Fractional Order Control of LCL Hybrid Resonant Electric-field Coupled Power Transfer System

Yun Tang, Hejin Xiong and Gaohan Zhou
School of Automation, Wuhan University of Technology, Wuhan, China

Abstract: Based on the transmission stability of LCL composite resonant Electric-field Coupled Power Transfer (ECPT) system, according to the voltage gain topology circuit model, the closed-loop control system model is established, and the control method based on PID and Fractional Order PID is proposed. By comparing the waveforms of the two control methods in the case of closed-loop, disturbance and impulse disturbance, a control method which makes the LCL type ECPT system have high response speed, strong robustness and strong anti-interference ability is obtained.

Keywords: ECPT; PID; Fractional Order PID; LCL.

1. Introduction
LCL composite resonant Electric-field Coupled Power Transfer system (ECPT) is a kind of transmission mode which uses high frequency electric field as carrier to transmit electric energy wirelessly. However, the output voltage of the energy transmission system is not very stable because of the position parameters of the plate, the component parameters of the circuit topology and the external interference. In order to solve this problem, this paper proposes the PID based and Fractional Order PID control methods, and compares the waveforms of the two control methods in the case of closed-loop, plus interference and plus pulse disturbance, and obtains a LCL type ECPT system The system has high response speed, strong robustness and strong anti-interference ability [1].

2. LCL ECPT Control System Modeling
The schematic diagram of ECPT system is shown in Figure 1.

![System schematic diagram](image)

Figure 1. System schematic diagram.

After the high-frequency inverter link, the DC power supply forms alternating voltage, enters the resonance compensation link, and then through the pick-up electrode in the high-frequency electric field, the potential difference $\Delta V$ is generated, and then supplies the load after the rectification and filtering link [1].

For the convenience of analysis, it is assumed that all switches are ideal switches, DC power supply and switches are combined into a half bridge inverter circuit, and the output voltage is alternating voltage, which can be equivalent to an AC power supply. After the capacitance of coupling mechanism is equivalent, the equivalent circuit as shown in Figure 2 can be constructed [1].
when selecting system component parameters, it should be kept within the range that can make the system work stably: \( C_1 = 9.68 \times 10^6 \), \( C_2 = 0.43 \times 10^6 \), \( C_3 = 2.93 \times 10^6 \), \( L_1 = 2.57 \mu H \), \( L_{2a} = 55.23 \mu H \), \( L_{2b} = 78.5 \mu H \), \( R_e = 10 \Omega \) [1].

In order to make the system more stable, PID control method and Fractional Order PID control method will be used to establish the closed-loop transfer function model of the system, as shown in Figure 3.

3. Fractional Order PID and Integer Order PID Controller
Fractional Order PID control theory is a relatively new control theory based on PID control theory. It’s general format is \( \mathcal{D}^\mu \mathcal{P}^\lambda \mathcal{I} \). Because the order parameters of integral and differential are introduced, the control range is wider and the object can be controlled flexibly. Fractional Order PID can make the system get better robustness and anti-interference [2].

The \( \mathcal{D}^\mu \mathcal{P}^\lambda \mathcal{I} \) controller including an integral order \( \lambda \) and differential order \( \mu \) in which \( \lambda \) and \( \mu \) can be any real number, and its transfer function is

\[
G_c(s) = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu, (\lambda, \mu > 0)
\]

(1)

The integral term here is \( s^\lambda \). in the log plot of phase frequency, its slope is -20 \( \lambda \) dB / DEC, not -20 dB / Dec [2].

PID is controlled by proportion, integral and differential according to the error between the actual output and the given value. In the complex process of non-linear, time-varying, coupling and uncertain parameter structure, the control effect of integer order PID is not very good, Fractional Order PID is better [2].

4. Simulation and Analysis
After the description of PID controller and Fractional Order PID controller model, the closed-loop LCL ECPT system will be simulated as follows. The simulation waveforms of the system in three different operation modes of closed-loop, PID control and Fractional Order PID control are analyzed. Through the analysis of the waveforms, the most stable control mode is obtained.

4.1. Simulation Results of System Operation without Interference
Given a sine wave with a voltage value of 10V, the simulation waveform of LCL ECPT system under three operation modes of closed-loop, PID control and Fractional Order PID control without external interference is shown in Figure 4.
Compared with the three operation modes of LCL ECPT system without interference, the data can be picked up from the figure to get table 1.

**Figure 4** Waveform without interference.  
**Figure 5.** Waveform with white noise.

**Table 1.** Simulation data without interference.

| Performance index | Operation mode   | Closed-loop control | PID      | Fractional Order PID |
|-------------------|------------------|---------------------|----------|----------------------|
| Rise time $t_r (\times 10^{-6})$ s | 5.342            | 13.294              | 13.231   |
| Adjustment Time $t_a (\times 10^{-5})$ s | 2.028            | 1.917               | 1.62     |
| Overshoot | 24.9%            | 0                   | 0        |

From the data in the table 1, we can get the following conclusions:

a. The rise time of LCL ECPT system is $5.342 (\times 10^{-6})$, $13.294 (\times 10^{-6})$ and $13.231 (\times 10^{-6})$ respectively when the voltage output rises from about 10% of the given value to about 90% of the given value. Therefore, when there is no disturbance, the response speed of fractional PID is faster than that of PID controller.

b. Under the closed-loop, PID and Fractional Order PID mode, the shortest time required for the voltage to stabilize from 0 to ± 5% of the given replication amplitude of LCL ECPT system is $2.028 (\times 10^{-5})$, $1.917 (\times 10^{-5})$ and $1.62 (\times 10^{-5})$, respectively. From this, so it can be seen that the Fractional Order PID has the fastest response speed.

c. The overshoot of the system is 24.9%, 0 and 0 respectively under the operation mode of closed-loop, PID and fractional PID. It can be seen that PID control and fractional PID control realize the system without overshoot.

4.2. Operation Simulation Results of the System under White Noise Interference

Given a sine wave with 10V, the simulation waveform of LCL ECPT system under the three operation modes of closed-loop, PID control and Fractional Order PID control is shown in Figure 5 when white noise interference is added at 0.0002s.

Compared with the three operation modes of LCL ECPT system with white noise, the data can be picked up from the figure to get table 2

**Table 2.** Simulation data with white noise.

| Performance index | Operation mode   | Closed-loop control | PID      | Fractional Order PID |
|-------------------|------------------|---------------------|----------|----------------------|
| Recovery time $(\times 10^{-5})$ s | 5.41             | 3.3                 | 2.31     |
| Overshoot | 142%             | 74.3%               | 56.1%    |

From the data in the table 2, we can get the following conclusions:

a. Under the three operation modes of closed-loop, PID and Fractional Order PID, the voltage amplitude of the system output exceeds 142%, 74.3% and 56.1% of the given voltage after the white noise interference is added, which shows that fractional Order PID has the strongest anti interference ability.
b. Under the three operation modes of closed-loop, PID and Fractional Order PID, the recovery time of the system output voltage from the maximum value disturbed to the stable output value is 5.41\((\times 10^{-5})\), 3.3\((\times 10^{-5})\) and 2.31 \((\times 10^{-5})\), respectively, after adding white noise interference, it can be seen that the Fractional Order PID controller has the fastest response speed and the shortest recovery time.

4.3. Simulation Results of System Operation under Pulse Interference

Given a sine wave with a voltage value of 10V, the simulation waveform of LCL EPCT system under three operation modes of closed-loop, PID control and fractional PID control is shown in Figure 6 when pulse interference is added at 0.0002s.

Compared with the three operation modes of LC L ECPT system under the condition of adding pulse, the data can be picked up from the figure to get table 3.

Table 3. Simulation data with pulse interference

| Performance index | Operation mode       | Closed-loop control | PID control | Fractional Order PID control |
|-------------------|----------------------|---------------------|------------|------------------------------|
|                   | Rising edge of pulse | 10.3%               | 3.1%       | 1.2%                         |
|                   | Pulse falling edge   | -11.75%             | -11.65%    | -3.63%                       |
| Recovery time     | Rising edge of pulse | 0.211               | 0.098      | 0.075                        |
| \((\times 10^{-5})s\) | Pulse falling edge  | 0.703               | 0.104      | 0.097                        |

Compared with the three operation modes of the system under the closed-loop, PID and fractional PID control, the system overshoot of the fractional PID controller is smaller than that of the PID controller and the closed-loop controller after the pulse interference is added, which shows that the suppression effect of the fractional PID controller on the pulse interference is better than that of the PID controller and without the controller. The recovery time of the system output voltage amplitude from the maximum value to stable at about ± 5% of the given voltage amplitude is less than that of PID and no controller.

![Figure 6. Waveform with pulse interference.](image)

5. Summary

This paper compares the control effect of PID controller and Fractional Order PID controller from three aspects of no interference, white noise interference and pulse interference. By comparing the parameters of overshoot, response speed and recovery time of the system, the performance of Fractional Order PID control is better than that of integral order PID, which can better guarantee the stability of output voltage waveform, and thus suppress the power transmission in the process of energy transmission, the instability of energy transmission caused by system parameters or external interference is important for the stability of wireless energy transmission.
References

[1] Su Yugang, Xie Shiyun, Hu Aiguo, Tang Chunsen, Zhou Wei. Analysis of transmission characteristics of LCL compound resonant electric field coupled radio energy transmission system[J]. Journal of electrical technology, 2015, 30(19):55-60. (China)

[2] Xue Dingyu, Zhao Chunna. Fractional PID controller design for fractional order system [J]. Control theory and application, 2007(05):771-776. (China)

[3] Lan Huili, Zhou Xiaohua, Luo Wenguang. Fractional order Buck converter optimal PI–lambdaD–mu control[J]. Electrical measurement and instrumentation, 2019, 56(16):134-141. (China)

[4] Zhao Jikang, Xu Da, Jiang Enyu. Application of fractional PID controller in automatic voltage regulation system[J]. Journal of Shanghai university of electric power, 2019,35(04):308-314. (China)

[5] Wang Miao. Fractional order controller design and simulation research [D]. Beijing jiaotong university, 2014. (China)

[6] Chen Yimei, Zhang Tianyun. Control of quadrotor aircraft based on fractional PID [J]. Journal of tianjin university of technology, 2019,38(04):58-63. (China)

[7] Tang Jian, Ding Yuedou, Chen Xi. Speed controller design of brushless dc motor based on adjustable fraction order PI– lambda D– mu [J]. Journal of hunan institute of technology (natural science edition), 2019,32(01):33-38. (China)

[8] Xue Dingyu, Zhao Chunna. Fractional PID controller design for fractional order system [J]. Control theory and application, 2007(05):771-776. (China)