Study of Digital High Power Switch Mode Power Supply Based on a New Fuzzy Immune Response PID Controller

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Abstract

We propose a new immune response PID controller and prove its ascendance over the traditional PID controller, and then we apply the new controller in a new digital locomotive 110V switching mode power supply which adopts the full-bridge buck convertor with insulated transformer as its structure. We use IGBT and the TMS320F2812 processor as the main switches and the control unit kernel respectively. Finally, the application of the sample indicates that, the practical performance of the new PID controller and the new switching power supply achieves the anticipative goal.
Keyword: Switch-mode power supply, immune response, integral-separate PID, incremental PID, DSP.

I. Introduction

The 110V power supply of the locomotive control unit, currently adopting a phase-controlled thyristor rectifier, has low power factor and feeds too much harmonic back to the power system. The switch mode power supply is based on a high frequency PWM rectifier. It has a much higher power factor but injects fewer harmonic into the power system. It also has advantages in weight and dynamic performance. The digital system, which can reduce the effects of environmental change, can raise the precision and lessen the power consumption of the control circuit. But due to the complex model and the rigorous requirement of the digital locomotive switch mode power supply, the traditional control method can hardly achieve satisfying effects. The digital switch mode power supply must adopt some advanced intelligent control strategy to enhance its performance in order to implement practical application. We propose a new digital high power high frequency switch mode power supply which is based on a novel fuzzy immune response PID controller. The frequency of the new locomotive power supply is 20 kHz; we use a DSP processor and a full-bridge buck convertor with insulated transformer as the controller kernel and the circuit topology respectively.

II. Control Strategy

In this section, we introduce 2 kinds of PID control algorithm as well as the mechanism of the immune response, and we propose a new controller based on the combination of those theories. To prove its efficiency, we conducted a simulation based on our methods proposed. The experiment results show that our new method yields excellent performance in efficiency.

A. Immune Response Mechanism

The Immune response controller is a nonlinear controller designed by referencing the adaptive immune response mechanism of biologic system. Figure 1 is the principle of the adaptive immune response [2].

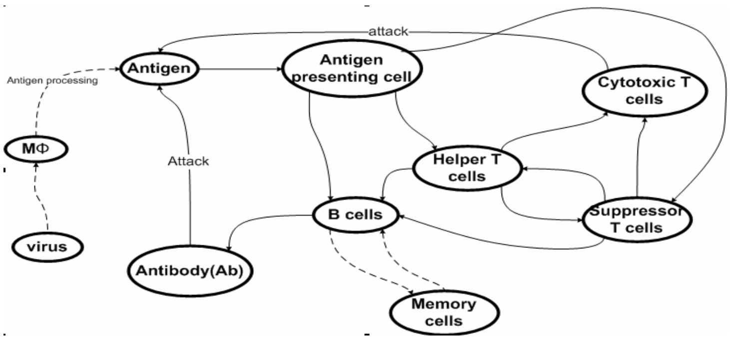


Fig. 1. Adaptive immune response

The $M\Phi$ (macrophages, a kind of phagocytic cell) phagocytizes the pathogens when the immune system is attacked by bacteria. The elements of the pathogens decompose into antigens by hydrolyzation, and then the antigens are released outside the $M\Phi$ cells, where they become dissolvable molecules and active B cells. The antigen can also join MHC (major histocompatibility complex) molecules to present itself to T cells via APC (antigen-presenting cell) and consequently activate T cells. T cells include CTL (cytotoxic T cells) and regulatory T cells, while he regulatory T cells can be categorized into Th(helper T cells) and Ts(suppressor T cells).The Th sends positive feedback to various immunocytes by using the cytokine which is secreted by the Th (for example, it can enhance the activation of B cells and increase the number of CTL, the B cells and CTL can operate directly on antigens).The Ts suppress other immunocyte's function(for instance, suppressing the activation of B cells and decreasing the number of CTL) to act as negative feedback on the adaptive immune response. Thus it can be seen that, the T cells play a primary role in the regulation of the whole adaptive immune response system. The Th cells neutralizes antigen by strengthening the activity of CTL and stimulating B cells to product more antibodies. It can respond to the antigen quickly because it increases simultaneously with the augment of antigen. The incensement of Th cells can also bring in the reinforcement of Ts cells. The Ts cells inhibit the activity of CTL, Th and B cells. When the antigens decrease to a certain degree, the effect of Ts cells preponderate over the effect of Th cells, and as a result, the antibodies decrease. Finally, the whole immune response system achieves equilibrium. Because of the cooperation between the enhancement and the inhibition, the adaptive immune response system can react to the attack quickly while stabilizing itself rapidly.

Moreover, after the cloning and expansion of T cells and B cells, the cell differentiation transforms a part of T cells and B cells into memory cells. The memory cells do not join the battle between immunocytes and antigens right away. When they encounter the same antigen that is met before, they convert to effect-cellular quickly by activation, proliferation and differentiation. Sequentially, the effect-cellular implements efficient immunity. Based on the before mentioned theory, we can obtain the immune response law as follow [2] (some necessary assumptions must be made):

1. The amount of antigen: $\varepsilon(k)=\alpha\varepsilon(k-1)-\mathrm{T}_{cytotoxic}(k-d)-B(k-d)$, where d is dead time of cellular, $\mathrm{T}_{cytotoxic}$ is the amount of CTL, and B is the amount of B cells.
2. The effect of the Helper T cells for B cells: $T_{help}(k)=K_1\varepsilon(k)$, where K_1 is a constant.
3. The effect of the suppressor T cells for B cells:
$T_{\mathrm{suppress}}(k)=K_2\{\mathrm{T}_{cytotoxic}(k-d)-T_{cytotoxic}(k-d-1)\}^2\varepsilon(k)$
4. The total stimulate received by B cells: $B(k)=T_{help}(k)-T_{\mathrm{sup}}(k)$

Based on the comparison between immune response mechanism and PID control mechanism, we assume the control error e(k) as the amount of antigen $\varepsilon(k)$ and treat the controller output u(k) as the total stimulate received by B cells B(k). The control law can be acquired as shown below [2]:

$$U(k)=K_1(1-\eta f(u(k),\Delta u(k)))e(k) \quad (1)$$

Where $f(u(k),\Delta u(k))=\{\mathrm{T}_{cytotoxic}(k-d)-T_{cytotoxic}(k-d-1)\}^2$, $\eta=K_2/K_1$.

B. Fuzzy Immune Response P Controller

It is easy to find that, the controller based on the immune response mechanism is actually a nonlinear P controller. The parameter K_1 affects the response speed. As K_1 grows larger, the system responds to control signal more rapidly. The parameter η controls the stability and overshoot, and functions just like the differential time of the traditional PID controller.

Because $f(u(k),\Delta u(k))$ is a nonlinear function, and the way to compute $\mathrm{T}_{cytotoxic}$ is still not clear, we utilize a fuzzy controller to approach it. Fuzzy controller can approximate both linear and nonlinear function as long as it is well designed. The fuzzy controller in this paper has 2 inputs ($u(k)$ and $\Delta u(k)$) and 1 output $f(u(k),\Delta u(k))$. The fuzzy set for both inputs are {PB, PS, Z, NS, NB}, the fuzzy set for the output is { PB, PM, PS, PT, Z, NT, NS, NM, NB } and the membership function is shown in figure 2.

According to the main idea of immune response, 25 rules can be obtained as shown in table 1.

The Mamdani inference method is used as the fuzzy inference mode, and the defuzzy method is centroid method. Obeying the above rules, we can get the control inquire table for $f(u(k),\Delta u(k))$.

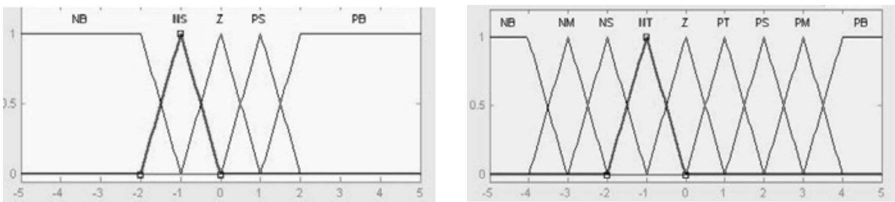


Fig. 2. Membership function (Left: MF of inputs; right: MF of output)

Table 1. Fuzzy rules

$u(k)$ \ $\Delta u(k)$	PB	PS	Z	NS	NB
PB	NB	NM	NS	NT	Z
PS	NM	NS	NT	Z	PT
Z	NS	NT	Z	PT	PS
NS	NT	Z	PT	PS	PM
NB	Z	PT	PS	PM	PB

Table. 2. Control inquire table

$f(u(k),\Delta u(k))$		$\Delta u(k)$				
		-2	-1	0	1	2
$u(k)$	-2	2.33	1.83	1.34	0.84	0.138
	-1	1.83	1	0.5	0	-0.741
	0	0.984	0.2	0	-0.2	-0.978
	1	0.748	0	-0.5	-1	-1.83
	2	-0.125	-0.834	-1.33	-1.83	-2.32

Although the DSP processor has high performance, it is not fast enough to implement online fuzzy inference. So we imitated the memory mechanism of the immune response. We worked out the control inquire table and put it into the memory of DSP processor. This can increase the implementing speed greatly. When the power supply is running, the output is sampled by the ADC module and preprocessed by signal process module. After that, the fuzzy inference module starts to search the corresponding controller output in the control inquire table and uses control output to generate the proper PWM wave. As a result of the analyses above, the fuzzy immune response P controller should have the structure shown in figure 3:

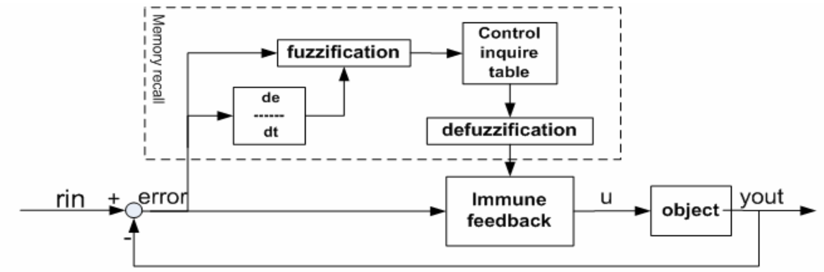


Fig. 3. Fuzzy immune response P controller

C. The Combination of Immune Response P Controller and Incremental Integral-Separate PID Controller

Pure immune response P controller is an inefficient control strategy for the switch power supply owing to the high order of the model. It is only suitable for the first-order system. Furthermore, the immune response controller can not eliminate control error brought by all kinds of disturbances. So we associate the immune response mechanism with the integral-separate PID control algorithm and the incremental PID control algorithm. It not only eliminates the system static error, but also improves the precision of the system and reduces the integral accumulation which harms system stability. And, because the control increment is only related to the latest k times samples, the influence of accidental disturbances is diminished. By this token, we should propose a new immune response PID controller.

System startup or shutdown can bring integral accumulation as well as the change set value greatly. Integral-separate PID algorithm can prevent large overshoot and oscillation aroused by integral accumulation. The primary principle of integral-separate PID algorithm is that it should not introduce integral operation until the control error has diminished to a certain degree. The algorithm is:

$$U(k)=k_p(e(k)-e(k-1))+\beta k_i^{'}\sum_{j=0}^{k}e(j)T+k_d^{'}(e(k)-2e(k-1)+e(k-2))/T \qquad (2)$$

Pick up U(k-1) at both side of the equation, it becomes the incremental integral-separate PID control algorithm:

$$U(k)=U(k-1)+k_p(e(k)-e(k-1))+\beta k_i e(k)+k_d(e(k)-2e(k-1)+e(k-2)) \quad (3)$$

Where $k_i = k_i^{'} \times T$, $k_d = k_d^{'} \div T$。

Treat the output of the immune response part as the input of the incremental integral-separate PID controller; it acquires a structure shown in figure 4:

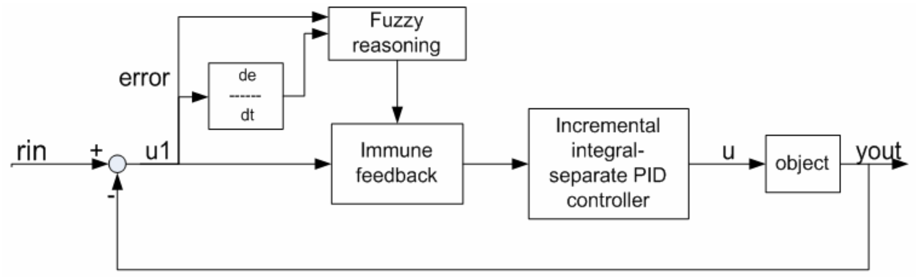


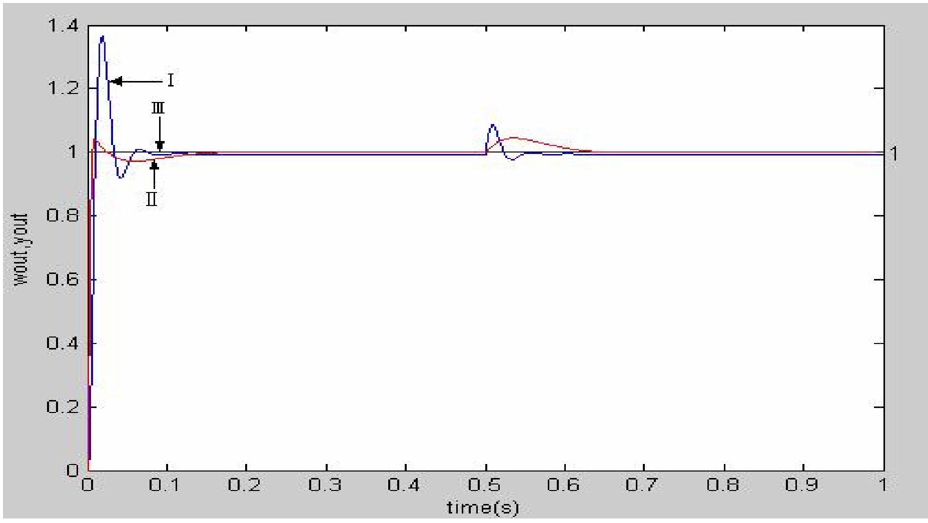
Fig. 4. The structure of immune response incremental integral-separate PID controller

The control law is shown below:

$$U(k)=U(k-1)+K_{AIS}((k_p+\beta k_i+k_d)e(k)+(k_p-2k_d)e(k-1)+k_d e(k-2)) \quad (4)$$

Where $K_{AIS} = K_1(1-\eta f(u(k), \Delta u(k)))$, β is the switch coefficient of the integral term.

D. Simulation



I: regular PID
II: Fuzzy immune response incremental integral-separate PID
III: Step signal

Fig. 5. Step response

The simplified transfer function of the switch power supply is $\Phi = \frac{4A}{s^2+Bs+A}$, where A=91.2 and B=23.9. We simulated the new controller in Matlab. The parameters are chosen according to the Ziegler-Nichols method and experience, here, K_1=46.2, η=0.0012, k_i=0.02, k_d=21.3, T_s=0.001, $\beta = \begin{cases} 1 & |e| < 0.2 \\ 0 & |e| \geq 0.2 \end{cases}$, To prove the anti-disturbance capacity of the system, we added a disturbance at the halfway of the simulation.

III. Circuit Design

This section is about the selection of the topology and components of the main circuit, and we also mention some idea of the control circuit design.

A. Main Circuit Topology

A full-bridge convertor with insulated transformer allows the switches to endure the minimum switching voltage and current, so the switches have the maximum safe operation area. Considering the locomotive 110V switch mode power supply is a high power step-down power supply, we adopted the full-bridge buck convertor with insulated transformer as its main circuit topology. The schematic figure is shown below:

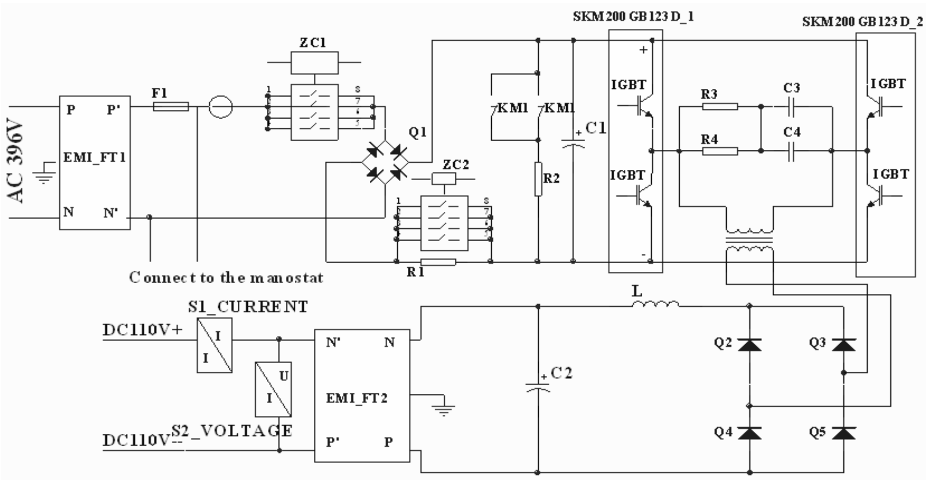


Fig. 6. The topology of the main circuit

B. Main Components Selection

We adopt the SKM200GB123D (SEMIKRON), which has an operating voltage of 1200V and a collector operating current of 200A, as the main switches. The bridge convertor takes the one whose input peak voltage is 1200V and the operational current is 80A; we utilize the fast recovery diode within the SKM200GB123D as the output rectifying diode. According to the requirements of the system, 2:1 is selected as the radio of the transformer; the smoothing inductance is $165\mu H$; the smoothing capacitor is $4700\mu F$. Keeping in mind the instability of the railway power system, EMI filters have been installed to the input, output of the power supply as well as the input of the control circuit.

C. Control Circuit Topology

The TMS320F2812 (150MIPS) is chosen to be the kernel of control unit. The primary control scheme comes from 2 aspects: the first aspect is related to the load and the circumstance; the second aspect is about the characteristic of the main circuit. The locomotive power supply is connected to the accumulator in parallel, so the control circuit should monitor both the output of the power supply and the charge current of the accumulator. Moreover, as a result of the large fluctuation of the railway power system, the voltage of the railway power system should be monitored and the main contactor should be shut down immediately when the voltage of the power system is out of boundary. This can keep the power supply working properly and keep the components safe. The schematic figure is shown below:

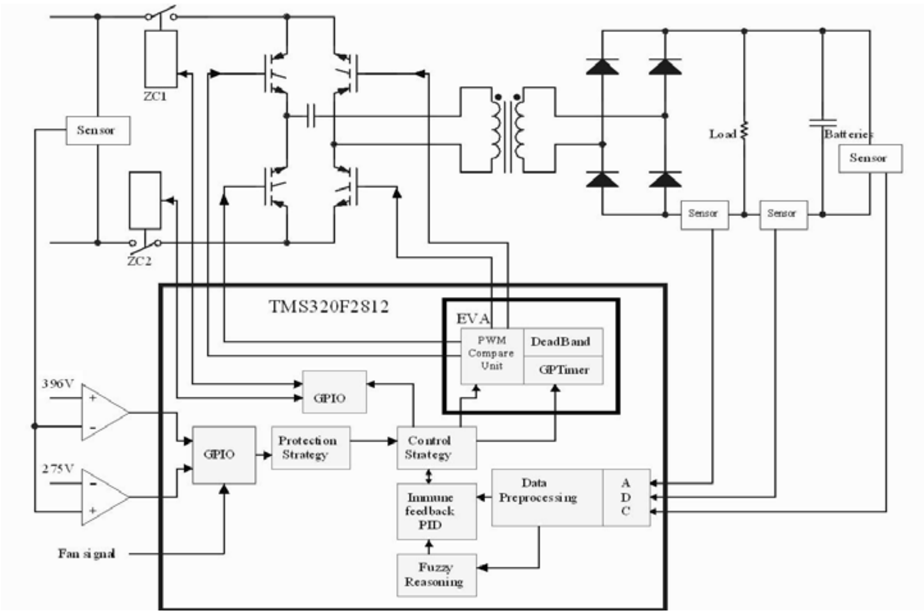


Fig. 7. Topology of control circuit

Ⅳ. Simulation and Trial-Manufacture

The trial power supply was created based on the theory mentioned above. Its working frequency is 20 kHz, and the precision of the output is 1%. There are 3 figures to show the performance of the trial power supply.

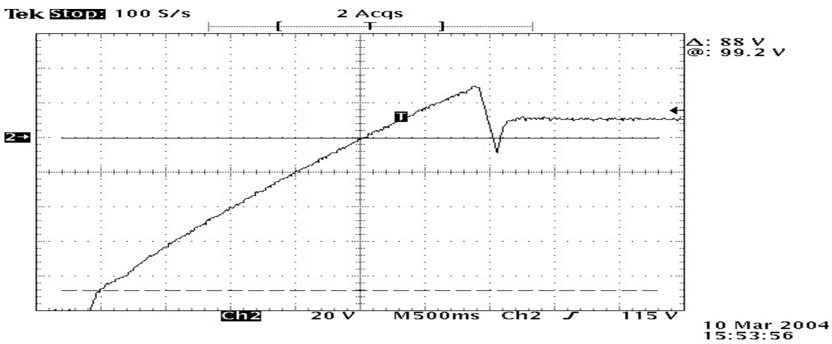


Fig. 8. Soft startup wave-forms

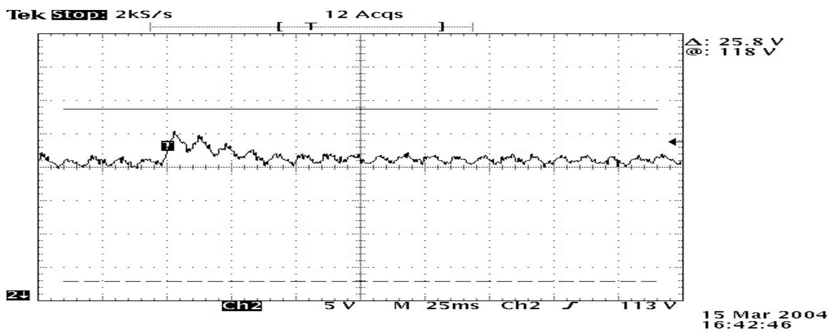


Fig. 9. Voltage saltation of the power system

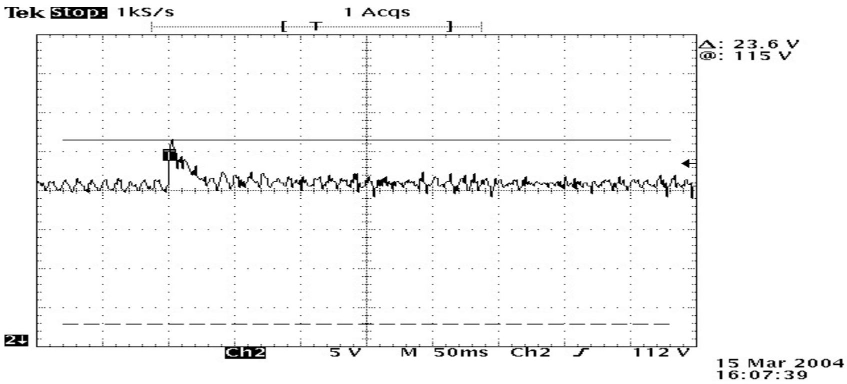


Fig. 10. Load saltation

Due to the large output smoothing capacitor, the abrupt jump of the output voltage can bring in a large charging current; this can damage the switches and the load. So it is necessary to establish a soft startup mechanism to avoid that damage.

Figure 8, 9 and 10 present the wave-forms of the trial power supply under various conditions respectively. They are practical wave-forms recorded by Tek oscillograph, where X axis represent time and Y axis represent voltage. The time unit is different in each plot, it is 500ms/grid in figure 8, 25ms/grid in figure 9 and 50ms/grid in figure 10. Δ is the potential difference value between the horizontal real line and the dashed, @ is the potential value represented by the real line.

Ⅴ. Conclusion

A new immune response incremental integral-separate PID controller has been designed and proven to be superior to the traditional PID controller. We applied it into the control strategy of the digital locomotive 110V switch power supply, and made a sample whose performance was much better than the conventional locomotive power supply. The next step is to study the technique of soft switching power supply, adopt digital control method to implement the control, and then utilize the advanced searching algorithm to round up the parameters, make the sample operating at the optimized point.

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