Model and Study on Cascade Control System Based on IGBT Chopping Control

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Abstract. Thyristor cascade control system has a wide range of applications in the industrial field, but the traditional cascade control system has some shortcomings, such as a low power factor, serious harmonic pollution. In this paper, not only analyzing its system structure and working principle, but also discussing the two main factors affecting the power factor. Chopping-control cascade control system, adopted a new power switching device IGBT, which could overcome traditional cascade control system’s two main drawbacks efficiently. The basic principle of this cascade control system is discussed in this paper and the model of speed control system is built by using MATLAB/Simulink software. Finally, the simulation results of the system shows that the system works efficiently. This system is worthy to be spread widely in engineering application.

1. Introduction

At present, China in such as power, petrochemical, mining, metallurgy and water supply and drainage and other industrial fields, high-pressure high-power fans and pumps and other motors are important production machinery, which generally uses a common thyristor cascade speed control. In this type of speed regulation system is not high cost, the winding asynchronous motor cascade speed control system compared to the most widely used, high dynamic performance, precision speed control frequency control, which is a more excellent speed control device. If the cascade speed control method, the inverter power for the full power of $\frac{1}{2} \sim \frac{1}{3}$ or so; using of frequency control, the inverter power at least full power. When the speed control system used in high-voltage large-capacity motor, cascade speed control system, because the rotor side of the low-pressure control, relative to the stator side of the high-voltage frequency control system, the inverter is much cheaper than the frequency converter used in the frequency control system, which can save a lot of investment; cascade speed control system also has the advantages of safe and reliable, that is, if the inverter device failure can easily exit the speed control device and switch to the rotor side short State running at full speed. But the ordinary cascade speed control system there is a big drawback, that is, the system power factor is low, harmonic current. High-speed full load operation of its total power factor of only about 0.6, low-speed operation of its total power factor is even lower. In the context of energy saving and emission reduction, the implementation of "green power system", improve the power factor of power electronic devices, reduce the system of harmonic pollution will become more and more meaningful. Therefore, it is necessary to find a way to
improve the power factor of cascade speed control system, reduce the harmonic pollution to the power grid and improve its efficiency.

Based on the above facts, this paper uses IGBT (Insulated-gate Bipolar Transistor) to do the system chopper, as the composition of the internal feedback cascade speed control system as the research object, the use of simulation software, in the MATLAB/Simulink environment, the SimPowerSystem toolbox is used to simulate and test the system, the simulation results show that it overcomes the shortcomings of the ordinary cascade speed control system and improves the running efficiency of the system.

2. Analysis of ordinary cascade speed control system

At present, thyristor cascade speed control system is widely used at home and abroad. Engineering access frequency and amplitude of the variable AC electromotive force is more difficult, so the general use of the introduction of an additional DC electromotive force to the DC circuit to deal with. In Fig. 1, M is a winding type asynchronous motor whose stator is connected to the AC power grid and the rotor side of the rotor power is rectified by the uncontrolled rectifier Ua to output the DC voltage Ud.Ui is active in the active state of the three-phase controllable rectifier device, which has two roles: First, as a rectifier device output motor speed required amplitude adjustable DC voltage Ui; Second, as the inverter device to Ud inverter AC frequency with the alternating frequency of AC power fed back to the grid, thereby improving the efficiency of the system. L is the rotor loop reactance, which maintains the cascade speed system in the minimum operating current current continuous; followed by reducing the current ripple, t and the additional loss caused by the pulsating component in the DC link in the motor rotor is controlled within the allowable range. T is the inverter transformer, it has two roles, the first is the isolation from the isolation of controllable power electronic devices and AC power grid to suppress the surge from the power grid on the thyristor impact; the second is as a transformer acquisition and exchange Grid matches the inverter voltage. Id is the rotor DC loop current.

As shown in Figure 1, available rotor DC circuit voltage balance equation:

\[ U_d = U_i + I_d R \]  (1)

\[ K_1 S E_{r0} = K_2 U_{T2} \cos \beta \]  (2)

\[ T_v = C_M \Phi M I_2 \cos \psi_2 \]  (3)

Where: \( K_1, K_2, U_R, U_i \) is the voltage rectification factor of the two rectifier devices; \( U_{T2} \) - transformer secondary phase voltage; \( U_i \) - inverter DC side voltage; \( R \) - rotor DC circuit total resistance; \( C_M \) - torque constant; \( \Phi M \) - flux; \( \beta \) - inverter Ui inverter angle; \( \cos \psi_2 \) - rotor power factor.
The speed control process of the system is as follows: Set the asynchronous motor with constant torque load at a certain speed stable operation, by controlling the inverter inverter angle $\beta$, change the motor speed. When the change in the angle $\beta$ increases, the inverter voltage $U_d$ decreases, but the motor by the mechanical inertia of the role of rotation speed will not immediately change, so $U_d$ remains the same. According to the above formula (1), the rotor DC circuit current $I_d$ will increase, the electromagnetic torque $T_e$ will increase, and the load torque does not change, then the motor speed will increase. During the acceleration of the induction motor, the amplitude of the rotor rectified voltage $U_d$ is gradually reduced and the rotor current $I_d$ is reduced until the new equilibrium state is reached again according to the formula (1) between $U_d$ and $I_d$. At last, the motor enters a new steady state at a higher speed at this time. On the contrary, to reduce the size of the inverter angle $\beta$, the asynchronous motor will run down. This is the winding asynchronous motor thyristor cascade speed control system speed control principle. Thus, in the cascade speed control system is by adjusting the size of the inverter angle $\beta$ to change the speed of asynchronous motor. Inverter angle $\beta$ can be smooth to adjust the size, so the speed of asynchronous motor can also achieve smooth continuous adjustment.

The low total power factor is the main drawback of the thyristor cascade speed control system. The main reasons can be summarized as the following two aspects. First: the absorption of reactive power increased. Three-phase thyristor active inverter device UI and AC power grating, the need to absorb a large number of reactive current from the grid; at the same time asynchronous motor work also need to absorb reactive current from the AC power grid, so the cascade speed control system than the inherent characteristics of asynchronous motor from the power grid to increase the reactive power. Second, the absorbed active power is reduced. The cascade speed regulation system feeds most of the slip power to the grid, reducing the active power absorbed by the system from the grid. Therefore, the above is caused by cascade speed control system to reduce the total power factor of the main reasons. In addition, cascade speed control system, the rotor rectifier circuit commutation overlap phenomenon and the rotor current distortion, will also reduce the total power factor of the system.

3. Analysis of cascade speed control system with chopping control

3.1. The composition of the speed control system
AC speed control system shown in Figure 2, in the ordinary thyristor cascade speed control system DC circuit, joined the high-frequency DC chopper IGBT. The active inverter UI always operates at the minimum inverter angle state, which minimizes the reactive power absorbed by the inverter from the grid, thereby increasing the system's power factor. The inverter angle is generally taken as 30° [5]. The reactor $L_1$ acts as a filter, it can inhibit the rotor current pulsation component, effectively reduce the stator current harmonics. Diode $D$ from the isolation, capacitance $C$ and diode $D$ together constitute a buffer network, capacitor $C$ for the buffer energy. Chopper, isolation diode $D$ and buffer capacitor $C$ constitute the three components of step-up chopper circuit [4]. When the IGBT is turned off, the DC circuit charges the capacitor $C$ to store energy; When the IGBT is closed, the capacitor $C$ supplies power to the active inverter UI. The effect of the reactor $L_2$ is to maintain the continuity of the power electronics UI current.

![Figure 2](image-url) Chopper control of the internal feedback cascade speed control system schematic
3.2. Chopper control of the speed control principle

The basic principle of cascade speed control system is in the rotor side of the DC circuit in the string into a variable amplitude of the additional DC electromotive force, by changing its size, you can change the rotor current $I_r$ size, in order to change the electromagnetic torque $T_e$. So that the power of the original system to stabilize the operating conditions $T_e = T_L$ is destroyed, in order to achieve asynchronous motor speed.

$$I_r = \frac{E_r \pm E_{add}}{\sqrt{R_r^2 + (sX_{r0})^2}}$$  \hspace{1cm} (4)

$$E_r = sE_{r0}$$  \hspace{1cm} (5)

Where: $R_r$-rotor winding resistance; $X_r$-rotor winding leakage reactance; $E_r$-rotor induced electromotive force; $s$- slip; $E_{r0}$-rotor open electromotive force.

From the formula (3) we can see that the motor’s electromagnetic torque is proportional to the rotor current. And then by the electric drive system motion equation

$$T_e - T_L = \frac{G\beta^2}{375} \frac{dn}{dt}$$  \hspace{1cm} (6)

Set the asynchronous motor with constant torque load stable operation at a certain speed, when the additional DC electromotive force is in the reverse direction, if the $E_{add}$ amplitude increases, the rotor current $I_r$ decreases and the electromagnetic torque $T_e$ decreases, and the motor load are stable at this time, so the load torque $T_L$ does not change. From the formula (6) we can see that the speed $n$ will decrease, and the speed $n$ decreases, the slip rate $s$ increases, the rotor induced electromotive force $E_r$ increases, the rotor current $I_r$ increases, the electromagnetic torque $T_e$ also picks up, with the moment $T_e$ and the load torque $T_L$ are again in equilibrium, the deceleration process is completed and the motor is operated at this new speed, thus achieving the purpose of speed regulation. The greater the amplitude of the reverse electromotive forces in the rotor DC loop, the greater the adjustable speed range of the motor.

![Figure 3. Chopper current Id waveform](image)

Cascade speed system core problem is how to obtain additional electromotive force, due to the project to obtain amplitude and frequency adjustable AC electromotive force is not convenient, so the use of the rotor DC circuit in the series variable amplitude of the DC additional electromotive force to achieve the purpose of system speed. As shown in Figure 2 cascade control device, the rotor side of the phase voltage rectifier bridge device rectifier DC voltage $U_d$, three-phase full-bridge active inverter always work in the minimum inverter angle $\beta_{min}$, to provide a constant reverse DC electromotive force $E_{add}$. 


Rotor DC circuit to join the high-frequency power electronic switching devices IGBT, by changing the chopper duty cycle, you can achieve the system speed. As shown in Fig. 3, the working period of the IGBT chopper is $T$, the IGBT is in the closed state at time $\tau$, the rectifier bridge $U_R$ is short-circuited; in the ($T-\tau$) time, and the IGBT is in the off state.

The following analysis of DC circuit equation:

$$U_d = 2.34 s E_{r0}$$

(7)

Inverter output voltage:

$$U_i = 2.34 U_{r2} \cos \beta_{min}$$

(8)

The output voltage of the chopper IGBT is:

$$U_b = \frac{T - \tau}{T} U_i$$

(9)

When the speed control system in the ideal no-load conditions, $U_d = U_b$, the rectifier bridge output voltage should be balanced with the chopper output voltage, there are:

$$U_d = \frac{T - \tau}{T} U_i$$

(10)

And then by the slip rate formula:

$$s = \frac{n_0 - n}{n_0}$$

(11)

And so,

$$s = \frac{T - \tau}{T} \cdot \frac{U_{r2}}{E_{r0}} \cos \beta_{min}$$

(12)

$$n = n_0 \left[ 1 - \left(1 - \frac{\tau}{T}\right) \cdot \frac{U_{r2}}{E_{r0}} \cos \beta_{min} \right]$$

(13)

Among them: $U_{r2}$ - Active inverter AC side line voltage, $n_0$ - Synchronous speed.

From (13), it can be seen that changing the turn-on time of the power electronic device IGBT, that is, changing the duty ratio, can change the speed of the asynchronous motor. When $\tau = T$, that is, IGBT in the whole cycle has been in the conduction state, then the asynchronous motor rotor short circuit, the motor to achieve synchronous speed no-load running. When $\tau = 0$, that is, the IGBT in the entire cycle has been in the off state, the system is equivalent to ordinary thyristor speed control system, the motor at this time the minimum speed:
\[ n = n_0 \left( 1 - \frac{U_{T2}}{E_{r0}} \cos \beta_{\text{min}} \right) \] (14)

Which can be IGBT chopper feedback cascade speed control system speed regulation law: the greater the duty cycle, that is, the longer the chopper IGBT conduction time, the higher the speed of asynchronous motor; the other hand, the duty The smaller the speed, the lower the speed of the asynchronous motor. At the same time, the system speed range is wide enough and speed control performance is more accurate, the system total power factor has been greatly improved.

4. System MATLAB simulation

Winding asynchronous motor chopper cascade speed control system main circuit mainly by the three-phase AC power grid, controllable three-phase full-controlled bridge active inverter, three-phase bridge uncontrollable rectifier, winding asynchronous motor, Inverter transformer, filter reactor, high-frequency chopper IGBT, diode and capacitor components. In order to obtain better speed accuracy and excellent dynamic performance, the speed control system uses the current closed loop and closed loop closed loop structure, constitute two feedback loops, so that the system can be more accurate speed. In accordance with chopper control speed control system of the main circuit schematic diagram to build Figure 2 shows the simulation model. In the simulation model, the thyristor three-phase full-bridge active inverter consists of a six-pulse generator to provide the drive signal to the thyristor. The package subsystem of the six-pulse generator is shown in Figure 1.

The simulation of IGBT chopping control cascade speed control system is carried out, and the system is simulated by SimPowerSystem toolbox in MATLAB / Simulink environment. The system parameters are set as follows: three-phase alternating current=220V; the rated power of the induction motor \( P_n = 40\text{kVA} \); Line voltage \( V_n = 380\text{V} \); Frequency \( f_n = 50\text{Hz} \); Stator resistance \( R_s = 0.096\Omega \); Stator inductance \( L_s = 0.86\text{mH} \); Rotor resistance \( R_r = 0.058\Omega \); Rotor inductance \( L_r = 0.86\text{mH} \); Mutual inductance \( L_m = 0.31\text{H} \); The number of pole pairs of the motor is \( p = 2 \). In order to improve the simulation speed, insert the powergui (power graphics user interface) module, set the work in discrete simulation mode, the simulation sampling period is set to \( T = 1 \times 10^{-6}\text{s} \). The simulation algorithm uses ode23tb.

![Figure 4. Schematic diagram of the subsystem of the six-pulse generator](image-url)
Figure 5. MATLAB simulation of chopping control cascade speed control system

The following simulation waveforms are obtained. Figure 6 for the current dynamic curve, Figure 7 for the speed dynamic curve.

Figure 6. Dynamic curve of rotor current

Figure 7. Dynamic curve of speed

Figure 8. Inverter transformer voltages after the exchange voltage
The simulation results of the speed control system are as follows: \( n = 157.03 \text{r/min} \); \( f = 50 \text{Hz} \); inverter transformer voltage feedback to the grid line voltage=380V.

Simulation results show that the speed control process is smooth and fast, with the increase of duty cycle, the speed of the speed control system from a speed balance to a higher speed of the new stable speed, that is, the greater the duty cycle, the greater the speed; the lower the duty cycle, the lower the speed. At the same time the system's dynamic performance is excellent, the response speed is faster, the overshoot amount is small, and the system can reach the stable speed operation quickly.

5. Conclusion
Using IGBT to do high-frequency chopper cascade speed control system can be smooth to achieve the increase and decrease the speed, the voltage waveform is good sinusoidal, harmonic content is small. Chopping control cascade speed control system by changing the IGBT turn-on time to change the slip power control mode, effectively improve the ordinary thyristor cascade speed control system exists low power factor, high harmonic content defects, while the rotor side of the power inverter feedback to the grid effectively improve the efficiency of the system, saving energy. For high pressure and high power fan and pump speed control system, the superiority of the system is shown, which provides theoretical basis and experimental simulation for engineering application.

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