Power Consumption Analysis of Stepping Motor and Its Driving Circuit

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Abstract. In this paper the computer numerical calculation was used to analysis the power consumption of the stepper motor and the driver circuit and improve the efficiency. The mathematics model build with the parameter of 10PM-K013B has been calculated with different driving voltage and plus frequency, the relationship between efficiency and driving voltage, and between efficiency and plus frequency was obtained. The result showed that, the efficiency improved as driving voltage reduce and plus frequency rise. The efficiency can rise from 20% to 50% with appropriate choice of driving voltage and plus frequency.

1. Introduction
Stepper motor can provide precise position drive in open-loop control, which is cheap, maintenance-free, and large torque without gearbox drive is conducive to reducing the volume of equipment, so it has been widely used in industrial equipment, consumer electronics, medical equipment and other fields [1] [2] [3]. However, its energy conversion efficiency is not high and its calorific value is high, especially at very low and high speed rotations. With the application of stepper motor in some miniature battery-powered equipment more and more widely, the producers and users of stepper motor are more and more urgent to improve the energy conversion efficiency of stepper motor [4] [5] [6] [7] [8] [9]. At present, the research on energy conversion efficiency of motor mainly focuses on three-phase asynchronous motor, brushless motor and so on. For stepper motor, it mainly focuses on the research of its driving circuit, ignoring the optimization of energy consumption in order to ensure its driving accuracy and response speed. With the rapid development of asynchronous motor servo drive, and its power conversion efficiency is much higher than that of brushless motor [10] [11] [12] [13] [14], the application advantages of stepping motor are becoming smaller and smaller, so it is necessary to improve the efficiency of stepping motor [15] [16] through analysis and research.

In this paper, the mathematical model of stepping motor is established. The current popular constant current drive circuit is used to drive the motor. By changing the parameters of the mathematical model, the influence of different parameters on the operation efficiency of stepping motor is analyzed, which provides a theoretical reference for improving the power of stepping motor.

2. Mathematical Model and Driving Circuit of Stepping Motor
Stepping motor is a complex mechanical and electrical system. Even though people have already studied mechanical mechanics and electromagnetic, it is still too complicated to establish an accurate mathematical model for the dynamic characteristics of stepping motor. In this paper, the mathematical model of stepper motor and the mathematical model of driving circuit will be simplified reasonably.
2.1. Mathematical Model of Stepping Motor
The mechanical and electrical parts of stepping motor are simplified properly and its mathematical model is established. The equivalent circuit assumes that the magnetic circuit is linear, unsaturated and the mutual inductance between phases is neglected [17] [18] [19] [20]. The mechanical system is simplified to a mathematical model with inertial torque and viscous damping effect. For hybrid stepping motor, the equivalent circuit of one phase is as follows.

![Fig. 1 Equivalent circuit for one phase of the stepper motor](image)

In the above model, the resistance Ra and the inductance La (theta) represent the resistance and inductance of one phase of the stepping motor respectively. Because of the large air gap of hybrid stepping motor, the relationship between phase inductance and rotation angle can be neglected. ea is the reverse electromotive force generated by the cutting magnetic field of the stator coil.

\[ e_a(\theta) = -p\psi_m \sin(p\theta) \frac{d\theta}{dt} \]  

(1)

In formula (1), \( p \) is the number of magnetic pole teeth \( \psi_m \) is the maximum magnetic flux of the motor.

The voltage balance equation of phase winding of hybrid stepping motor is

\[ v_a(t) = R_a I_a(t) + L_a(\theta) \frac{dI_a(t)}{dt} + I_a(t) \frac{\partial L_a(\theta)}{\partial \theta} \frac{d\theta}{dt} \]  

(2)

In formula (2), the first term is the resistance voltage drop on the winding, the second term is the back electromotive force generated by cutting the magnetic induction line of the winding coil, and the third term is the voltage value generated by the change of the current on the inductance of the phase winding.

For hybrid stepping motors, the torque generated by the motor is mainly determined by the phase current, magnetic flux and detent torque which has a significant impact on the motor.

\[ T_p = -p\psi_m i_a \sin(p\theta) + p\psi_m' i_b \sin(p\theta - \frac{\pi}{2}) - T_{det} \sin(2p\theta) \]  

(3)

Formula (3) \( T_{det} \) is the detent torque of the motor.

2.2. Constant Current Driving Circuit
Constant current drive converts the winding current value of stepping motor into a certain proportion of voltage value through feedback resistance, and controls the switch of power transistor according to the result of comparison with the preset current value, so as to achieve the purpose of current control. The driving circuit is complex, the switch frequency of the power transistor is high, and the components are easy to aging. However, compared with constant voltage driving, the driving speed
and noise are relatively small. It can be driven by higher subdivision. It is a widely used driving control method.

Fig. 2 Schematic diagram of the stepper motor driver circuit

In the figure above, Rf1 and Rf2 are feedback resistors connected in series to the winding, P1 and P2 are pulse signals modulated according to the pulse amplitude of the set phase current. After subtracting the voltage value on the resistance from the pulse signal, a high frequency switching signal is formed through Schmidt flip-flops U1 and U2 to control the switching power transistor, so that the phase current through the winding is controlled near the preset value. Because the stepper motor may produce a large reverse electromotive force when it rotates, and the voltage is even greater than the driving voltage, thus forming a reverse current which damages the power supply of the driving circuit, so D1 and D2 power diodes are usually connected in series to prevent the reverse current from flowing to the power supply of the driving circuit for circuit protection.

3. Parametric test and results

In order to improve the efficiency of stepping motor, it is necessary to analyze the influence of various parameters on the energy conversion efficiency of stepping motor. In this paper, the numerical simulation of stepping motor and its driving circuit is carried out by using the numerical sequence model established above. When the stepper motor design and users expect to reduce the power consumption of the stepper motor, the parameters of the stepper motor can be adjusted according to the relevant test results, so as to improve the efficiency of the motor. This paper analyses the influence of driving voltage, phase inductance and motor speed on motor power consumption and efficiency. The driving voltage can be adjusted by the designer and user of stepping motor drive circuit, the phase inductance can be adjusted by the designer of stepping motor, and the speed can be adjusted by the designer of equipment according to the final speed of equipment.

3.1. Effect of Variation of Driving Voltage on Power Consumption

The mathematical model of the stepper motor was established with the specification parameters of 10PM-K013B. The parameters of the motor are as follows. Based on the parameters of the motor, the influence of the change of driving voltage on power consumption is investigated.
Tab. 1 The parameter of stepper motor 10PM-K013B

| Stepping angle | Driving mode | Rated current | Phase resistance | Keep torque | Inductance | Rotor inertia | Braking torque |
|----------------|--------------|---------------|------------------|-------------|------------|--------------|----------------|
| 1.8°           | Bipolar      | 0.21A         | 47Ω              | 49mNm       | 30mH       | 3g·cm        | 2.5mNm         |

Fig. 3 The relationship between the driving frequency and the driving voltage as driving current is 0.21A, motor load is 20mNm

![Figure 3](image)

Fig. 4 The relationship between the power and driving voltage and between the efficiency and driving voltage

a. Partial power b. Energy conversion efficiency

With the increase of speed, the higher the counter electromagnetic force of stepping motor is, the higher the driving voltage is required. For a certain driving voltage, the maximum pulse frequency that can drive the load to rotate is called the limit pulse frequency. From Figure 3, it can be seen that when the driving voltage is less than 20V, the extreme speed of the limit pulse frequency decreases. Driving voltage over 30V limit pulse frequency increases slowly with the increase of voltage, but the change is not obvious. As can be seen from Figure 4.a, when the pulse frequency is constant, the output power of the stepping motor will not increase with the increase of the driving voltage. From Figure 4.b, it can be seen that the efficiency of driving circuit and stepping motor decreases with the increase of driving voltage. When driving voltage is less than 20V, the energy conversion efficiency increases rapidly with the decrease of driving voltage. When driving voltage is more than 20V, the energy conversion efficiency does not change much with the increase of driving voltage.
3.2. Influence of Phase Inductance Change on Power Consumption

![Graph showing the relationship between phase inductance and power/efficiency](image)

a. Power of each part  
b. Energy conversion efficiency

**Fig. 5** The relationship between the power and phase inductance and between the efficiency and phase inductance as coil turns stay the same.

Fig. 5 shows that the phase inductance has little effect on the efficiency of stepping motor when the number of coil turns is the same. Reducing the phase inductance can reduce the loss of high frequency switching current passing through the winding.

3.3. Effect of Output Speed on Motor Efficiency

![Graph showing the relationship between pulse frequency and power/efficiency](image)

a. Power of each part  
b. Energy conversion efficiency

**Fig. 6** The relationship between the power and impulse frequency and between the efficiency and impulse frequency.

Figure 6 shows that with the increase of pulse frequency, the input power of the power supply does not change much, and the output power of the motor increases with the increase of pulse frequency. The energy conversion efficiency of driving circuit and stepping motor increases with the increase of pulse frequency.

4. Conclusion and Prospect

In this paper, the mathematical model of hybrid stepping motor and its driving circuit is established, and the power consumption of each part is analyzed, which provides a theoretical reference for achieving the goal of energy saving in the process of using stepping motor. The results of the previous experiments show that the energy conversion efficiency of stepping motor and its driving circuit increases with the decrease of driving voltage and the increase of pulse frequency. By reasonably choosing driving voltage and pulse frequency, the energy conversion efficiency can be increased from about 20% to about 50%.
The computer numerical simulation test of stepping motor and its driving system using mathematical model can save the test time and cost greatly. It is hoped that this method can be used to further study the method of improving the energy conversion efficiency of stepping motor, and provide reference for the design of stepping driver, driving circuit and stepping motor.

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