Research Article

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Voltage regulation and power-saving method of asynchronous motor based on fuzzy control theory

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Abstract: The load rate of asynchronous motors is low, the operation efficiency is low, and the waste of electric energy is very serious. Therefore, a voltage regulation and electricity saving method for asynchronous motors based on fuzzy control theory is proposed. According to the principle of voltage regulation and power saving of asynchronous motor, the stator current and its variation of are selected as input variables, the deviation of current variation is selected as output variable, and a two-dimensional fuzzy control algorithm model is constructed. Fuzzy control theory is used for voltage regulation and power saving of asynchronous motors. The simulation results show that the proposed method is based on fuzzy control theory for voltage regulation and electricity saving of asynchronous motors; after the voltage regulation and electricity saving control, the phase current of the motor is lower, and the active power and reactive power of the motor are reduced. The power factor of the motor is higher, and the power-saving effect is remarkable.

Keywords: fuzzy control theory, asynchronous motor, voltage regulation and power saving, power factor

1 Introduction

Asynchronous motors are widely used in industry, agriculture, transportation, national defense and military, and daily life due to their simple structure, convenient manufacturing, low price, sturdiness and durability, reliable operation, little maintenance and can be used in harsh environments. Most of the current industrial drives are powered by asynchronous motors, including fans, water pumps, oil pumps, and compressors, which consume huge amounts of electricity, especially in the petrochemical industry. More than 80% of the total power consumption. These asynchronous motors are generally selected according to the design to meet high load operation, but in actual use, most of them often run under light load or even under no load. Therefore, the phenomenon of "big horse-drawn carts" is almost common. For example, belt conveyors, scrapers, draw works, compressors, machine tools, and other equipment commonly used in coal mines have large changes in motor load during most of the operating time, and the ratio of average output power to maximum output power is generally 0.3–0.4, and some are even lower, the load rate of the motor is low, the efficiency is not high, and the waste of electric energy is very serious [1–3]. According to statistics, a single improvement of the asynchronous motor production process can save only 3.3% of the annual energy consumption of the motor. The power-saving transformation of the asynchronous motor drive system can save 88 billion kW·h per year, which allows the motor to reduce energy consumption by 15.5%. This electric energy is equivalent to the power supply capacity of 12.1 million kW power stations, and the corresponding annual CO_2 emission can be reduced by 5.62 million tons. Therefore, it is imperative to control the voltage and power saving of asynchronous motors [4,5].

At present, although there are many voltage-regulating and power-saving control strategies for asynchronous motors, there are still many problems. For example, the most suitable application occasions are ambiguous, their power-saving space and power-saving effects cannot be verified, and node control requires relation. The investment cost of the installation equipment has not been considered in conjunction with the actual situation. In particular, there are still few research studies on the voltage regulation and power saving of asynchronous motors, and asynchronous motors are an important part of the industrial scale, representing an important direction of the development of motor technology. With the increase in

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industrial production of large-scale motor manufacturing and as it develops toward higher power, asynchronous motors have become the prime mover that consumes the most power in a single machine for industrial equipment. Therefore, it is of great significance to study the voltage regulation and power saving of asynchronous motors. Literature [6] proposed a dynamic balance-voltage regulation comprehensive power-saving control method suitable for periodic potential energy load motor systems. First, the balance real-time dynamic adjustment method is used to reduce the peak power of the system, and on this basis, to meet the maximum load demand of the system as a limit Conditions, minimum energy consumption is the goal, the system efficiency is improved through multi-stage voltage regulation and power-saving methods, and the corresponding prototype is developed based on the proposed power-saving method, and the experimental verification is carried out on the 37 kW standard well experimental platform of the oil field. The results show that the proposed comprehensive and the power-saving control method has an average power-saving effect of more than 10% under different operating conditions, which has well verified its versatility and practicability. Literature [7] proposed a step-down and power-saving technology for asynchronous motors based on linear active disturbance rejection control (LADRC). First, the light-load operation of the motor and the principle of voltage regulation and power saving was analyzed; the optimal voltage value under different load rates was derived. Principle and then the design of a linear active disturbance rejection controller were obtained. When the load changes, the voltage-regulating circuit is used to change the motor input voltage so that it can track the optimal voltage to save power. Finally, through simulation analysis, the results show that the linear active disturbance rejection controller is better than the traditional. The proportional integral derivative control has a better tracking effect and response speed. However, after the above two methods of voltage regulation and power-saving control, the phase current of the motor is higher, which increases the active power and reactive power of the motor, and the power factor of the motor is lower, resulting in insignificant power-saving effect.

In view of the problems of the above methods, this article proposes a method for voltage regulation and power saving of asynchronous motors based on fuzzy control theory. The effectiveness of this method is verified using simulation experiments, which solve the problems of traditional methods and lay a foundation for my country's industrial production motor manufacturing industry.

2 A method of voltage regulation and power saving of asynchronous motor based on fuzzy control theory

In order to realize voltage regulation and power saving of asynchronous motor, the fuzzy control theory is first analyzed, and the stator current and its change of asynchronous motor are selected as input variables, and the deviation of current change is selected as output variable, and a two-dimensional fuzzy control algorithm model is established. The fuzzy control theory is used to regulate the voltage of the asynchronous motor and save power.

2.1 Fuzzy control theory

Fuzzy control belongs to intelligent control. It is an automatic control method that is summarized by expert experience, describes control strategy with control language, and uses a computer to realize it [8]. In 1965, Professor Zadeh from the United States combined multi-valued logic with classical sets and used numbers or functions to express fuzzy concepts. He established the fuzzy set theory for the first time and pioneered the study of fuzzy control. Fuzzy control converts knowledge or theories in life into mathematical functions, so that machines can recognize, process, and use. Fuzzy control is not established using a mathematical model of the control system, but through "fuzzy rules" converted from expert experience since it was established, it has been widely used in industrial control and other industries [9–11]. The value of fuzzy control is mainly reflected in two aspects:

1) Fuzzy control proposes a new mechanism to realize the control law based on knowledge (rule) and even semantic description.
2) Fuzzy control proposes an easier design method for nonlinear controllers, especially when the controlled device (object or process) contains uncertainties and is difficult to deal with by conventional linear control theory, fuzzy control is more effective. A typical fuzzy control system is shown in Figure 1, including input interface (A/D), fuzzy controller, output interface (D/A), actuator, controlled object, and detection device (sensor). The biggest difference in the control system is that the fuzzy controller replaces the traditional controller.

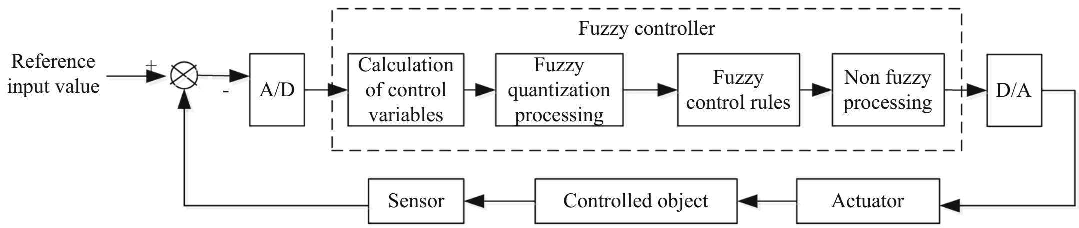

Figure 1: Block diagram of the fuzzy control system.

The fuzzy controller is mainly composed of three parts: input fuzzification, fuzzy inference, and output inverse fuzzification. The input to the fuzzy controller is an accurate quantity. It needs to be fuzzified before fuzzy inference can be carried out. The fuzzy quantity obtained after fuzzy inference is a fuzzy quantity. Similarly, it needs to be de-fuzzified to obtain an accurate quantity and to output [12,13].

The voltage regulation and power-saving control of asynchronous motors is a nonlinear control problem. If traditional control methods are used, the mathematical model of the system must be established first, and then, an ideal control model should be designed according to the nonlinear control theory and motor characteristics [14–16]. However, many factors affect the voltage regulation and power saving of asynchronous motors, which causes great inconvenience to the control [17]. The fuzzy control theory is based on the knowledge and experience of experts and does not require precise mathematical models of the controlled system. It is especially suitable for the control of complex systems with the strong coupling of variables, time-varying parameters, and nonlinear models. Therefore, the use of fuzzy control theory in this article can avoid the influence of various non-linear factors and realize the effective voltage regulation and power-saving control of asynchronous motors [18–21].

2.2 Principle of voltage regulation and energy saving of asynchronous motor

Figure 2 is the Γ equivalent circuit of an asynchronous motor, where U is the input voltage; I_1 is the stator current; R_1, X_1 is the resistance and leakage reactance of the stator winding; R_m, X_m is the excitation resistance and leakage reactance; R_2', X_2' is the reduced rotor resistance and leakage reactance; s is the slip ratio; the coefficient D is a complex number with an amplitude approximately equal to 1, and a small complex angle [22–24].

According to Figure 2 of the equivalent circuit, when the input voltage of the asynchronous motor is constant, the active power on resistors R_1 and R_m has nothing to do with the change of the load and is proportional to the square of the voltage. This loss is the constant part of the stator copper loss and iron loss, and its magnitude is as follows:

$$P_u = 3\frac{R_1 + R_m}{(R_1 + R_m)^2 + (X_1 + X_m)^2}U^2. \tag{1}$$

The active power on $C_1^2R_2'$ and $C_1^2R_2'(1-s)/s$ represents the electromagnetic power P_{em} of the asynchronous motor. In order to simplify the calculation, take $C_1 = 1$. According to the torque formula:

$$P_{\mathrm{em}} = T_e\Omega_1 = 3I_2'^2R_2'/s = 3\frac{U^2}{(R_1 + R_2'/s)^2 + (X_1 + X_2')^2}\frac{R_2'}{s}, \tag{2}$$

where T_e is the electromagnetic torque of the motor, and Ω_1 is the synchronous mechanical angular velocity of the motor. According to formula (2), we can obtain:

$$I_2' = \sqrt{\frac{T_e\Omega_1 s}{3R_2'}}, \tag{3}$$

$$T_e = \frac{3U^2sR_2'/\Omega_1}{R_2'^2 + 2sR_1R_2' + s^2[R_1^2 + (X_1 + X_2')^2]}. \tag{4}$$

Since the slip ratio s is very small, the polynomial containing s^2 in formula (4) can be ignored, and the formula for the slip ratio s can be obtained as follows:

$$s \approx \frac{R_2'T_e\Omega_1}{3U^2 - 2R_1T_e\Omega_1}. \tag{5}$$

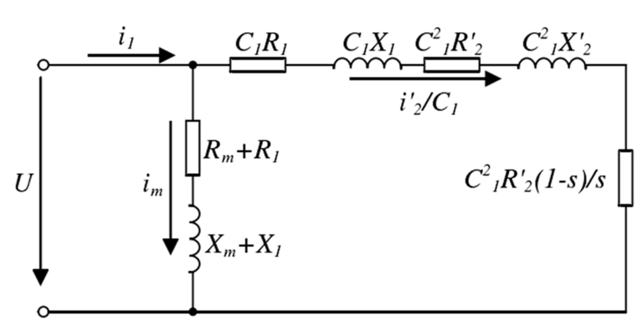

Figure 2: Γ-type equivalent circuit of the asynchronous motor.

The loss on resistance C_1R_1, $C_1^2R'_2$ is the variable loss related to the load change, where the loss on C_1R_1 represents the variable part of the stator copper loss and iron loss related to the load change, and the loss on $C_1^2R_2'$ represents the rotor copper loss [25–27]. According to the above formula, the size of this part of the loss can be obtained as follows:

$$P_V = 3I_2'^2(R_1 + R_2') = \frac{(T_e\Omega_1)^2(R_1 + R_2')}{3U^2 - 2R_1T_e\Omega_1}. \tag{6}$$

Then, the total loss of the asynchronous motor is the sum of the loss on the resistance R_1, R_m that is not related to the load change and the loss on the resistance C_1R_1 and $C_1^2R_2'$ related to the load change; that is, the total loss can be expressed as:

$$\sum P = P_u + P_V. \tag{7}$$

When the load changes periodically, if the speed change is not large, the influence of the speed change can be ignored, and the electromagnetic torque T_e of the motor and the load torque T_L are always equal. Therefore, the total loss can be expressed as:

$$\sum P = 3\frac{R_1 + R_m}{(R_1 + R_m)^2 + (X_1 + X_m)^2}U^2 + \frac{(T_L\Omega_1)^2(R_1 + R_2')}{3U^2 - 2R_1T_L\Omega_1}. \tag{8}$$

According to Eq. (8), if the parameters of the asynchronous motor are unchanged, the total loss is a function of load torque and input voltage, which is:

$$\sum P = f(U, T_L). \tag{9}$$

If you want to make the asynchronous motor under the corresponding load torque, by adjusting the input voltage to minimize the total loss of the motor, the total loss is derived from the input voltage:

$$\mathrm{d}\sum P/\mathrm{d}U = 0. \tag{10}$$

The optimal voltage U' can be found to be:

$$U' = \sqrt{[|T_L|\sqrt{(R_1 + R_2')/g} + 2R_1T_L]\Omega_1/3}, \tag{11}$$

where g is the equivalent conductance of the constant loss branch, and the expression is as follows:

$$g = \frac{R_1 + R_m}{(R_1 + R_m)^2 + (X_1 + X_m)^2}. \tag{12}$$

When the load torque is T_L and the input voltage is U', the total loss of the asynchronous motor is the smallest. At this time, the minimum value of the total loss is expressed as:

$$\sum P_{\min} = 2\,|T_L|\,\Omega_1\sqrt{g(R_1 + R'_2)} + 2gR_1T_L\Omega_1. \tag{13}$$

From the above analysis, it can be seen that if the load torque of the periodically changing load at any time is known, the optimal voltage value U' corresponding to the load at this time can be obtained according to formula (13), so as to minimize the loss of the motor. This is the principle of voltage regulation and power saving of asynchronous motors.

2.3 Asynchronous motor voltage regulation and power-saving control

According to the principle of voltage regulation and power saving of asynchronous motor, this article uses fuzzy control theory to control the voltage and power saving of asynchronous motor. In order to ensure a good voltage regulation and power-saving effect of the asynchronous motor, the stator current I_1 and its change ΔI_E of the asynchronous motor are selected as input variables in the design of the fuzzy control algorithm. The stator current I_1 of the asynchronous motor is [28]:

$$I_1 = \frac{P}{P^N}\sum P_{\min}, \tag{14}$$

where P is the actual output current of the motor; P^N is the rated output current of the motor.

The variation ΔI_E of the stator current of the asynchronous motor is as follows:

$$\Delta I_E = \frac{k(i) - k(i-1)}{I_1k(i)} \times 100\%. \tag{15}$$

The current variation deviation is selected as the output variable, and the output of the fuzzy controller is selected as $\Delta\alpha$, which constitutes a two-dimensional fuzzy control algorithm model as shown in Figure 3.

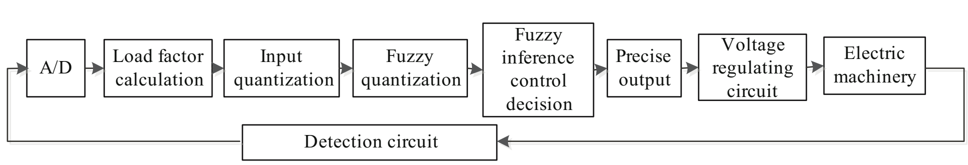

Figure 3: Fuzzy control algorithm model of voltage regulation.

It can be seen from the fuzzy control algorithm model of voltage regulation, without loss of generality, the values of the membership function are positive (PB), positive (PM), positive (PS), zero (ZE), negative (NS), negative (NM), and negative (NB). The stator currents I_1, ΔI_E, and $\Delta\alpha$ of the asynchronous motor are selected, which have 3, 5, and 7 subsets, respectively, and their membership functions are shown in Figure 4.

The current load status of the motor and whether it can run with power saving is determined by I_1. And $\Delta\alpha$ is determined by ΔI_E and ΔI_{EC}, and its membership function is shown in Figure 4(d). Through the relationship between the control quantity and the target quantity, the rule base of $\Delta\alpha$ can be determined, and the corresponding target quantity can be obtained accordingly, as shown in Table 1.

According to motor I_1, judge whether the motor can enter the power-saving operation state. If so, adjust $\Delta\alpha$ according to Table 1. According to the closed-loop quantity, it can track the changes of the system in real time and make timely responses. Once the current change is detected from negative to positive, it means that the input current has reached the minimum value, and α will no longer change at this time, achieving the purpose of saving power [29].

To sum up, the flowchart of the induction motor voltage regulation and power-saving control algorithm is shown in Figure 5.

Table 1: Fuzzy control rule of firing angle increment

ΔI_{EC}	ΔI_E					
	NM	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	PB	PB	PS	PS	PM	PB
NM	PB	PB	PS	PS	PM	PB
NS	PB	PB	PS	PS	PB	PB
ZE	PB	PB	PS	PS	PB	PB
PS	PB	PM	PS	PS	PB	PB
PM	PB	PM	PS	PS	PB	PB
PB	PB	PM	PS	PS	PB	PB

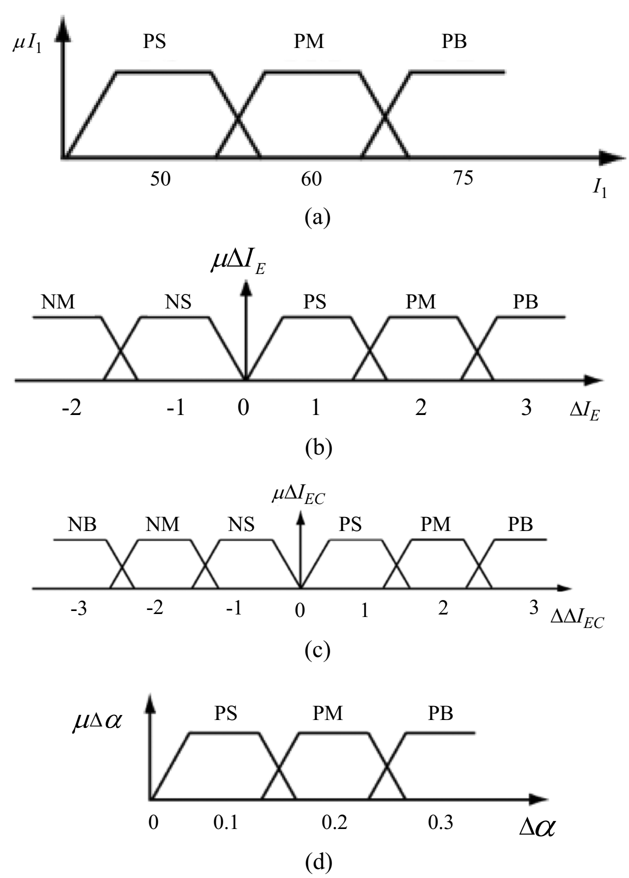

Figure 4: Membership function of fuzzy quantity: (a) the stator current membership function, (b) membership function of stator current variation, (c) membership function of stator current variation deviation, and (d) membership function of thyristor firing angle increment.

3 Simulation experiment analysis

In order to verify the performance of the asynchronous motor voltage-saving and power-saving method proposed in this article based on fuzzy control theory, Matlab simulation software is used to simulate the voltage-saving and power-saving control device with a 0.75 kW small asynchronous motor.

Set the total simulation time to 20 s, set the load to the rated load (6,000 N m) at the beginning, and set the load to 20% of the rated load (1,200 N m) after the 2 s, respectively.

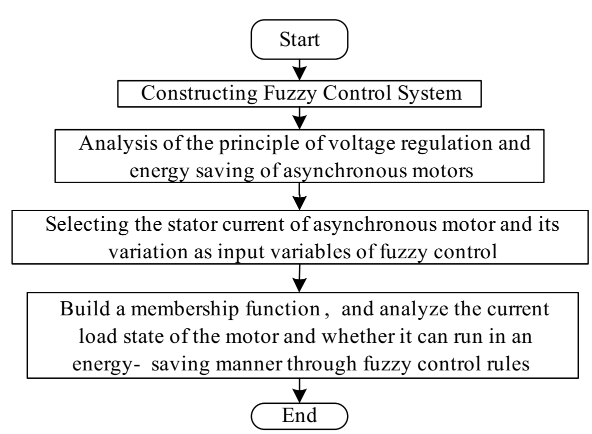

Figure 5: Flowchart of the induction motor voltage regulation and power-saving control algorithm.

Table 2: Comparison of power-saving data

	A phase average current (A)	B phase average current (A)	C phase average current (A)	Average active power (kW)	Average reactive power (kVA)	Average apparent power (kVA)
Before energy-saving control	24.2132	24.0701	23.8661	4.3462	14.909	15.867
After energy-saving control	10.8311	10.5349	10.4132	3.9594	4.0029	6.4117

The motor rotor circuit is short-circuited during the simulation. Under periodic load, compare the data before the motor power-saving control with the data after the power-saving control to observe the power-saving effect. The comparison of power-saving data is shown in Table 2.

From the comparison data, it can be seen that after adopting voltage regulation and power-saving control on the motor, the average phase current is reduced by about 56.25%, the active power is reduced by about 8.9%, and the reactive power is reduced by about 73.15%. The power-saving effect is obvious and is shown in Figure 6.

The experimental results show that through voltage regulation and power-saving control, the phase current of the motor can be significantly reduced, the active power and reactive power of the motor can be reduced, and the power factor of the motor can be improved. For the asynchronous motor under periodic load, adopting the voltage regulation and power-saving control method designed in this article will have great economic and social benefits. The method in this article adjusts the voltage of the asynchronous motor by establishing a two-dimensional fuzzy control algorithm model, and the control accuracy is high, so the phase current of the motor is low, and the power factor of the motor is improved.

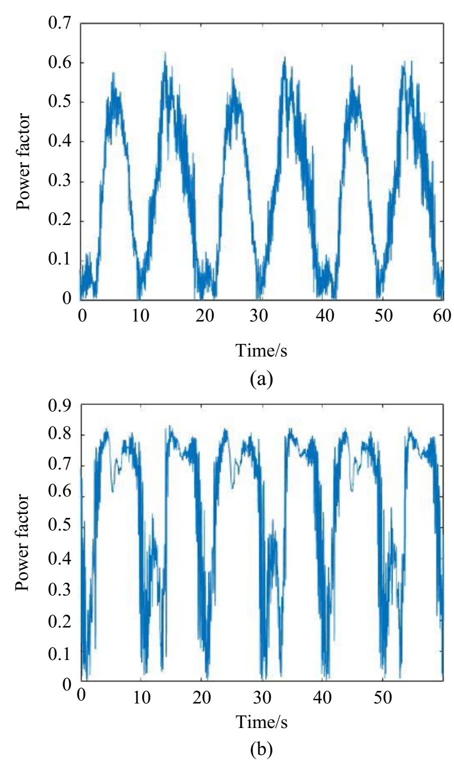

Figure 6: Motor power factor before and after power-saving control: (a) power factor of the motor under periodic load before power-saving control and (b) power factor of the motor under periodic load after power-saving control.

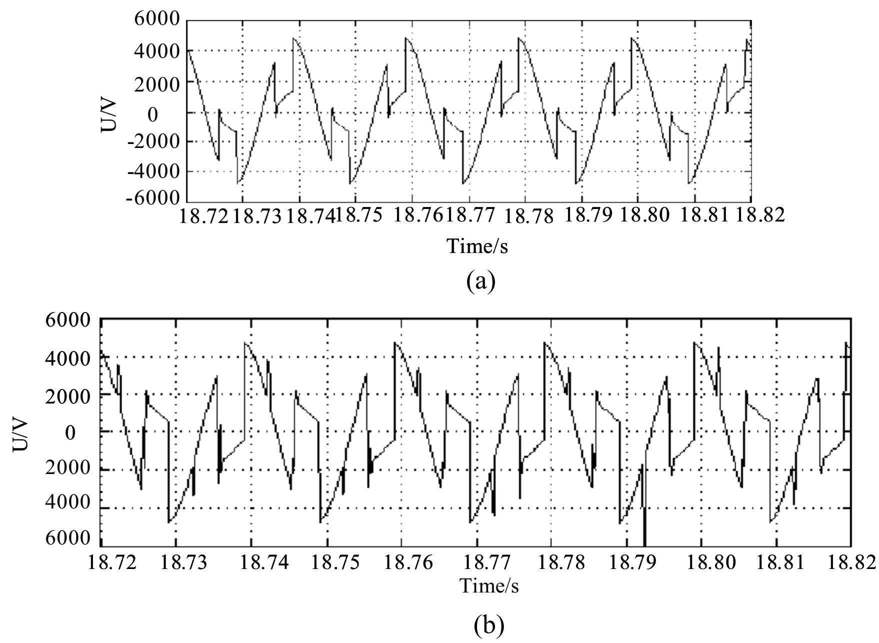

Figure 7: Stator voltage waveform: (a) stator voltage waveform at 25% motor load and (b) stator voltage waveform diagram at 15% motor load.

In order to verify the reliability of the method, this article additionally selects 25% rated load (1,500 N m) and 15% rated load (900 N m) for simulation. When 15% load and 25% load are obtained, the asynchronous motor is in the voltage regulation, and the stator voltage waveform under power-saving control is shown in Figure 7.

According to Figure 7, the stator voltage drops deeper at 15% load than at 25% load, indicating that the asynchronous motor has a general power-saving effect in voltage regulation and power-saving control. By selecting the stator current of the asynchronous motor and its variation as the input variable, and the deviation of the current variation as the output variable, a two-dimensional fuzzy control algorithm model is established for the voltage regulation and power saving of the asynchronous motor, and a better power-saving effect is achieved. In summary, the proposed method can reduce the iron loss of the motor, reduce the total loss, improve the efficiency of the motor, and realize the purpose of voltage regulation and power saving of the motor.

4 Conclusion

When the voltage of the motor drops to a certain level, if the voltage drops again, the current of the motor will increase again, so the copper consumption of the motor will increase and the efficiency will decrease. In addition, reducing the voltage too much will cause the electromagnetic torque of the motor to drop, resulting in the phenomenon of stalling without moving the load. Therefore, in order to achieve the best power-saving effect, the best voltage regulation coefficient must be selected according to the motor load factor (or load rate). The thyristor voltage regulation circuit is usually used to adjust the motor stator voltage, but because there is no accurate mathematical model to follow between the motor load factor and the thyristor conduction angle, it is difficult to obtain the best voltage regulation effect of the thyristor. Therefore, this article proposes a voltage regulation and power-saving method for asynchronous motors based on fuzzy control theory. The experimental results show that after voltage regulation and power-saving control, the phase current of the motor is reduced, and the active power and reactive power of the motor are reduced. The power factor of the motor is high, and the power-saving effect is remarkable.

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