TELKOMNIKA, Vol. 11, No. 6, June 2013, pp. 3285 ~ 3292
e-ISSN: 2087-278X

Decoupling Control Strategy of D-STATCOM

Guangzheng Wang*[1], Zeng Ping[1], Juan Zhang[1], Yujie Guo[2]
[1]North China University of Water Resources and Electric Power, ZhengZhou, China,15903603087
[2]Luoyang Power Company, Luoyang, China, 13698888928
Corresponding author, e-mail: xiaoxiaosasa198789@163.com, 631108421@qq.com

Abstract

In Distribution Network, Distribution Static Synchronous Compensator (D-STATCOM) can stabilize turn-on point voltage, effectively reduce the transmission losses in power, improve the power factor and prevent the non-linear load. But under the circumstance of the d- and q-axis, D-STATCOM is a non-linear and strong coupling system, so decoupling control is very useful, that is because the decoupling control can ensure the output current fast track and have on different with the setting values. Study the decoupling control strategy of D-STATCOM, through the analysis of its basic structure, and then get the model of the coupling term. Due to avoid active and reactive current coupling, Fuzzy Immune PI Controller and inverse system method are combined to be used in the original system. Finally, the results are shown by the MATLAB simulation that the proposed decoupling control strategy is very good, because the performance is excellent, the structure is simple and easy to be implemented.

Keywords: *distribution static synchronous compensator, fuzzy immune PI controller, decoupling control, distribution network*

1. Introduction

In Distribution Network, compared to some developed countries, the network loss of the 10kV and below the distribution system accounted for about 43% in china [1-3], so it is very important to save energy [4]. Reactive power compensation in Distribution Network can effectively reduce the network loss, and at the same time improve the quality of the power [5]. Now, D-STATCOM is used in high-voltage and large-capacity, but in the low-voltage distribution, the condition of the unbalanced three-phase load and the low power factor are often found. So it is very useful to study D-STATCOM in Distribution Network.

In Distribution Network, D-STATCOM can improve the quality of the power [6], but it is a system which is highly non-linear and coupled. According to the characteristic of D-STATCOM, using the decoupling control strategy of Fuzzy Immune PI Controller and inverse system are combined together to study the decoupling of D-STATCOM. Finally, the results are shown by the simulation that the dynamic and the static performance of D-STATCOM are greatly improved under the circumstance of the control strategy.

2. The Mathematical Model of D-STATCOM System

D-STATCOM system is shown as Figure 1: C represents the capacitor of DC side; R represents the resistance; L represents the inductance; U_{sa}, U_{sb}, U_{sc} represent three phase network voltages. It is assumed that the IGBT of switching devices is an ideal device, three phase network voltages are balanced, and the high harmonics are not considered.

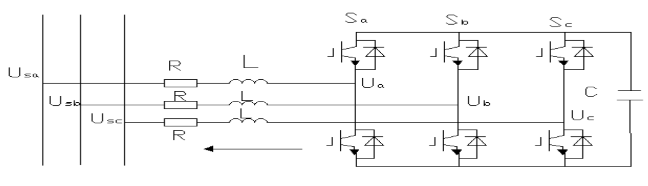

Figure 1. The Basic Structure of D-STATCOM

Received January 7, 2013; Revised April 11, 2013; Accepted April 24, 2013

Under the circumstance of the ABC coordinate axis, the mathematical model of D-STATCOM is shown as Formula (1):

$$\begin{cases} L\dfrac{di_a}{dt} = U_a - Ri_a - U_{sa} \\ L\dfrac{di_b}{dt} = U_b - Ri_b - U_{sb} \\ L\dfrac{di_c}{dt} = U_c - Ri_c - U_{sc} \\ C\dfrac{dU_{dc}}{dt} = s_a i_a + s_b i_b + s_c i_c \end{cases} \quad (1)$$

In Formula (1): s_k represents the switching function,

$$s_k = \begin{cases} 1\text{on the bridge arm conduction,and under the bridge arm off} \\ 0\text{on the bridge arm off,and under the bridge arm conduction} \end{cases} k = a, b, c \quad (2)$$

Under the circumstance of ABC coordinate axis, the mathematical model is shown as Formula (1), this mathematical model has a clear physical meaning, but it is very difficult to design the control system, because the AC side variables of the mathematical model variables have time-varying. So, ABC coordinate axis is converted into a two-phase coordinate axis of the power network fundamental frequency synchronous rotation by PARK. The AC side variables of the ABC coordinate axis can be converted into straight variable of two-phase rotating coordinate axis by using this method, which can solve the problem of the AC side variables have time-varying under the circumstance of the ABC coordinate axis. The matrix of the ABC coordinate axis converted into the two-phase synchronously rotating coordinate axis is shown as Formula (3):

$$T = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ \dfrac{\sqrt{2}}{2} & \dfrac{\sqrt{2}}{2} & \dfrac{\sqrt{2}}{2} \end{bmatrix} \quad (3)$$

The Formula (3) is substituted into the Formula (1), and then get the Formula (4):

$$\begin{cases} L\dfrac{di_d}{dt} = s_d U_{dc} - Ri_d - U_{sd} + Lwi_q \\ L\dfrac{di_q}{dt} = s_q U_{dc} - Ri_q - U_{sq} - Lwi_d \\ C\dfrac{dU_{dc}}{dt} = \dfrac{3}{2}(s_d i_d + s_q i_q) \end{cases} \quad (4)$$

In Formula (4), i_d , i_q represent the direct-current component of the two-phase rotating coordinate axis; s_d , s_q represent the switching function. System equation has been greatly simplified by Formula (4), according to the instantaneous reactive power theory [7], and then can get the active power $P = U_d i_d$ and the reactive power $Q = U_q i_q$, which sent to the power network. So, i_d and i_q are controlled, and can dynamically control the system which sent active power and reactive power to the power network.

3. Feed-forward Decoupling Control Strategy of D-STATCOM

Under the circumstance of the *d- and q*-axis, the mathematical model of D-STATCOM is two inputs and two outputs, and strong coupling of the non-linear system and it is very difficult to design the control system of D-STATCOM. So it is very useful to decouple under the circumstance of the *d- and q-* axis, so as to achieve the purpose of the current independent control. D-STATCOM control systems are generally use the dual closed-loop control, that is the outer loop control of the voltage and the inner loop control of the current: the function of the outer loop control of the voltage is control the DC capacitor voltage and the public point of access to the system voltage; in order to realize the direct control of the current, the output current of the outer voltage and the feedback current are becoming very important. The process of the dual closed-loop control is shown as Figure 2:

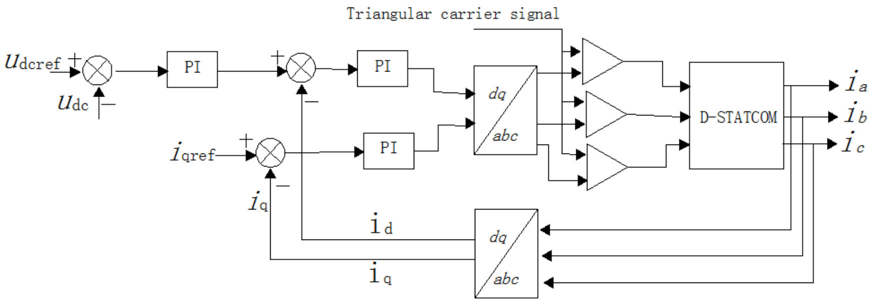

Figure 2. Schematic Diagram of the Dual Closed-loop Control

In Formula (4), the relationships of the coupling exist in d, q two channels. Therefore, the coupled problem is solved by the general feed-forward decoupling control strategy of D-STATCOM. Assumed $U_d = s_d U_{dc}$, $U_q = s_q U_{dc}$, the control equations are shown as Formula (5):

$$\begin{cases} U_d = -(k_{iP} + \frac{k_{iI}}{s})(i_d{}^* - i_d) - wLi_q + U_{sd} \\ U_q = -(k_{iP} + \frac{k_{iI}}{s})(i_q{}^* - i_q) + wLi_d + U_{sq} \end{cases} \quad (5)$$

In Formula (5), k_{iP} represents the proportional control parameters of the current inner loop; k_{iI} represents the integral control parameters of the current inner loop. Formula (5) is substituted into Formula (4), and then can get the equation of the decoupling control such as shown in Formula (6):

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \frac{(k_{ip} + \frac{k_{iI}}{s}) - R}{L} & 0 \\ 0 & \frac{(k_{ip} + \frac{k_{iI}}{s}) - R}{L} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \frac{1}{L}(k_{ip} + \frac{k_{iI}}{s}) \begin{bmatrix} i_d{}^* \\ i_q{}^* \end{bmatrix} \quad (6)$$

In Formula (6), in order to achieve decoupling, feed-forward decoupling control should be adopted by the current inner. But the dynamic performance of D-STATCOM is not very satisfactory, because the feed-forward decoupling control can not achieve precise decoupling, and often make the system unstable after decoupling [8]. Under the circumstance of the d- and q-axis, voltage outer loop doesn't have the relationship of the coupling, that is to say, the DC side capacitor voltage correspond to the active current and the connection point of Public voltage correspond to the reactive current, but the relationships are non-linear. Therefore, under the circumstance of the strategy of the dual closed-loop control, the traditional PI Controller can not meet the requirement of control strategy. In addition, the adaptive of the fixed parameters of the PI regulator has poor performance [9].

4. The Control Strategy of this Paper

Fuzzy Immune PI Controller and inverse system are combined together to be used in this paper that is because the shortcomings of the feed-forward decoupling control strategy. Fuzzy Immune PI Controller is used in voltage outer loop, so the dynamic properties of the voltage outer loop can be improved, in order to realize the decoupling control of the active current and reactive current, the current inner loop use the method of inverse system control, and the influence of the control design can be avoided.

4.1. The Control Strategy of the DC Side Capacitor Voltage

Using Fuzzy Immune PI Controller is very useful to the control strategy of the DC side capacitor voltage [10], and the regulating effect of the fuzzy control system is very good, especially for the control of highly non-linear and susceptible to outside interference, that is because the Fuzzy Controller can fit the inaccurate mathematical model. But because the reasoning of the Fuzzy Controller is very similar to the thinking of the way people and the establishment of membership functions and fuzzy rule base are greatly influenced by the experience of the operator, so some errors will be produced, and will generate oscillation in the small range of settings. Because immune system has a strong ability to resist antigen, so Fuzzy Controller, immune feedback principle and PI Controller are combined together in order to achieve the automatic adjustment of the PI parameters.

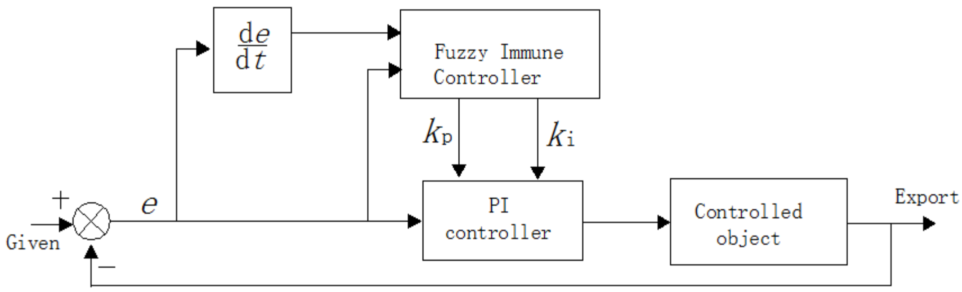

Figure 3. The Structure of the Fuzzy Immune PI Controller

In Figure 3, under the circumstance of the Fuzzy Immune PI Controller, the automatic adjustment of PI parameters is to identify the fuzzy relationships of the error and the changes in the error of the proportional and integral factor. In the process of the operation, the error and the changes in the error should be detected over and over again. According to the principle of the Fuzzy Immune Controller, the proportional and the integral factors of PI Controller system are able to adjust on line, so that the dynamic and static performance of D-STATCOM can reach a good state.

4.2. Control Strategy of Current Inner

Due to the strong coupling of D-STATCOM system, using the method of inverse system can realize the function of decoupling. The method of inverse system is very useful to study the design of the control system by using feedback linearization method [11]. The basic idea of the method is: the inverse system of the controlled object can constitute a system, that is "α-order integral inverse system" which can be achieved by using feedback method, and then original controlled system can be compensated for the system which have the factor is linear transfer, that is pseudo-linear system, and next the system can be integrated by using the theory of the linear system [12]. According to the linearization of the inverse system is shown in Figure 4

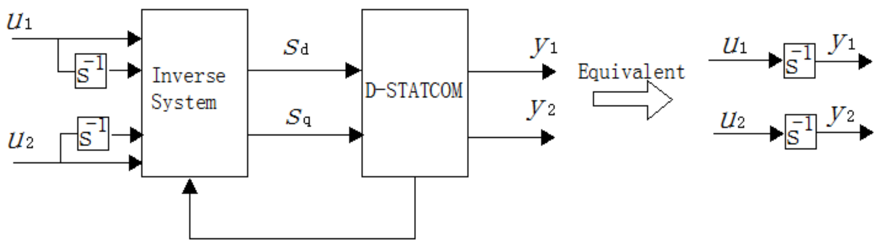

Figure 4. Linearization and Decoupling of D-STATCOM System

In Figure 4, a system is arranged before the control input of D-STATCOM, according to some control laws, the inputs are structured at this time, and allow the output of the system being connected in series as the input of D-STATCOM. The following is the design method of the inverse system [13]: according to Formula (4), and the following is the assumptions:
The state variables of the system:

$$x=\left[x_1,x_2,x_3\right]^T=\left[i_d,i_q,u_{dc}\right]^T$$

The output of the system:

$$y=\left[y_1,y_2\right]^T=\left[x_1,x_2\right]^T$$

The control variables:

$$s=\left[s_d,s_q\right]^T$$

At this time, the state equation can be shown as Formula (7):

$$\dot{x}=\begin{cases}\dfrac{s_d x_3}{L}-\dfrac{Rx_2}{L}-\dfrac{u_{sd}}{L}+wx_2\\ \dfrac{s_q x_3}{L}-\dfrac{Rx_2}{L}-\dfrac{u_{sq}}{L}-wx_1\\ \dfrac{3}{2C}(s_d x_1+s_q x_2)\end{cases} \tag{7}$$

Seeking α-order derivative of y_1,y_2 until the control inputs s_d,s_q are appeared in the expression, and assuming $y_1^{(a)}$ represents u_1 and $y_2^{(a)}$ represents u_2, according to the theory of the implicit function, the α-order inverse system of D-STATCOM can be shown as Formula (8):

$$\begin{cases}u_1=\dfrac{s_d u_{dc}}{L}-\dfrac{Ri_d}{L}-\dfrac{u_d}{L}+wi_q\\ u_2=\dfrac{s_q u_{dc}}{L}-\dfrac{Ri_q}{L}-\dfrac{u_q}{L}-wi_d\end{cases} \tag{8}$$

Formula (8) is be arranged and then can get Formula(9):

$$\begin{cases}s_d=\dfrac{Lu_1+Ri_d+u_d-Lwi_q}{u_{dc}}\\ s_q=\dfrac{Lu_2-Ri_q-u_q+Lwi_d}{u_{dc}}\end{cases} \tag{9}$$

The α-order inverse system is arranged at the front of D-STATCOM and can structure the pseudo-linear composite system which can be viewed as two first-order integral linear subsystems, and then active current and reactive current decoupling of D-STATCOM system can be achieved. Figure 5 represents the inverse system control structure of D-STATCOM:

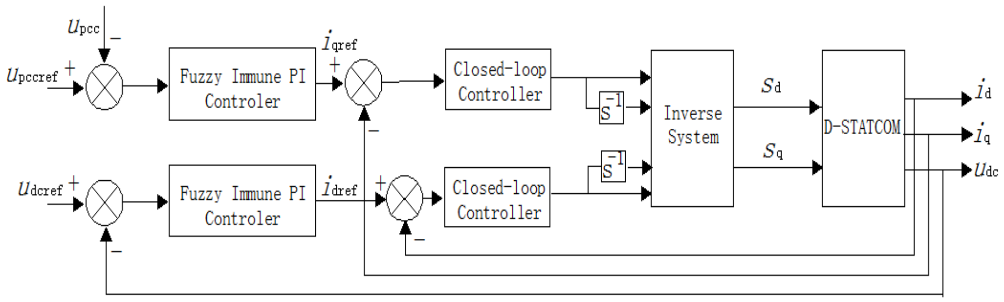

Figure 5. Inverse System Control Structure of D-STATCOM

4. Simulation of D-STATCOM

In order to verify the validity of the theoretical analysis and the effectiveness of the control strategy, so MATLAB simulation is adopted. The followings are the simulation parameters; System voltage is 380 V; Frequency is 50Hz; DC capacitor is 2200μF; Operating voltage is 800V; PWM carrier frequency is 12 kHz; Equivalent inductance of the filter inductor is 1mH; Equivalent resistance is 0.3Ω.

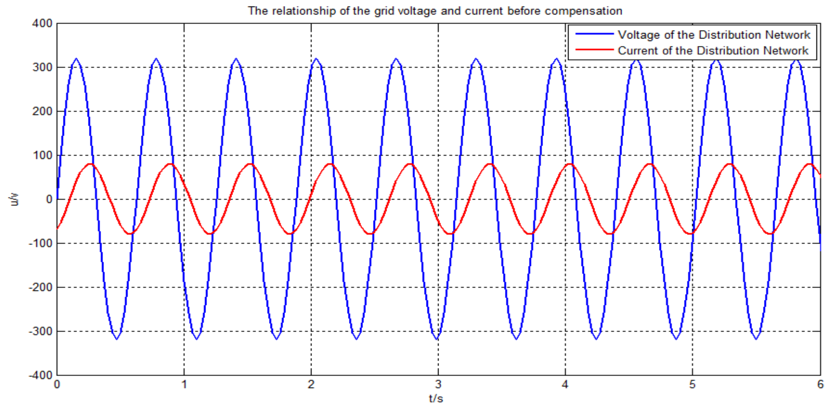

Figure 6. The relationship of the grid voltage and current before compensation

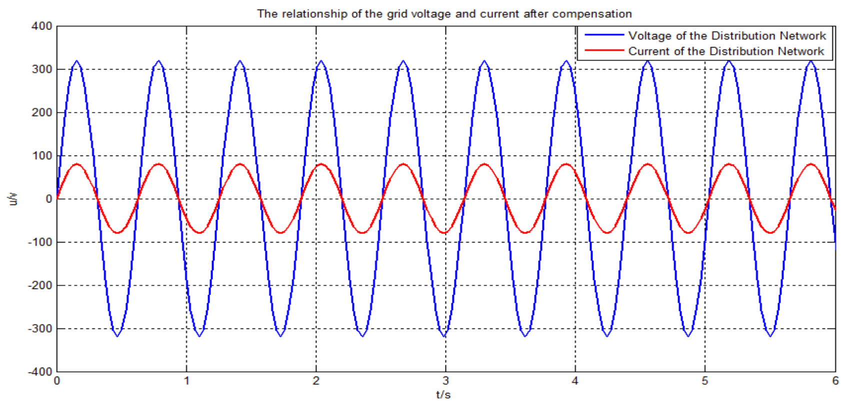

Figure 7. The Relationship of the Grid Voltage and Current after Compensation

As can be seen from Figure 6 and Figure 7, the power factor of the power system is low before D-STATCOM is used, and the power factor is improved after D-STATCOM is used and reactive get a good compensation. The voltage and current of the power network are almost the same phase after compensated, and the power factor is improved. So in the system, D-STATCOM can track the reactive of the control system in time and maintain the stability of the system.

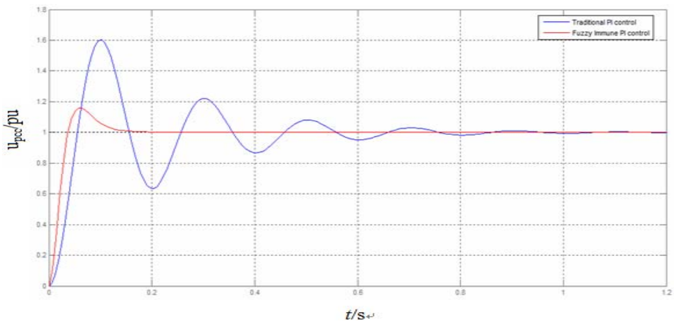

Figure 8. Common Connection Point of the Voltage Waveform under Different PI Controller

In Figure 8, the adjusted time and the overshoot of the traditional PI Controller are all long; but the overshoot of the Fuzzy Immune PI Controller is very short and the stability can be achieved in a short time. The simulation results show that the outer voltage uses fuzzy adaptive PI Controller can make the outer voltage controller have good dynamic and adaptive performance, so the dynamic performance of the Fuzzy Immune PI Controller is much better.

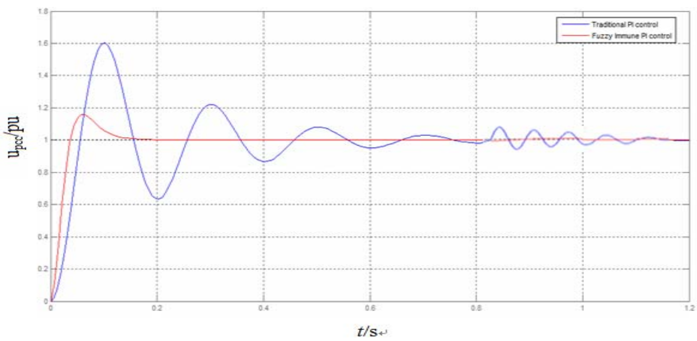

Figure 9. Public Junction Voltage Response Curve of D-STATCOM

In Figure 9, under the circumstance of the dynamic performance, overshoot and the control time, the proposed control strategy in this paper is superior to the feed-forward decoupling control strategy. When the electrical parameters are changed the robust is manifested much better.

5. Conclusion

Studying the decoupling control of D-STATCOM in this paper, Fuzzy Immune PI Controller is used in the voltage outer loop controller of D-STATCOM, and the inverse system controller is used in the inner current loop controller. Under the circumstance of the stability, speed of response and robustness, Fuzzy Immune PI Controller is much better than the traditional PI Controller, and the inverse system controller is used to achieve the decoupling control of the active current and reactive current in current inner loop. The simulation results demonstrate that the control strategy adopted in this paper is very feasible and effective.

References

[1] Hui JIANG, Jianchun PENG. *A Methodology for Allocating Transmission Losses to Pool and Bilateral Transactions and Its Features*. Proceedings of the CSEE. 2006; 26(8): 49-54.

[2] Guangming Lu, Hai BAO, Yihan Yang. Study of transmission loss allbcation methods. *East China Electric Power*. 2008; 36(5): 37-40.

[3] Hui JIANG, Youqing ZHOU, Jianchun PENG, Chun HUANG. *A Universal Procedure for Allocating Losses in Distribution Networks By Perturbing Shunt Susceptance*. Proceedings of the CSEE. 2005; 25(6): 42-48.

[4] Ke LI, Fang ZHUO, Hongyu LI, Zhao-an WANG. Investigation on Static VAR Generator with a Direct Current Control Strategy. *Power Electronics*. 2003; 37(3): 8-11.

[5] Harikrishna D, Srikanth NV. Dynamic Stability Enhancement of power Systems Using Neural-Network Controlled Static-Compensator. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2012; 10(1): 9-16.

[6] Ruifeng TIAN. Design of a distribution network power quality monitoring system based on metering automation systems and its application. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2012; 10(7): 1547-1553.

[7] Yanbing ZHANG, Juan ZHOU. A New Harmonic Detection Algorithms Based on the Instantaneous Reactive Power Theory. *Electrical Measurement & Instrumentation*. 2012; 49(4): 9-13.

[8] Singh B, Solanki J, Verma V. Neural network based control of reduced rating DSTATCOM[C]//IEEE Indicon Conference. Chennai, India: *IEEE*. 2005.

[9] Jie TANG, Yuejin WANG, Li LIU, Jintian YI. Double Closed Loop Control Strategy of Distribution Static Synchronous Compensator. *High Voltage Engineering*. 2010; 36(2): 495-500.

[10] Min ZHANG, Xiao-yang YE, Jing-xiang LIU. The inverse system method for electrical power system with static synchronous compensator. *Journal XIANGTAN MIN. INST*. 2003; 16(2)：2-4.

[11] Benxian XIAO, Mingyang ZHAO, Dongliu QI, Haixia LIU, Qunjing WANG. Research of AGV Tracking Strategy Based on Fuzzy Immune PI and Cross-coupling Control. *Journal Of System Simulation*. 2005; 17 (12): 300-307.

[12] Chunwen LI, Yan MIAO, Yuankun FENG. Inverse System Method for Nonlinear Systems Control (II) Multivariable Control Theory. *Control and Decision*. 1997; 12(6): 625-630.

[13] Jingxiang LIU, Min ZHANG, Xin-jun LI. Decoupling Control Based on the Inverse System Method for Electric Power System with Static VAR Generator. Journai of Changsha University Of Electric Power (Natural Science). 2006; 21(4): 22-26.