

Three-phase PFC control strategy based on fractional-order PID controller

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Abstract. With the development of power electronics, more and more power electronic devices are being put into use in the power grid, causing serious harmonic current pollution to the power grid. Active power factor correction (APFC) technology is an important technology for solving harmonic current pollution and has been widely studied and developed. Three-phase PFC based on PWM technology can eliminate harmonic pollution on the grid side and improve power factor and work efficiency. Traditional three-phase PFC generally adopts double PI control strategy of voltage outer loop and current inner loop. However, this traditional control strategy has been unable to adapt to the increasingly complex grid situation. This paper proposes a control strategy that adopts PI controller for voltage outer loop and fractional-order PID controller for current inner loop. And through the Simulink simulation experiment, the result proves that the improved three-phase PFC control strategy presented in this paper has a more stable output voltage and less ripple compared with the traditional dual PI control strategy.

List of abbreviations and nomenclature

Abbreviation	Full name
APFC	Active Power Factor Correction
PFC	Power Factor Correction
PWM	Pulse-Width Modulation
PID	Proportion Integration Differentiation
UPS	Uninterruptible Power System
HVDC	High-Voltage Direct Current

1. Introduction

This year, power electronic equipment has become more and more popular. It has been widely used in the fields of UPS, electrified railway traction and HVDC transmission [1]. At the same time, as more and more power equipment is used, the situation of the load becomes more and more complex, and the harmonic pollution brought to the power grid becomes more and more difficult to control. Therefore, people have come up with various ways to deal with harmonic pollution in the power grid. The first appeared is passive PFC technology. It is a passive harmonic cancellation method that eliminates higher harmonics through the use of an LC filter network of inductors and capacitors. Although the circuit is simple, low cost, and high reliability, it is bulky and heavy and it is difficult to obtain high power factor, etc. And it cannot meet the requirements of PFC in many occasions [2]. Subsequently,



active PFC technology emerged. Its basic principle is: Place the inductor between the AC input rectification circuit and the APFC output filter capacitor. High-frequency switch controls the power frequency current to track the input voltage, that is, the input current is sinusoidal, reducing the generation of harmonics. Its working condition is not affected by grid impedance and load impedance [3]. Applying the APFC technology to a three-phase power supply forms a three-phase active PFC circuit. With the advancement of control theory and the emergence of a variety of control strategies, such as PID controllers, many active PFCs use advanced control methods in response to increasingly complex grid conditions to improve the stability of the system output, reduce the harmonic components and enhance the ability to resist interference. For example, reference [4] proposed a dual-loop PI control technology that can obtain good voltage output; People later realized that many things in nature are fractional systems, so people put forward Fractional-order PID Controller [5]. Compared with the traditional PID controller, it has higher control accuracy and stronger anti-interference ability. Therefore, this paper replaces the current inner-loop PI controller in traditional three-loop active PFC control strategy with a fractional-order PID controller, and obtains better results than traditional dual-loop PI control. However, only by making the controller's parameters optimal can the system work under optimal conditions. Abd-Elazim and Ali [6] proposed a method based on imperialist competitive algorithm parameter optimization for the controller and successfully applied to the power system; Abd-Elazim and Ali [7] proposed a method based on bacterial foraging optimization algorithm (BFOA) parameter optimization for the PID controller. This paper uses genetic algorithm to optimize the parameters of fractional PID controller.

2. The establishment of three-phase active PFC simulation model

This article uses a three-phase full-bridge PFC circuit, the topology shown in figure 1 [8].

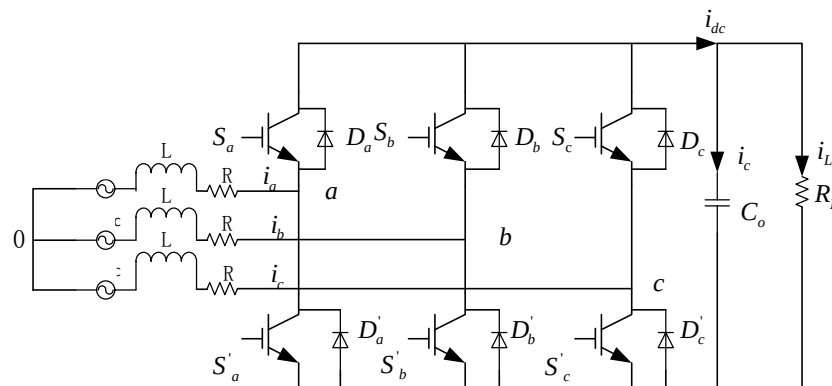


Figure 1. Topology of a three-phase full-bridge PFC circuit.

According to the basic principle of circuit science, the current and voltage of each node and network of the three-phase full-bridge PFC circuit are analyzed and calculated, and the mathematical model of the three-phase PFC main circuit structure is established. First, the symbols in the above figure are explained [9].

- $\{e_a, e_b, e_c\}$ – Three-phase AC phase voltage
- $\{i_a, i_b, i_c\}$ – Three-phase AC input current
- $\{L\}$ – Input side filter inductor
- $\{R\}$ – Input side equivalent resistance
- $\{S_k, S'_k (k = a, b, c)\}$ – Power Switch Devices
- $\{D_k, D'_k (k = a, b, c)\}$ – Freewheeling diode

$$\begin{cases} C_o - \text{DC side output capacitor} \\ R_L - \text{The equivalent load of the system} \\ i_L - \text{System load current} \\ V_{dc} - \text{System-side output voltage} \end{cases}$$

Assume that in the ideal state, the circuit meets the following conditions:

- AC input voltage and current are ideal input signals, there is a fundamental wave component, and they are balanced, they are:

$$e_a + e_b + e_c = \sum_{k=a,b,c} e_k = 0 \quad (1)$$

$$i_a + i_b + i_c = \sum_{k=a,b,c} i_k = 0 \quad (2)$$

- The switching frequency of the three-phase PFC circuit system is large enough and it is an ideal device with no dead time delay.
- During the operation of the transistor, the influence of harmonics caused by switching operations is ignored.
- The inductor on the input side is linear, and each inductor has the same value and no saturation occurs.

Because the transistor on each leg of the rectifier side of the three-phase PFC circuit cannot be turned on, at most one of the two transistors on each leg is at the ON state. At the same time, the transistors on the bridge arm are also not allowed to be in the OFF state. Therefore, set the switch function of the system as follows:

$$S_k + S'_k = 1 (k = a, b, c) \quad (3)$$

The switching function for setting the three-phase PFC circuit is as follows:

$$S_k = \begin{cases} 0, \text{Upper arm off} \\ 1, \text{Upper arm on} \end{cases} (k = a, b, c) \quad (4)$$

Its input voltage on the grid side can be expressed as:

$$\begin{cases} e_a = E_m \sin \omega t \\ e_b = E_m \sin(\omega t + \frac{2}{3}\pi) \\ e_c = E_m \sin(\omega t - \frac{2}{3}\pi) \end{cases} \quad (5)$$

where, $\begin{cases} E_m - \text{The peak value of the phase voltage at the input side} \\ \omega - \text{Net-side input voltage fundamental frequency} \end{cases}$

Under the above premise, after appropriate analysis, the mathematical model of three-phase PFC in three-phase stationary (abc) coordinate system, two-phase stationary ($\alpha\beta$) coordinate system and two-phase rotation (dq) coordinate system can be deduced. No longer described in detail here, just list the mathematical model under various coordinate systems.

- Mathematical model in three-phase stationary (abc) coordinate system:

$$\begin{cases} \sum_{k=a,b,c} e_k = \sum_{k=a,b,c} i_k = 0 \\ L \frac{di_k}{dt} = e_k - i_k R - (S_k - \frac{1}{3} \sum_{k=a,b,c} S_k) V_{dc} \\ C \frac{dV_{dc}}{dt} = \sum_{k=a,b,c} i_k S_k - \frac{V_{dc}}{R_L} \end{cases} \quad (6)$$

- Mathematical model in two-phase stationary ($\alpha\beta$) coordinate system:

$$\begin{cases} E = e_\alpha + je_\beta = \sqrt{\frac{2}{3}}(e_a + \delta e_b + \delta^2 e_c) = \sqrt{\frac{3}{2}} E_m e^{j(\theta - \frac{\pi}{2})} \\ I = i_\alpha + ji_\beta = \sqrt{\frac{2}{3}}(i_a + \delta i_b + \delta^2 i_c) = \sqrt{\frac{3}{2}} I_m e^{j(\theta - \frac{\pi}{2} + \delta)} \\ V = v_\alpha + jv_\beta = \sqrt{\frac{2}{3}}(v_a + \delta v_b + \delta^2 v_c) = V_m e^{j(\theta - \frac{\pi}{2} + \gamma)} \end{cases} \quad (7)$$

where: $\delta = e^{j\frac{2}{3}\pi}$, $\theta = \omega t$

- Mathematical model in the two-phase rotation (dq) coordinate system:

$$\begin{cases} E = e_d + je_q = \sqrt{\frac{2}{3}}(e_a + \sigma e_b + \sigma^2 e_c) e^{-j\theta} = \sqrt{\frac{3}{2}} E_m \\ I = i_d + ji_q = \sqrt{\frac{2}{3}}(i_a + \sigma i_b + \sigma^2 i_c) e^{-j\theta} = \sqrt{\frac{3}{2}} I_m e^{j\sigma} \\ V = v_d + jv_q = \sqrt{\frac{2}{3}}(v_{an} + \sigma v_{bn} + \sigma^2 v_{cn}) e^{-j\theta} = V_m e^{j\lambda} \end{cases} \quad (8)$$

where: $\sigma = e^{j\frac{2}{3}\pi}$

Based on the mathematical models listed in the previous section, we built a model of three-phase active PFC with fractional-order PID controller on Simulink platform, as shown in figure 2.

As can be seen from figure 2, the model sets the load to a continuously changing resistance load. This is to simulate the load of the real-life equipment. The load of the equipment when working is often not constant, on the contrary, the load in real life is often constantly changing. The main function of the decouple module in the figure is to remove the harmonic pollution from the three-phase power input. Its working principle is: The module receives the feedback signal of the output, and then adjusts the duty cycle of the corresponding power transistor in the PFC circuit according to the difference between the feedback signal and the reference value, thereby suppressing the harmonic pollution. Decouple's internal structure is shown in figure 3.

From decouple's internal structure, it can be seen that the controller is controlled by the voltage outer loop and the current inner loop. The voltage outer loop is used to stabilize the output voltage, while the inner current loop is complementary to the outer voltage loop. The output of the current inner loop serves as an input reference for the voltage outer loop, thereby suppressing sudden changes in the input. However, problems such as the distortion of the input current in the current loop and the inability to have no completely sinusoidal current, and have a great impact on the output of the system. Therefore, the voltage outer loop is adopted PI control and the current inner loop is controlled by a fractional-order PID controller (npid module in figures 2 and 3) to improve the

control accuracy and stability of the current inner loop, thereby improving the overall stability of the system in this paper.

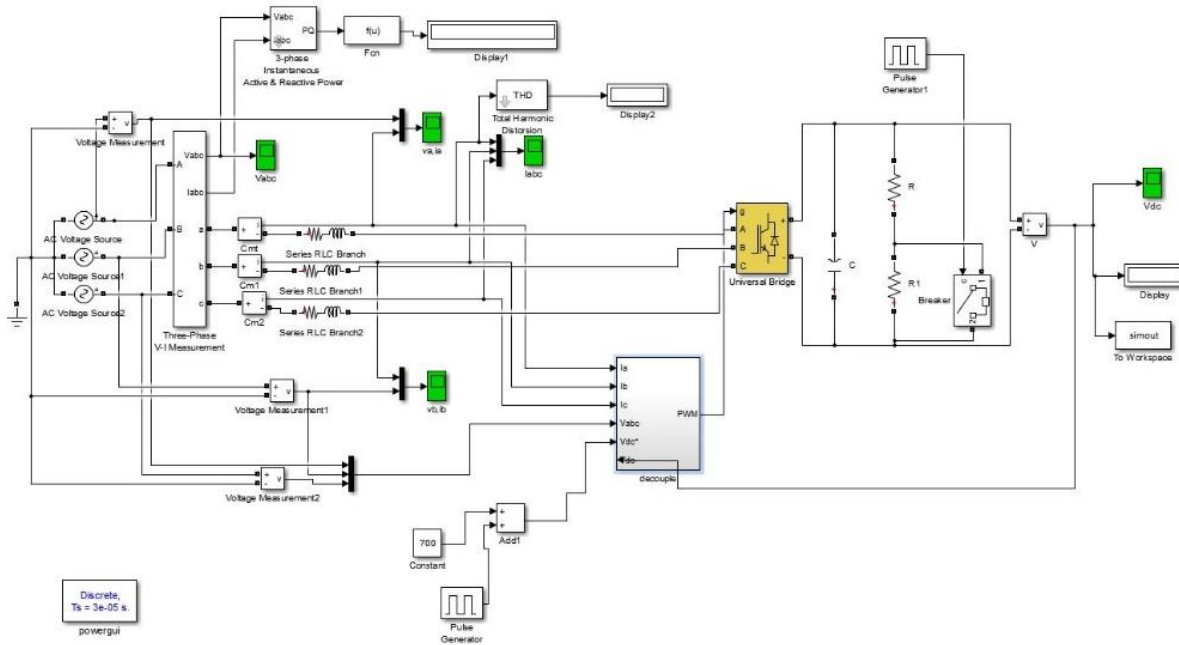


Figure 2. Simulink model of three-phase active PFC with fractional-order PID controller.

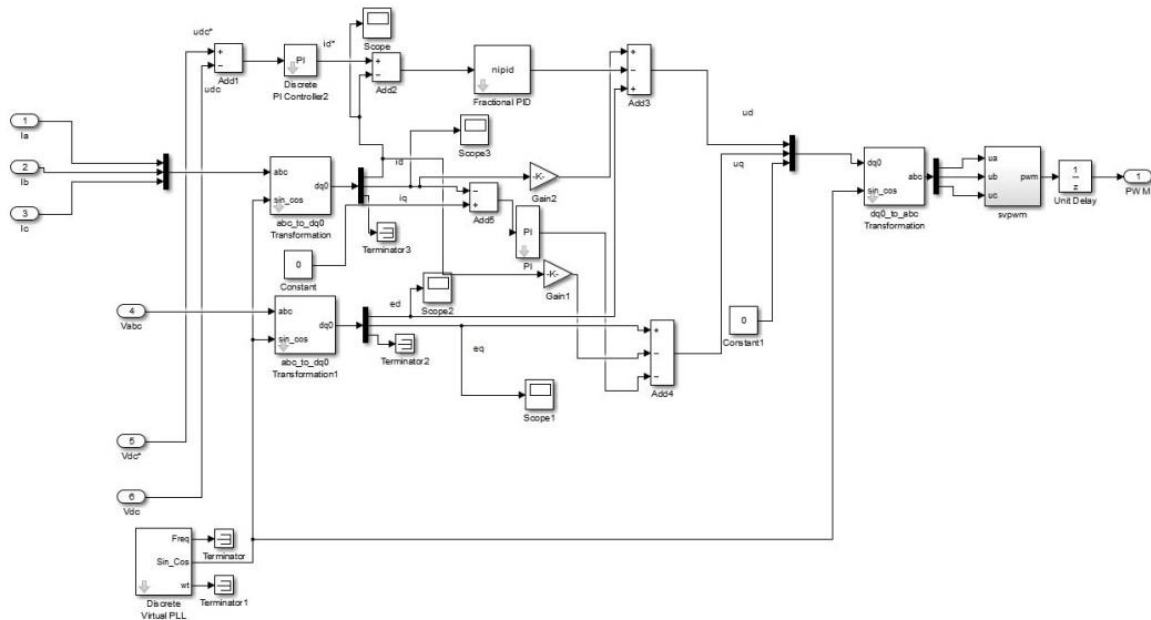


Figure 3. Decouple's internal structure.

3. Fractional-order PID controller [10,11,12]

Fractional calculus allows differential orders and integral orders to be arbitrary, as a natural extension of traditional calculus, and it has its own unique logic and language regulations. The basic operation operator of fractional calculus is $t_0 D_t^\alpha$ as follows,

$${}_t D_t^\alpha = \begin{cases} \frac{d^\alpha}{dt^\alpha}, & R(\alpha) > 0 \\ 1, & R(\alpha) = 0 \\ \int_t^{t_0} (d\tau)^{(-\alpha)}, & R(\alpha) < 0 \end{cases} \quad (9)$$

where, t_0 and t are the upper and lower bounds of calculus; α is any plural number.

In the definition of fractional calculus, the most widely used is Grünwald-Letnikov (GL). The GL definition is expressed as follows,

$${}_x D_t^\alpha f(x) = \lim_{h \rightarrow 0} \frac{1}{\Gamma(n)} h^{-n} \sum_{k=0}^{\frac{x-\beta}{h}} \frac{\Gamma(n+k)}{\Gamma(k+1)} f(x-kh) \quad (10)$$

where, h is the calculation step; $\Gamma(\square)$ is the famous Euler Gamma function.

Laplace transform of fractional calculus defined by GL, the fractional-order PID controller's transfer function is

$$G_c(s) = \frac{U(s)}{E(s)} = k_p + k_i s^{-\lambda} + k_d s^\mu \quad (11)$$

In the time domain, the control signal of the fractional-order PID controller $u(t)$ is,

$$u(t) = k_p e(t) + k_i D^{-\lambda} e(t) + k_d D^\mu e(t) \quad (12)$$

Where, λ is the integral order, μ is a differential order; k_p , k_i and k_d are proportional, integral and differential parameters respectively; $e(t)$ is error input for the controller. When $\lambda = \mu = 1$, (3-4) is a conventional PID controller; When $\lambda = 0$, $\mu = 1$, (3-4) is the PI controller; When $\lambda = 0$, $\mu = 1$, (3-4) is the PD controller. It can be seen that the PID controller is only a special case of fractional-order PID. By reasonable selection of parameters, the stability of the control process of the system can be improved. Obviously, this controller has more flexibility.

4. Simulation results

The parameters of the fractional-order PID controller are optimized by the genetic algorithm [13], and the results are shown in table 1:

Table 1. Results of optimization.

number	1	2	3	4	5	6	7	8	9	10
k_p	1.3666	2.8094	1.7390	2.5748	2.4457	2.7625	2.1877	0.5367	0.5367	0.3959
k_i	0.7312	1.7322	0.8270	1.6637	0.5181	1.3372	1.3978	0.8602	0.8602	0.7390
k_d	0.3675	1.2199	0.4379	1.4272	1.4409	1.4897	0.3578	1.3060	1.2786	0.4477
λ	1.8729	0.6843	0.3226	1.4917	0.6471	1.4917	1.0557	1.2864	1.6481	1.4897
μ	1.3959	0.2111	0.7918	0.4477	1.1320	0.3011	0.5865	0.6628	0.8680	0.6628
number	11	12	13	14	15	16	17	18	19	20
k_p	0.7478	0.7478	0.5073	2.1877	2.4721	0.3284	2.5748	0.4370	2.2522	2.1994

k_i	0.7390	0.7410	0.0450	1.3978	1.1398	0.6022	0.3969	0.0391	0.7390	1.3881
k_d	0.4653	0.4653	1.2532	0.2659	1.2571	0.1408	0.2659	0.3030	0.4399	1.4682
λ	1.6481	1.6481	0.6334	0.9912	0.7136	0.8192	0.9912	0.5357	0.6413	0.9619
μ	0.1251	0.1251	0.3011	0.3011	0.6628	0.1310	0.3011	0.6804	0.8680	1.9550

After repeated optimization and debugging, the fractional-order PID parameters finally obtained are: $k_p=2.1994$, $k_i=1.3881$, $k_d=1.4682$, $\lambda=0.9619$, $\mu=1.9550$. Substituting this parameter into a fractional-order PID controller to simulate the three-phase active PFC of Simulink, there is basically no phase difference between the single-phase voltage and its corresponding current. Simulation results are shown in figure 4.

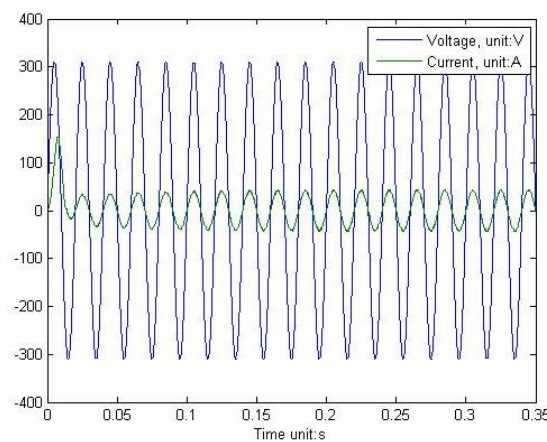


Figure 4. Single-phase voltage and current waveforms.

The three-phase active PFC of the PI voltage outer loop and fractional-order PID current inner loop designed in this paper has less ripple and smoother waveform compared with the traditional dual-PI loop active PFC and three-phase active PFC output waveform with PI voltage outer loop and PID current inner loop. The comparison waveforms are shown in figure 5, figure 6 and figure 7

As can be seen from figure 7 and figure 8, the three-phase PFC designed in this paper can ensure that the system still has a stable voltage and current output under the condition of non-linear load.

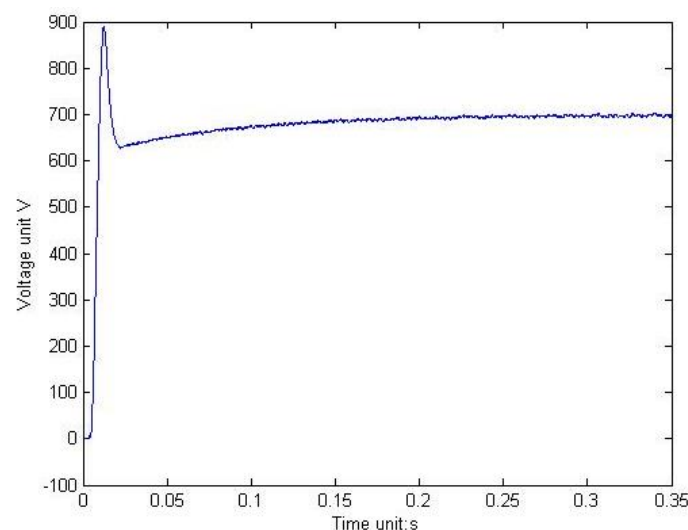


Figure 5. Traditional PI Dual-loop active PFC output voltage waveform.

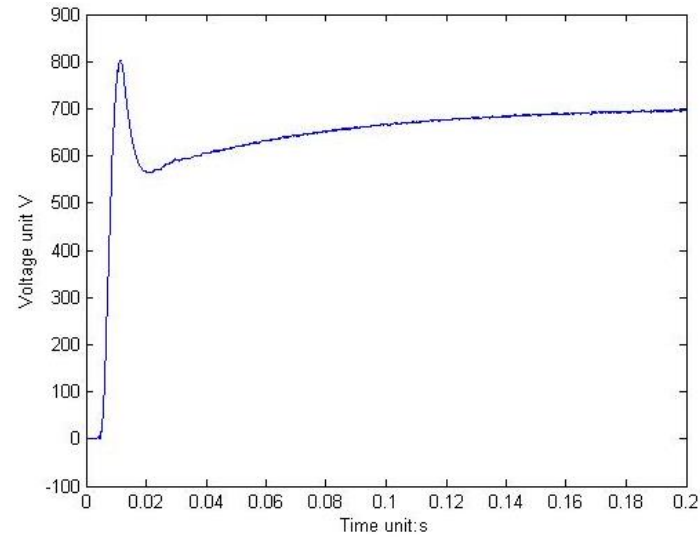


Figure 6. Three-phase active PFC output voltage waveform with PI voltage outer loop and PID current inner loop.

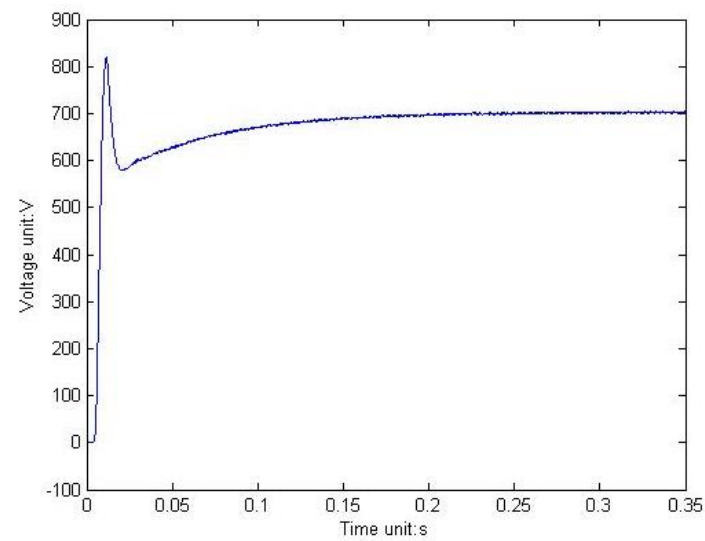


Figure 7. Three-phase active PFC output voltage waveform with PI voltage outer loop and fractional-order PID current inner loop.

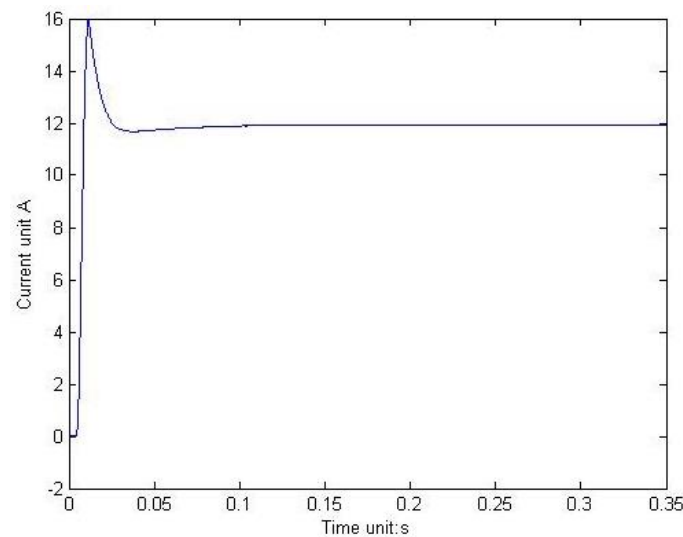


Figure 8. Three-phase active PFC output current waveform with PI voltage outer loop and fractional-order PID current inner loop.

As can be seen from the above comparison chart, the three-phase active PFC output waveforms of the PI voltage outer loop and fractional-order PID current inner loop designed in this paper are smoother and have less ripple. According to the collected ripple rate, the ripple rate of the three-phase active PFC with PI voltage outer loop and fractional-order PID current inner loop designed in this paper is 0.01986, which is lower than the traditional PI double loop active three-phase PFC simulation model, 0.02725 and three-phase active PFC output waveform with PI voltage outer loop and PID current inner loop simulation model, 0.02108.

5. Conclusion

This article realizes the simulation of three-phase active PFC with fractional-order PID current inner loop and PI voltage outer loop through Simulink. Simulation results show,

- The three-phase PFC designed in this paper can ensure that the system still has a stable voltage and current output under the condition of non-linear load.
- The three-phase active PFC of PI voltage outer loop and fractional-order PID current inner loop designed in this paper can well eliminate the phase difference between current and voltage.
- The output waveform of the control strategy designed in this paper is smooth and the ripple rate is low. The performance is superior to the traditional PI double loop active three phase PFC and three-phase active PFC output waveform with PI voltage outer loop and PID current inner loop.
- The control strategy of three-phase PFC with PI control voltage outer loop and fractional-order PID control current inner loop have a positive effect on the use of the new control method in the power industry.

References

- [1] Chang G W, Hsin W L and Shin K 2004 Modeling characteristics of harmonic currents generated by high-speed railway traction drive converters *IEEE T Power Delivery* **19** 766-73
- [2] Wang Han 2009 Research and implementation of high-power single-phase digital APFC (in Chinese) (Shanghai: Shanghai Jiaotong University)
- [3] Kolar W J and Friedli T 2014 The essence of three-phase PFC rectifier systems-part II *IEEE T*

- Power Electr* **29** 543-60
- [4] Zhu J 2008 Annabelle pratt. capacitor ripple current in an interleaved PFC converter *IEEE PESC* **2008** 3444-50
 - [5] Li Y, Chen Y Q and Ahn H S 2011 Fractional-order iterative learning control for fractional-order linear systems *Asian J Control* **13** 54-63
 - [6] Abd-Elazim S M and Ali E S 2016 Imperialist competitive algorithm for optimal STATCOM design in a multimachine power system *IJEPES Elsevier* **76** 136-46
 - [7] Abd-Elazim S M and Ali E S 2013 BFOA based design of PID controller for two area load frequency control with nonlinearities *IJEPES Elsevier* **51** 224-31
 - [8] Guo X 2016 Control strategies for high efficiency and high power factor three phase power supply (Shaanxi, China: Xi'an University of Technology) (in Chinese)
 - [9] Liu MY 2013 SVC Fractional PID controller design (Beijing, China: North China Electric Power University) (in Chinese)
 - [10] Caponetto R F and Porto D L 2004 A new tuning strategy for a non integer order pid controller *IFAC* **18** 246-50
 - [11] Fu H, Li YF and Xu YS 2015 Air volume regulating method for local ventilator based on fuzzy fractional order PID control *Computer Simulation* **32** 374-7 (in Chinese)
 - [12] Li HQ 2016 Research on digital control of three-phase PFC circuit (Shaanxi, China: Xi'an University of Science and Technology) (in Chinese)
 - [13] Alanara S M 2013 Adaptive multi-rate codec bit rate control in a wireless system *U.S. Patent* 8,422,373