2 \dfrac{2(y_i^1 - m_j)}{{\sigma_{lj}}^2}, & -\infty < y_i^1 \le m_j \\ \eta_m \delta_j^2 \dfrac{2(y_i^1 - m_j)}{{\sigma_{rj}}^2}, & m_j < y_i^1 < \infty \end{cases}
\end{aligned} \qquad (4.18)$$

$$\begin{aligned}\Delta\sigma_{lj} &= -\eta_{l\sigma}\frac{\partial E}{\partial\sigma_{lj}(N)} \\ &= -\eta_{l\sigma}\frac{\partial E}{\partial y_o^5(N)}\frac{\partial y_o^5(N)}{\partial y_k^4(N)}\frac{\partial y_k^4(N)\partial y_k^3(N)}{\partial y_k^3(N)\partial y_j^2(N)}\frac{\partial y_j^2(N)}{\partial net_j^2(N)}\frac{\partial net_j^2(N)}{\partial\sigma_{lj}(N)} \\ &= \eta_{l\sigma}\delta_j^2\frac{2(y_i^1-m_j)^2}{\sigma_{lj}{}^3}\end{aligned} \tag{4.19}$$

$$\begin{aligned}\Delta\sigma_{rj} &= -\eta_{r\sigma}\frac{\partial E}{\partial\sigma_{rj}(N)} \\ &= -\eta_{r\sigma}\frac{\partial E}{\partial y_o^5(N)}\frac{\partial y_o^5(N)}{\partial y_k^4(N)}\frac{\partial y_k^4(N)\partial y_k^3(N)}{\partial y_k^3(N)\partial y_j^2(N)}\frac{\partial y_j^2(N)}{\partial net_j^2(N)}\frac{\partial net_j^2(N)}{\partial\sigma_{rj}(N)} \\ &= \eta_{r\sigma}\delta_j^2\frac{2(y_i^1-m_j)^2}{\sigma_{rj}{}^3}\end{aligned} \tag{4.20}$$

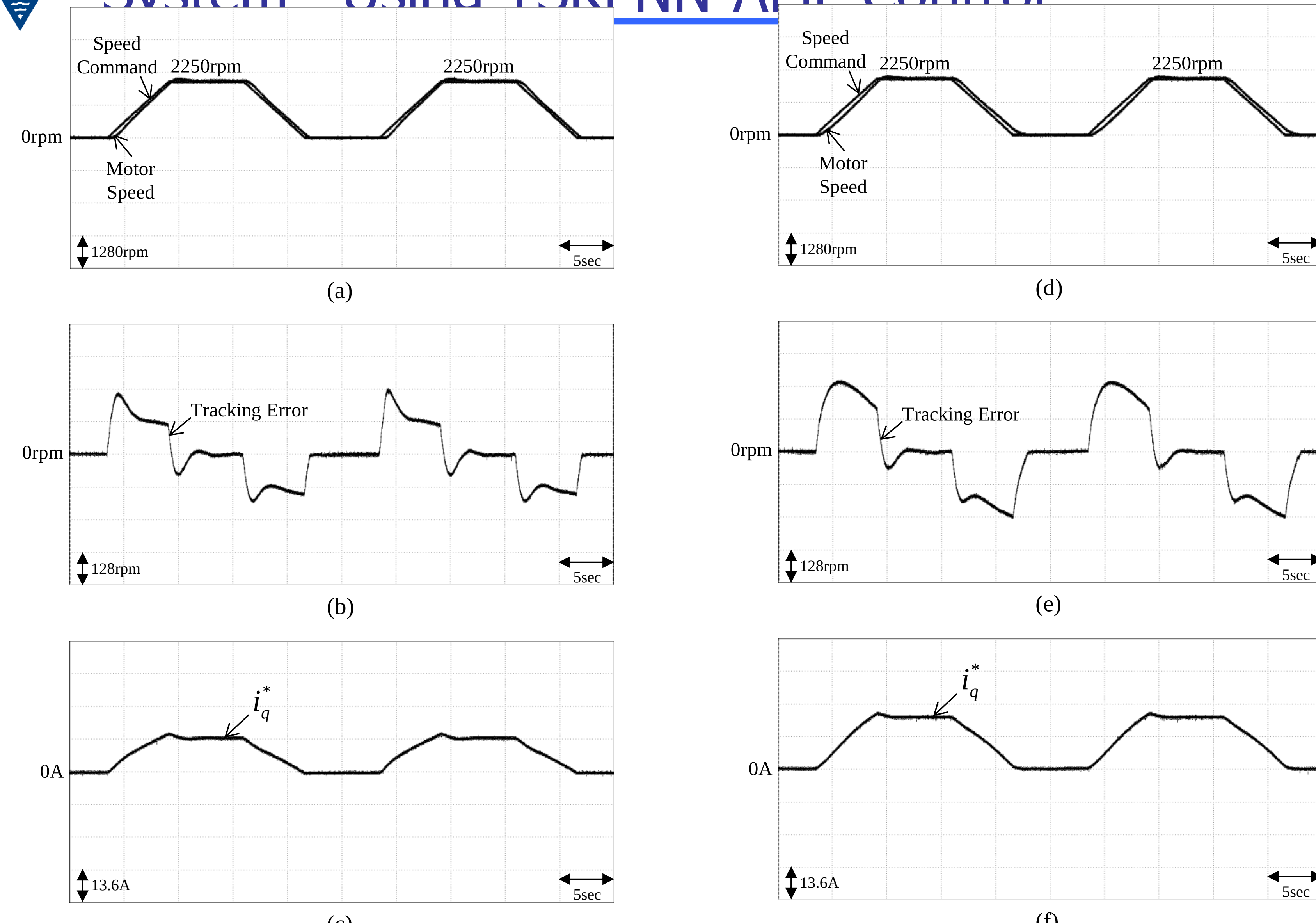
- The exact calculation of the sensitivity of the system, $\partial\omega_r / \partial y_o^5(N)$, is difficult to be determined due to the uncertainties and unmodeled dynamics of the six-phase PMSM drive system. The error term shown in (4.10) is assumed to approximate as follows:

$$\delta_o^5 \cong (\omega_r^* - \omega_r) + (\dot{\omega}_r^* - \dot{\omega}_r) = e + \dot{e} \tag{4.24}$$

- Healthy condition in experiment:
  - Periodical trapezoidal wave (0.056Hz) reference speed profile.
    - Y-connected three-phase resistive load 7Ω for the PMSG (Case 1)
    - Y-connected three-phase resistive load 3.5Ω for the PMSG (Case 2)

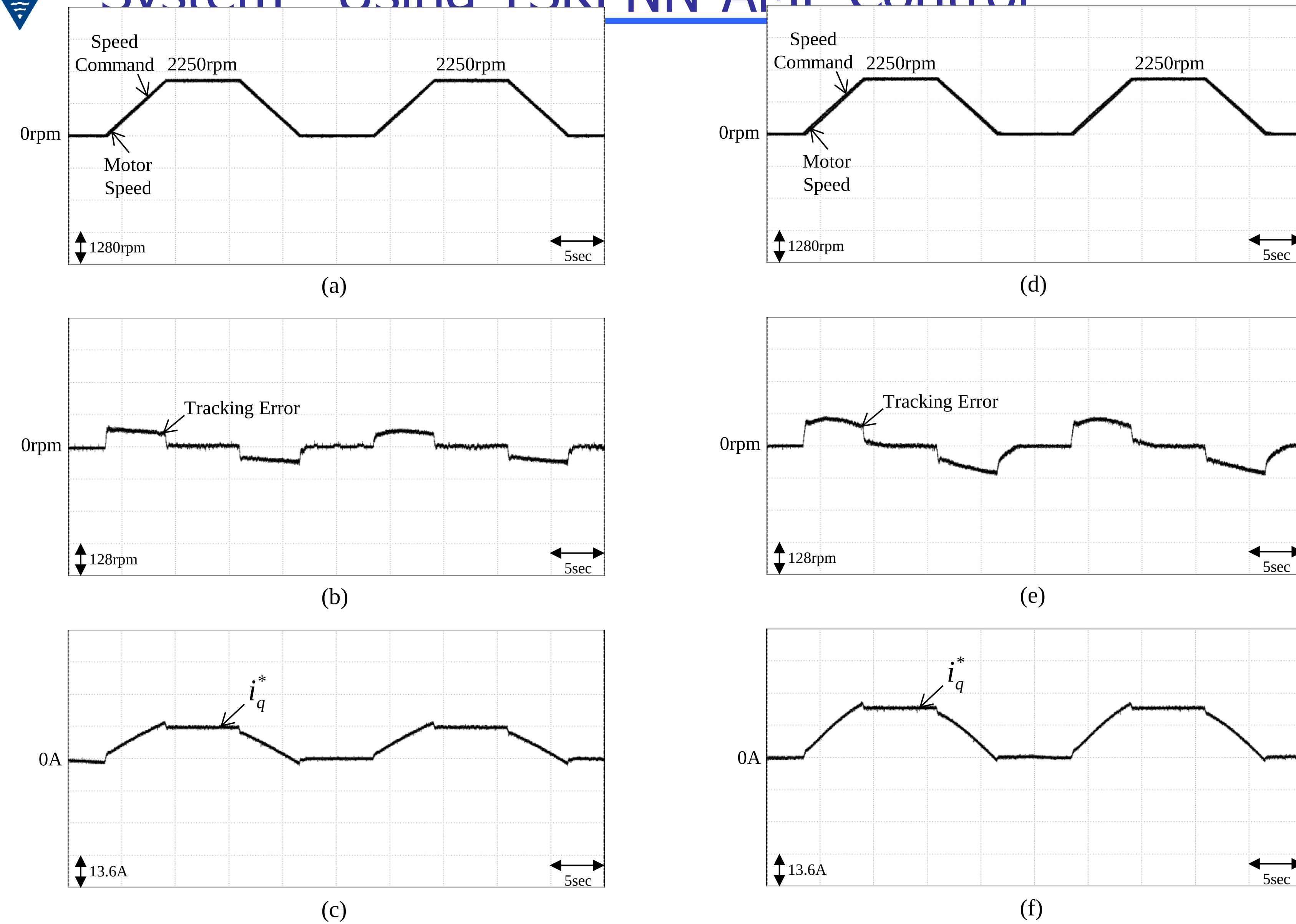
- Faulty condition in experiment:
  - Speed profile is set as 2250rpm at the beginning and reduced to half of the speed after three seconds when the fault detected. The three-phase resistive load will also be changed from 3.5Ω to 7Ω immediately by using the SSR when the fault is detected, and then changed to 3.5Ω after six seconds.
    - abc winding open (Case 3)
    - xyz winding open (Case 4)

Fault Tolerant Control of Six-Phase PMSM Drive System—Using TSKFNN-AMF Control



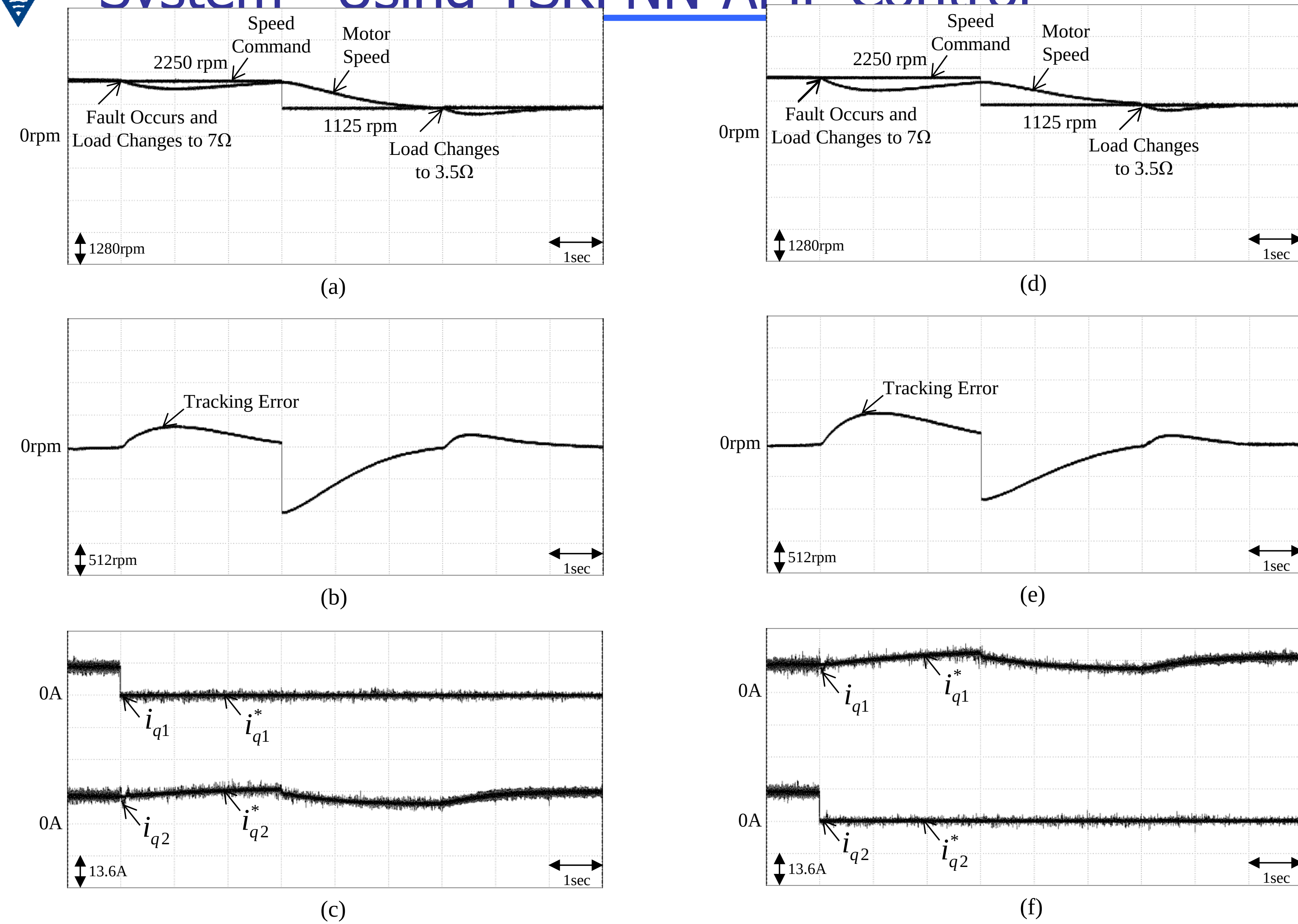
Experimental results of PI control at Case 1(left) and Case 2(right)

Fault Tolerant Control of Six-Phase PMSM Drive System—Using TSKFNN-AMF Control



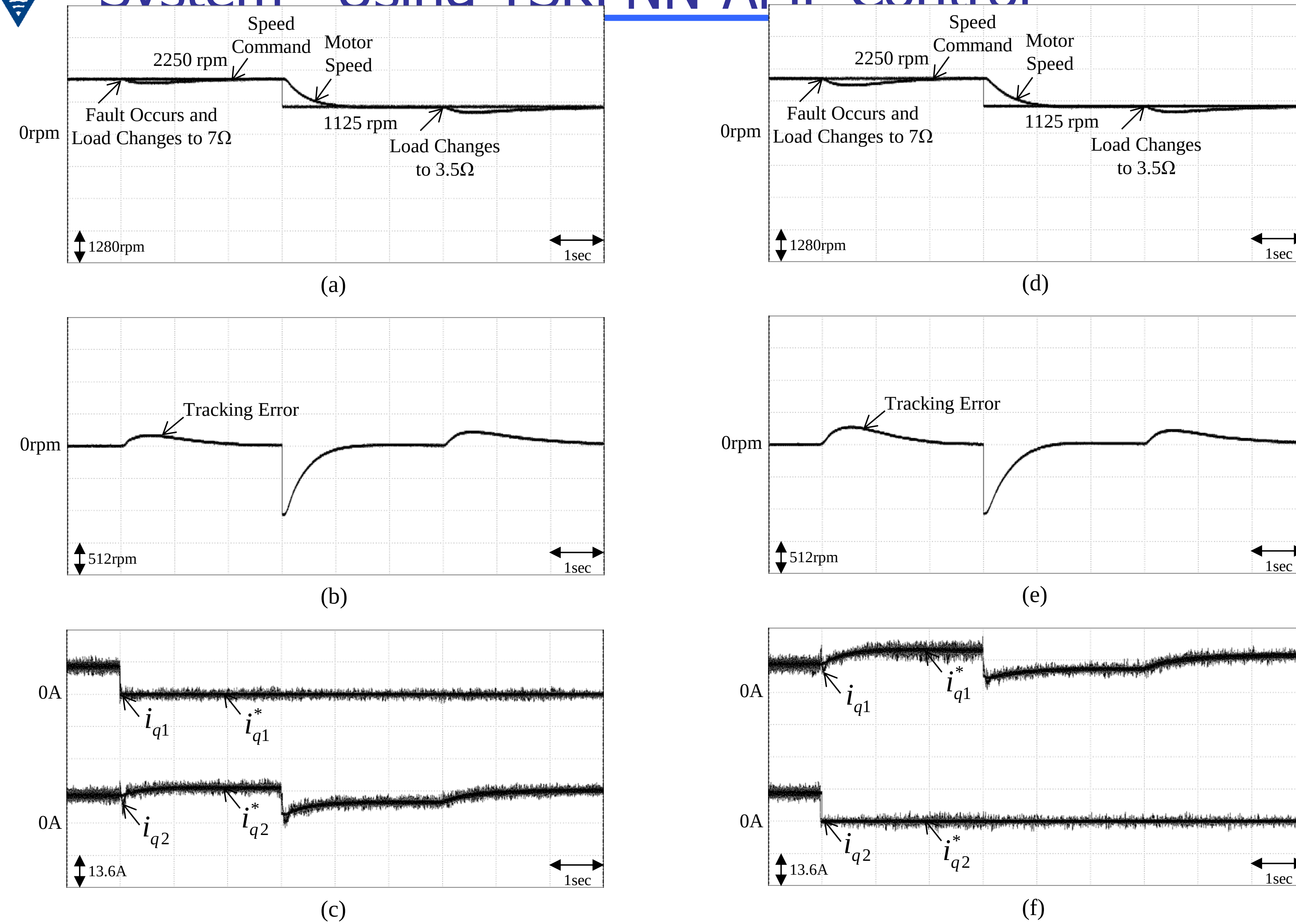
Experimental results of TSKFNN-AMF control at Case 1(left) and Case 2(right)

Fault Tolerant Control of Six-Phase PMSM Drive System—Using TSKFNN-AMF Control



Experimental results of PI fault tolerant control at Case 3(left) and Case 4(right)

Fault Tolerant Control of Six-Phase PMSM Drive System—Using TSKFNN-AMF Control



Experimental results of TSKFNN-AMF fault tolerant control at Case 3(left) and Case 4(right)

Fault Tolerant Control of Six-Phase PMSM Drive System—Using TSKFNN-AMF Control

- The performance measurings of the PI and the proposed TSKFNN-AMF controls under healthy (Cases 1 and 2) and faulty (Cases 3 and 4) conditions are shown in Table 4.1 and Table 4.2 respectively.
- The proposed fault detection and operating decision method can detect the open phases of the motor effectively.

Table 4.1 Performance measurings of PI and TSKFNN-AMF controls under healthy condition.

Tracking Errors, rpm	PI Control		TSKFNN-AMF Control	
	Case 1	Case 2	Case 1	Case 2
Maximum	261.12	281.6	71.68	107.52
Average	14.51	15.31	11.06	13.39
Standard Deviation	103.23	146.5	37.71	58.92

Table 4.2 Performance measurings of PI and TSKFNN-AMF controls under faulty condition.

Tracking Errors, rpm	PI Control		TSKFNN-AMF Control	
	Case 3	Case 4	Case 3	Case 4
Maximum	348.16	522.24	245.76	307.2
Average	23.47	32.88	19.06	25.82
Standard Deviation	350.77	357.73	191.74	211.72

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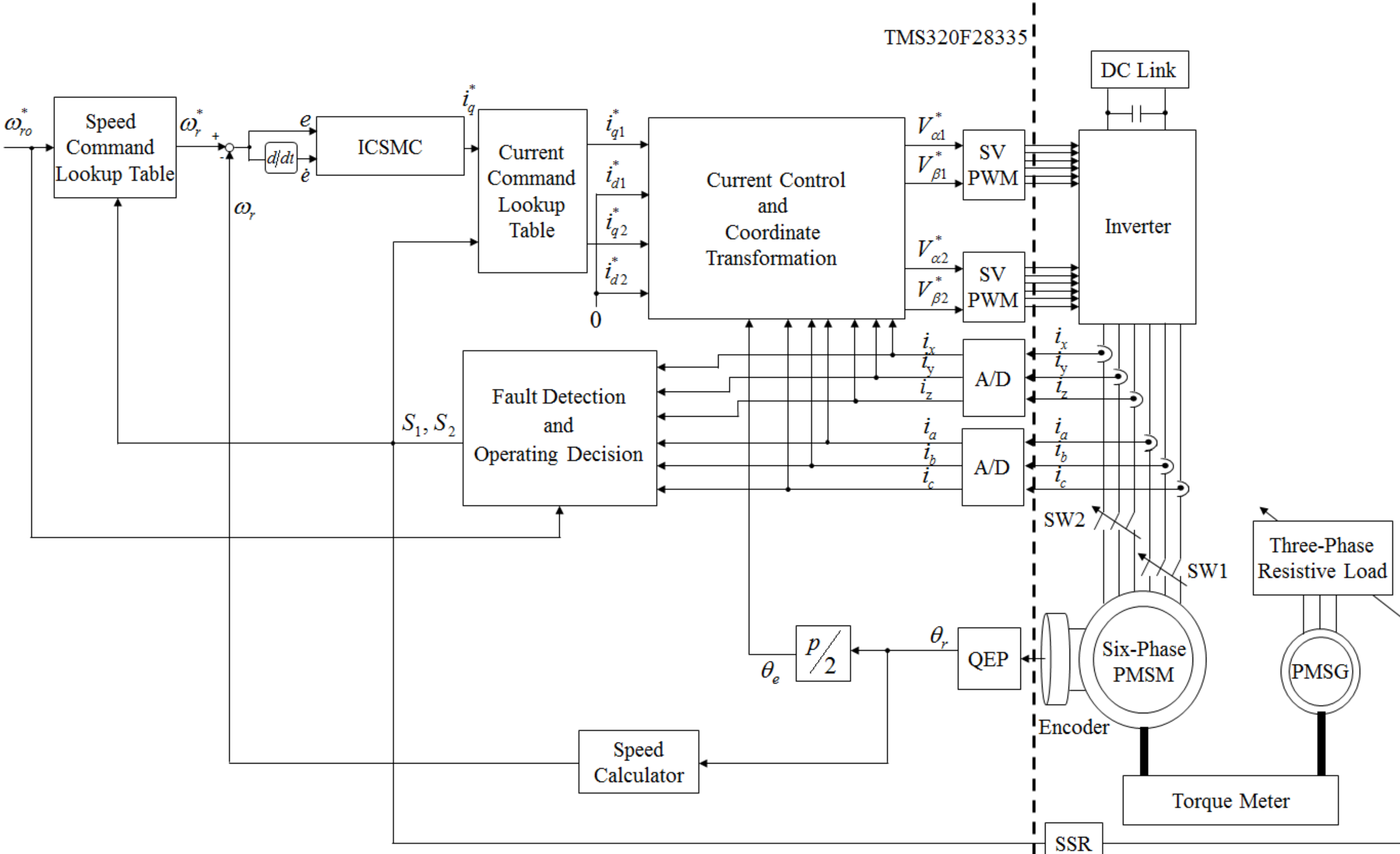
Fault Tolerant Control of Six-Phase PMSM Drive System—Using ICSMC

- Fault tolerant control six-phase PMSM drive system using ICSMC



Fault Tolerant Control of Six-Phase PMSM Drive System—Using ICSMC

- Assuming that the system parameter variations and external disturbance are absent, then field-oriented control six-phase PMSM drive system can be formulated by rewriting (3.27) and (3.29) as:

$$\dot{\omega}_r = -\frac{\overline{B}}{\overline{J}}\omega_r + \frac{K_t}{\overline{J}} i_q^* \equiv A_n \omega_r + B_n i_q^* \tag{5.1}$$

- The above dynamic model is rewritten considering the existence of parameter variations and external disturbance as

$$\begin{aligned} \dot{\omega}_r &= (A_n + \Delta A)\omega_r + (B_n + \Delta B) i_q^* + (C_n + \Delta C) T_L \\ &= A_n \omega_r + B_n i_q^* + H \end{aligned} \tag{5.2}$$

where H is called the lumped uncertainty and defined as

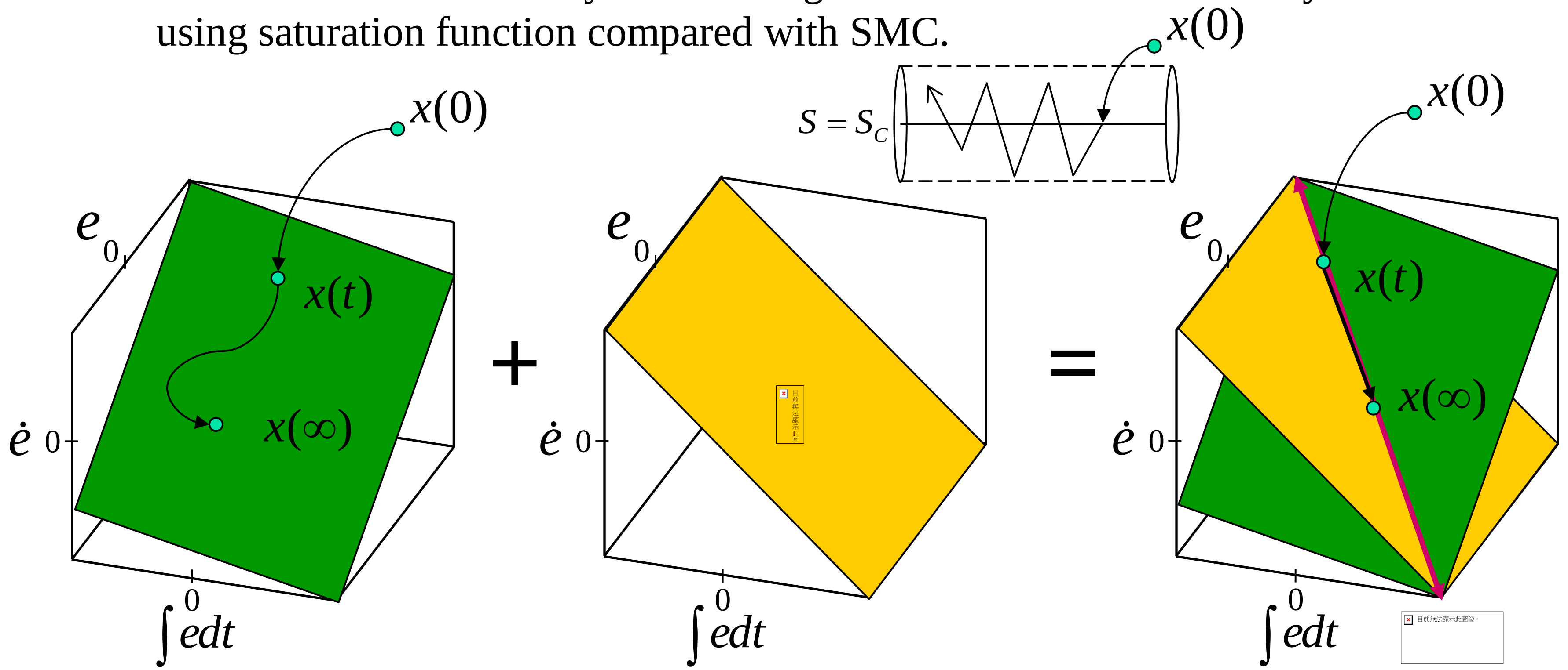
$$H \equiv \Delta A \omega_r + \Delta B i_q^* + (C_n + \Delta C) T_L \tag{5.3}$$

- Here, the lumped uncertainty is assumed to be bounded

$$|H| \le \rho \tag{5.4}$$

Fault Tolerant Control of Six-Phase PMSM Drive System—Using ICSMC

- *A. Complementary Sliding-Mode Control (CSMC)*
  - The CSMC can efficiently reduce the guaranteed ultimate bounds by half while using saturation function compared with SMC.



Generalized sliding surface

$$S = e + \lambda\int_0^t e d\tau$$

Complementary sliding surface

Generalized + Complementary sliding surfaces

Relationship between S and S_c:

Fault Tolerant Control of Six-Phase PMSM Drive System—Using ICSMC

- ***Theorem 5.1***: Considering the system dynamic equation represented by (5.2), if the proposed CSMC law is designed as (5.10), which is composed of an equivalent control law designed as (5.11) and a hitting control law designed as (5.12), then the stability of the proposed CSMC system can be guaranteed.

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$$i_{eq} = \frac{1}{B_n}\left[\dot{\omega}_r^* - A_n \omega_r + \lambda(e+S)\right] \quad (5.11)$$

$$i_{hit} = \frac{1}{B_n}\left[\rho \,\mathbf{sat}\left(\frac{S+S_C}{\Phi}\right)\right] \quad (5.12)$$

- ***Proof***: Choose the Lyapunov function candidate V_{CSMC} as

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- Taking the time derivative of the first Lyapunov function, and using above equations, then

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whenever $|S+S_C| \geq \Phi$.

This only ensures that any tracking error trajectory will reach the boundary layer in finite time.

Fault Tolerant Control of Six-Phase PMSM Drive System—Using ICSMC

- *B. TSKFNN-AMF Estimator*
  - The TSKFNN-AMF estimator with two inputs and one output is developed to estimate the lumped uncertainty H online.
  - Here, the output vector of the TSKFNN-AMF is

$$H(e(t)|\,\mathbf{W}) \equiv \mathbf{r}^T \mathbf{W}\boldsymbol{\Gamma} \qquad (5.17)$$

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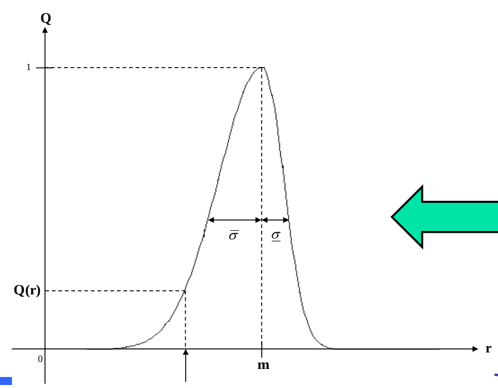
$$\mathbf{Q}(\mathbf{r}) = \exp\left\{-[\mathbf{r}-\mathbf{m}]^2 / \boldsymbol{\sigma}^2\right\},$$

$$\boldsymbol{\sigma} = [\overline{\boldsymbol{\sigma}} \quad \underline{\boldsymbol{\sigma}}],$$

$$\mathbf{r}^T = \left[e(t) \quad \dot{e}(t)\right].$$



- *C. Intelligent Complementary Sliding Mode Control (ICSMC)*
  - ***Theorem 5.2***: Considering the system dynamic equation represented by (5.2), if the proposed ICSMC is designed as (5.26), which is composed of the equivalent control law designed as (5.27), the robust controller designed as (5.28) with its adaptive learning algorithm designed as (5.33), and the adaptive learning algorithms of the TSKFNN-AMF estimator designed as (5.29) to (5.32), then the proposed ICSMC system guarantees the asymptotical stability of the tracking error simultaneously.

$$i_q^* = i_{ICSMC} + u_r \tag{5.26}$$

$$i_{ICSMC} = \frac{1}{B_n}[\dot{\omega}_r^* - A_n\omega_r + \lambda(e+S) - \mathbf{r}^T\hat{\mathbf{W}}\hat{\mathbf{\Gamma}}] \tag{5.27}$$

$$u_r = \hat{F} \tag{5.28}$$

$$\dot{\hat{\mathbf{W}}}_1^T = -\eta_1(S+S_C)e\hat{\mathbf{\Gamma}} \tag{5.29}$$

$$\dot{\hat{\mathbf{W}}}_2^T = -\eta_2(S+S_C)\dot{e}\hat{\mathbf{\Gamma}} \tag{5.30}$$

$$\dot{\hat{\mathbf{m}}}^T = -\eta_3(S+S_C)\mathbf{r}^T\hat{\mathbf{W}}\mathbf{\Gamma}_{\mathbf{m}}^T \tag{5.31}$$

$$\dot{\hat{\boldsymbol{\sigma}}}^T = -\eta_4(S+S_C)\mathbf{r}^T\hat{\mathbf{W}}\mathbf{\Gamma}_{\boldsymbol{\sigma}}^T \tag{5.32}$$

$$\dot{\hat{F}} = -\eta_5(S+S_C) \tag{5.33}$$

- ***Proof***: Choose the Lyapunov function candidate as

$$V_{ICSMC} = \frac{1}{2}\left(S^2 + S_C^2\right) + \frac{1}{2\eta_1}\tilde{\mathbf{W}}_1\tilde{\mathbf{W}}_1^{\,T} + \frac{1}{2\eta_2}\tilde{\mathbf{W}}_2\tilde{\mathbf{W}}_2^{\,T} + \frac{1}{2\eta_3}\tilde{\mathbf{m}}^T\tilde{\mathbf{m}} + \frac{1}{2\eta_4}\tilde{\boldsymbol{\sigma}}^T\tilde{\boldsymbol{\sigma}} + \frac{1}{2\eta_5}\tilde{F}^T\tilde{F} \qquad (5.34)$$

- Taking the time derivative of V_{ICSMC}. Then

$$\begin{aligned}\dot{V}_{ICSMC} &= S\dot{S} + S_C\dot{S}_C - \frac{1}{\eta_1}\tilde{\mathbf{W}}_1\dot{\hat{\mathbf{W}}}_1^{\,T} - \frac{1}{\eta_2}\tilde{\mathbf{W}}_2\dot{\hat{\mathbf{W}}}_2^{\,T} - \frac{1}{\eta_3}\dot{\hat{\mathbf{m}}}^T\tilde{\mathbf{m}} \\ &\quad - \frac{1}{\eta_4}\dot{\hat{\boldsymbol{\sigma}}}^T\tilde{\boldsymbol{\sigma}} - \frac{1}{\eta_5}\dot{\hat{F}}^T\tilde{F} \qquad (5.35) \\ &\quad \vdots \\ &= -\lambda(S + S_C)^2 \le 0\end{aligned}$$

Define

$$P_{ICSMC}(t) \equiv \lambda(S + S_C)^2 \le -\dot{V}_{ICSMC}(S(t), S_C(t)) \qquad (5.36)$$

Fault Tolerant Control of Six-Phase PMSM Drive System—Using ICSMC

Then

$$\int_0^t P_{ICSMC}(\tau)\, d\tau \le V_{ICSMC}(S(0), S_C(0)) - V_{ICSMC}(S(t), S_C(t)) \qquad (5.37)$$

Since $V_{ICSMC}(S(0), S_C(0))$ is bounded and $V_{ICSMC}(S(t), S_C(t))$ is nonincreasing and bounded, then

$$\lim_{t\to\infty} \int_0^t P_{ICSMC}(\tau)\, d\tau < \infty \qquad (5.38)$$

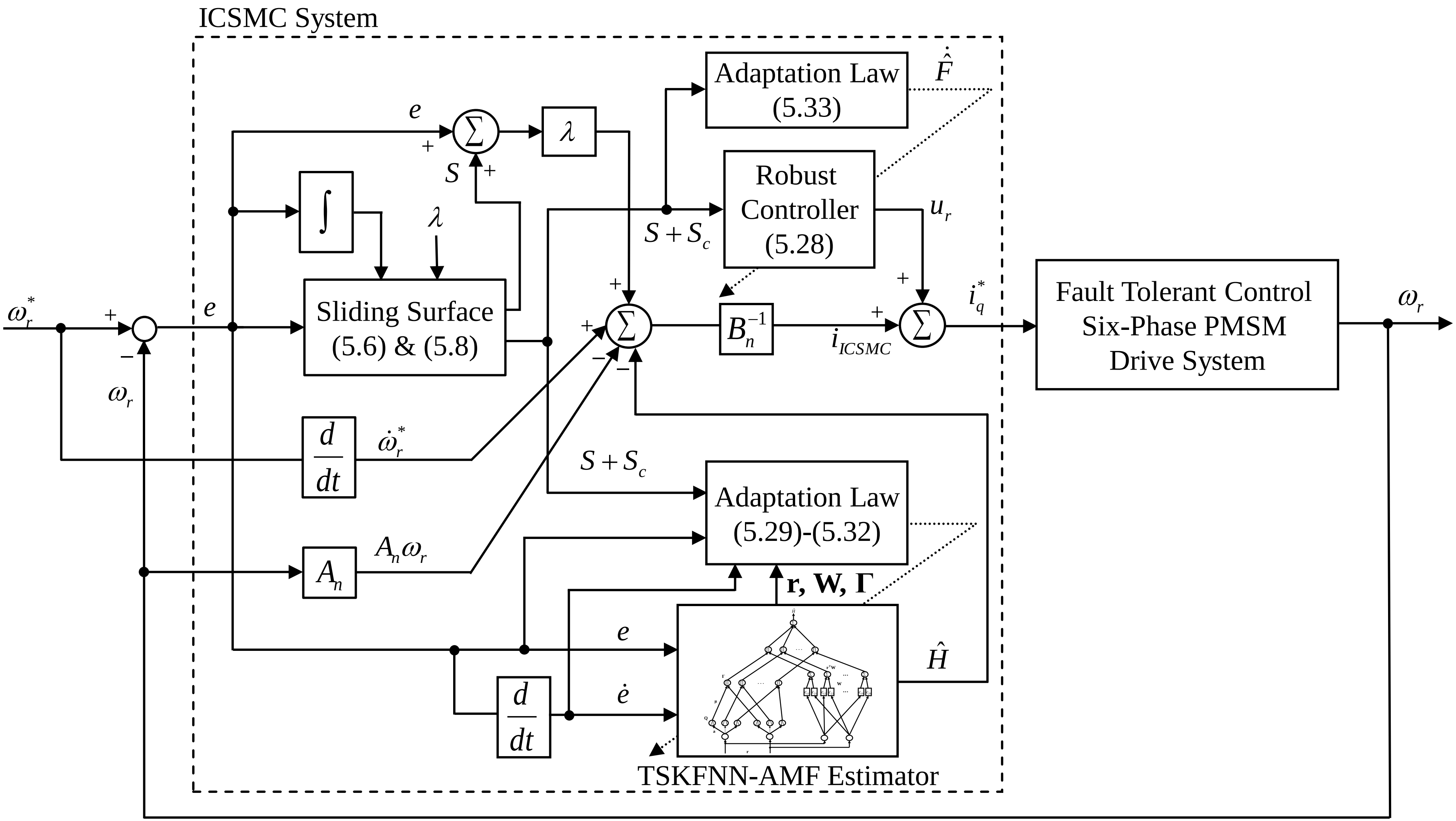
Furthermore, $\dot{P}_{ICSMC}(t)$ is also bounded. Then, $P_{ICSMC}(t)$ is uniformly continuous. Using Barbalat's lemma, then

$$\lim_{t\to\infty} P_{ICSMC}(t) = 0 \qquad (5.39)$$

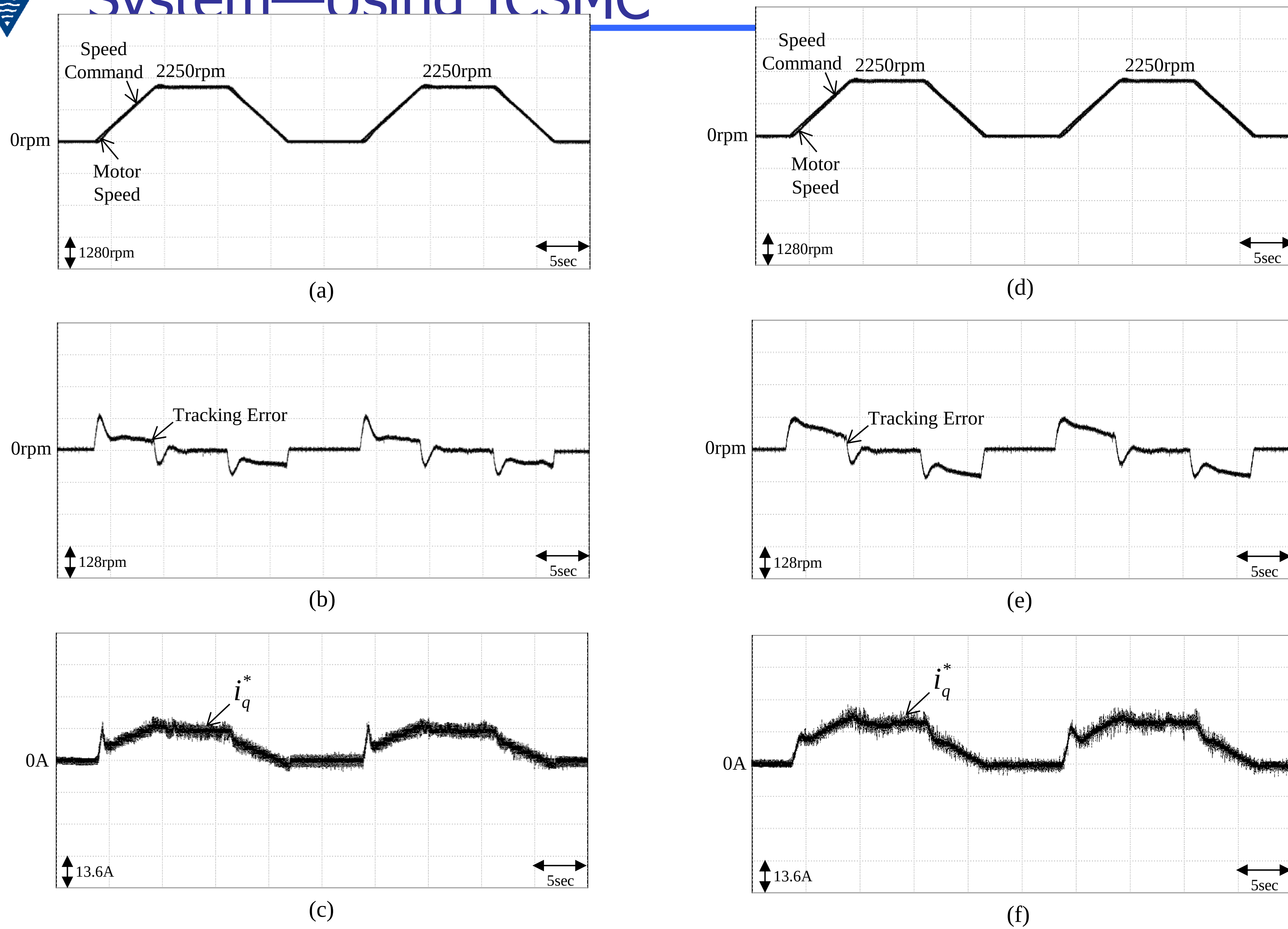
Asymptotic stability is guaranteed.

Fault Tolerant Control of Six-Phase PMSM Drive System—Using ICSMC

- The configuration of the proposed ICSMC system is shown as follows:



Fault Tolerant Control of Six-Phase PMSM Drive System—Using ICSMC



Experimental results of CSMC at Case 1(left) and Case 2(right)

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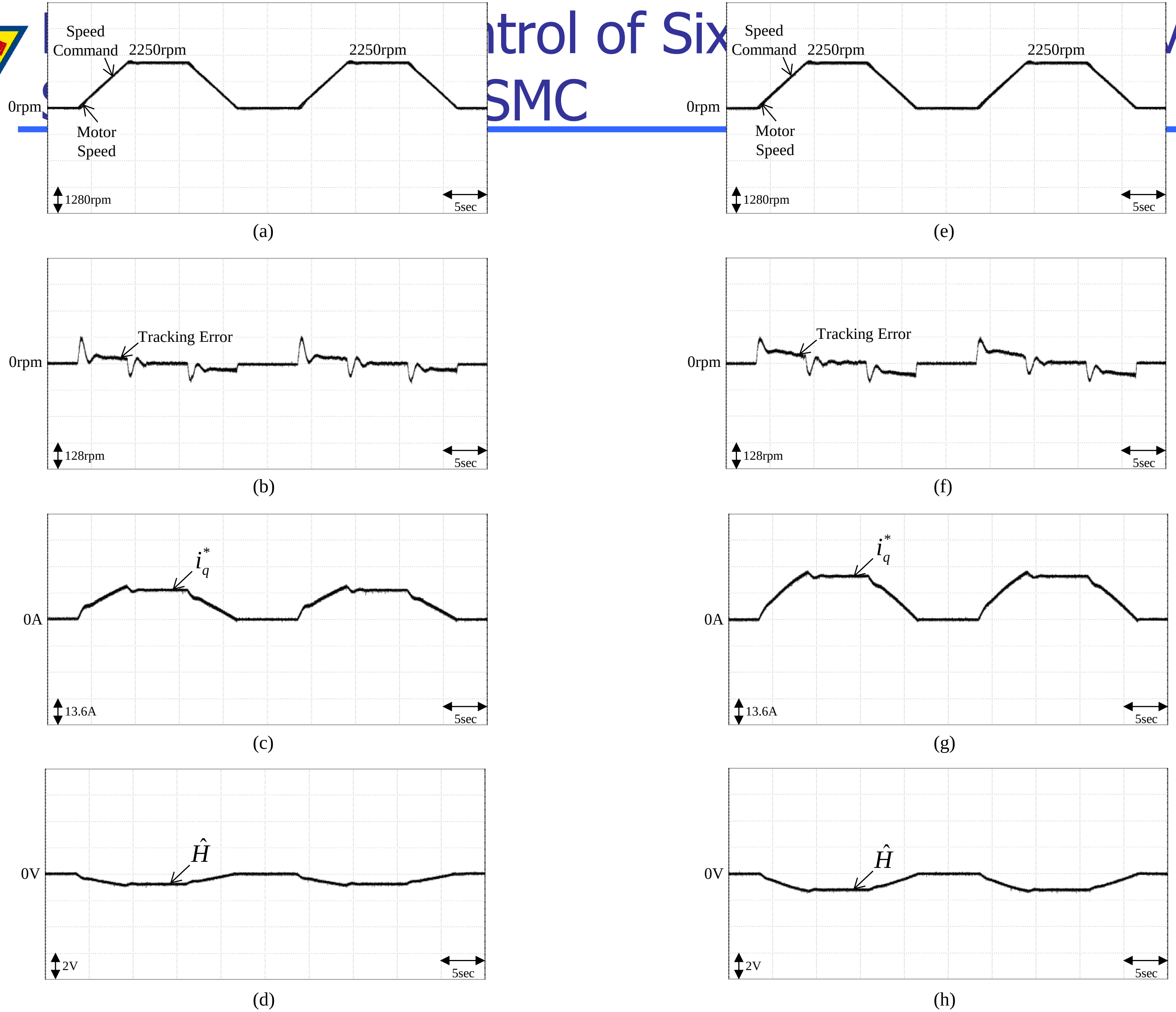
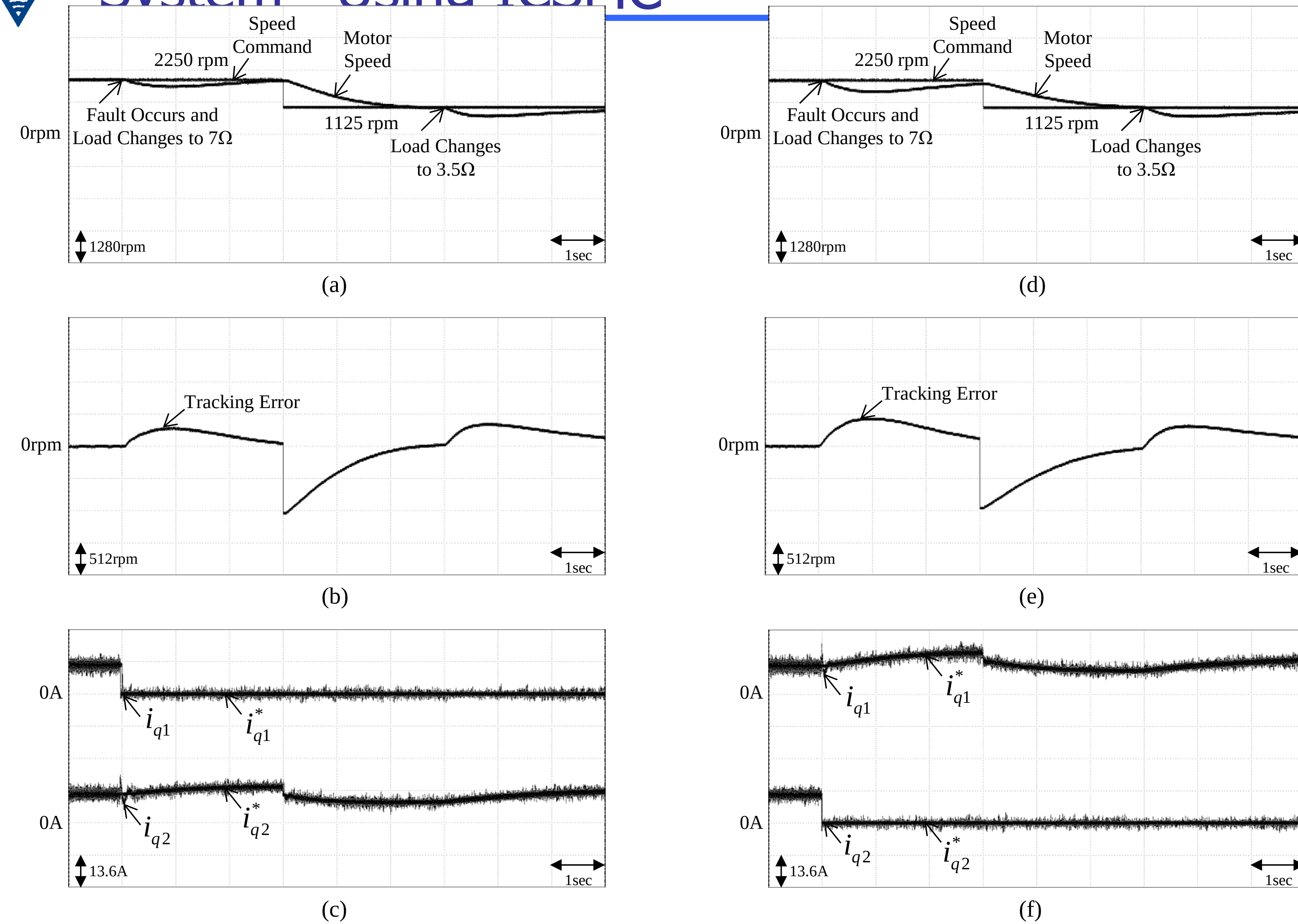
SMC



Experimental results of ICSMC at Case 1(left) and Case 2(right)

Fault Tolerant Control of Six-Phase PMSM Drive System—Using ICSMC



Experimental results of fault tolerant control via CSMC at Case 3(left) and Case 4(right)

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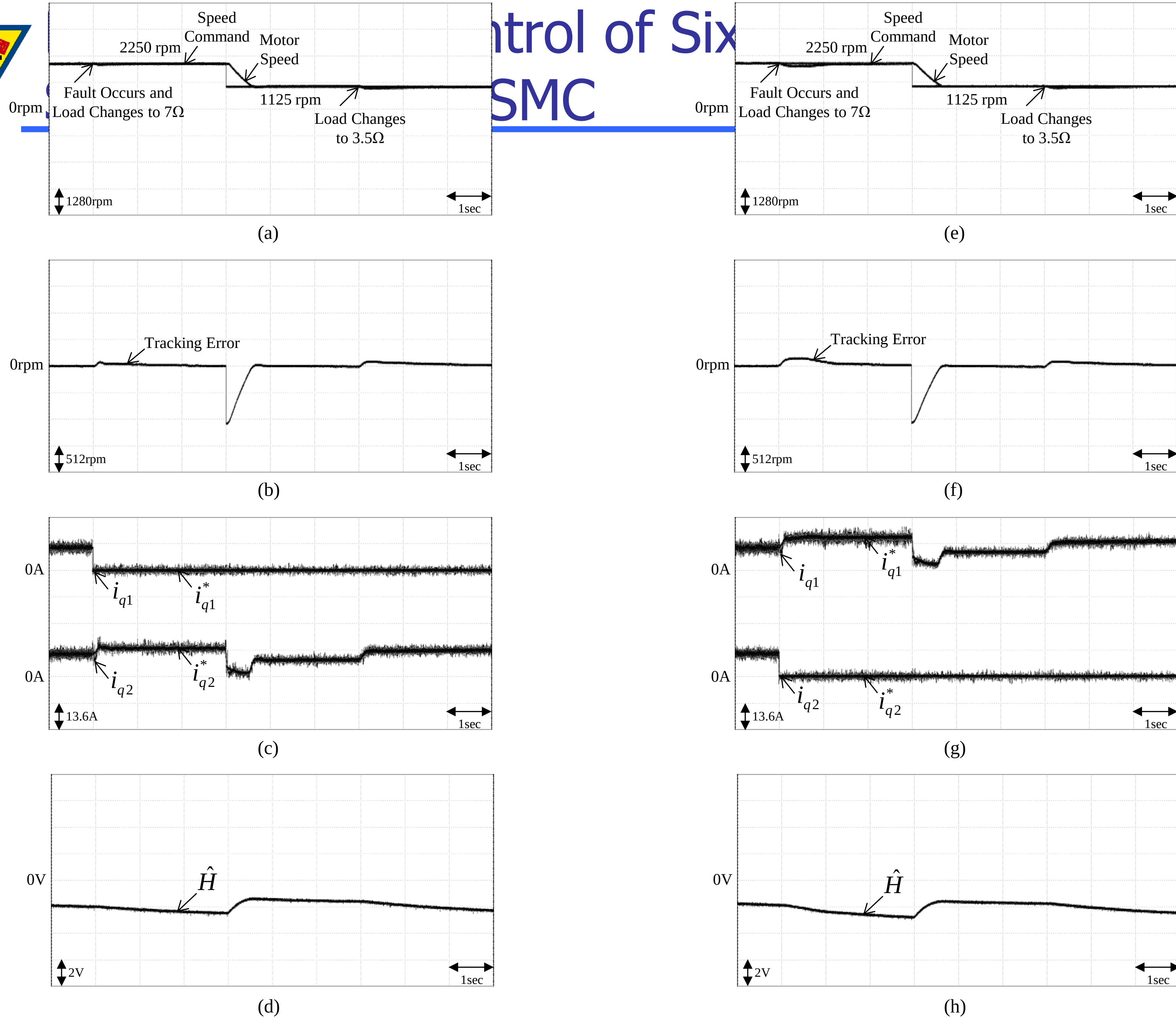
SMC



Experimental results of fault tolerant control via ICSMC at Case 3(left) and Case 4(right)

Fault Tolerant Control of Six-Phase PMSM Drive System—Using ICSMC

- The performance measurings of the CSMC and the proposed ICSMC under healthy and faulty conditions are shown in Table 5.1 and Table 5.2 respectively.
- The fault tolerant control via ICSMC can provide better control performance of the motor under faulty condition.

Table 5.1 Performance measurings of CSMC and ICSMC under healthy condition.

Tracking Errors, rpm	CSMC		ICSMC	
	Case 1	Case 2	Case 1	Case 2
Maximum	138.24	153.6	133.12	138.24
Average	3.93	5.41	2.88	2.91
Standard Deviation	41.04	61.61	28.25	37.78

Table 5.2 Performance measurings of CSMC and ICSMC under faulty condition.

Tracking Errors, rpm	CSMC		ICSMC	
	Case 3	Case 4	Case 3	Case 4
Maximum	368.64	458.24	133.12	194.56
Average	25.29	39.15	15.66	25.45
Standard Deviation	310.63	340.38	167.79	179.13

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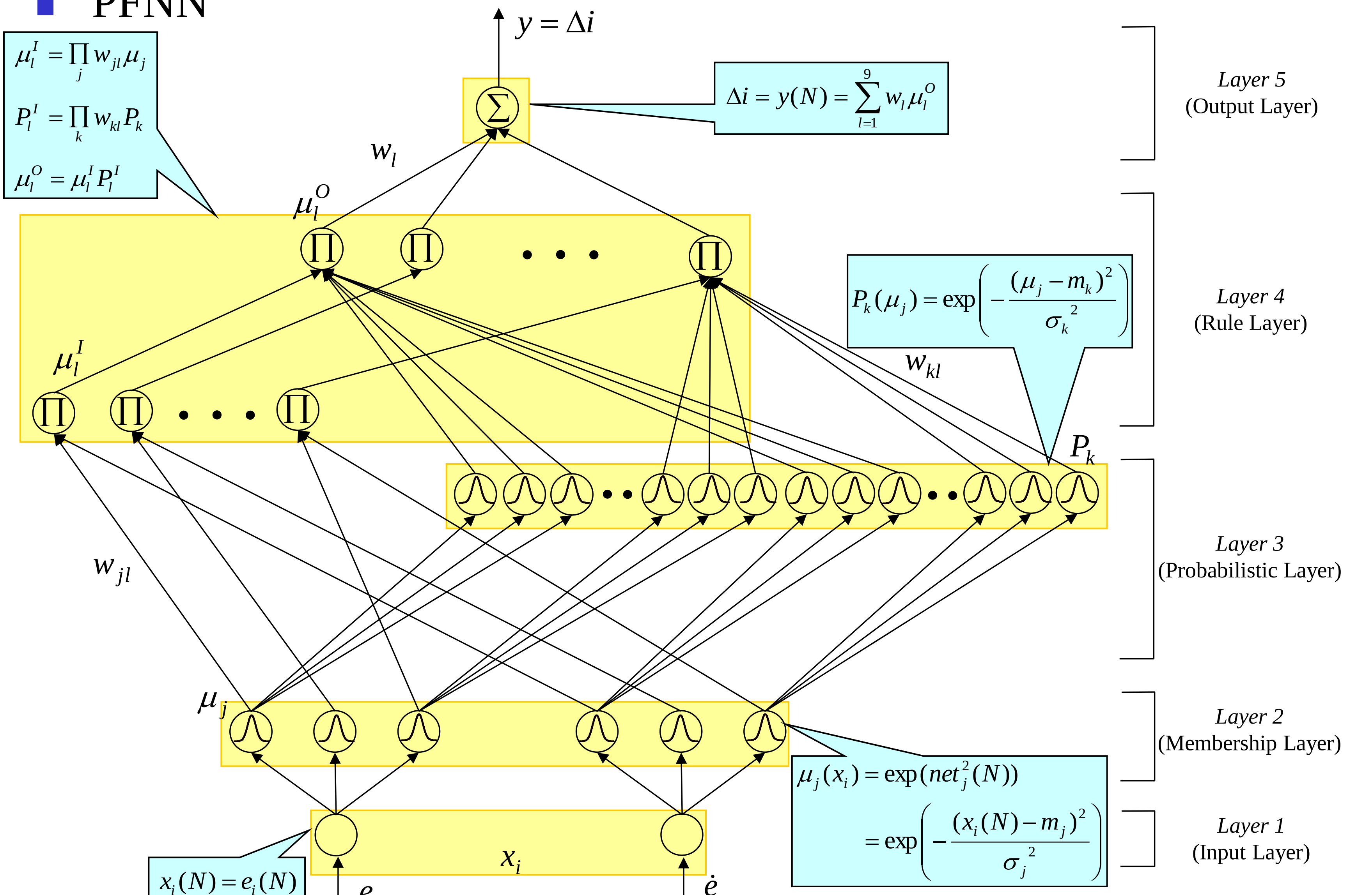
Fault Tolerant Control of In-Wheel Motor Drive System Using Six-Phase PMSM via PFNN Control

- PFNN



- To obtain the leaning algorithm for the PFNN, the BP learning rule is adopted here. First, the energy function is defined as:

$$E = \frac{1}{2}(\omega_r^* - \omega_r)^2 = \frac{1}{2}e^2 \quad (6.8)$$

- Then, the update laws are:

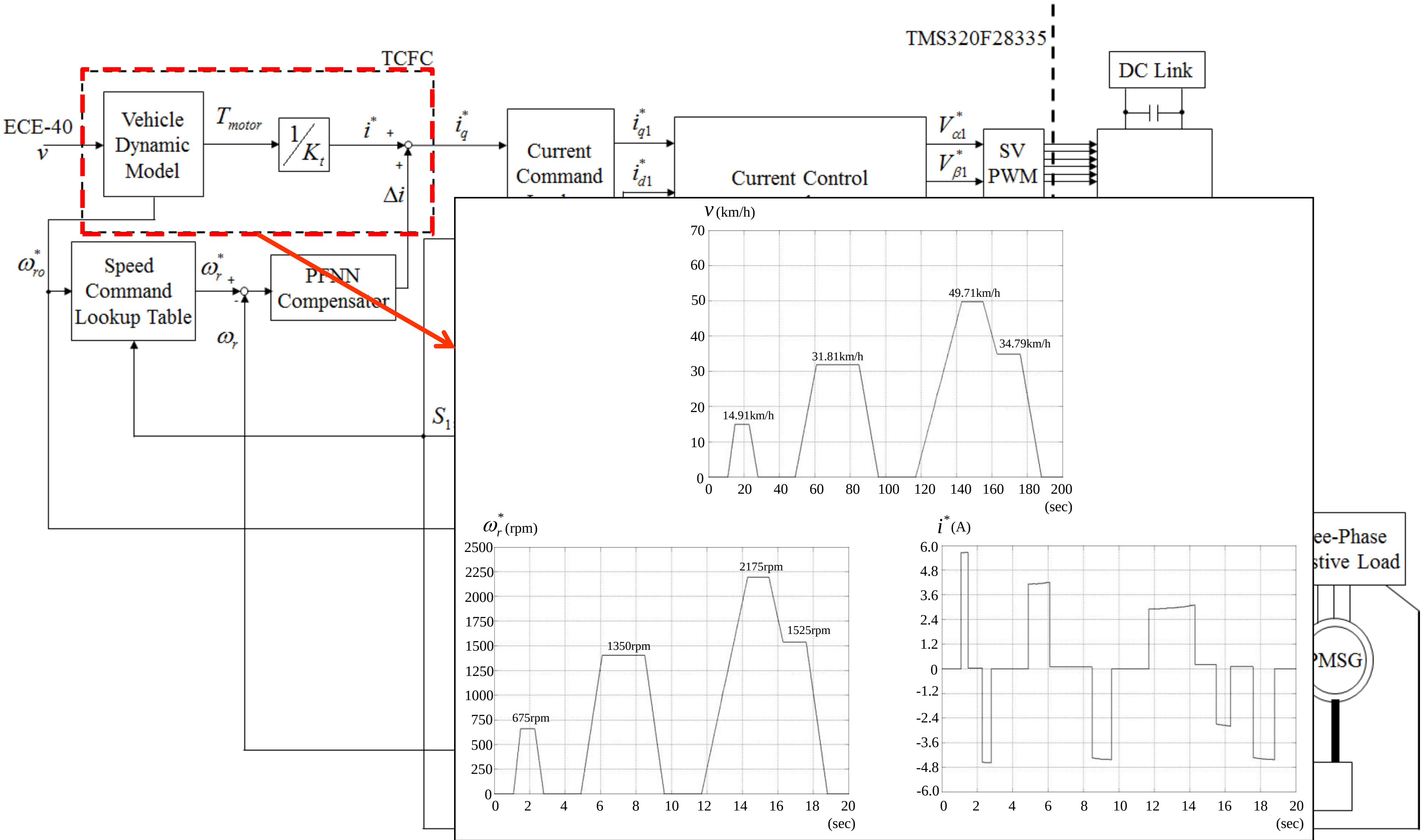
$$\Delta w_l = -\eta_1 \frac{\partial E}{\partial w_l} = -\eta_1 \frac{\partial E}{\partial y(N)} \frac{\partial y(N)}{\partial w_l} = \eta_1 \delta_o \mu_l^O \quad (6.10)$$

$$\begin{aligned}\Delta m_j &= -\eta_2 \frac{\partial E}{\partial m_j} \\ &= -\eta_2 \frac{\partial E}{\partial y(N)} \frac{\partial y(N)}{\partial \mu_l^o} \frac{\partial \mu_l^O}{\partial \mu_l^I} \frac{\partial \mu_l^I}{\partial \mu_j} \frac{\partial \mu_j}{\partial net_j^2} \frac{\partial net_j^2}{\partial m_j} = \eta_2 \delta_j \frac{2(x_i - m_j)}{\sigma_j^{\ 2}}\end{aligned} \quad (6.14)$$

$$\begin{aligned}\Delta \sigma_j &= -\eta_3 \frac{\partial E}{\partial \sigma_j} \\ &= -\eta_3 \frac{\partial E}{\partial y(N)} \frac{\partial y(N)}{\partial \mu_l^o} \frac{\partial \mu_l^O}{\partial \mu_l^I} \frac{\partial \mu_l^I}{\partial \mu_j} \frac{\partial \mu_j}{\partial net_j^2} \frac{\partial net_j^2}{\partial \sigma_j} = \eta_3 \delta_j \frac{2(x_i - m_j)^2}{\sigma_j^{\ 3}}\end{aligned} \quad (6.15)$$

Fault Tolerant Control of In-Wheel Motor Drive System Using Six-Phase PMSM via PFNN Control

- Fault tolerant control of in-wheel motor drive system

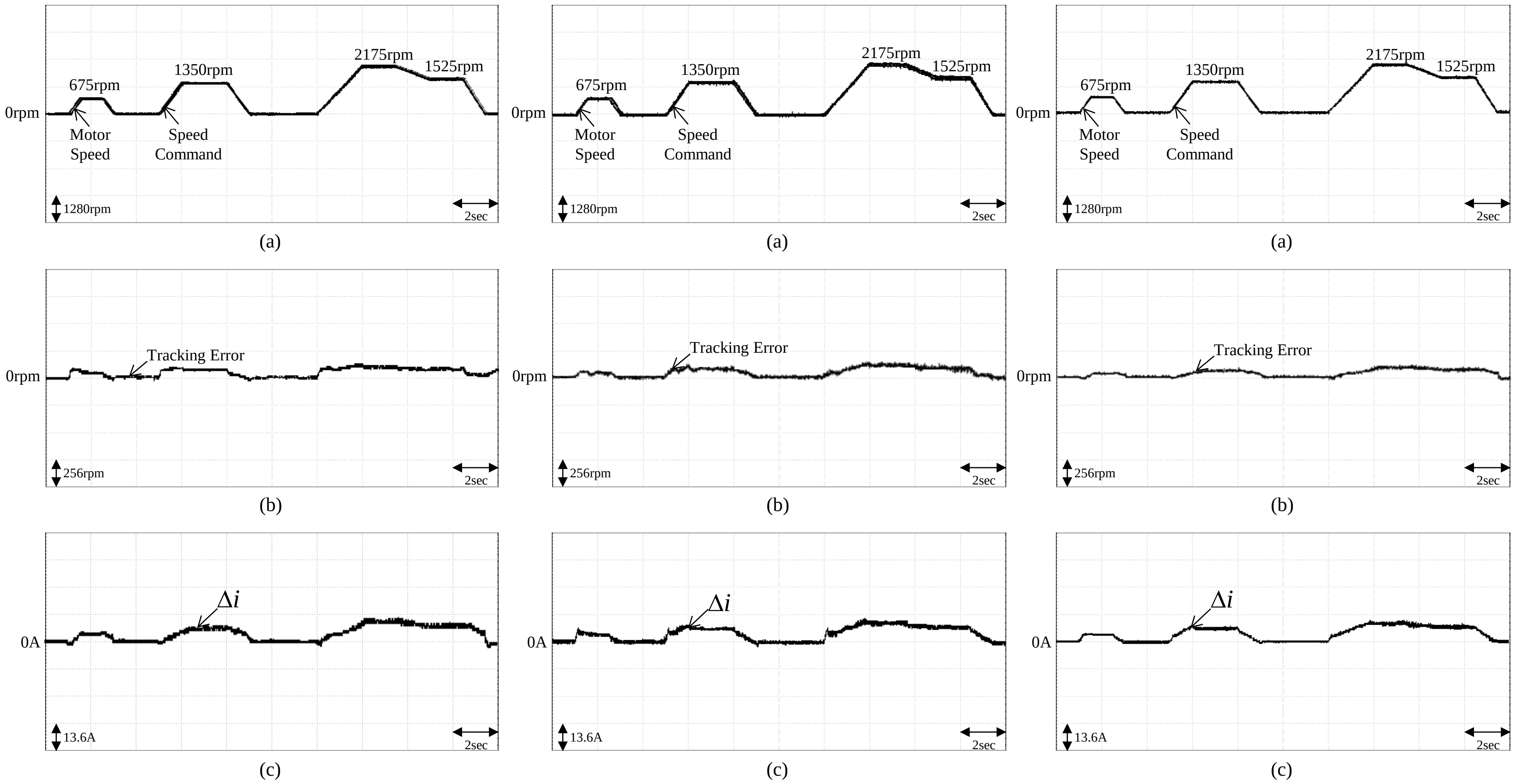


Fault Tolerant Control of In-Wheel Motor Drive System Using Six-Phase PMSM via PFNN Control

- Healthy condition in experiment:
  - Modified ECE-40 driving cycle:
    - Y-connected three-phase resistive load 7Ω for the PMSG (Case 5)
    - Y-connected three-phase resistive load 3.5Ω for the PMSG (Case 6)

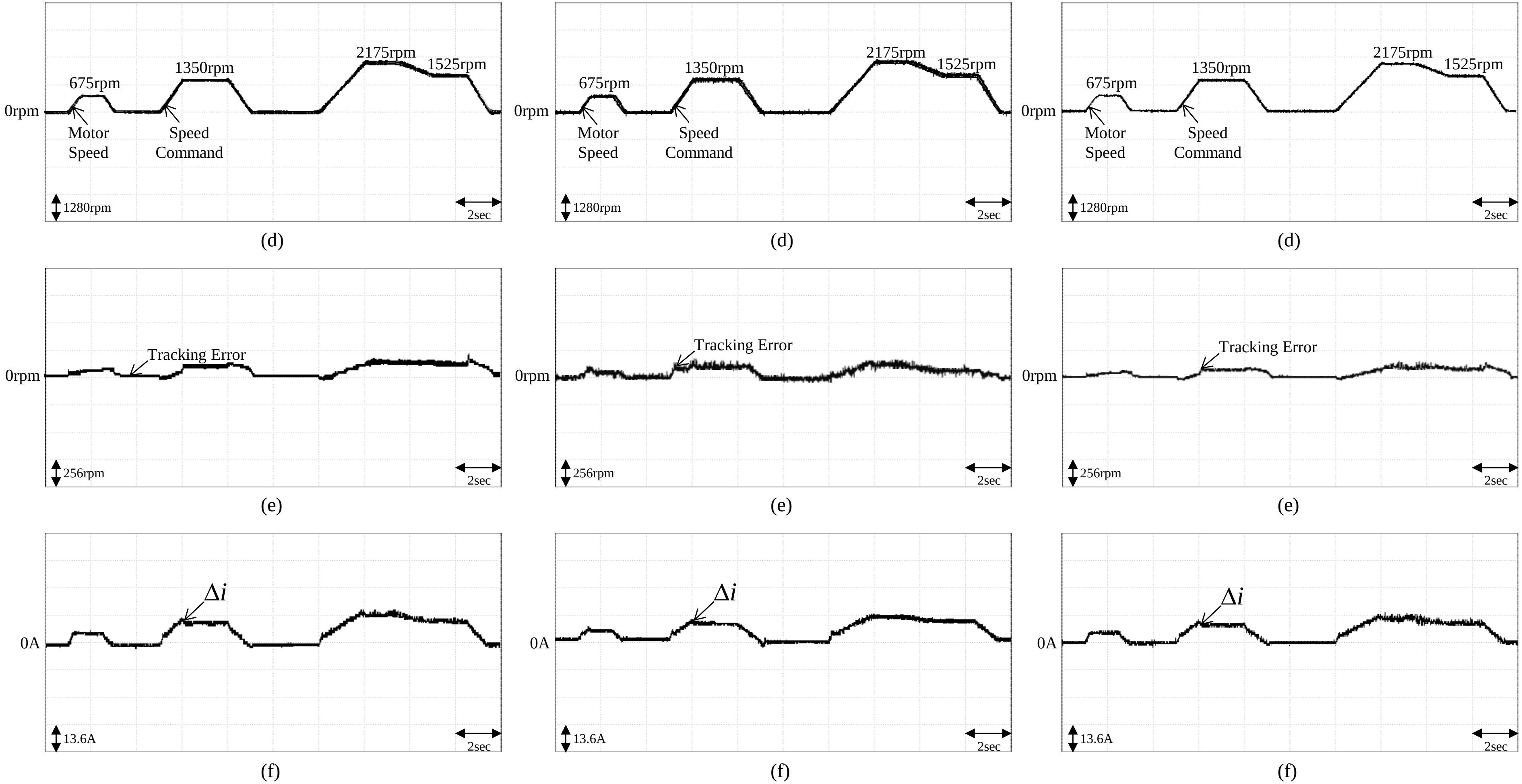
- Faulty condition in experiment:
  - Speed profile is set as 2250 rpm at the beginning and reduced to half of the speed after three seconds when the fault detected, and then reduced to 0 rpm after three more seconds in order to shutdown the system and avoid the damage:
    - *abc* winding open (Case 7) and *xyz* winding open (Case 8)
  - Speed profile is set as 2250 rpm at the beginning and keeps the speed when the fault detected:
    - *abc* winding open (Case 9) and *xyz* winding open (Case 10)

Fault Tolerant Control of In-Wheel Motor Drive System Using Six-Phase PMSM via PFNN Control



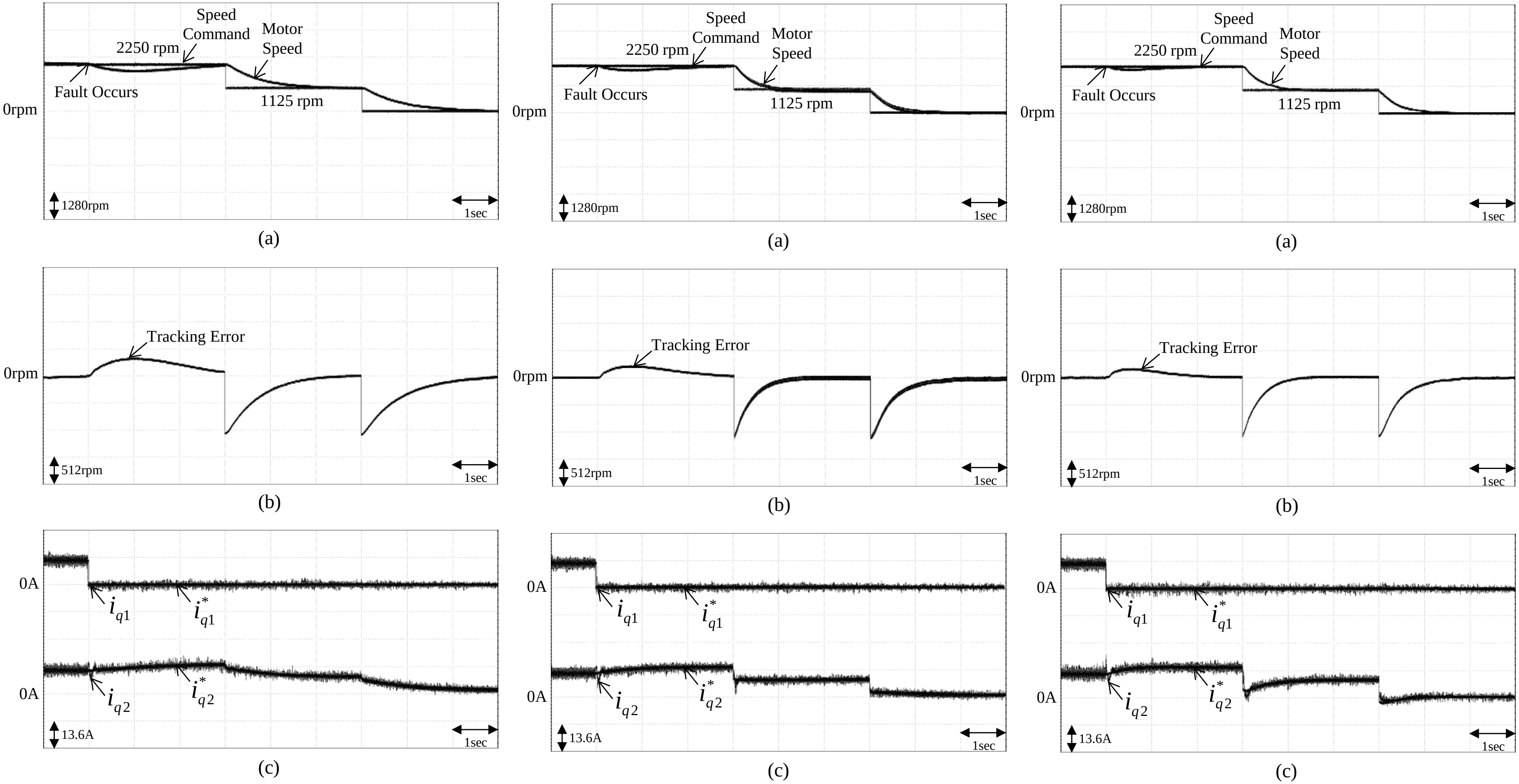
Experimental results of PI control (left), FNN control (middle) and PFNN control (right) at Case 5.

Fault Tolerant Control of In-Wheel Motor Drive System Using Six-Phase PMSM via PFNN Control



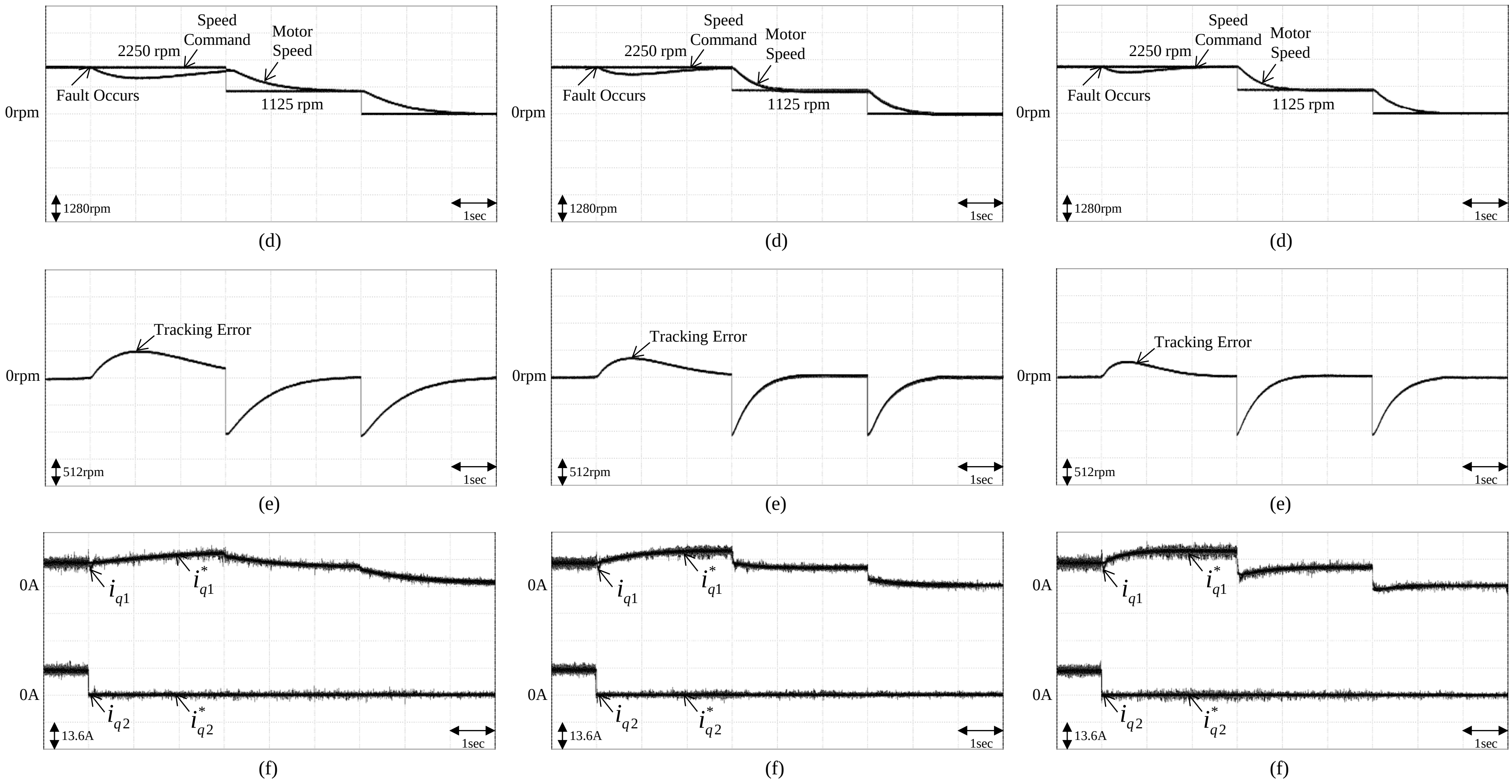
Experimental results of PI control (left), FNN control (middle) and PFNN control (right) at Case 6.

Fault Tolerant Control of In-Wheel Motor Drive System Using Six-Phase PMSM via PFNN Control



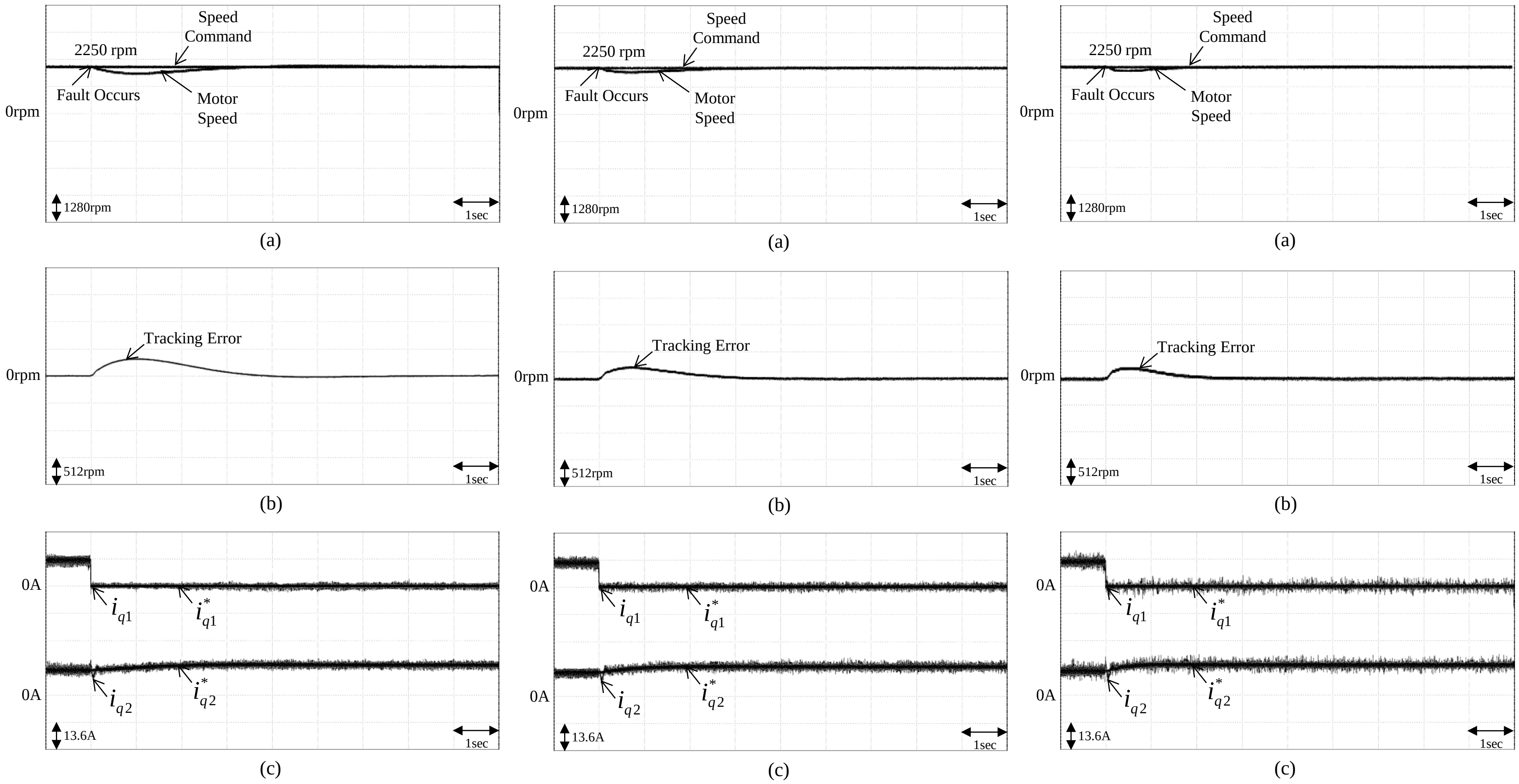
Experimental results of PI fault tolerant control (left), FNN fault tolerant control (middle) and PFNN fault tolerant control (right) at Case 7.

Fault Tolerant Control of In-Wheel Motor Drive System Using Six-Phase PMSM via PFNN Control



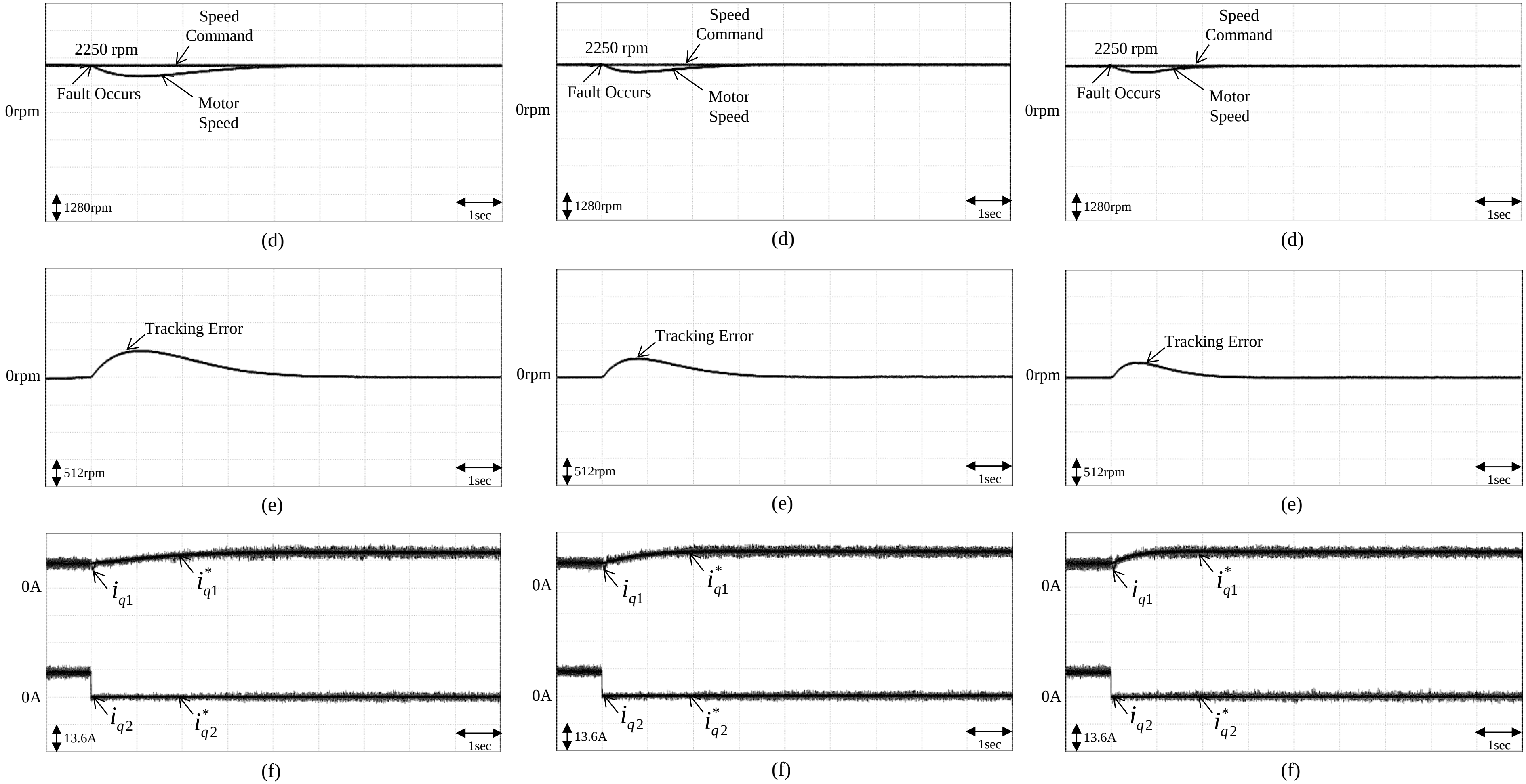
Experimental results of PI fault tolerant control (left), FNN fault tolerant control (middle) and PFNN fault tolerant control (right) at Case 8.

Fault Tolerant Control of In-Wheel Motor Drive System Using Six-Phase PMSM via PFNN Control



Experimental results of PI fault tolerant control (left), FNN fault tolerant control (middle) and PFNN fault tolerant control (right) at Case 9.

Fault Tolerant Control of In-Wheel Motor Drive System Using Six-Phase PMSM via PFNN Control



Experimental results of PI fault tolerant control (left), FNN fault tolerant control (middle) and PFNN fault tolerant control (right) at Case 10.

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Discussions

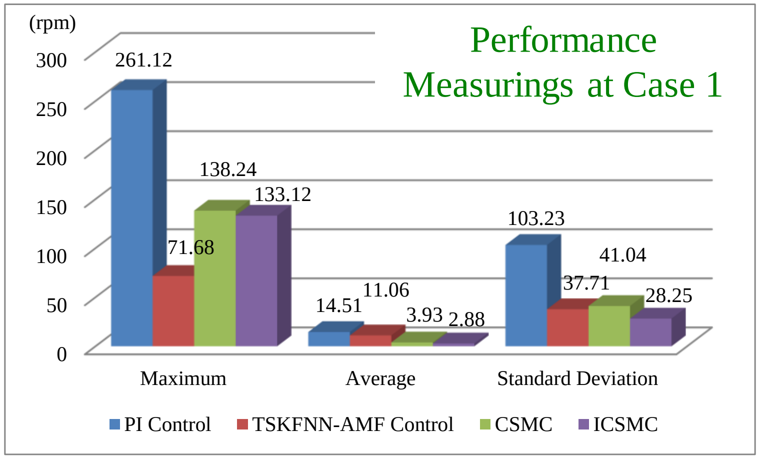
- A DSP-based intelligent fault tolerant control of six-phase PMSM drive system, which fulfills the requirements of safety and system stability of in-wheel motor drive system in the LEV applications, was developed in this dissertation.

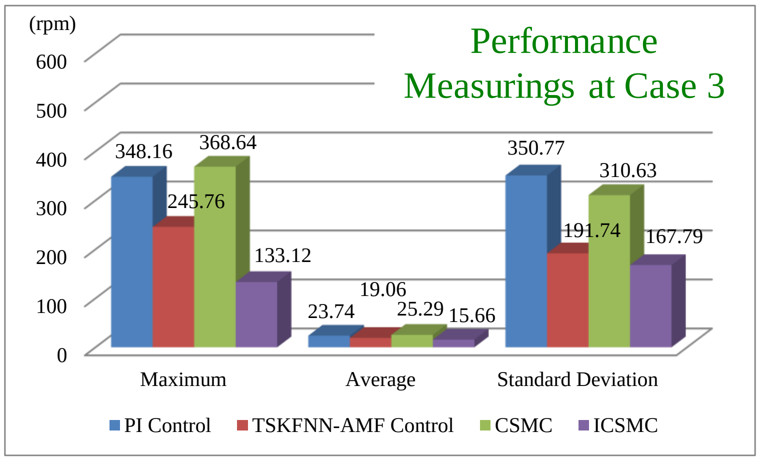
- Two control approaches were proposed to improve the control performance and to maintain the stability of fault tolerant control six-phase PMSM drive system under faulty condition.

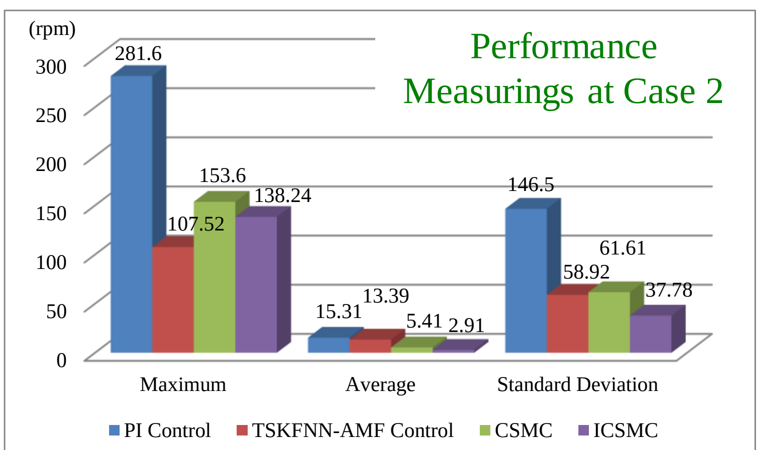
- The developed intelligent fault tolerant control system was adopted to control the in-wheel motor drive system using six-phase PMSM for LEV and make the driving more comfortable with safety for the driver and the passengers.

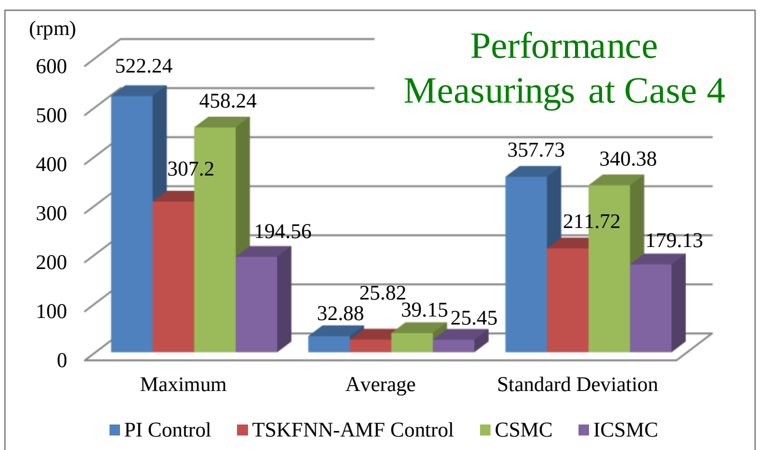
Discussions

- Comparisons of different control approaches for fault tolerant control six-phase PMSM drive system
  - The ranking of control performance in accordance with the performance measurings are ICSMC, TSKFNN-AMF control, CSMC, and PI control.



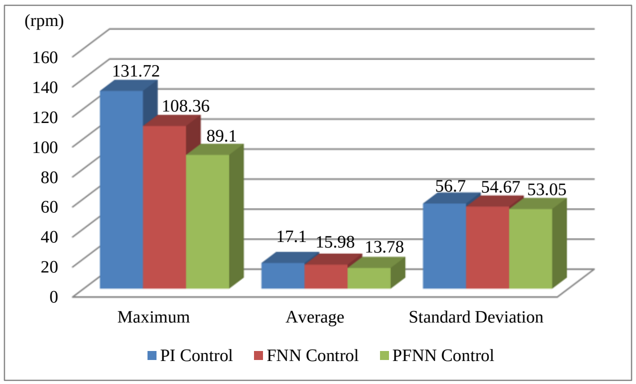




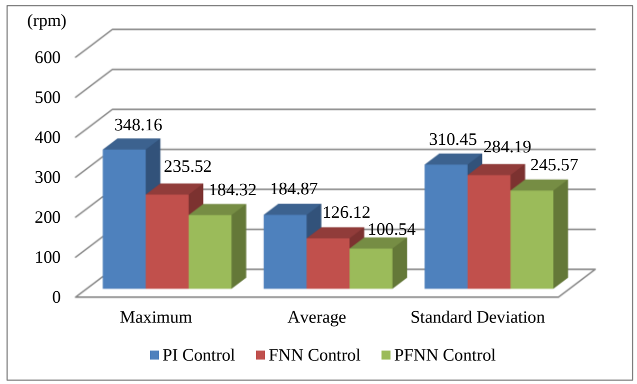


Discussions

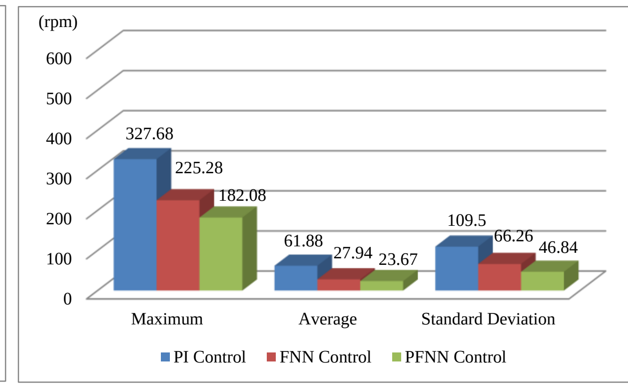
- Comparisons of different control approaches fault tolerant control of in-wheel motor drive system using six-phase PMSM in LEV



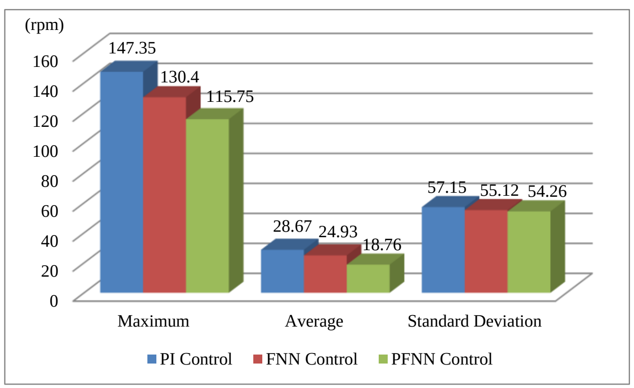
Performance Measurings at Case 5



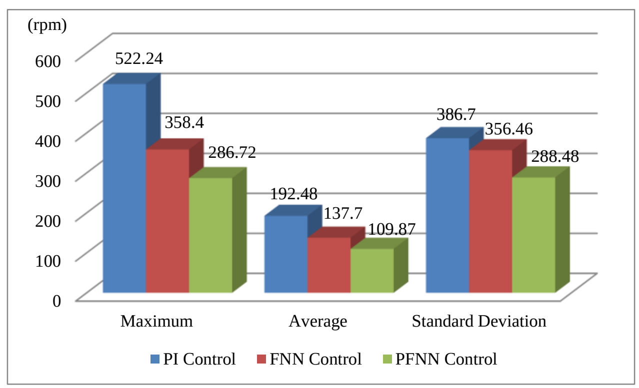
Performance Measurings at Case 7



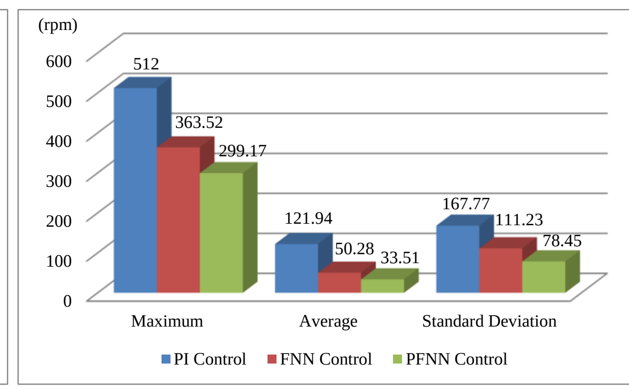
Performance Measurings at Case 9



Performance Measurings at Case 6



Performance Measurings at Case 8



Performance Measurings at Case 10

Conclusions

- The major contributions of this dissertation are concluded as follows:
  1) the successful development of the DSP-based control system using 32-bit floating-point DSP, TMS320F28335;
  2) the complete analysis of the dynamics and detailed discussion of the six-phase PMSM and its drive system;
  3) the complete analyses of the dynamics of the LEV and in-wheel motor drive system;
  4) the successful development of the fault detection and operating decision method for the fault tolerant control;
  5) the successful development of the DSP-based fault tolerant control for the six-phase PMSM drive system;
  6) the successful development of the various controllers for the fault tolerant control of six-phase PMSM drive system with guaranteed system stability under both healthy and faulty conditions;
  7) the successful development of the DSP-based fault tolerant control for the in-wheel motor drive system using six-phase PMSM;
  8) the successful development of the various controllers for the fault tolerant control of in-wheel motor drive system with guaranteed system stability for LEV under both healthy and faulty conditions.

Suggestions for Future Works

- The suggestions for the future works of this dissertation are summarized as follows:
  1) to develop an intelligent position control of the fault tolerant control six-phase PMSM drive system;
  2) to apply the developed fault tolerant control six-phase PMSM drive system in the industrial applications such as compressor, robotic arms, or electric power steering system;
  3) to realize the developed fault tolerant control in-wheel motor drive system in a real EV with more vehicle performance testing and to communicate with other electronic modules in EV via CAN Bus.

Publications of This Dissertation

[1] F. J. Lin, **<u>Y. C. Hung</u>**, and M. T. Tsai, "Fault tolerant control for six-phase PMSM drive system via intelligent complementary sliding mode control using TSKFNN-AMF," *IEEE Trans. Industrial Electronics*, vol. 60, no. 12, pp. 5747-5762, Dec. 2013. (SCI, Impact Factor: 5.160)

5 Fault Tolerant Control of Six-Phase PMSM Drive System via Intelligent Complementary Sliding Mode Control Using TSKFNN-AMF

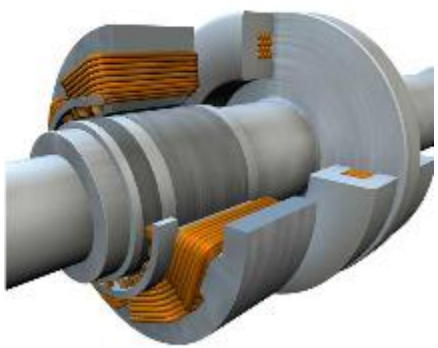
[2] F. J. Lin, **<u>Y. C. Hung</u>**, J. C. Hwang, and M. T. Tsai, "Fault-tolerant control of a six-phase motor drive system using a Takagi-Sugeno-Kang type fuzzy neural network with asymmetric membership function," *IEEE Trans. Power Electronics*, vol. 28, no. 7, pp. 3557-3572, Jul. 2013. (SCI, Impact Factor: 4.650)

4 Fault Tolerant Control of Six-Phase PMSM Drive System Using TSK Type Fuzzy Neural Network with Asymmetric Membership Function

[3] F. J. Lin, **<u>Y. C. Hung</u>**, J. C. Hwang, I. P. Chang, and M. T. Tsai, "Digital signal processor-based probabilistic fuzzy neural network control of in-wheel motor drive for light electric vehicle," *IET Electric Power Applications*, vol. 6, no. 2, pp. 47-61, Feb. 2012. (SCI, Impact Factor: 1.173)

6 Fault Tolerant Control of In-Wheel Motor Drive System Using Six-Phase PMSM via Probabilistic Fuzzy Neural Network Control

Thank You for Your Attention!



Questions?