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THE SIMULATION OF VVVF CHARACTERISTICS WITH SCALAR CONTROL

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ABSTRACT

The three-phase AC asynchronous motor has complex dynamic and static characteristics. Consequently, effective control of the rotational speed and flux linkage experiences a troubling scenario. Numerous control strategies have been reported in the literature and the v/f control method is among easily realizable control methods with fewer controller parameters. In this paper, analysis of the constant voltage- frequency ratio control method of induction motor is presented based on the steady-state equivalent model. Furthermore, the performance of open-loop and closed-loop v/f control of induction machine is presented considering different operational conditions. A MATLAB/Simulink environment is adopted to model the system.

KEYWORDS: Constant voltage frequency ratio control, induction motor, variable voltage variable frequency speed regulation.

I. INTRODUCTION

The synchronous rotation speed of a three-phase AC asynchronous electric motor depends on the frequency of the rest of the paper is organized as follows. Section II introduces the model of induction motor, while the scalar control methods are discussed in section III. The constant v/f control is validated through simulation results in section IV. Finally, a concluding remark is given in section V.

II. The Model Of The Induction Motor

Induction motor is also called asynchronous motors. The steady-state mathematical model of asynchronous motor includes the steady-state equivalent circuit and mechanical characteristics. The steady-state equivalent circuit describes the steady-state electrical performance of the motor at a certain slip rate, while the mechanical performance characterizes the steady-state relationship between torque and speed.

According to the principles of electrical engineering, underthe condition of sinusoidal voltage power supply, ignoring iron loss, saturating, and ignoring space and time harmonics, the steady-state equivalent circuit of a three-phase asynchronous motor is: power supply and its number of pole-pairs. The change in supply frequency will result in change of the rotation speed. Hence, we often control the speed of asynchronous motor by controlling its supply frequency. An important factor that needsto be considered while adjusting the asynchronous motor speedis keeping the magnetic flux of each pole in the asynchronous motor constant to ascertain effective utilization of the iron core. To small magnetic flux will result in a negative impact on the resultant output torque, while too high magnetic flux resulted in iron core saturation that renders an overly large excitation current (may damage the whole system). The flux is generated by the combination of the stator and rotor electromagnetic forces in an AC asynchronous motor, and it takes some troubleto keep the flux constant.

The constant voltage-frequency ratio control method is widely adopted for variable speed variable frequency drive of induction machine. Conventionally, the constant voltage frequency ratio control can effectively keep the flux constant, but it is insufficient for the torque control. Consequently, load capacity of the system is poor and the response speed is slow. It has to be understood that conventional v/f speed regulation is simple and practical. Besides, it can still be applied or system that did not require a high controller performance such as fans.

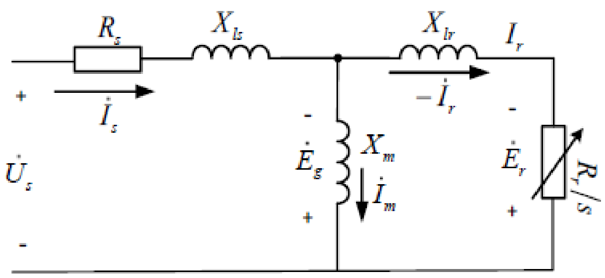

Fig. 1: The equivalent circuit of three-phase asynchronous motor.

Where $\dot{U}_S$ is the phase voltage of the power supply;I_S is stator current of the motor;I_r is the rotor current calculated to the stator side;$\dot{E}_g$ is the induced electromotive force of the air gap magnetic flux;$\dot{E}_r$ is the induced electromotive force of the full magnetic flux of the rotor calculated to the stator side in the rotor winding, s is the slip, R_S 、 X_{lS} is the stator winding resistance and leakage reactance respectively, R_r 、 X_{lr} is the rotor resistance and leakage reactance calculated to the stator side respectively, and X_m is the excitation (mutual) reactance.

Pem is the electromagnetic power transmitted to the rotor through the air gap, the expression is as follows and water pumps.

$$P_e = mE_g I_r \cos\varphi_r \qquad (1)$$

Where $\cos\varphi r$ is the power factor of the rotor; m is the number of stator phases of the motor. Relationship between electromagnetic torque Te and electromagnetic power Pecan be depicted as

$$T_e = \frac{P_e}{\omega_s} = \frac{mn_p}{2\pi f_s} E_g I_r \cos\varphi_r \qquad (2)$$

Furthermore, the rotor current can be expressed using theinduced electromagnetic force as:

$$T_e = C_M \Phi_m I_r \cos\varphi_r \qquad (3)$$

Where np is the number of pole pairs;ω_s is the synchronous angular speed. On the other hand, the lectromagnetic torque Hence, a new Terepresentation using E_r and $f_s$is obtained. Te could also be expressed as:

Where$C$M= $(mnpCE)/2\pi$ is the torque constant.

$$T_e = \frac{mn_p}{2\pi f_s} I_r^2 R_r / s \qquad (4)$$

Since the electromagnetic power can be expressed as:P_e = mI^2R $/s$, the electromagnetic torque can also be represented

$$I_r = \frac{U_s}{\sqrt{(R_s + \frac{R_r}{s})^2 + (X_{ls} + X_{lr})^2}} \qquad (5)$$

Hence, substituting (5) in (4) yields:

$$T_e = \frac{mn_p}{2\pi}\left(\frac{U_s}{f_s}\right)^2 \frac{sf_s R_r}{(sR_s + R_r)^2 + s^2(X_{ls} + X_{lr})^2} \quad (6)$$

2. Torque equation expressed by E_g、f_s

The rotor current I_r can be expressed by using the air gap electromagnetic force as:

$$I_r = \frac{E_g}{\sqrt{(R_r/s)^2 + X_{lr}^2}} \quad (7)$$

Similarly, substituting (7) in (4) yields:

$$T_e = \frac{mn_p}{2\pi}\left(\frac{E_g}{f_s}\right)^2 \left[\frac{f_{sl} R_r}{R_r^2 + (2\pi f_{sl} L_{lr})^2}\right] \quad (8)$$

3. Torque equation expressed by E_r、f_s

$$I_r = \frac{E_r}{R_r/s} \quad (9)$$

Hence, a new $T_e$representation using E_r and $f_s$is obtained.

$$T_e = \frac{mn_p}{2\pi}\left(\frac{E_r}{f_s}\right)^2 \frac{sf_s}{R_r} = \frac{mn_p}{2\pi}\left(\frac{E_r}{f_s}\right)^2 \frac{f_{sl}}{R_r} \quad (10)$$

III. The Control of The Induction Motor

The speed of the induction motor is related to thefrequency of the power supply, the slip rate, and the number of pole pairs of the motor. The best way to adjust the speed of the AC motor is to change the frequency of the power supply. When the speed of AC induction motor varies, the magnetic flux Φmis supposed to maintain constant, so that the core can work in the most economical state. The synchronous speed of the asynchronous motor is determined by the frequency of the power supply and the number of pole pairs. In other words, when the power frequency changes, the synchronous speed of the motor will change as well. Only when the ratio between the voltage of the control power and the change of the frequency is constant (V/f constant)that the constant characteristic of the motor flux Φmcould be substantially guaranteed. The inducedelectromotive force of motor in the stator could be expressed as:

$$E_g = 4.44 f_s N_s k_{N_s} \Phi_m \quad (11)$$

1. Torque equation expressed using U_S、f_S

The rotor current I_r can be expressed as :(neglecting the magnetizing current) work in the most economical state. The synchronous speed of the asynchronous motor is determined by the frequency of the power supply and the number of pole pairs. In other words, when the power frequency changes, the synchronous speed of the motor will change as well. Only when the ratio between the voltage of the control power and the change of the frequency is constant (V/f constant) that the constant characteristic of the motor flux Φm could be substantially guaranteed. The induced electromotive force of motor in the stator could be expressed as:

$$\frac{E_g}{f_s} = C_E \Phi_m \qquad (12)$$

Hence, substituting (5) in (4) yields

According to the requirements of the design of the frequency conversion system and load, the different control.

2. Torque equation expressed by E_g、f_S

The rotor current I_r can be expressed by using the air gap electromagnetic force as: modes of the torque can be obtained from the values of E_g, Φm, I_r and U_S /f_S. The scalar control of induction motor mainly includes voltage-frequency coordinated control and constant power control. Among them, sections A, B, and C in the following are voltage-frequency coordinated control, and section D is constant power control.

A. Constant Air Gap Flux Control

Equation (11) can be rearranged as Similarly, substituting (7) in (4) yields Considering (12) and (8), it can be seen that the electromagnetic torque is proportional to the square of the air Torque equation expressed by E_r、f_S gap magnetic flux. Therefore, if we keep the E_g/f_S constant, then the air gap flux remains constant. This leads the control of the torque $T_e$is with the slip frequency of the rotor (f_{sl}). In addition, the maximum torque (T_{em}) can be kept constant regardless of the supply frequency (f_S). The torque speed characteristic of the motor is shown in Fig. 2.

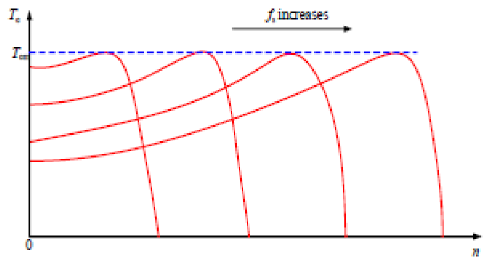

Fig.2 Characteristic of constant air gapfiux control

Fig. 2: Characteristic of constant air gapfiux control.

B. Constant Volts/Hz Control

In actual circuits, it is not easy to control E_g directly. In general, the voltage drop caused by the leakage resistance of the stator winding is negligible compared with the terminal voltage of the motor. Therefore, U_S and E_g can be considered to be approximately equal. Hence, (13) can be considered instead of (12).

$$\frac{U_s}{f_s} = const \qquad (13)$$

In the condition of a constant rotor flux, the torque is a linear function of the slip frequencyf_{sl}, as shown by curve 'c'ofFig.4. It can be easily observed that there is no maximum torque, which allows achieving a good steady-state performance. In addition, in the Fig.4, curve 'a' and curve 'b' are the torque-slip characteristics of constant volts/hz control and constant air gap flux control respectively.

$$E_r = 4.44 f_s N_s k_{Ns} \Phi_r \qquad (14)$$

This is the constant voltage/frequency control. We can keep the flux Φm unchanged by maintaining the ratio of the U_S/f_S constant.

$$T_e \propto f_{sl} \propto s \qquad (15)$$

This control method uses the inverter to maintain a constant voltage/frequency ratio. Although this method is easier to implement, it is not suitable for low frequency applications. In low-frequency, this method is affected by the stator resistance drop and cannot maintain the air gap flux constant. The best solution for such a problem is increasing the output voltage of the inverter, compensating the stator resistance drop. The characteristics of the constant voltage/frequency control are shown in Fig. 3, where the characteristic without compensated control characteristic is curve ‘a’, and the characteristic with stator voltage drop compensation is curve ‘b’.

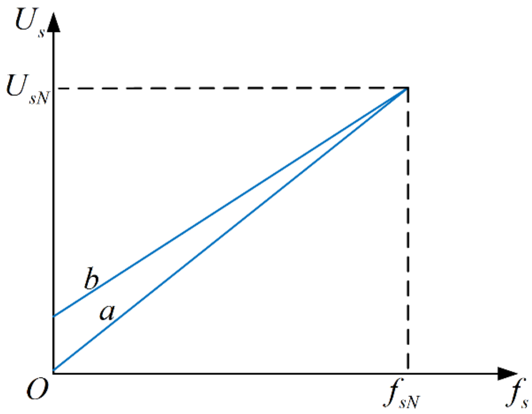

Fig. 3: The characteristics of the constant voltage/frequency control.

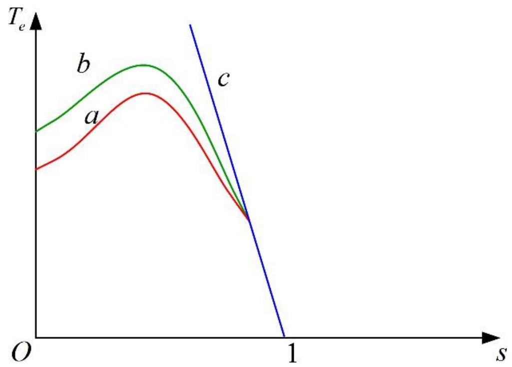

Fig. 4: Torque-slip frequency curve in different conditions.

D. Constant Power Control Design with Field-Weakening

In the aforementioned three control methods, an increasein speed of the motor will result in an increase of the stator voltage. Eventually, at the right edge of the constant torque region, the stator voltage reaches its full or rated value, which is restricted by the rated voltage of inverter or motor. Hence, beyond he rated speed of the motor extra control method must be introduced.

In constant flux operation, as the frequency and speed increase, the voltage U_S also increases accordingly, and the output power of the motor increases. However, the increase in voltage will be limited by the motor power or the maximum voltage of the inverter. Generally, when the frequency is higher than the reference frequency ($f_S > f_{Sl}$), the voltage will remain unchanged after increasing to a certain value, or it will no longer be proportional to the increase of f_S. After that, the motor will perform voltage and frequency control under the condition of constant electromagnetic power.

$$T_e f_s \approx \frac{mnP}{2\pi R_r} U_s^2 \frac{f_{sl}}{f_s} \qquad (16)$$

In higher speed region, the stator resistor voltage can be neglected ($E_g \approx U_S$), therefore equation (10) can be approximated as:

$$P_{out} \propto T_e f_s \propto U_s^{\,2} \frac{f_{sl}}{f_s} = const \qquad (17)$$

From (2), it is easy to observe that the output power $Pout$ is proportional to $Tefs$. Therefore, in order to keep the motor output power constant, traditionally, there are two control methods.

$$P_{out} \propto T_e f_s \propto \frac{U_s^{\,2}}{f_s} f_{sl} = const \qquad (18)$$

1. At any frequency (f_S), keep U_S unchanged while f_{Sl} and f_S are changing proportionally. In this regard, the output power $Pout$ can be formulated as (17), ensuring a constant power operation.

In order to verify the static and dynamic performance of the AC asynchronous motor control system, the system is started at no-load. When it's in the steady-state the speed of asynchronous motor is changed from 1430rpm to 1000rpm at 2s, the electromagnetic torque of 10N*m is added to the motor through the step signal at 3s. The simulation results are shown in Fig.6, 7 and 8, which show the waveforms of stator current, rotor speed, and electromagnetic torque, respectively.

A. The simulation of open-loop constant voltage-frequency control

Simulation model of the three-phase AC asynchronous motor control system is established using Matlab/Simulink. The simulation test of open-loop constant voltage-frequency ratio control system test is conducted. The control block diagram of the open-loop constant voltage-frequency ratio is shown in Fig. 5. The method involves controlling the motor speed from the angular speed ωs. The voltage Us is obtained through the constant voltage-frequency ratio characteristic curve. SVPWM is then applied for pulse generation. This way, we enforce the motor to follow the reference speed. The major challenge of this approach is that the controller doesn't know its performance, and there is no adjustment mechanism depending on the actual motor speed.

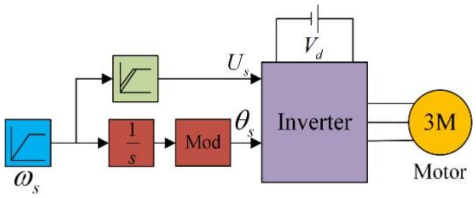

Fig.7: The waveform of rotor speed.

Table 1: Simulation parameters.

Parameters	Value	Parameters	Value
*U*n	400V	*n*N	1430r/min
*P*n	4kW	*f*N	50Hz
Lm	0.1722H	*np*	2
Ls	0.005839H	*Udc*	500V
Lr	0.005839H	*J*	0.0131kg·m2
Rs	1.395Ω	*Ts*	0.001s
*R*r	1.405Ω		

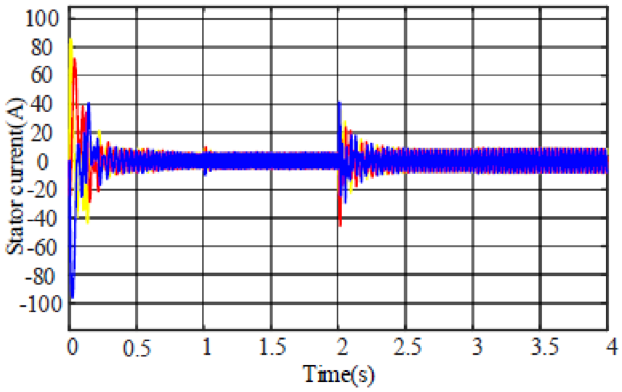

Fig. 6: Stator three-phase current.

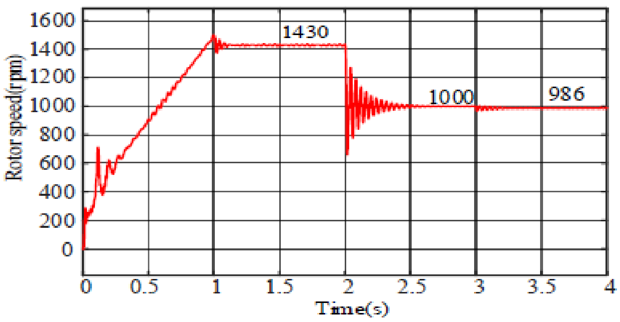

Fig.7: The waveform of rotor speed.

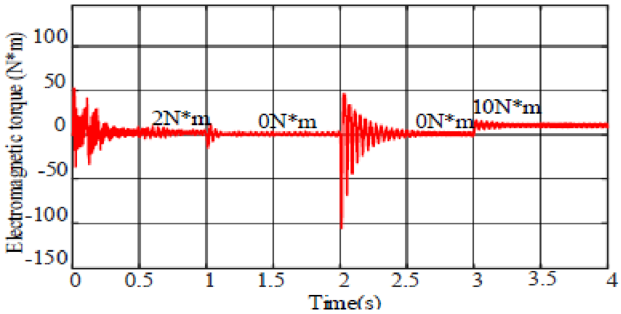

Fig. 8: The waveform of Electromagnetic torque.

It can be seen from the simulation results that at the beginning of the simulation, the oscillation of the torqueoccurred and resulting in the oscillation of speed, due to large starting current. Then the electromagnetic torque is stable at 2N*m, and at this time, the rotor speed rises linearly. Then theelectromagnetic torque is quickly stabilized at 0 N.m and at 2.4s, the rotor speed is stabilized at the expected value of 1000rpm.At 3s, when the motor is loaded, the electromagnetic torque is stabilized at 10 N*m, the rotor speed is changed from 1000rpm to 986rpm, which indicates that the load performance of the control method is not good. This is due to the open-loop control characteristic, where the controller does not have knowledge of the speed tracking performance upon external disturbance.

B. The simulation of closed-loop constant voltage-frequencyratio

The Constant Volts/Hz Control is the most common scalar method for the speed control of induction motor drives. Since the magnitude of flux is proportional to the ratio between the magnitude and frequency of stator voltage, if this ratio ismaintained constant, the stator flux will remain constant and so the motor torque will only depend on the slip frequency. The block diagram for the closed loop speed control by constant V/f method is shown in Fig. 9.

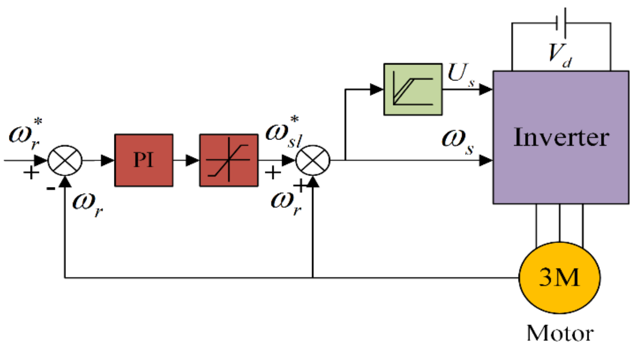

Fig. 9: Control block diagram of closed-loop constant voltage-frequency ratio.

The closed loop speed controlled drive employs inner slip speed loop with a slip limiter and outer speed loop. The error inspeed is processed through a PI controller and a slip regulator.

The PI controller is used to get good steady-state accuracy and to attenuate noise. The slip regulator sets the slip speed command ωsr, whose maximum value is limited to limit the inverter current to a permissible value. The synchronous speed, obtained by adding the actual speed ωr, and slip speed ωsr, determines the frequency of the inverter output. The frequency command f_d also generates the voltage command through a Volts/Hz function generator. The voltage command V_d is then fed to the three phase voltage source inverter. Finally, the modulation signal of the three-phase voltage source inverter is generated to control the speed of the motor. The simulation parameters of asynchronous motor are shown in the table 1.

To verify the dynamic and static performance of the control method a variable condition closed loop control test is conducted. Fig. 10 shows the ramp frequency tracking at a rated load, and it can be easily observed that the low speed region experiences a certain chattering. This normally is expected due to resistance drop. The steady-state performance of the closed-loop control strategy is effective. Fig. 11 shows the performance of the closed-loop control system for variable load condition. Unlike the open-loop control system, the closed-loop control ensures efficient speed tracking during external load change. Furthermore, a step reference speed change performance under rated load condition is shown in Fig.12.

Generally, the closed loop v/f control for asynchronous motor can improve the low speed performance required. It can be seen from the simulation results that the dynamic and static performance of this control method is good, and this control method is reasonable and effective.

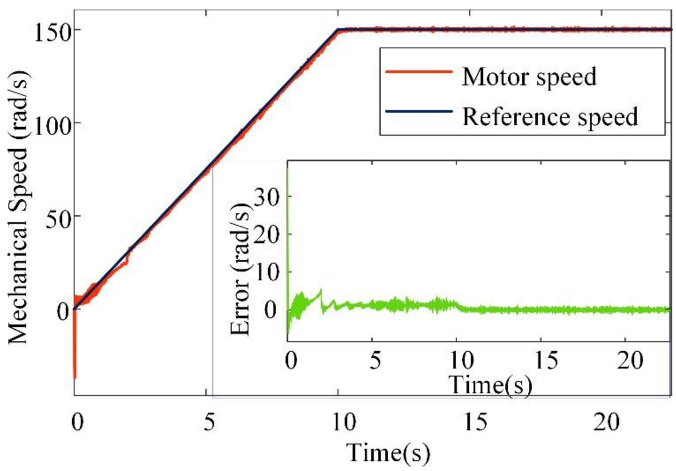

Fig. 10: Ramp frequency performance at rated load.

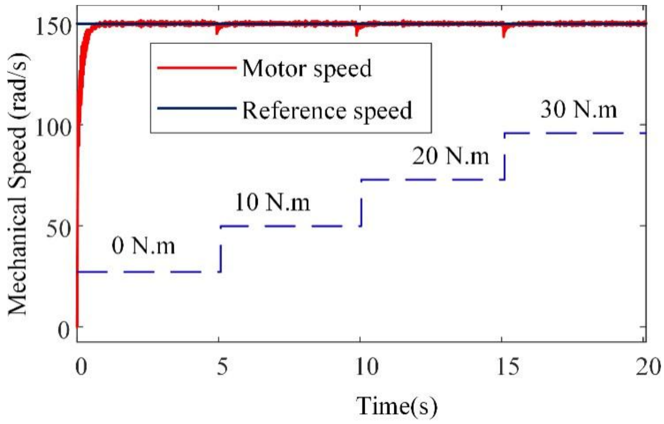

Fig. 11: Load change at rated speed.

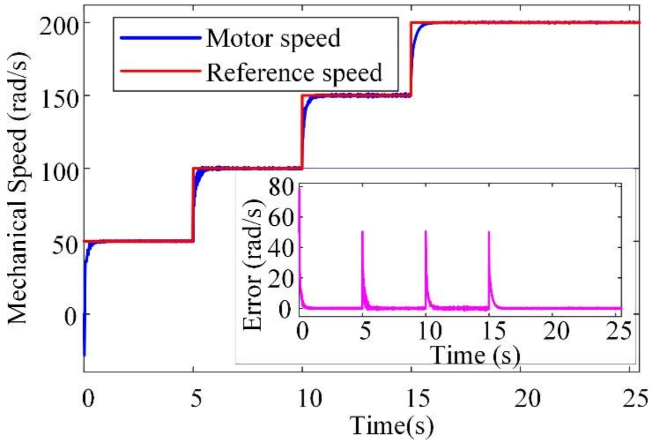

Fig. 12: Performance for step reference speed.

IV. CONCLUSION

Scalar control is a cheap and well-implementable method. The performance of the controller, however, is slow and limited. This paper briefly analyzes several scalar control methods of asynchronous motor based on the steady-state model of the AC asynchronous motor. The major scalar control methods include constant flux control, constant voltage- frequency ratio control, constant rotor full flux control, and constant power control. The open-loop and closed-loop constant voltage frequency ratio control methods of three- phase AC asynchronous motor are simulated in MATLAB/Simulink environment. The simulation results show that the waveform confirms the theoretical analysis, the system can run smoothly, and the closed-loop control method has better dynamic performance in comparison to the open-loop control method.

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