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A Kind of Discrete Variable Frequency Heavy-Load Soft Start System

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Abstract

A kind of discrete variable frequency heavy-load soft start system was designed in order to realize heavy-load soft starting of motor. It consisted of variable reactance converter, discrete variable frequency converter and controller. The system structure was described in detail and the principle of discrete variable frequency heavy-load soft starting was analyzed. Also the model of the system was made and simulation of the system was done. The simulation results proved that the system can not only start motor smoothly, but also increase the motor start torque greatly, thus heavy load soft-starting of motor can be realized perfectly. In addition, the experiment of the system was done. The experiment results proved that the simulation was correct and the designed discrete variable frequency heavy-load soft start system can realize heavy-load soft start of motor.

Keywords: *heavy load, discrete variable frequency, soft start*

1. Introduction

AC motor needs to be soft-started to lessen the current impact, voltage drop and damage, as well as save energy and reduce cost. There are many soft start ways for wound rotor motors such as Y/△ start, autoformer reduced-voltage starting, stator resistance starting, series-connected thyristor voltage-drop starting [1-3]. These soft start methods are aimed to start motor softly by reducing start voltage of motor . However, motor starting torque could reduce sharply when stator voltage reduced [4, 5]. Therefore, for it could not provide big enough starting torque, reducing-voltage soft start method could not be fit for heavy load start and could be fit for no-load start and light-load start.

In this paper, a kind of discrete variable frequency heavy-load soft start system was proposed. It consisted of variable reactance converter, discrete variable frequency converter and controller. It used the special structure of variable reactance converter and controlled the high voltage circuit with low voltage circuit. By controlling current in the low voltage circuit, the current in the high voltage circuit can be controlled. Reducing stator current frequency of motor in the high voltage circuit, the start torque can be raised and start current can be dropped, and then heavy load soft start of high-voltage motor can be realized.

2. Proposed Approach

2.1. Structure Design of Discrete Variable Frequency Heavy-load Soft Start System

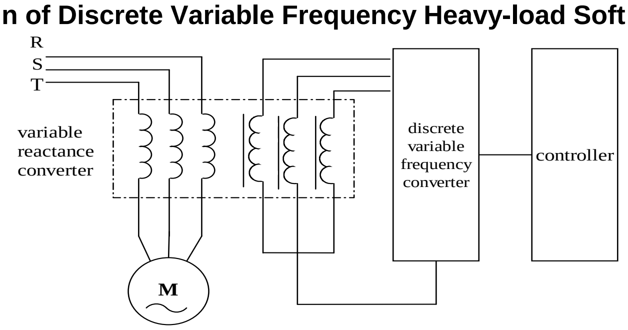

Figure 1. The Structure Diagram of the Discrete Variable Frequency Heavy-load Soft Start System

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The structure diagram of discrete variable frequency heavy-load soft start system is shown in Figure 1. The system mainly consists of variable reactance converter, discrete variable frequency converter and controller [6-8].

The principle of variable reactance converter was described in the reference [9] in detail. Controller consists of stator current detect circuit, control circuit, and drive circuit. Control circuit adopts microchip 80C196KC. Discrete variable frequency converter is mainly made up of three pairs of reverse parallel thyristor. RC series circuits are connected with thyristors in parallel in order to protect the thyristors through the cache function of capacitance C. Discrete variable frequency converter structure is shown in Figure 2 as follows:

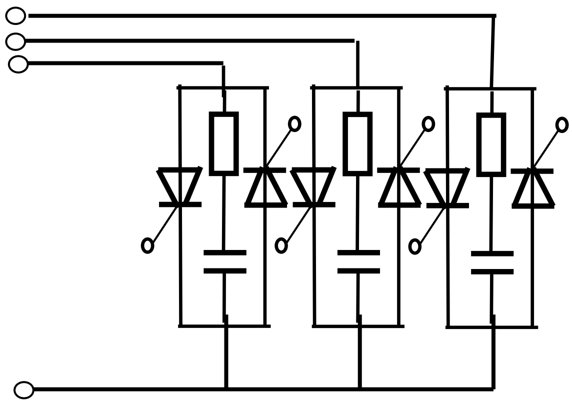


Figure 2. The Structure Diagram of Discrete Variable Frequency Converter

2.2. Principle of the System

When motor starts, stator start current I_{st} and start torque T_{st} can be expressed into expression (1) and expression (2) respectively [10, 11].

$$I_{st} = \frac{U_1}{\sqrt{(r_1 + r_2')^2 + (x_{1\sigma} + x_{2\sigma}')^2}} \tag{1}$$

$$T_{st} = \frac{m_1 p}{2\pi f_1} \frac{U_1^2 r_2'}{(r_1 + r_2')^2 + (x_{1\sigma} + x_{2\sigma}')^2} \tag{2}$$

In expression (1) and expression (2), stator resistance is r_1、stator winding leakage impedance is $x_{1\sigma}$、equivalent rotor resistance after converting is r_2'、rotor winding equivalent leakage impedance after converting is $x_{2\sigma}'$、the frequency of stator current or voltage is f_1、the phase number of stator winding is m_1、number of pole-pairs is p、stator voltage is U_1.

According to the expression (1), it can be seen that stator start current is proportional to stator start voltage. As stator voltage decreases, the stator start current decreases. Meanwhile, according to the expression (2), stator start torque is proportional to the square of the stator voltage and is inversely proportional to the frequency of stator current or stator voltage. When stator voltage decreases, stator start torque decreases sharply, which may lead to motor not being started. But if reducing the frequency of the stator current (or voltage) to 1/k (k is a natural number) of the power frequency, the start torque can increase by k times compared with directly voltage-reduced starting, thus the start torque can be enhanced greatly.

Controller controls the triggering time and triggering angle of thyristors in the discrete variable frequency converter which connected in series with secondary side of variable reactance converter in order to change trigger frequency of thyristors. The trigger frequency can be increased step by step from 1/k of the power frequency to the power frequency. Thus the frequency and amplitude of current in the secondary side of the variable reactance converter can be changed. Consequently, the frequency and amplitude of current in the primary side of the variable reactance converter can also be changed accordingly due to the electromagnetic induction. Once the current frequency of stator reduced, the start torque of the motor would be raised and discrete variable frequency soft start with heavy load can be realized.

Take 4-division frequency for example, trigger the thyristors in the time of the shaded part of the following Figure 3. That is to say, trigger the thyristors in the period of the first positive half-wave, the second positive half-wave, the third negative half-wave, and the fourth negative half-wave, current (or voltage) whose frequency is 12.5Hz can be formed, which called 4-division frequency current (voltage). The principle of other division frequency is similar to the 4-division frequency. The schematic diagram of 4-division frequency is shown in Figure 3 as follows.

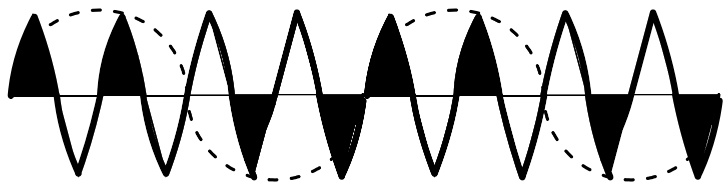


Figure 3. The Schematic Diagram of 4-division Frequency

The power frequency can be divided into different levels of frequency whose frequency value is 1/k of the power frequency value. The relationship between the power frequency value ω and these different levels of frequency value ω_s can be expressed into expression (3) as follows (k is a natural number).

$$\omega = \omega_s * k \tag{3}$$

Assuming that initial A-phase phase angle of the power frequency is zero, phase angles of B phase and C phase are $\omega t = \frac{2}{3}\pi + 2n\pi$ and $\omega t = \frac{4}{3}\pi + 2n\pi$ (n is integer). So if initial A-phase phase angle of k-division frequency is assumed as zero, phase angles of B phase and C phase are $\omega_s t = \frac{\frac{2}{3}\pi + 2n\pi}{k}$ and $\omega_s t = \frac{\frac{4}{3}\pi + 2n\pi}{k}$ respectively.

Appropriate initial phase angle combination must be choosed to maximize positive phase-sequence current of division frequency. As a result, positive maximum torque could be created. If k is equal to (1+3n), that is to say, k is equal is 1, 4, 7, 10, 13, 16……., division frequency current is three-phase symmetric positive sequence current, and positive sequence component is maximum value. And its initial phase angle of three phase are 0°, 120° and 240°. If k is equal to (1+3n)/2, that is to say, k is equal is 2, 5, 8, 11, 14, 17……., division frequency current is three-phase symmetric negative sequence current. If k is equal to 3, 6, 9, 12, 15, 18……., division frequency current is three-phase asymmetric phase sequence current. For three-phase asymmetric phase sequence current and three-phase symmetric negative sequence current, initial phase angle must be combined to maximize positive phase-sequence component.

Table 1. Three Phase Optimal Initial Phase Angle Combination of Different Levels of Frequency

K	**Phase sequence**	***f(HZ)***	**Group1**	**Group2**	**Group3**
2	negative sequence	25	(0°,60°,210°)	(0°,150°,210°)	(0°,240°,120°)
4	positive sequence	12.5	(0°,120°,240°)	\	\
7	positive sequence	7.14	(0°,120°,240°)	\	\
13	positive sequence	3.85	(0°,120°,240°)	\	\

According to corresponding theory [12-16], three phase optimal initial phase angle combination of different levels of frequency is shown in Table 1 as follows.

As controller changed frequency, frequency was often required to be proportional to voltage, namely, the ratio between frequency and voltage was often required to be a constant. Considering the compensation of voltage, trigger angles of the thyristors corresponding to each corresponding level division frequency can be deduced as shown in Table 2 as follows.

Table 2. Trigger Angles of the Thyristors Corresponding to each Corresponding Level Division Frequency

f1(HZ)	25	12.5	7.14	**5**
U1(V)	110	60	40	30
Trigger angle	75°	90°	96°	100°

3. Simulation and Analysis

Using Power System Blockset in Matlab/Simulink, the discrete variable frequency system can be simulated. The simulation model of discrete variable frequency system is shown in Figure 4 [17]. The motor's rated power is 11kW, stator rated voltage is 380V, stator rated current is 16A, and frequency is 50Hz. The motor's pole pairs is 2. Variable reactance converter's rated power is 10kW. Its primary winding's phase voltage is 220V, resistance R is 0.002Ω, and reactance X=0.01H. Its secondary winding's phase voltage is 55V, and resistance R is 0.00051Ω, reactance X=0.002H. The simulation algorithm is ode23tb. The simulation model of discrete variable frequency system is shown in Figure 4 as follows.

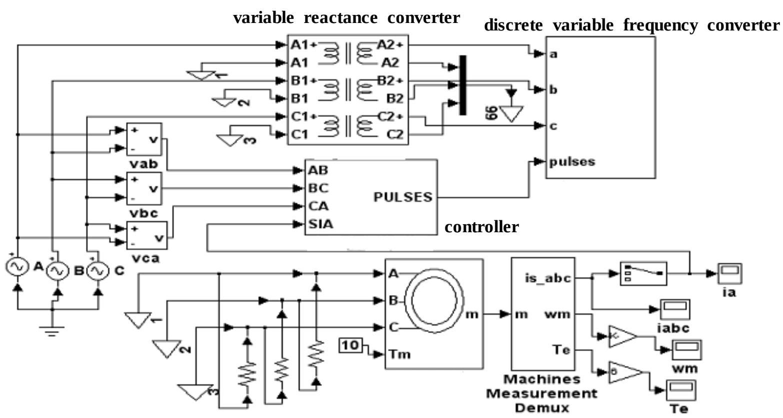
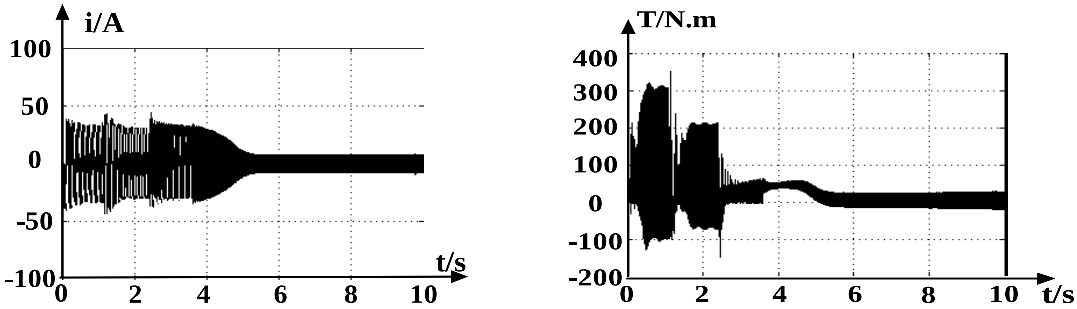


Figure 4. Simulation Model of Discrete Variable Frequency System

According to the simulation model of discrete variable frequency system, using hierarchical start mode like 1/7f⇨1/4f⇨1/2f⇨f (f is power frequency), discrete variable frequency current wave and start torque wave are shown in Figure 5. While drop-voltage soft start torque wave is shown in Figure 6.

As shown in Figure 5, start frequency varies from 1/7f (f is power frequency) to 1/4f , then from 1/4f to 1/2f, then from 1/2f to f. Start current maximum value is about 2 times the rated current. Compared Figure 5 and Figure 6, it can be seen that start torque of discrete variable frequency system is nearly 3 times bigger than that of drop-voltage soft start system. Therefore, a conclusion can be drawn that discrete variable frequency start system can realize soft start and has so large start torque that it can carry heavy load.



(a) Simulation wave of current (b) Simulation wave of start torque

Figure 5. Simulation Wave of (a) discrete variable frequency current and (b) start torque

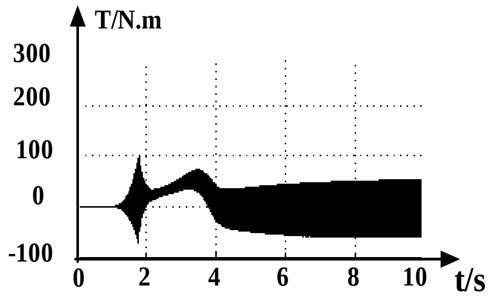
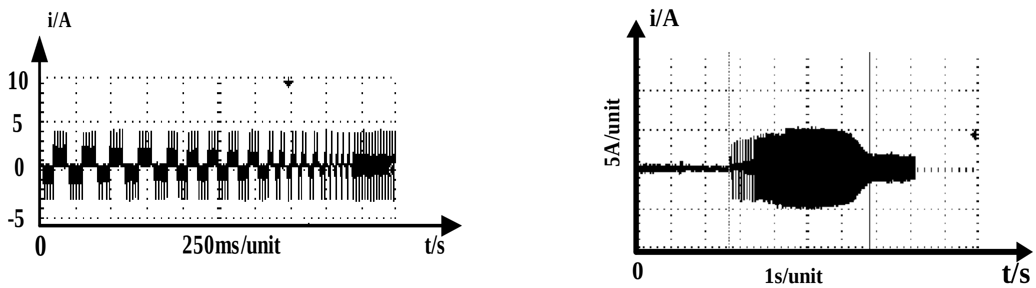


Figure 6. Simulation Wave of Drop-voltage Soft Start Torque

4. Experiment

Discrete variable frequency start system experiment was done based on the simulation of the system above. The start motor is Y90S-4 asynchronous motor whose rated power was 1.1 KW, stator rated voltage was 380V and stator rated current was 2.7A. Synchronous speed was 1500r/min. The rated start torque was 7N.M. Variable reactance converter's rated power was 11kW. Start mode adopted 5 levels start. The 5 levels were 1/10f, 1/7f, 1/4f, 1/2f and f. Start current wave of discrete variable frequency start system is shown in Figure 7.



(a) 5 levels start current wave (b) discrete variable frequency soft start current wave

Figure 7. Start current wave of discrete variable frequency start system

Figure 7(a) shows 5 levels start current clearly. The current frequency varies from 1/10f to 1/7f, then from 1/7f to 1/4f, then from 1/4f to 1/2f, finally from 1/2f to the power frequency f. From Figure 7(b), it can be seen that start current is about 2.5 times the rated current.

Load was magnetic powder brake. The magnetic powder brake's maximum exciting current was 1.0A and its rated torque was 100N.M. The magnetic powder brake' torque was nearly proportional to the exciting current. Hence, controlling the brake's exciting current can control the load torque. The relationship between torque and exciting current is shown in Figure 8.

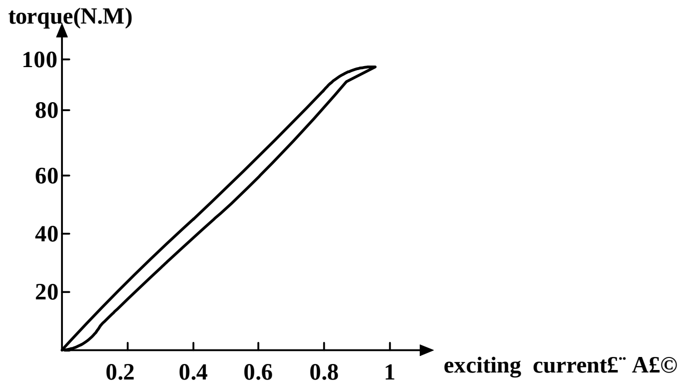


Figure 8. The Relationship between Torque and Exciting Current

Assuming that the magnetic powder brake's exciting current is $\dot{I}_a$、motor stator current is $\dot{I}_s$、motor run current is $\dot{I}_r$. Measuring data of current is shown in Table 3.

Table 3. Measuring Data of Current

i_a (A)	i_s (A)	i_r (A)
0(No load)	6.3→2.04	2.04
0.1	7.0→2.65	2.65

According to Figure 7, it can be seen that when exciting current as 0.1, the load torque was about 7N.M, almost reaching motor rated torque. That is to say, the motor started with heavy load. According to the Table 3, the start current varied from 7.0A to 2.65A, its maximum value was merely about 2.6 times the rated current. This discrete variable frequency start system can start motor softly with heavy load.

5. Conclusion

A discrete variable frequency start system was studied. It can realize discrete variable frequency soft start with heavy load. It controlled the stator start current by controlling the discrete variable frequency converter. By controlling the triggering time and triggering angle of thyristors in discrete variable frequency converter connected in series with the secondary side of variable reactance converter, the power frequency can be divided into different levels of frequency. Thus the frequency and amplitude of current in the primary side of the variable reactance converter can be changed, and the start torque of the motor would be raised. So, the discrete variable frequency start system can start motor softly with heavy load. In addition, the system could be more safety because it controlled motor in high voltage circuit by controlling discrete variable frequency converter in low voltage circuit.

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