Research on Intelligent Control System of High Power Soft Starter Based on Discrete Frequency Conversion Technology

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Abstract: Thyristor soft starter can effectively solve the three-phase asynchronous motor starting current problem, but its reduced starting current is achieved by reducing the output voltage and inevitably reducing the motor starting torque, it is difficult to use for heavy start of the occasion. A kind of soft starter based on discrete frequency conversion method is designed for the problem that the starting torque is small, the starting current is large, and the overloading cannot start. Based on the analysis of the working principle of the thyristor soft starter, this paper makes a deep research on the soft start control mode and realization method of the discrete frequency conversion without changing the main circuit structure of the original thyristor soft starter. Firstly, the soft starter hardware based on the three-phase anti-parallel thyristor main circuit and the current effective value is calculated using high-speed A/D. Then, the soft start control strategy based on discrete frequency conversion is analyzed, with a 3kW/380V three-phase asynchronous motor for the test motor, respectively, the motor started a different way to simulate and test.

Keywords: asynchronous motor; soft starter; discrete frequency conversion; current detection

1. Introduction
AC induction motor has been widely used in all walks of life, which is so far important electrical and mechanical energy conversion equipment, accounting for about 60% of industrial power consumption. However, the starting torque of traditional step-down soft starter is small, which can only be limited to start the no-load or light load motor [1, 2]. Modern electronic regulator soft starter can be more flexible to adjust the motor voltage. But the starting torque of the motor is proportional to the square of the voltage, while the regulator also significantly reduces the starting torque, which essentially belongs to the step-down soft start.

Frequency conversion is a direct and effective way to solve the small starting torque of asynchronous motor. With the advance of power electronics technology, vector control and direct torque control of high-performance frequency converter has been able to start with overload or even over rated load of asynchronous motor. However, it is difficult to apply to the speed requirements of the low occasion, due to a large number of power switching devices and the higher cost of the inverter. Inverter output is AC-AC frequency, which is equivalent to the frequency of the grid, the phase is
isolated [3-5]. It is difficult to bypass the switch to the grid after the motor has finished starting. If it has been running online, it increases the loss of the inverter and shortens its service life. In 1999, the American scholar Antonio Ginart proposed a three-phase anti-parallel thyristor based on the discrete frequency control method to get positive and negative half-wave symmetrical conduction of the inverter voltage, through the continuous selection of the power grid and turn off some sine half-wave and in the modern electronic soft starter on the basis of the main circuit. The variable frequency voltage combined with the phase control voltage can be achieved asynchronous motor variable frequency control, so as to increase the starting torque and reduce the starting current effect.

Based on the above analysis, this paper designs a discrete frequency soft starter based on three-phase anti-parallel thyristor. First of all, this paper designs the soft starter hardware circuit, with a strong numerical operation and fast logic processing capabilities of high-performance DSP OR PLC OR PLC28335 as the main controller. Then, the working principle of discrete frequency conversion and its controller strategy are analyzed, and the soft starting method of frequency conversion after 7-4-3 frequency conversion is proposed [6]. Finally, the designed discrete frequency soft starter can increase the starting torque or lower the starting current at the same load rate by designing and verifying the pulp mill in a paper mill.

2. Soft starter control system

Industrial site environment is more complex, strong electromagnetic interference, which puts forward higher requirements of stability for soft starter control system. Based on the high-performance DSP OR PLC OR PLC28335 control system which can process the various signals of the start-up process quickly, it can quickly calculate the appropriate trigger angle by detecting the voltage and current of the motor starting process, so as to ensure the fast and smooth start of the motor [7].

2.1 Introduction of control core DSP OR PLC OR PLC28335

TMS320F28335 digital signal processor is TI's new 32-bit, clocked at 150 MHz microcontrollers. The new DSP OR PLC OR PLC adds floating-point unit (FPU) and controllable DMA function, making data processing and transmission more flexible and faster. Up to 18 PWM and 6 high-precision HRPWM, which make DSP OR PLC OR PLC having more advantages in the field of motor controller. At the same time, DSP OR PLC OR PLC28335 ADC internal benchmark accuracy is higher and the sampling error is smaller [8]. The sampled data can be used directly for the control loop, which can use high-speed ADC function to directly sample current and calculate the current rms.

2.2 Analysis of Soft Start Soft Stop

The asynchronous motor soft starter control system takes the three-phase anti parallel thyristor as the main circuit. The control system based on DSP OR PLC OR PLC is used to detect the voltage and current signals of the motor starting process in real time, and the zero crossing point of the voltage synchronous signal is used as the trigger angle. A variety of functions such as soft start, soft stop, detection and protection functions, including discrete frequency conversion can be implemented by software algorithms [9]. The soft starter system block diagram is shown in figure 1.
2.3 The key circuit design of part soft starter

An effective working system is formed by the circuit of the soft starter and any circuit of the missing will affect the overall function of the control system to play. Limited to space, this article only introduces some of the key circuit.

2.3.1 Current detection circuit based on A/D high speed sampling

In AC current detection, the Holzer sensor is used to isolate the signals, and then the voltage signals are reduced by a certain proportion of the sampling resistance. The Hall sensor power supply needs positive and negative power supply, which is not conducive to the use of this. A current detection circuit based on DSP OR PLC OR PLC high speed A/D sampling is designed. First, the AC voltage rms is defined as equation (1).

$$U_{\text{rms}} = \sqrt{\frac{1}{T} \int_0^T u^2(t) dt}$$

In equation (1), $T$ is the period of the AC signal and $u(t)$ is the instantaneous value of the AC voltage. $u(1), u(2), u(3) \ldots u(N)$ are obtained by sampling the voltage $u(t)$ at equal intervals according to Nyquist using the theorem. The $N$ instantaneous values sampled in a voltage cycle are used instead of the continuously changing function values. Suppose the sampling angle is $\sigma$, $\sigma = T / N$, for the $i$-th sampling value is expressed as:

$$U_i = \sqrt{2U_{\text{rms}}} \sin(i-1)\sigma.
$$

Let the arithmetic mean of the square sum of the $N$-th sample value is $U$, then $U$ is the equation (2).

$$U^2 = \frac{1}{N} \sum_{i=1}^{N} U_i^2 = \frac{U_{\text{rms}}^2}{N} \left[ N - \frac{\sin N\sigma \cos(N-1)\sigma}{\sin \sigma} \right]$$

When $N > 2$, $\sin N\sigma = 0$, and $\sin \sigma \neq 0$. So there is $U = U_{\text{rms}}$, that is, type (3).

$$U_{\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} U_i^2}$$

As can be seen from equation (3), when the sampling frequency is high enough, the error is small. Using the DSP OR PLC OR PLC28335 up to 80ns A/D conversion speed uninterrupted acquisition.
current value, and in the motor discrete frequency switching to change the cycle time value, which can achieve the effective value of the current calculation. Current detection hardware circuit is relatively simple to control the system zero potential as a benchmark. Current through the transformer after the sampling resistor obtained by the alternating voltage signal from the DSP OR PLC OR PLC A / D port can be directly sampled.

2.3.2 Three-phase voltage synchronization signal
The power supply sync signal is the basis for calculating the triggering angle of the thyristor and that is also the source of the soft starter system timing. Three-phase voltage synchronization signal detection circuit is shown in figure 2, by the voltage divider directly from the power grid to get equal to the proportion of reduced AC voltage signal. It is easy to compare the comparator using the regulator D55 to float the AC signal as a whole 5 V. At the same time, the voltage of the grid is collected from the A/D port of VAL-A, VAL-B and VAL-C, and used for detecting and protecting the soft starter of DSP or PLC.

![Figure 2. Three-phase voltage synchronization signal detection circuit](image)

2.4 Control system anti-jamming design
Soft starter is mainly used in industrial environments, subject to more interference in the environment, especially high-power equipment, electromagnetic interference is serious. And the consequences of electromagnetic interference are that the system is unstable, or simply cannot work. System anti-jamming design is generally divided into hardware anti-jamming and software anti-jamming. The method of absorbing interference on the hardware is generally by adding filters to the vicinity of the device or critical signals, coupling the capacitor [10]. The software can be offset by the elimination of specific interference, but for unforeseen interference is mainly manifested as software protection, when an error occurs through the software watchdog or custom protection program in time to block the trigger pulse or reset control system.

3. Discrete frequency conversion principle and its realization

3.1 The principle of discrete frequency conversion
Discrete frequency conversion is achieved by selectively turning on and off several positive half or negative half waves on the sinusoidal grid to obtain a new variable frequency power supply. Since the grid period is 50 Hz, the resulting discrete frequency can only be 50/n Hz, where the division order n =
1, 2, 3 ... is an integer, and the discrete frequency conversion 7 frequency voltage conduction waveform.

In theory, it can achieve \( n = 1, 2, 3 \ldots \) integer frequency based on the fixed 40Hz frequency conversion, but some frequency cannot be stable operation, and even make the motor reverse electromagnetic torque. Because the stability of the magnetic field is the formation of three-phase voltage difference between the two-phase motor 120°, for the discrete frequency is also applicable, there are formula (4) and formula (5).

\[
\frac{2\pi}{3} = \frac{2\pi + 2k\pi}{\nu} 
\]

\[
\nu = \frac{3k}{2} + 1
\]

Therefore, the positive sequence voltage can be obtained when frequency coefficient \( \nu = 1, 4, 7 \ldots \), and the performance is positive electromagnetic torque. Similarly, the negative sequence voltage can be obtained when \( \nu = 2, 5, 8 \ldots \) resulting in reverse electromagnetic torque; the frequency is asymmetrical voltage when \( \nu = 3, 6, \) and \( 9 \ldots \), with positive and negative electromagnetic torque.

### 3.2 Discrete control of the realization of frequency

From the previous analysis, the discrete frequency in the positive sequence voltage can be obtained under the positive electromagnetic torque. This topic uses the 7-4-3 frequency to achieve the soft-start and switching of the discrete frequency conversion, and in the frequency of the power grid when the slope to increase the slope to reduce the torque fluctuations, and ultimately complete the motor to start [11]. Based on the 7-frequency, we can obtain discrete frequency conversion 4-frequency three-phase voltage conduction waveform, according to the symmetrical component method.

Figure 3 is a discrete frequency conversion 3-way voltage conduction waveform. In figure 3, 3 frequencies is asymmetrical voltage, but the 3 frequency of the third harmonic is just 50 Hz and cancel each other, so the positive electromagnetic torque, load capacity is strong.

![Figure 3. Discrete frequency conversions by 3-way voltage conduction waveform](image-url)
Discrete frequency conversion from 7 to start after the need to switch to the next level of frequency, the frequency of switching between: a cycle after the operation of the switch; b cycle to select the appropriate time to switch. Taking into account the discrete frequency of the 3 frequency as asymmetric frequency, the text selected in the frequency of the entire cycle after the end of the operation to switch. 3 frequency, that is, 16.7Hz, if the direct control by the v/f switch to the power frequency 50 Hz, then because of the sudden increase in voltage and frequency, resulting in a sudden increase in the current, torque changes over time, leading to motor failure easily. Therefore, when the 3 frequency division switches to the power frequency, the voltage is lowered appropriately, and then started by the ramp boost.

4. Design of discrete frequency conversion software
The design of discrete frequency conversion hardware circuit based on DSP OR PLC OR PLC is completed, based on the design of discrete frequency soft start program. According to the principle of discrete frequency conversion, which can achieve the frequency conversion on the basis of adjusting the size of the trigger angle $\alpha$ can keep the main motor flux can be basically constant, so as to avoid excessive torque ripple. The principle of programming is shown in figure 4.

![Figure 4. Principles of discrete frequency programming.](image)

Discrete frequency conversion is used for soft starting of motor. It has short working time and is usually operated with open loop. First of all, the system self-test, after testing correctly, set the discrete frequency conversion, starting voltage and series. Each frequency is only running within the corresponding time. When the operation is completed, it will automatically switch to the next level of discrete frequency and change the trigger angle to keep the main flux of the motor constant. After the 3-way operation is completed, the system will automatically switch to the power frequency ramp to complete the start of the motor.

5. Simulation and test results analysis
A three phase induction motor based on matlab/simulink is designed by using a 15 kW three-phase induction motor. The motor starts from the 7th frequency start, when the motor reaches a stable switch to 4 frequency operation, according to U/f control law to increase the appropriate voltage. Similarly, 4-way operation is stable to switch to 3-way frequency. When the 3 frequency conversion cloud is stabilized, it switches directly to the power frequency, in order to reduce the impact current, reduce the voltage properly, and then press the ramp to complete the start of the asynchronous motor. The discrete variable frequency soft starting and direct starting simulation are shown in figure 5.
Figure 5. The discrete variable frequency soft starting

In figure 6, the discrete frequency conversion 7 frequency operation time is 0 to 0.56 s, the 4 frequency division running time is 0.56 to 0.96 s, the 3 frequency division running time is 0.96 to 1.2 s, and the ramp boost running time is 1.2 to 1.5 s. It can be seen that the starting current is small and the initial speed of the motor is smoother. The frequency switching process has no obvious current impact, and the motor accelerates well when the ramp is raised. Compared to the direct start of the asynchronous motor has significantly reduced the starting speed is more smooth.

Figure 6. The discrete frequency conversion 7 frequency operation time

Using the 15kW asynchronous motor in the pulp mill, the soft variable test of discrete frequency conversion is completed. The motor is effectively reduced in the process of discrete frequency conversion because the cycle becomes longer and the current rms is small, and the process is accelerated at the frequency of 7 and the frequency is switched to 4. When the 4 frequency division is switched to the 3 frequency division, the same speed is obvious, but considering the asymmetry of the 3 frequency divider, the operation time is shorter. After 3 frequency division, switch to the power frequency 50 Hz ramp to boost the motor starting process. It can be seen that the maximum current in the whole process occurs in the ramp boost stage, and the discrete frequency conversion can effectively reduce the starting current.

6. Conclusion

Based on the high performance DSP OR PLC OR PLC28335, this paper designs a soft starter with discrete frequency conversion function, using DSP OR PLC OR PLC's high speed A/D real-time acquisition current and calculates the effective value. At the same time, voltage detection is realized when synchronous signals are detected, thus saving development cost. By analyzing the principle of discrete frequency conversion, a 7-4-3 frequency ramp-up method is proposed. By using the discrete frequency after switching the whole period, the frequency of bumpless switching is realized, which reduces the current impact. Finally, through the simulation and testing in the pulp mill, it is verified that the designed discrete soft starter can effectively reduce the starting current of the motor at the same load rate.
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