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Research on Variable Structure High Voltage Power Supply Control Strategy Based on Predictive PI control algorithm

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Abstract: The research and verification of a variable structure high voltage power supply unit and its control strategy are introduced. According to the mathematical modeling method, the variable structure system is linearized equivalent analysis and closed-loop system design. The actual parameter verification and theoretical verification of the system are carried out by means of experimental identification, and the research of subsequent control strategies is guided. According to the analysis results and the dynamic parameters of the power supply, a control strategy based on Predictive PI is proposed and simulated. In addition, in order to realize the actual verification of the power supply control algorithm, a power controller based on the ARM and FPGA architecture is designed to be applied to the system. Experiments show that the control strategy can solve the complex variation of the nonlinear and variable structure of the power supply under dynamic conditions, and ensure that the system completes the established parameter indicators.

1. Introduction

The topology of the variable structure high voltage power supply is shown in figures (*Fig. 1*), which is a high voltage power supply device for auxiliary heating of EAST (Experimental dvanced Superconducting Tokamak) [1]. The power supply adopts two isolation transformers to realize phase-unlocked rectification of 7.5° with positive and negative phase shifting, and uses 144 PSM power modules to achieve high voltage output. The topology of the power supply determines that the total inductance of the dynamic response process will vary with the number of modules. In addition, the distributed capacitance parameter (Cap) varies with the increase of the voltage level, and the leakage inductance of the transformer has a certain influence on the voltage output. Therefore, the power supply is a non-linear and variable structure system. In addition, the power supply requires a system rise time of 100us, an overshoot of less than 1%, and an adjustment time of 2ms[2]. This paper will analyze the power supply through the combination of mathematical modeling and experimental identification, and propose a Predictive PI control strategy. At the same time, in order to verify the effect of the algorithm, this paper also develops a high voltage power controller based on ARM and FPGA architecture to realize the control of the power supply.

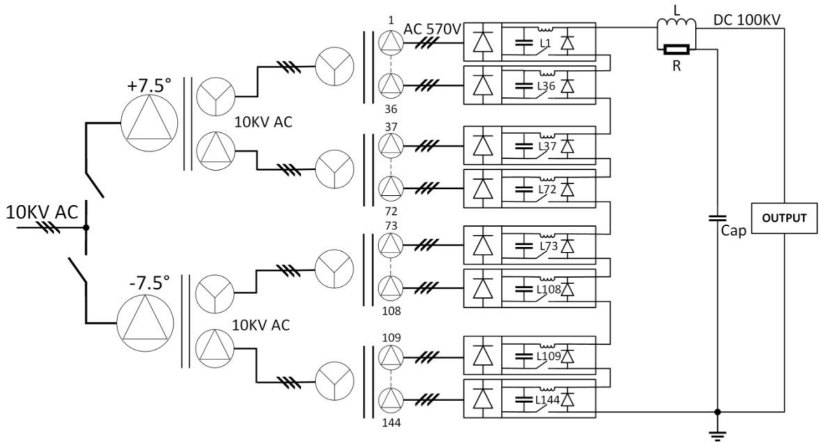

Figure 1. Topology of a variable structure high voltage power supply.

2. System modeling and experimental analysis

In order to better understand the system dynamics and steady-state operating characteristics, this paper analyzes the system modeling and experimental identification methods. The analysis results are used as the basis for control system algorithm design and hardware and software design.

2.1. Mathematical modeling analysis

The variable structure power supply is formed by cascading 144 sub-modules. The actual model of a single sub-module is shown in figures (*Fig. 2*), where C=5.67mF; C1=0.1uF; C2=40nF; R0=0.635Ω; R1=20Ω; R2=20Ω; R3=500Ω; D1 and D2 are the same diode withstand voltage of 1800V; D3 adopts IGBT reverse parallel diode of type FF300R17ME4; L1=77uH; L2=6mH; L3=125uH; R=1000Ω; wherein R0 is the equivalent voltage of the transformer leakage voltage drop to the equivalent resistance on the DC side, L3 is the equivalent series inductance of the transmission cable, and the distributed capacitance C2 is the transmission cable and the equivalent distributed capacitance between the modules. Superimposed and, the actual test is approximately equal to the above parameters above 50KV. At the same time, according to the actual experiment and simulation verification, it is shown that the distributed inductance of the transmission line has little effect on the actual power supply output, and the influence of the RCD circuit and the RD circuit connected in parallel on the main system can be ignored. Since the circuit is a topology of the cascade superposition principle, ignoring the line impedance and the equivalent diode drop can approximately satisfy the circuit superposition theorem. Among them, the variables of the system are excitation sources U1, R0 and L1. They will change with the change in the number of input modules N. Therefore, this paper takes the variable structure high-voltage power supply as the whole system linearization equivalent treatment[3], and the equivalent model of the opening is shown in figures (*Fig.3*).

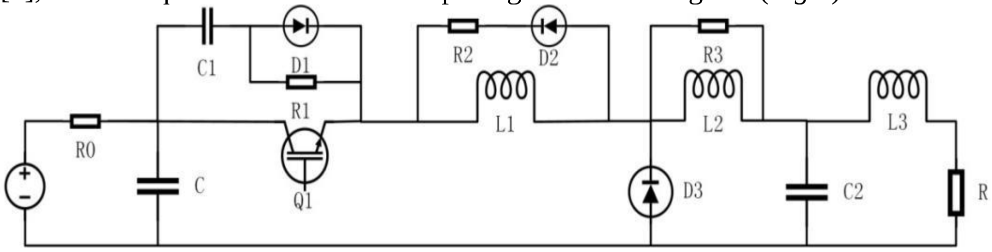

Figure 2. Single module actual equivalent model.

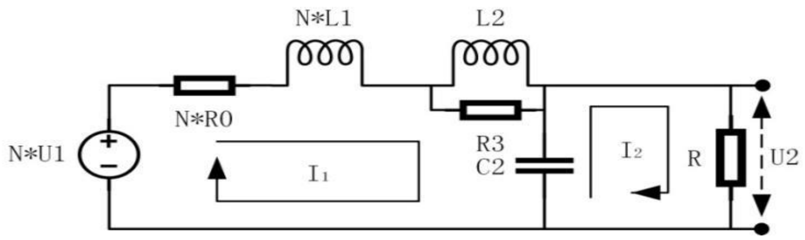

Figure 3. Power system turn-on equivalent model.

According to the mesh method: (Laplace transform)

$$\begin{cases} (R_0 + sL_1 + \frac{SR_3L_2}{SL_2 + R_3} + \frac{1}{sc_2}) * I_1(s) - \frac{1}{sc_2} * I_2(s) = U_1(s) & (1) \\ -\frac{1}{sc_2} * I_1(s) + \left(\frac{1}{sc_2} + sL_3 + R\right) * I_2(s) = 0 & (2) \end{cases}$$

From the above formulas (1) and (2):

$$G(s) = \frac{U_2(s)}{U_1(s)}$$

$$= \frac{R * (6 * 10^{-3}s + 500)}{s^3(N * 1.848 * 10^{-11}) + s^2(N * 2.154 * 10^{-6} + 1.2 * 10^{-4}) + s(N * 5.5 * 10^{-2} + 9) + N * 317.5 + 500 * R}$$

According to the experiment, the single module voltage is about 790V. If the steady-state output voltage of the system is set to 50KV, the number of input modules is 64, which can be obtained:

$$G(s) = \frac{6\,s + 500000}{1.183 * 10^{-9}\,s^3 + 2.579 * 10^{-4}\,s^2 + 12.52\,s + 520320}$$

Through the Matlab closed-loop system analysis, and observe the closed-loop Bode diagram of the system, the pole-pole distribution map and the unit step response diagram are shown in figures (*Fig. 4*) below[4]. First, the system is a closed-loop stable system. Second, it is also a closed-loop feedback system with a zero, a real pole and a pair of conjugate complex poles, and the closed-loop bandwidth of the system is about 60KHz. According to the sampling theorem proposed by Franklin, the sampling rate must be twice the highest frequency included in the signal, and the lower limit of the sampling rate of the system is generally determined according to twice the bandwidth of the closed-loop system. Therefore, the sampling rate of the discrete controller of the controlled object is about 120KHz. Since the gain of the controller in the above figure is 1, it is lower than the gain 1 due to the leakage inductance of the transformer added to the model. In order to obtain a closed-loop system that meets the requirements of the system specifications, the closed-loop system must be calibrated by designing a suitable control system transfer function.

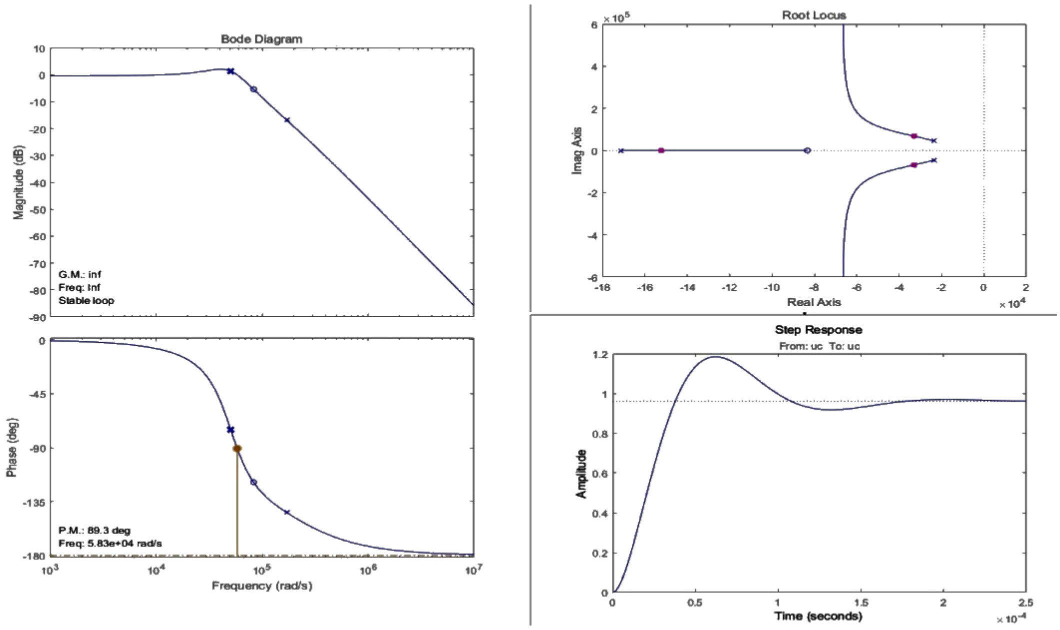

Figure 4. Analysis of a closed loop system.

2.2. Experimental identification analysis

The variable structure high voltage power supply is linearly equivalently analyzed by mathematical modeling analysis, and the related characteristics of the closed loop system are known. In order to further understand the system, the waveform obtained by the open-loop system test is applied by means of an external step response. The Matlab processing is shown in figures (*Fig. 5*). Among them, the ordinate of the figure is voltage, using a Ross voltage divider (1:20KV), and the abscissa is time. The number N of system modules is increased by 12 to 68 in multiples of 4, the system step rise time is about 75us, and the adjustment time is about 450us. Therefore, the response of the power supply has no phase deviation, and the linear equivalent analysis method of mathematical modeling is feasible. Due to changes in the parameters such as the distributed capacitance of the system, the overshoot of the system is nonlinear. When the power supply voltage exceeds 30KV, it can be seen that the system overshoot is approximately linearly increasing[5].

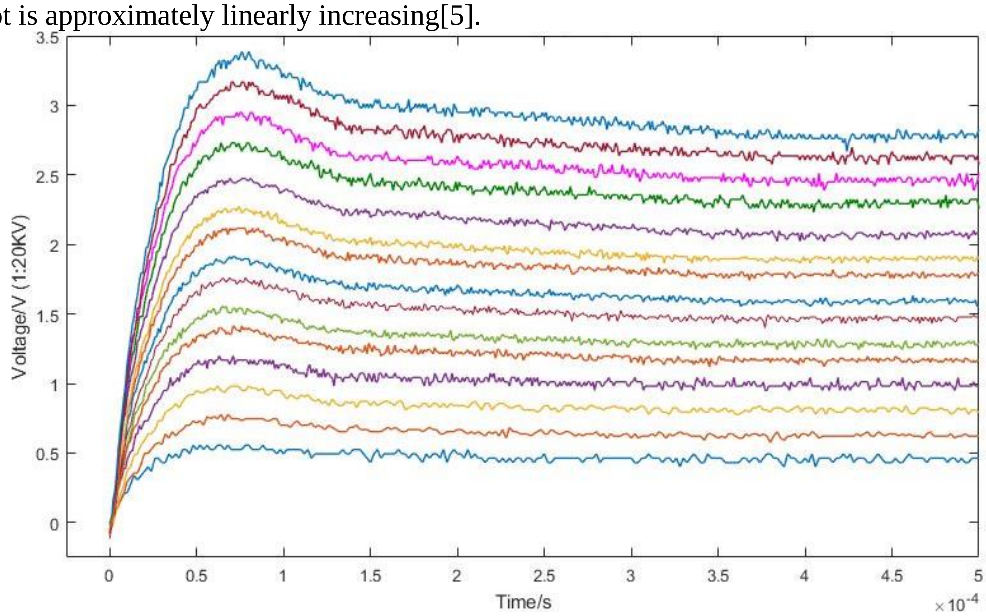

Figure 5. High Voltage Power supply Step Waveform.

3. System algorithm and platform design

The system algorithm is based on mathematical modeling and experimental identification. Mathematical modeling can derive the linear equivalent transfer function of the system, and the transfer function can be directly PI-corrected to achieve the system closed loop. The experimentally identified functional equations are added to the series-corrected PI controller to implement the pedictive PI algorithm. Finally, the system algorithm is transformed into a software language combined with a hardware platform.

3.1. Predictive PI algorithm

The predictive PI algorithm is composed of a PI algorithm and a prediction algorithm. The PI algorithm implements a common series correction, and the prediction algorithm performs a second prediction correction on the output of the PI algorithm[6]. Therefore, it is first necessary to perform PI series tuning according to the mathematically modeled transfer function, and then add the experimentally identified prediction algorithm to the latter stage of the PI corrector to implement the predictive PI algorithm. Finally, the PI algorithm is used to correct the system transfer function. The block diagram is shown in figures (*Fig. 6*), where G(PI) is the series PI correction controller and Gp is the predictive correction controller.

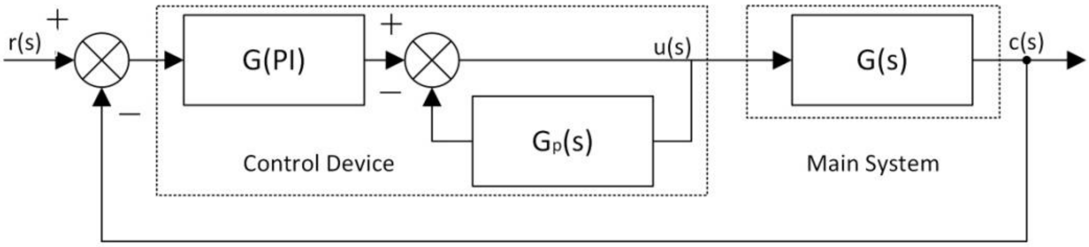

Figure 6. High Voltage Power supply Step Waveform.

3.1.1. PI controller parameter tuning

Since the equivalent model of the power supply is a third-order system, the direct equivalent of the low-order system cannot be achieved directly by reducing the order. Therefore, the PI parameters of the system can be determined by the Z-N tuning method (critical proportional method) and the C-C tuning method (dynamic characteristic parameter method). The C-C tuning method adds a step signal u(s) to the input of G(s) and records the output response curve c(s). From this curve, the dynamic characteristic parameters representing the generalized process are obtained (τ----process Lag time, T----the time constant of the process, K----balance the final value). According to the C-C principle and combined with the experimental identification, the 50KV step curve is shown in figures (*Fig. 7*), where K =2.5V, T =20us, τ =0.1ns.Then according to the values of these parameters, the corresponding formula values of the regulator are calculated by applying the corresponding formulas of tables (*Table 1*). Thus, when the sampling time T=10us, the series correction PI parameter can be obtained as kp = 0.72 and ki=24000.

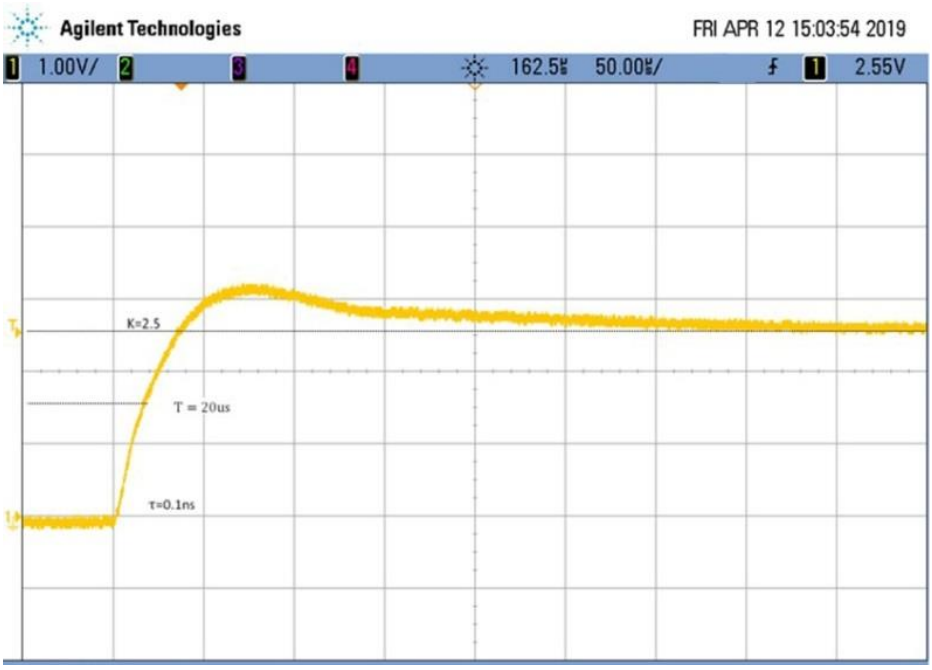

Figure 7. High Voltage Power supply Step Waveform.

Table 1. PID parameter setting table based on C-C method.

Controller	Kp	T_i	T_d
P	T/ 2(K*τ)	----	----
PI	0.9T/2(K*τ)	3τ	----
PID	1.2T/2(K*τ)	2τ	0.5τ

3.1.2. Predictive algorithm design

The prediction algorithm is based on the rising edge curve of the step response of the actual model and calculates the rising ramp voltage rate when the step input is different modules. According to the slope of the climbing slope, the voltage and time approximation can be derived under different module inputs. The linear function relationship UT = N * Kv * T, where Kv is the ramping voltage rate, N is the number of modules, and T is the running time. Due to the nonlinearity of the system, segmentation fitting is required, and the fitting function is added to the post-stage output of the PI correction for secondary prediction correction[7]. Through a large number of step experiments and step modulation experiments, Using the matlab curve tools to fit the piecewise function of the nonlinear climb is as follows:

$$\begin{cases} U=\left[\left(52670+1500*(N-12)\right)\sin(t-\pi)-(75*(N-12)+2634)(t-10)^2+(75*(N-12)+2634)\right]*10^5 \ (12<N<24) \\ U=\left[\left(86930+1750*(N-28)\right)\sin(t-\pi)-(75*(N-28)+4347)(t-10)^2+(75*(N-28)+4347)\right]*10^5 \ (28<N<52) \\ U=\left[\left(157000+2000*(N-52)\right)\sin(t-\pi)-(75*(N-52)+7852)(t-10)^2+(75*(N-52)+7852)\right]*10^5 (56<N<68) \end{cases}$$

According to the function, the dynamic rising process, the relationship between the number of modules and the voltage can be approximated, and then the secondary correction is performed under the condition that the PI correction is not good, the rising process is accelerated and the system is stabilized.By establishing the simulation model of the transfer function, the simulation waveform can be obtained as shown in figures (*Fig. 8*).

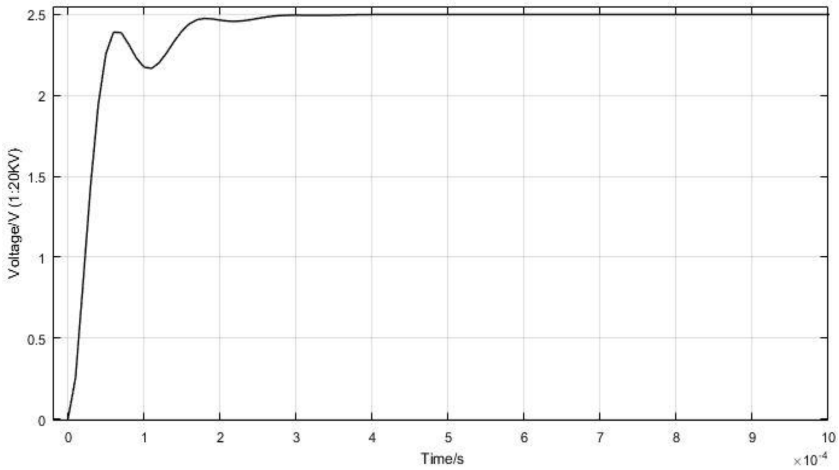

Figure 8. Simulation waveform based on predictive PI algorithm.

3.2. System platform design
In order to verify the modeling and simulation based on predictive PI algorithm, a power controller based on ARM and FPGA architecture[8] is designed as shown in figures (*Fig. 9*). It can realize the functions of human-computer interaction, system algorithm and data interface conversion to ensure the experiment. platform. The ARM processor adopts STM32F407ZGT6, the FPGA chip adopts Cyclone IV series EP4C15F23C8N, and the upper computer adopts Labview graphical programming interface.

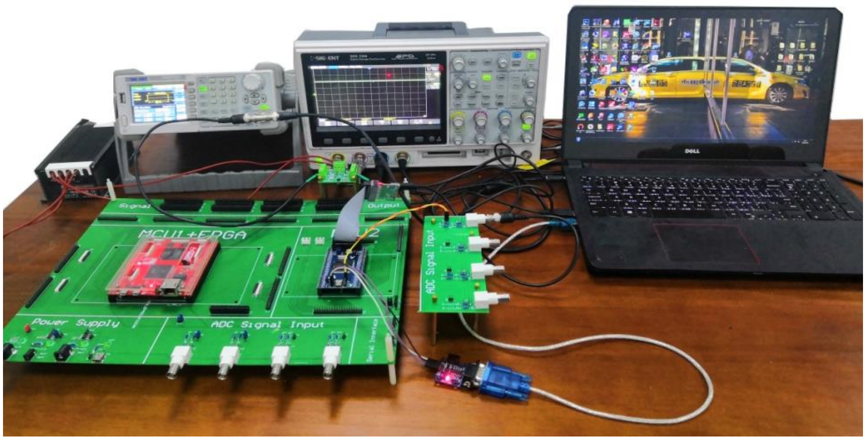

Figure 9. System experimental control platform based on ARM and FPGA architecture.

4. Experiment and result analysis
The experiment is expected to be 50KV, and a 1:20KV Ross voltage divider is used as the voltage transmitter. The final steady-state output voltage is 2.5V. The rise time is 100us, the overshoot is 0%, and the adjustment time is 600us.Through the experiment, the actual output power waveform shown in figures (*Fig. 9*) can be obtained, which satisfies the system parameter requirements. Because there is a certain error between the actual engineering experiment and the simulation model, it is normal for the actual power waveform to be longer than the simulated waveform in the dynamic adjustment time. The experimental waveform shows that the algorithm not only has good dynamic control performance, but also has a stable steady-state output and good robustness.

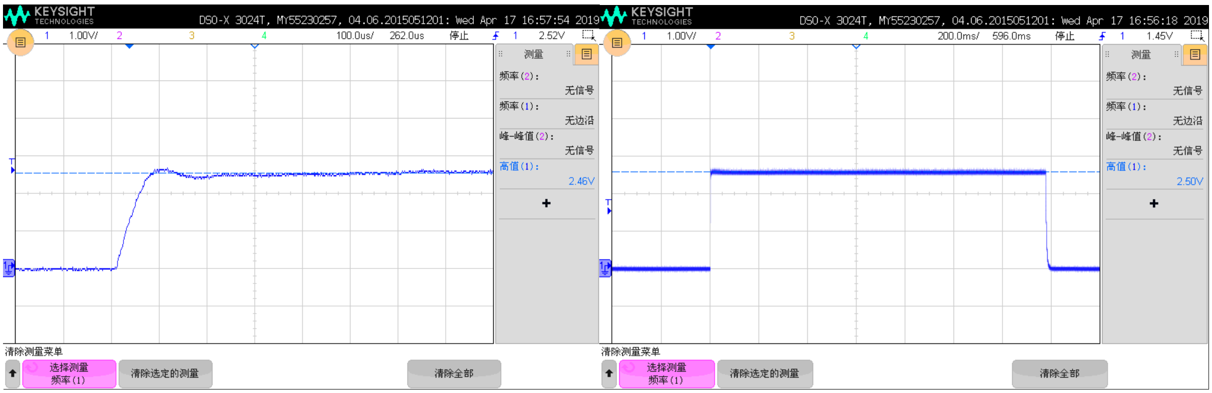

Figure 10. Variable structure high voltage power supply waveform based on predictive PI algorithm.

5. Conclusion

The object of this study is a variable structure and nonlinear high voltage power supply, and its system parameters will change in the dynamic process. In this paper, the equivalent simplification problem is solved by mathematical modeling, and the nonlinear problem is equivalent linearized by experimental identification. Then the predictive PI algorithm is used to realize the control problem of the complex power system. Finally, the control strategy can meet the established performance parameter requirements of the power supply. Since this study only models and analyzes the 50KV voltage level, it can be used as a typical case to guide the design of the predicted PI algorithm for other voltage levels.

Acknowledgements

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