Fractional Order PID PLL Controller Based on Particle Swarm Optimization Algorithm

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Abstract: In this paper, a Fractional Order PID PLL controller based on particle swarm optimization algorithm is proposed for power grid system. The parameters of Fractional Order PID controller are optimized by particle swarm optimization algorithm, so as to control the orthogonal signal generator in PLL, realize accurate phase discrimination and effectively suppress grid harmonics. In this paper, firstly, the mathematical model of PLL is established, and then the PID controller and Fractional Order PID controller are compared and controlled. Finally, the parameters of Fractional Order PID controller are optimized by particle swarm optimization algorithm to achieve the optimal control. In this paper, the simulation of PLL controller is completed based on MATLAB / Simulink. The simulation results show that the Fractional Order PID based on PSO algorithm can automatically find the optimal control parameters, realize the precise control of PLL, and improve the ability of filtering harmonic and dynamic performance of power grid.

1. Introduction

In power grid system, in order to reduce the impact of harmonics or faults on the power grid waveform, and to track the grid voltage waveform in real time and reasonably control the waveform stability under sudden conditions, high performance phase locked loop (PLL) is the key to power grid regulation. On the basis of detecting the instantaneous value of voltage, it is required to complete the synchronization of fundamental component of power grid voltage quickly and accurately, reduce the interference to the minimum, and make the power grid system quickly achieve stability. The high-performance synchronous phase-locked loop proposed in this paper is based on the differential link phase-locked loop. By combining the differential link with the second-order filter, an orthogonal signal generator is constructed. The input signal generates two-phase orthogonal signals through the orthogonal signal generator, and then the phase error signal is accurately obtained by eliminating the phase deviation between the input and output of the differential link by two identical micro dividing links. The obtained error signal is adjusted by PID controller to adjust the performance of PLL.

This paper presents a Fractional Order PID control method based on particle swarm optimization algorithm, which is used to adjust the PLL controller, so as to achieve the optimal system control for the grid connected problems such as voltage sudden change, phase lead, frequency sudden change and voltage harmonic. Firstly, the PLL model is established, and then the Fractional Order PID and particle swarm optimization algorithm are introduced. Then the simulation results of Fractional Order PID controller based on particle swarm optimization algorithm are given. Finally, the superiority of the design is verified by comparison.
2. Structure design of high performance phase locked loop

2.1. Design of phase detector for PLL

Phase locked loop (PLL) is a feedback control circuit, which uses external input reference circuit to control the frequency and phase of internal oscillation signal. When the frequency of the output signal is the same as that of the input signal, the phase of the output voltage keeps a certain difference with the phase of the input voltage, that is phase-locked. PLL is usually composed of PD (phase detector), loop filter (LF) and voltage controlled oscillator (VCO). The phase detector in PLL is also called comparator, which is used to detect the phase difference between input signal and output signal, and convert the detected phase difference into voltage signal. The loop filter filters the voltage signal into the input signal of the VCO and controls the frequency of the output signal of the oscillator. The general loop filter can be replaced by PID controller to adjust the parameters of PID to adjust the performance of PLL. The voltage controlled oscillator can be replaced by an integrator to obtain the phase signal by integrating the frequency signal. The performance of phase detector is very important, which requires that the phase difference of input and output signals can be detected quickly and accurately.

The key of constructing high precision phase locked loop is to construct high precision phase detector. In this paper, the high performance quadrature signal generator (QSG) designed in reference [1] is used to construct the phase detector of PLL. The quadrature signal generator is obtained by combining the differential unit (DU) with the second-order filter, which can attenuate the harmonics and effectively reduce the transient components of the output.

The transfer function is as follows:

\[
G_1(s) = \frac{v'}{v} = \frac{w_n^2}{s^2 + 2w_n\omega_0 s + w_n^2}, \\
G_2(s) = \frac{qv'}{v} = \frac{w_n^2}{s^2 + 2w_n\omega_0 s + w_n^2},
\]

Considering its application to the power grid, \(\omega_0 = 314\, \text{rad/s}\).

For the above orthogonal signal generator:

1. (1) for any signal, \(v'\) and \(qv'\). The phase difference is 90 degrees.

2. (2) \(G_1\) Equivalent to the turning frequency of \(\omega_0\). Low pass filter of \(G_2\) Equivalent to the turning frequency of \(\omega_0\). Band pass filter. At the center frequency of \(\omega_0\), the signal nearby can pass smoothly without high-order harmonics.

3. (3) The phase and amplitude of the output signal of the quadrature generator are only related to the input signal. The quadrature signal generator based on differential link (DU-QSG) can produce good quadrature sinusoidal signal, so it can be further used to construct high-precision PLL.

2.2. Structure Design Of PLL

Because of the phase shift of the input and output signals of the differential link, the phase difference of the input and output signals of the PLL can not be accurately tracked. Therefore, two identical DU-QSGs (DU1 and DU2) are used to eliminate the phase difference. Set the input signal as grid voltage \(v_2 = \sin (\omega_2 t + \theta_2)\). The differential link based phase-locked loop (DU-PLL) as shown in Fig.1 is constructed. The output of DU1 is \(v'_1, qv'_1\). The output of DU2 is \(v'_2, qv'_2\). \(G(s)\) is the controller. Phase locked loop output phase signal \(\tilde{\theta}\). After sinusoidal change, as the input signal of DU2, DU2 outputs \(v'_2, qv'_2\). After the signal, and DU1 output \(v', qv',\) The phase error is calculated and the phase...
error is obtained $\epsilon_{pd}$. The gain is proportional to the phase difference of the input and output signals $k_{pd} = \omega_z / 4$.

Figure 1. PLL control block diagram

3. Design of PLL controller
After the input signal passes through the high precision phase detector, the output signal is the phase error of PLL input and output $\epsilon_{pd}$. It can be equivalent to the gain of the input signal $k_{pd}$. Using fractional order controller to adjust the phase error of signal can optimize the control effect.

3.1. Fractional Order PID controller
Fractional Order PID controller is a generalization of traditional PID controller. Compared with the traditional integer order controller, the integral and differential times in Fractional Order PID are not integers. Two new coefficients, differential order $\mu$ and integral order $\lambda$. The adjustable parameters of the controller are increased from three to five. The increase of the parameter dimension of the controller makes the parameter adjustment range of the controller wider and the regulation accuracy more accurate, which makes the controlled object obtain better dynamic and static characteristics.

The fractional order controller consists of a proportional coefficient $k_p$, integral coefficient $k_i$, differential coefficient $k_d$, integral order $\lambda$, differential order $\mu$. The transfer function is as follows:

$$G(s) = k_p + k_i/s^\lambda + k_d s^\mu, \quad \lambda > 0, \quad \mu > 0$$

The system model of fractional order controller is shown in Figure 2.

Figure 2. block diagram of Fractional Order PID control system

4. Parameter optimization of Fractional Order PID based on particle swarm optimization

4.1. Parameters of Fractional Order PID controller based on PSO
PSO algorithm optimizes the parameters of Fractional Order PID controller, including proportional coefficient $k_p$, integral coefficient $k_i$, differential coefficient $k_d$, integral order $\lambda$, differential order $\mu$. These five parameters take $k_p, k_i, k_d, \lambda, \mu$. As the input of PSO, the dimension of PSO is 5 and inertia factor $\omega$. Take 0.6 as acceleration constant $c_1$ and $c_2$. The particle swarm size is 50 and the maximum number of iterations is 10. Given the optimal objective function, the optimal control parameters are searched out in the space. Because of the complexity of the model in this paper, we call the Sin function to calculate the Simulink model in real time, and finally draw the image of five parameters and the final fitness value. The block diagram of adjusting parameters is shown in Fig. 2.
5. Analysis of simulation results
Matlab / Simulink is used to build the model of PLL, and the controller part of PLL is divided into PID controller, Fractional Order PID controller and Fractional Order PID controller based on particle swarm optimization algorithm. The PLL is applied to the voltage amplitude mutation, phase mutation, frequency mutation and power grid harmonic state to compare the anti-interference ability. The frequency signal of the output signal is given w’. Compared with the waveform of input and output phase error signal e. The input voltage is 100V / 50Hz.

The results of grid voltage amplitude mutation are shown in Fig. 3.1-3.3. When t=50s, it is incorporated. The output signal frequency w’ waveform under the three control modes is shown in Figure 3.1, the phase error signal e waveform of input and output signal is shown in Figure 3.2, and the optimal fitness curve calculated by particle swarm optimization algorithm is shown in Figure 3.3. The simulation results are shown in table 4-1. It can be seen from the chart that the particle swarm optimization algorithm can find the optimal fractional order PID parameters. In the case of voltage amplitude mutation, the output signal frequency can be basically unaffected. Compared with Fractional Order PID and integer order PID, the phase error has less response speed and overshoot, and the optimal individual fitness value has been found in the second iteration.

The results of power grid frequency mutation are shown in Fig. 3.4-3.6. When the grid frequency changes from 50 Hz to 55 Hz when t = 5 s, the frequency w’ waveform of output signal under three control modes is shown in Figure 3.4, the waveform of phase error signal e of input and output signal is shown in Figure 3.5, and the optimal fitness curve calculated by particle swarm optimization algorithm is shown in Figure 3.6. The simulation results are shown in Table 4-2. It can be seen from the chart that under the condition of grid frequency mutation, the parameters found by particle swarm optimization are optimal for the control effect of system frequency, and the phase error of phase input and output signals is also minimum. When the number of iterations reaches the sixth generation, the optimal fitness value has been found.

The results of power grid phase mutation are shown in Fig. 3.7-3.9. When t = 5 s, the phase of power grid is ahead of 90° suddenly. Under the three control modes, the frequency w’ waveform of the output signal is shown in Fig. 3.7, the waveform of the phase error signal e of the input and output signal is shown in Fig. 3.8, and the optimal fitness curve calculated by particle swarm optimization algorithm is shown in Fig. 3.9. The simulation results are shown in table 4-3. It can be seen from the chart that the parameters found by PSO have large overshoot for frequency signal, but the adjustment speed is fast, and the phase error of signal is better than FPID and PID.

The results of the third and fifth harmonics are shown in Fig. 3.10-3.12. Under the three control modes, the frequency w’ waveform of the output signal is shown in Fig. 3.10, the waveform of the phase error signal e of the input and output signal is shown in Fig. 3.11, and the optimal fitness curve calculated by the particle swarm optimization algorithm is shown in Fig. 3.12. It can be seen from the figure that for the third and fifth harmonic signals, the optimal parameters found by particle swarm optimization can accurately restore the tracking transmitted signal and maintain the frequency and phase of the original signal. The high precision PLL can effectively filter out the interference of harmonic signal to the original voltage signal.

![Fig. 3.1 w’ under three controllers when voltage amplitude changes suddenly](image1)

![Fig. 3.2 e under three controllers when voltage amplitude changes suddenly](image2)
Table 4.1 performance index of each controller under voltage amplitude variation

| Controller | Overshoot M/% | Adjustment time Ts/s |
|------------|---------------|---------------------|
| PID        | 0.29          | 17                  |
| FPID       | 2.74          | 0.53                |
| PSO        | 0             | 0                   |

Table 4.2 performance index of each controller under voltage and frequency variation

| Controller | Overshoot M/% | Adjustment time Ts/s |
|------------|---------------|---------------------|
| PID        | 18.79         | 3.639               |
| FPID       | 18.09         | 0.958               |
| PSO        | 15.9          | 0.083               |

Fig. 3.3 optimal individual adaptive value of voltage amplitude mutation

Fig. 3.5 $e$ under three kinds of controllers in case of voltage frequency mutation

Fig. 3.7 $w'$ under three controllers when voltage phase changes suddenly

Fig. 3.8 $e$ under three controllers when voltage phase changes suddenly

Fig. 3.10 $w'$ under three controllers when third and fifth harmonics are added

Fig. 3.12 optimal individual fitness value with third and fifth harmonics

6. Conclusion
This paper presents a control method of Fractional Order PID PLL based on particle swarm optimization algorithm. The controller parameters obtained can control the system performance more accurately and efficiently. The effectiveness of the control method is verified by Matlab / Simulink simulation. From the above simulation results, it can be seen that the performance of the high-precision...
PLL under the three controllers is obvious. When the grid voltage is affected by voltage amplitude mutation, voltage frequency mutation, voltage phase mutation and harmonic interference, particle swarm optimization algorithm has obvious advantages in finding Fractional Order PID parameters, which can control the system more accurately than Fractional Order PID. The system has fast corresponding and accurate tracking, and has high robustness. The high-precision phase-locked loop can filter the harmonics, track the signal accurately and reduce the system overshoot to improve the regulation speed. Compared with the traditional integer order PID, the advantages are more obvious. And from the optimal individual fitness curve calculated by particle swarm optimization algorithm, it can be seen that the particle swarm optimization algorithm can find the optimal individual fitness in a very short number of iterations, which greatly simplifies the process of manually adjusting Fractional Order PID parameters, and makes the adjustment process more accurate. This paper can be used as the basis to optimize the particle swarm optimization algorithm, and realize the control of the system performance more accurately and quickly.

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