Extension Robust Control of a Three-Level Converter for High-Speed Railway Tractions

Kuei-Hsiang Chao

National Chin-Yi University of Technology, Department of Electrical Engineering, 35, 215 Lane, Sec. 1, Chung Shan Road, Taiping, Taichung, Taiwan, R.O.C.
chaokh@ncut.edu.tw

Abstract. In this paper, the dynamic model of a three-level neutral point clamped (NPC) converter with neutral-point voltage-balance control (NPVBC) and input power factor correction for high-speed railway tractions is derived. And accordingly, a feedback controller is designed to meet the given voltage regulation control specifications. As the variation of converter parameters occurs, a compensation signal is yielded by an extension robust controller (ERC) to preserve the prescribed response. The compensation signal is adaptively tuned by a model error driven extension weighting controller. Some simulation results are presented to demonstrate the effectiveness of the proposed controller.

Keywords: Three-level converter, power factor correction, extension robust controller, high-speed railway tractions.

1 Introduction

Several numerous three-level converters circuit topologies have been developed [1,2] to reduce the voltage stress of power semiconductors, voltage harmonics, and EMI in medium and high power applications. Although the input current of three-level NPC converters can be regulated to be sinusoidal and maintained almost in phase with the input voltage [3,4], the dynamic modeling and quantitative controller design to obtain well-regulated dc output voltage under good input power factor correction have not get been performed. In addition, it is well known that robust control is one of the most effective techniques for dealing with parameter variations. Although a robust control technique has been applied to many processes [5,6], it is seldom used for control of three-level converters. Moreover, most of the existing robust control techniques are too theoretically complex for use by practical engineers. It follows that good control performance generally can not be achieved.

In this paper, the dynamic model of the proposed three-level converter is firstly derived from the system parameters and measured data for a nominal case by averaged power method and circuit theory. Then, a quantitative design procedure is developed to find the parameters of the voltage controller according to prescribed control specifications. Finally, an extension robust controller is proposed to overcome the control performance degradation due to system parameter and load current changes. The key feature of the proposed ERC is that its weighting factor is adaptively set by an extension

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weighting controller. In addition, the compromise between control effort and response is considered through tuning the weighting factor automatically. Since the model error is used as the input of the extension controller and the linguistic algorithms for tuning the weighting factor are properly set, more robust and better voltage control performance than those of the conventional robust control [7,8] are obtained by the proposed controller. The performance of the developed quantitative robust controller is demonstrated by some simulation results with the PSIM software package [9].

2 Small Signal Model of Three-Level Converter

The system configuration of the proposed three-level NPC converter with NPVBC and hysteresis current control for high-speed railway tractions is shown in Fig.1. The dynamic model of the proposed three-level NPC converter can be derived at the nominal case as follows [10]:

$$\Delta V_{dc} = \frac{\hat{V}_{ac}^{*}/(2K_s\bar{V}_{dc})}{(1/2)Cs+1/(Z_a+Z_b)}\Delta\hat{I}_{ac}^{*} - \frac{1}{(1/2)Cs+1/(Z_a+Z_b)}\Delta i_o \stackrel{\Delta}{=} \left(\Delta\hat{I}_{ac}^{*} - \frac{1}{K_x}\Delta i_o\right)\frac{\beta}{s+\alpha} \quad (1)$$

where

$$K_x \stackrel{\Delta}{=} \frac{\hat{V}_{ac}^{*}}{2K_s\bar{V}_{dc}},\ \alpha \stackrel{\Delta}{=} \frac{2}{Z_T C},\ \beta \stackrel{\Delta}{=} \frac{\hat{V}_{ac}^{*}K_v}{C\bar{V}_{dc}K_s},\ Z_T \stackrel{\Delta}{=} Z_a + Z_b$$

and K_v is the conversion constant of voltage sensor.

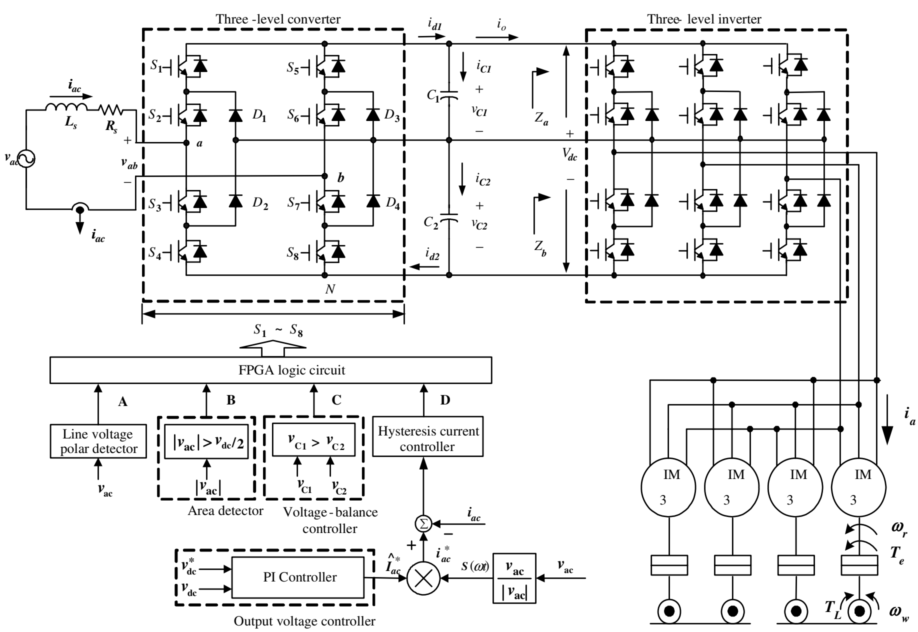

Fig. 1. System configuration of the three-level NPC converter for high-speed railway tractions

The relative parameters of the proposed three-level NPC converter at nominal case are listed in Table 1. Then the parameters of the small-signal model at nominal case can be determined as: $K_x = 73.26$, $\alpha = 12.76$ and $\beta = 26.16$.

Table 1. Some parameters of the proposed three-level NPC converter at nominal case

P_{out}	500kW	$C = C_1 = C_2$	0.01 F
$\hat{V}_{ac}$	$2050.6V$	K_s	$1/200$
R_s	$13.5m\Omega$	K_v	$1/560$
L_s	$1.75mH$	$Z_a = Z_b$	7.84Ω
$\overline{V}_{dc}$	$2800V$	Z_T	15.68Ω

3 Quantitative PI Type Voltage Controller Design

To achieve the desired control requirements with easy implementation, the following PI controller $G_{cv}(s)$ is chosen:

$$G_{cv}(s) = K_{Pv} + \frac{K_{Iv}}{s}. \tag{2}$$

The following control requirements for the response of ΔV_{dc} due to step load current change at nominal case ($\overline{V}_{dc} = 2800V$, $P_{out} = 500kW$) are specified:

(i) Steady state error=0;
(ii) Overshoot=0;
(iii) The maximum voltage dip due to step load current change Δi_o =20A is $\Delta\hat{v}_{dc,\max} = 115V$;
(iv) The restore time is $t_r = 0.3\sec$, which is defined as the time at which $\Delta v_{dc}(t = t_r) = 0.05\hat{v}_{dc,\max}$.

Following the design procedure developed in [10], one can find the parameters of voltage controller $G_{cv}(s)$ as follows:

$$K_{Pv} = 0.58 \,,\, K_{Iv} = 7.4 \,. \tag{3}$$

4 The Proposed Robust Controller Based on Extension Theory

The robust control technique based on direct cancellation of uncertainties presented in [10] is easy to apply and effective in reducing the effects of system parameter variations. However, since the weighting factor set to determine the extent of disturbance compensation is fixed, it lacks control adaptability. This will lead to the performance degradation and even the stability problem during wide operation range, especially for the system having some kinds of nonlinearities. Before introducing the proposed ERC, the conventional robust control is briefly described.

4.1 Robust Controller with Fixed Weighting Factor

When system configuration and plant parameter variations occur, the PI-type voltage controller designed for the nominal case can no longer satisfy the prescribed control requirements. To overcome this problem, a robust voltage controller based on direct cancellation of uncertainties is proposed in Fig. 2. A model error, denoted by e, is extracted using an inverse nominal plant model $G_I(s) \overset{\Delta}{=} (s+\bar{\alpha})/(\bar{\beta}K_v)$, and then a compensation control signal, $\Delta I = we$, ($0 < w \le 1$), is generated for disturbance cancellation.

The transfer function of load disturbance Δi_o to output voltage ΔV_{dc} is derived as:

$$\Delta V_{dc} = \frac{\Delta \hat{I}_{ac} - (1-w)/K_x \Delta i_o}{\left[\bar{\alpha} + (1-w)\Delta\alpha\right]s + \left[\bar{\beta} + (1-w)\Delta\beta\right]} K_v. \tag{4}$$

where $\bar{\alpha}, \bar{\beta}$ are plant parameters for the nominal case and $\Delta\alpha, \Delta\beta$ are system uncertainties.

For the ideal case ($w = 1$), one can find from (4) that

$$\Delta V_{dc} = \frac{\Delta \hat{I}_{ac}}{\bar{\alpha}s + \bar{\beta}} K_v. \tag{5}$$

That is, all the load disturbances and uncertainties have completely eliminated by the compensation control signal ΔI. However, this ideal case is practically unrealizable, and so suitable compromise between control performance and operating stability should be made. Hence for obtaining good performance without overshoot and taking into account the maximum control effort, the value w must be regulated automatically.

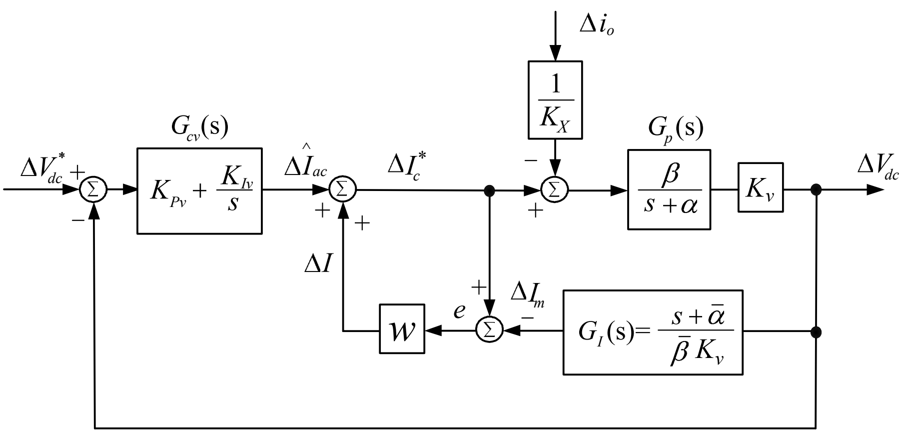

Fig. 2. The proposed robust control scheme based on direct cancellation of uncertainties

4.2 The Proposed Extension Robust Controller

4.2.1 Matter-Element Theory

In extension theory, a matter-element (***R***) contains three fundamental elements: matter name (*N*), matter characteristics (***C***) and matter characteristics of values (***V***). The matter-element can be described as follows [11]:

$$R = (N, C, V) \tag{6}$$

Where ***C*** is a matter characteristic or a characteristic vector, ex: $\boldsymbol{C}=[c_1,c_2,\ldots,c_n]$, and ***V*** the same as ***C*** is a value or a vector, ex: $\boldsymbol{V}=[v_1,v_2,\ldots,v_n]$.

4.2.2 Application of Correlation Function

The correlation functions have many forms dependent on application. If we set $X_o = < k_1, k_2 >$, $X = < n_1, n_2 >$, and $X_o \in X$, then the extended correlation function can be defined as follows [11]:

$$K(x) = \frac{\rho(x, X_o)}{D(x, X_o, X)} \tag{7}$$

If one wants to set K(x) = 1, then

$$\rho(x, X_o) = \left| x - \frac{k_1 + k_2}{2} \right| - \frac{k_2 - k_1}{2} \tag{8}$$

$$D(x, X_o, X) = \begin{cases} \rho(x, X) - \rho(x, X_o) & x \notin X_o \\ -\dfrac{|(k_2 - k_1)|}{2} & x \in X_o \end{cases} \tag{9}$$

where

$$\rho(x, X) = \left| x - \frac{n_1 + n_2}{2} \right| - \frac{n_2 - n_1}{2} \tag{10}$$

The correlation function can be used to calculate the membership grade between x and X_o. The extended correlation function is shown in Fig. 3. When K(x) = 0, this indicates the degrees to which x belongs to X_o. When K(x) < 0 it describes the degree to which x does not belong to X_o. When -1 < K(x) < 0, it is called the extension domain, which means the element x still has a chance to become part of the set if conditions change.

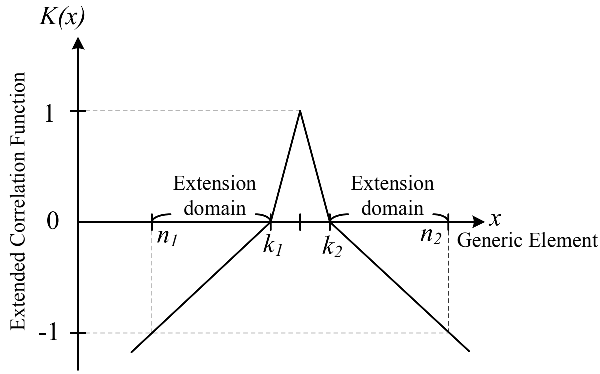

Fig. 3. The extension correlation function

4.2.3 Extension Weighting Controller

To let the robust controller (RC) possess adaptive capability, it is proposed that the weighting factor of the RC is adaptively tuned by the extension error tuning scheme, which is driven by a model error and its change defined as $e(k) \overset{\Delta}{=} \Delta I_c^*(k) - \Delta I_m(k)$ and $e(k) \overset{\Delta}{=} (1-B)e(k) = e(k) - e(k-1)$ with I_m and I_c^* being the output of the inverse model and the plant model input at k-th sampling interval, respectively. The major purpose of the proposed controller is to let the resulted output voltage tracking response closely follow those of reference. Thus the general model error trajectory can be predicted and plotted in Fig. 4. Incorporating with the extension matter-element, the numbers of quantization levels of the input variables $e(k)$ and $\Delta e(k)$ are chosen to be 13 and listed in Table 2 (The scaling is set as 1V to 10A). Based on the experience about the three-level converter to be controlled and the

Table 2. Quantized error and error change

error e(V)	error change Δe(V)	quantized level
$-3.2 < e \le -1.6$	$-3.2 < \Delta e \le -1.6$	-6
$-1.6 < e \le -0.8$	$-1.6 < \Delta e \le -0.8$	-5
$-0.8 < e \le -0.4$	$-0.8 < \Delta e \le -0.4$	-4
$-0.4 < e \le -0.2$	$-0.4 < \Delta e \le -0.2$	-3
$-0.2 < e \le -0.1$	$-0.2 < \Delta e \le -0.1$	-2
$-0.1 < e \le -0.05$	$-0.1 < \Delta e \le -0.05$	-1
$-0.05 < e \le 0.05$	$-0.05 < \Delta e \le 0.05$	0
$0.05 < e \le 0.1$	$0.05 < \Delta e \le 0.1$	1
$0.1 < e \le 0.2$	$0.1 < \Delta e \le 0.2$	2
$0.2 < e \le 0.4$	$0.2 < \Delta e \le 0.4$	3
$0.4 < e \le 0.8$	$0.4 < \Delta e \le 0.8$	4
$0.8 < e \le 1.6$	$0.8 < \Delta e \le 1.6$	5
$1.6 < e \le 3.2$	$1.6 < \Delta e \le 3.2$	6

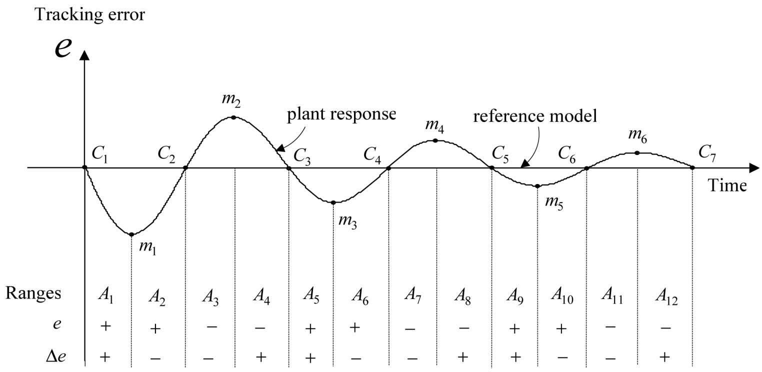

Fig. 4. General model reference tracking error dynamic behavior

Table 3. The decision weight of the proposed extension robust controller

Δe \ e (w_Δ)	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
-6	1	1	1	1	1	1	1	-5/6	-4/6	-3/6	-2/6	-1/6	0
-5	1	1	1	1	1	1	-5/6	-4/6	-3/6	-2/6	-1/6	0	1/6
-4	1	1	1	1	1	-5/6	-4/6	-3/6	-2/6	-1/6	0	1/6	2/6
-3	1	1	1	1	-5/6	-4/6	-3/6	-2/6	-1/6	0	1/6	2/6	3/6
-2	1	1	1	-5/6	-4/6	-3/6	-2/6	-1/6	0	1/6	2/6	3/6	4/6
-1	1	1	-5/6	-4/6	-3/6	-2/6	-1/6	0	1/6	2/6	3/6	4/6	5/6
0	1	-5/6	-4/6	-3/6	-2/6	-1/6	0	1/6	2/6	3/6	4/6	5/6	1
1	-5/6	-4/6	-3/6	-2/6	-1/6	0	1/6	2/6	3/6	4/6	5/6	1	1
2	-4/6	-3/6	-2/6	-1/6	0	1/6	2/6	3/6	4/6	5/6	1	1	1
3	-3/6	-2/6	-1/6	0	1/6	2/6	3/6	4/6	5/6	1	1	1	1
4	-2/6	-1/6	0	1/6	2/6	3/6	4/6	5/6	1	1	1	1	1
5	-1/6	0	1/6	2/6	3/6	4/6	5/6	1	1	1	1	1	1
6	0	1/6	2/6	3/6	4/6	5/6	1	1	1	1	1	1	1

properties of dynamic signal analyses made in [10], the linguistic rules of the extension error tuning scheme are decided and listed in the Table 3.

According to the measured model error and error change of the three-level converter, the matter-elements have been summarized in Table 2. The value ranges <k1, k2> of classical regions for each characteristic are assigned by the lower and upper boundary of model errors and error changes. In addition, one can set a matter-element model to express the neighborhood domain of every characteristic for describing the possible range of all model errors and error changes. The value range < n1, n2 > of the neighborhood domain could be determined from the maximum and minimum values of every characteristic in the measured records. For the controlled converter, it can be represented as:

$$R_s = (N_s, C_s, V_s) = \begin{bmatrix} N_s, & c_1, & <-3.2,\ 3.2> \\ & c_2, & <-3.2,\ 3.2> \end{bmatrix} \tag{11}$$

where matter name (N_s) is three-level converter, matter characteristics c_1 and c_2 represent the model error and error change, respectively.

The process of the proposed control method is shown below:

Step 1) Establish the matter-element model of model error and error changes category, which is performed as follows:

$$R_j = (N_j, C_j, V_j) = \begin{bmatrix} N_j, & c_1, & V_{j1} \\ & c_2, & V_{j2} \end{bmatrix} \quad j = 1, 2, ..., 13 \tag{12}$$

where $V_{jk} = \langle a_{jk}, b_{jk} \rangle$ is the classical region of every characteristic sets. In this paper, the classical region of each matter-element is assigned by the maximum and minimum values of model error and model error change at any instant.

Step 2) Set the matter-element of the input model error and error change as (13):

$$R_{new} = \begin{bmatrix} N_{new}, & c_1, & V_{new1} \\ & c_2, & V_{new2} \end{bmatrix} \tag{13}$$

Step 3) Calculate the correlation degrees of the input model errors and error changes with the characteristic of each matter-element by the proposed extended correlation function as follows:

$$K(v_{new,k}) = \frac{\rho(v_{new,k}, V_j)}{D(v_{new,k}, V_j, V_s)}, \quad k = 1, 2 \tag{14}$$

Step 4) Assign weights to the matter characteristic such as W_{j1}, W_{j2} denoting the significance of every characteristic. In this paper, W_{j1},W_{j2} are set as $W_{j1} = W_{j2} = 0.5$.

Step 5) Calculate the correlation degrees of every category:

$$\lambda_j = \sum_{k=1}^{2} W_{jk} K_{jk}, \quad (j = 1,\ 2,\ ...\ ,13) \tag{15}$$

Step 6) Select the maximum value from the normal correlation degrees to recognize the reference range of the input model error and error change and determine the weighting factor w_Δ from Table 3. To increase the sensitivity and adaptive capability, the weighting factor w_Δ of the extension robust controller at the instant is determined as follows:

$$w = w_\Delta * \lambda_j . \tag{16}$$

5 Simulation Results

In order to demonstrate the effectiveness of the proposed quantitative designed voltage controller ($K_{Pv} = 0.58$, $K_{Iv} = 7.4$) for the proposed three-level NPC converter, some simulations are made using the PSIM software package. The simulated voltage response due to step load current change Δi_o =20A by the quantitative designed PI controller at nominal case is shown in Fig. 5. It can be seen from the results that the given specifications $\hat{v}_{dc,\max} = 115V$, $t_r = 0.3$ sec are fully satisfied. For comparison, the simulated dynamic output voltage responses of PI controller without and with the proposed extension robust controllers under the load current changes Δi_o =30A are shown in Fig. 6. The results clearly show that better control performance is obtained by adding the proposed extension robust controller when load current change occurs.

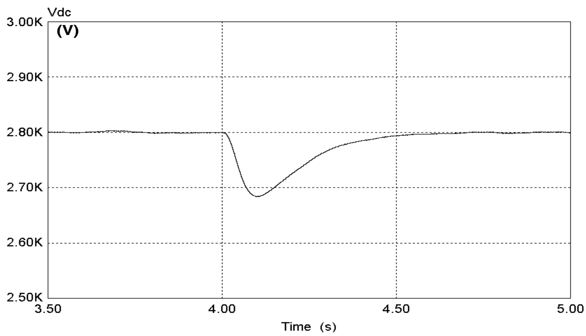

Fig. 5. The simulated result of output voltage Δv_{dc} due to step load current change of $\Delta i_o = 20A$ with the proposed PI-type voltage controller

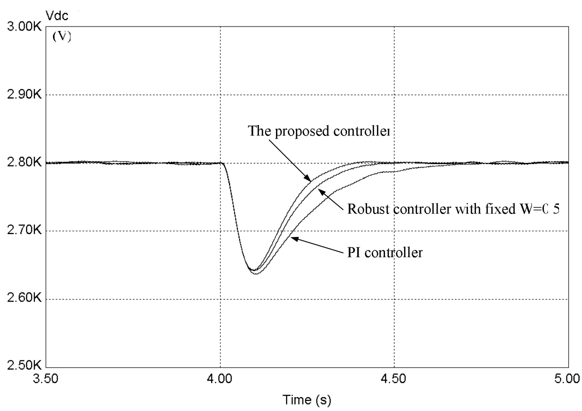

Fig. 6. The simulated result of output voltage Δv_{dc} due to step load current change of $\Delta i_o = 30A$ with PI-type, robust controller with fixed weighting factor $w = 05$ and the proposed extension robust controller

6 Conclusions

An extension robust controller for a three-level converter considering the parameter variation is proposed. First, the dynamic modeling and quantitative design of an output voltage controller for a three-level NPC converter have been presented. Voltage regulation performance can be achieved according to the prescribed specifications. In addition, the dynamic responses of the proposed three-level NPC converter are insensitive to operating conditions and parameter changes, as the PI controller is augmented with the extension robust controller. The simulation results indicate that good control performance in load regulation are achieved.

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References

1. Lai, J.S., Peng, F.Z.: Multilevel converters - a new breed of power converters. IEEE Trans. Industry Applications 21, 509–517 (1996)
2. Osawa, C., Matsumoto, T., Mizukami, T., Ozaki, S.: A state-space modeling and a neutral point voltage control for an NPC power converter. In: IEEE Power Conversion Conf., pp. 225–230. IEEE Press, New York (1997)
3. Bendre, A., Venkataramanan, G.: Modeling and design of a neutral point regulator for a three level diode clamped rectifier. In: IEEE Industry Applications Conf., pp. 1758–1765. IEEE Press, New York (2003)
4. Lin, B.R., Chen, D.J.: Power factor correction based on diode clamped rectifier. International Journal of Electronics 88, 595–614 (2001)
5. Hsia, T.C.: A new technique for robust control of servo systems. IEEE Trans. Industrial Electronics 36, 1–7 (1989)
6. Iftar, A., Ozgune, U.: Techniques in modeling uncertain dynamics for robust control system design. Control Dynamic System 50, 255–296 (1992)
7. Liaw, C.M., Lin, F.J.: Control of indirect field-oriented induction motor drives considering the effects of dead-time and parameter variations. IEEE Trans. Ind. Electron 40, 486–495 (1993)
8. Hong, K., Nam, K.: A load torque compensation scheme under the speed measurement delay. IEEE Trans. Ind. Electron 45, 283–290 (1998)
9. PSIM User's Guide: Powersim Inc. (2001-2003)
10. Chao, K.H., Chen, P.Y., Cheng, C.H.: A three-level converter with output voltage control for high-speed railway tractions. In: 33rd IEEE Annual Conference on Industrial Electronics, pp. 1793–1798. IEEE Press, New York (2007)
11. Cai, W.: Extension set and incompatible problems. Science Exploration 3(1), 83–97 (1983)