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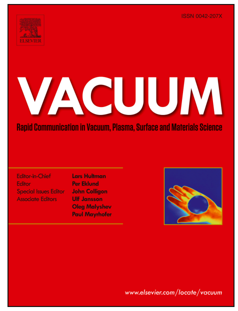

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[Title Page]

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An improved braking control method for the magnetically levitated TMP with a fast transient response

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Abstract

In the vacuum application based on the turbo-molecular pump (TMP), the pump rotor has to be stopped completely to prevent the blade from the air impact before trapping air into the vacuum chamber. However, due to the vacuum environment and high speed, the TMP braking process lasts much longer than that of the high-speed rotating machinery in the air. Particularly, the active magnetic bearings, which have been widely used in the TMP, eliminate the bearing friction resistance. In this case, the traditional electric braking method based on a non-controllable rectification cannot stop the rotor efficiently. Hence, a novel braking control method for the magnetically levitated TMP with a fast transient is proposed. When the TMP runs at high speed, it works like the traditional braking method, but with a temperature close-loop control, which is used to prevent the stator from overheat with the maximum current. Meanwhile, in the low speed range, the power switches of the inverter are controlled specifically to increase the DC-bus voltage. Thererfore, the barking current could be remained at a high level to reduce the braking time. At last, the proposed braking method is verified on a magnetically levitated TMP with 4100L/s pumping speed.

Keywords: vacuum; turbo-molecular pump; active magnetic bearing; high-speed permanent magnet (PM) motor; brake

1. Introduction

The magnetically levitated turbo-molecular pump (TMP) equipped with a high-speed permanent magnet (PM) motor have many advantages over the traditional turbo- molecular pump, such as high power-to-volume ratio, no-friction, oil-free and active vibration control, which improve the performance significantly. Furthermore, with the active magnetic bearings, the TMP could be installed in any direction flexibly. Therefore, it has been used more and more widely in the high vacuum applications [1-6].

The typical TMP control includes two basic aspects: drive and brake. Firstly, the rotor of the TMP must be driven by a high-speed motor to the rated working speed. In order to reduce the start time as much as possible, the motor is controlled with its maximum current to accelerate. According to the shape of drive currents, the control methods could be classified as sinusoidal currents and square currents, which have been studied widely and deeply in the last decades [7-11].

Due to the air resistance and the bearing friction resistance, the braking process of a traditional high-speed PM motor could be simply by shutting off the power electronics of the inverter. However, in the high vacuum environment, this method would be invalid with no air. Besides, the mechanical braking methods such as disc brake are also unpractical because of the high-speed TMP rotor and vacuum environment. Hence, only the electric braking method is feasible. The electric regenerative braking methods of the PM motors have been widely applied in the electric vehicles (EV) to recharge the chemical batteries with an extra DC/DC converter [12-14]. In reference [15], J. W. Dixon. et al. proposed a novel regenerative system based on the ultra-capacitor and a DC/DC converter. In order to improve the regenerative energy efficient, J. Moreno and his partners developed an energy-management with the neural networks algorithm [16]. M. Marchesoni and C. Vaccas analyzed the energy storage system efficiency in fuel cell hybrid electric vehicles. The convention of regenerative energy is also based on the Bi-directional DC/DC converter [17].

Although many researches of the braking methods have been carried out, there are rare studies about the braking control method for the TMP in the high vacuum environment. The regenerative braking method of the TMP based on an asynchronous motor is proposed [18]. However, it still needs an extra active front-end rectifier for the energy conversion. Besides, more and more high-speed PM motor has been used in the TMP.

When the TMP to brake, a simple and effective method is shutting off the main power and the power switches of the inverter. In this case, the motor works as a generator and the rotor kinetic energy would be converted into electric power, which is dissipated as heat via a power resistor at last. Although the braking current and torque could be remained at a high level while the motor runs at high speed, the performance of this method is getting worse as the motor speed decreases due to the non-rectification of the back electromagnetic force (EMF) by the anti-parallel diodes. With the contact free ability of the active magnetic bearings, the bearing friction resistance, which is helpful for the rotor stop, could be negligible. Therefore, the exiting braking method needs to be more efficient to shorten the braking process. In addition, although the TMP is equipped with cooling device, the stator temperature would also increase quickly with a high braking current value. It is crucial to prevent the stator from overheat in all condition.

The paper is organized as followings. Firstly, the traditional braking method is 2 analyzed in Section II. It is shown that the performance of the traditional braking 3 method depends on the rotor speed. Besides, the braking efficiency decreases sharply 4 when the rotor speed is low. In Section III, an improved braking control method for the 5 TMP is proposed. The power switches of the inverter are controlled actively to improve 6 the braking efficiency without extra hardware. Besides, the temperature close-loop 7 control is also used. Then, the braking method is tested on a magnetically levitated TMP 8 with 4100L/s pumping speed, which is shown in Section IV. The result shows that the 9 braking time could be greatly reduced. At last, Section V concludes the paper.

2. Review of the traditional TMP braking method

The typical TMP controller based on a high-speed PM motor is depicted as Fig. 1. It consists of a rectifier, an AC/DC converter, a power switch S1, a braking switch S2, a braking resistor R1, a DC-bus capacitor C, a digital control unit and the inverter circuit.

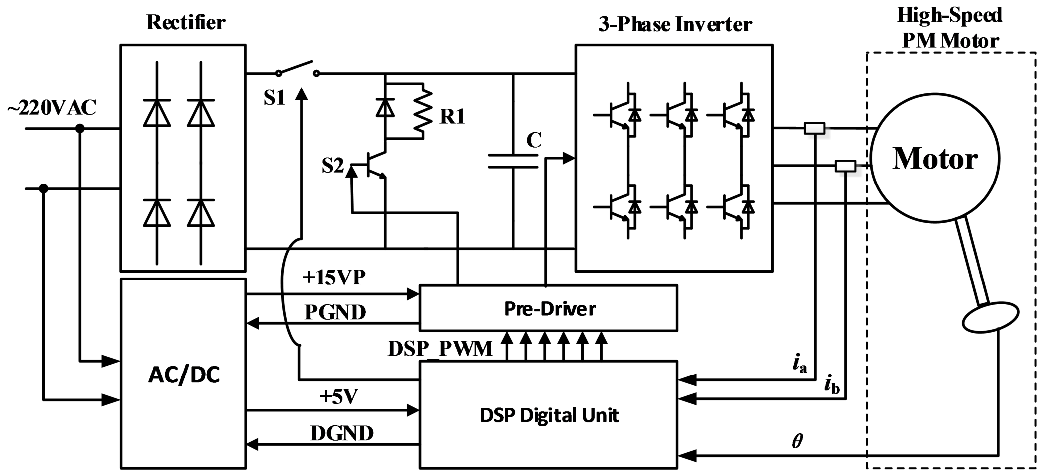


Fig. 1 The diagram of a TMP controller.

When the motor accelerates, the power switches T1 to T6 could be controlled according to the rotor position with square currents or sinusoidal currents. For facilitate analysis, the square currents drive method is analyzed in this paper. The relationship between phase back EMF and rotor position could be shown in Fig. 2. The proposed braking process needs the rotor position information which could be got by the posiiton sensors or sensorless algortihms. Therefore, it could also be applied on the sensorless control system.

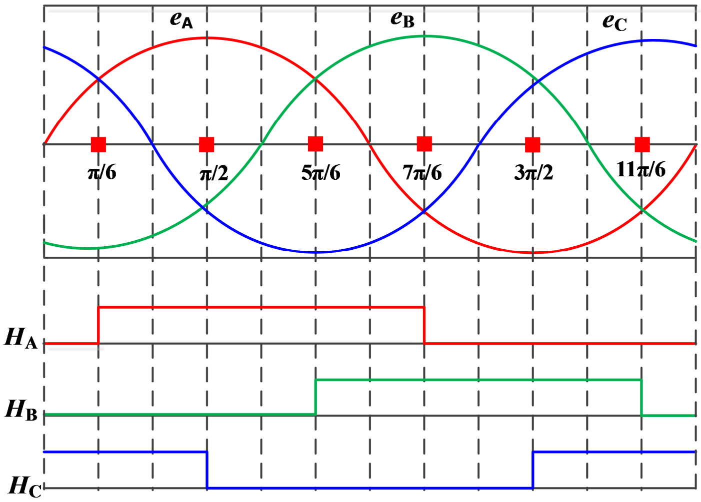


Fig. 2 The relationship between phase back EMF and rotor position.

When the TMP needs to decelerate from the high rated working speed, the braking process is as followings: The main power switch S1 as well as the power switches T1 to T6 are shut off firstly. The high speed PM motor works as a generator and the back EMF would be rectified by the anti-parallel diodes of the power switches. The controller works as Fig. 3.

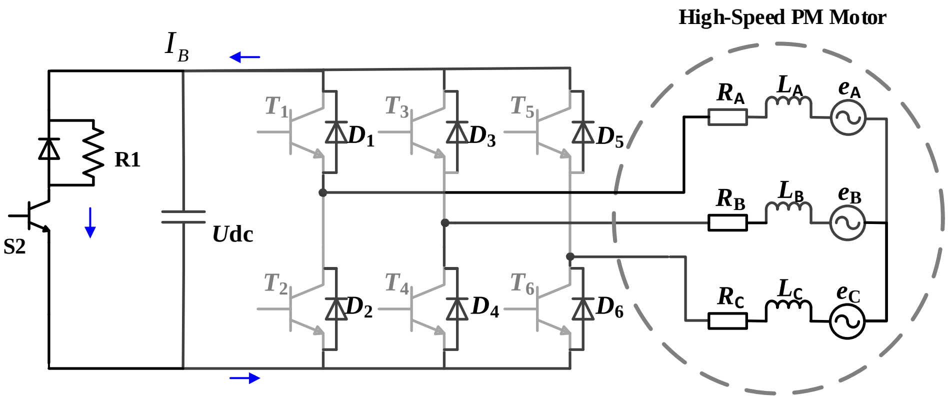


Fig. 3 The controller when the TMP brakes.

In this situation, the voltage of the DC-bus U_{dc} could expressed as

$$\begin{aligned} U_{dc} &= \sqrt{2} \cdot e_{ab} \\ &= \sqrt{2} \cdot k \cdot p \cdot \omega \end{aligned} \tag{1}$$

where e_{ab} is the line-to-line back EMF of the motor, k is the coefficient of the line-to-line back EMF, p is the number of the pole pairs and ω is the rotor speed. As k and p are both constants, U_{dc} is proportional to the rotor speed ω.

The kinetic energy of the rotor is converted into the electric power when the motor decelerates. In order to consume this energy, a power resistor R1 and its switch S2 are connected to the DC-bus in parallel. The switch S2 is used to regulate the braking current to prevent the stator from overheating. The braking current I_B could be expressed as

$$I_B = D \cdot U_{dc} / R_P \tag{2}$$

where D is the PWM duty of S2 and R_P is the resistance value of R1.

The electric braking torque T_B is determined by I_B and could be derived as

$$T_B = K_T \cdot I_B \tag{2}$$

where K_T is the electric torque constant of the PM motor.

Apparently, the braking process could be shorten by increasing I_B since the electric braking torque T_B is also proportional to I_B. With a fixed R_P, the braking current is less than U_{dc}/R_P because the maximum value of D is 1. According to the Eq. 1, U_{dc} and I_B would decrease as the motor is decelerating. Furthermore, I_B and T_B are very small and hard to be regulated. Therefore, although the braking efficiency is high at first, the whole braking process still lasts one to two hours because of the small braking torque when the motor runs at low speed.

The copper loss of the motor P_{COP} could be described as

$$P_{COP} = 2 \cdot R \cdot I_B^{\ 2} \tag{2}$$

current probably cause temperature rise of the TMP stator. The traditional braking method controls the braking current in an open-loop way, which is hard to regulate the braking current in real time according to the stator temperature.

3. The improved braking method

Based on the above analysis, the braking time of the TMP could be reduced by increasing the braking current I_B when the motor speed is low. As I_B is regulated by the DC-bus voltage U_{dc}, an improved braking method with active controllable rectification is proposed to achieve and maintain high U_{dc} value in a wide speed range. The temperature close-loop control strategy is also used to prevent the stator from overheat.

3.1 Braking method at high speed

The switches of the inverter and the main power switch S1 are turned off firstly once the TMP starts to brake in high speed rang. Then, the switch S2 is regulated to control the braking current. Although the braking time could be reduced with the maximum current, there is also more heat generated on the power resistor and the TMP stator. In order to prevent overheat of the stator, a temperature close-loop controller base on hysteresis algorithm is designed as shown in Fig. 4.

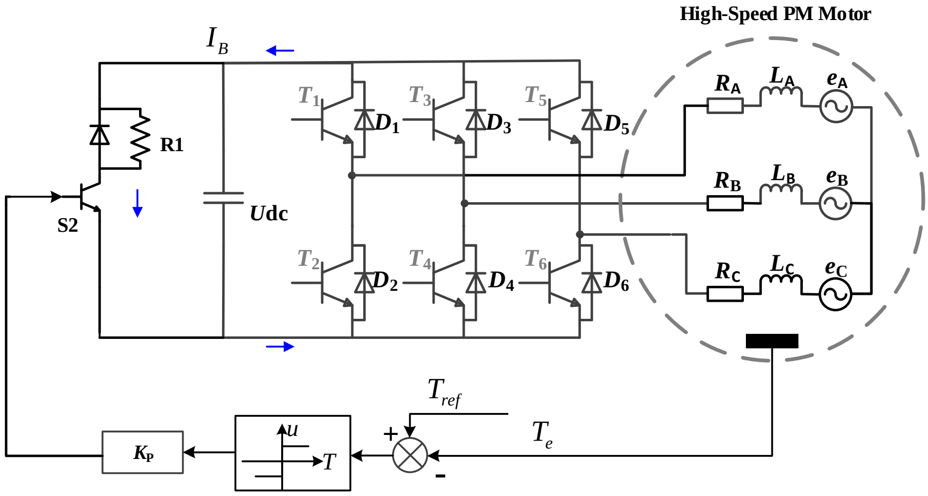


Fig. 4 Diagram of the temperature close-loop controller.

When the TMP starts to brake, the stator temperature T_e is measured in real time. Meanwhile the digital controller continuously calculates an error value e as the difference between the reference temperature T_{ref} and T_e. Then it applies a correction based on the hysteresis algorithm. The output would be used to control the power switch S2 to regulate the braking current. The hysteresis controller could be expressed as

$$u = \begin{cases} 1, & T_{ref} \geq T_e + \Delta T \\ 0, & T_{ref} < T_e - \Delta T \end{cases} \tag{2}$$

Where u is the controller output and ΔT is the hysteresis band width.

3.2 Braking method at low speed

In order to maintain the braking current and torque at a high value, an improved regenerative braking method with active controllable rectification of the back EMF is proposed as followings: The power switches T1, T3, T5 are kept off and T2, T4, T6 are turned on by PWM according to the rotor position. In order to simplify the analysis, the principle of this method is described when the rotor position θ is between π/6 and π/2. In this case, the T4 and T6 are kept off and T2 is regulated by the PWM.

When T2 is turned on, the kinetic energy of the rotor would be converted and stored in the windings as magnetic energy. The current flows through T2, D4, D6, motor phase B and motor Phase A. Once T2 is turned off, the magnetic energy is feedback to the DC-bus capacitor and sets up the DC-bus voltage U_{dc} as shown in Fig. 5.

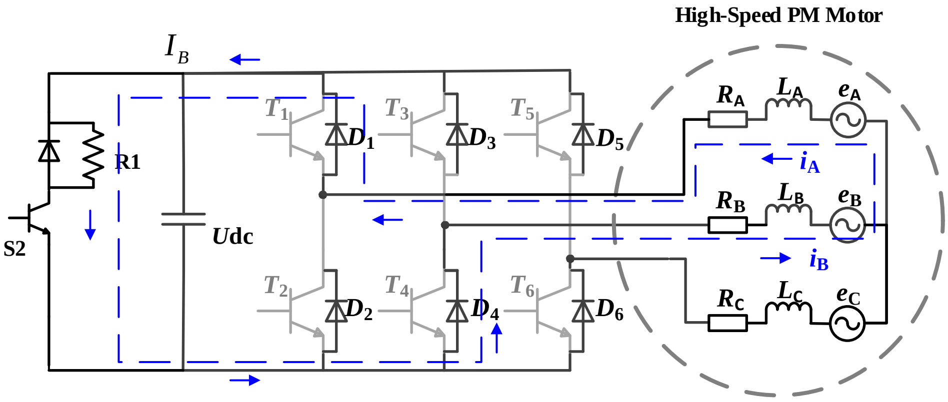


Fig. 5 Current flowing path of the braking control circuits.

If θ reaches to other value, the control principle is similar. Apparently, there is only one switch needs to be controlled, which simplify the power control. It is as shown in Table I.

Table 1 Active Controllable Switches with different θ

Position Angle θ	Active Controllable Switch
[π/6, π/2)	T2
[π/2, 5π/6)	T6
[5π/6, 7π/6)	T6
[7π/6, 2π/3)	T4
[2π/3, 11π/6)	T4
[11π/6, 2π) U [0, π/6)	T2

Apparently, the proposed braking circuit with a simple voltage PI controller works like a boost DC/DC converter which is depicted as Fig. 6.

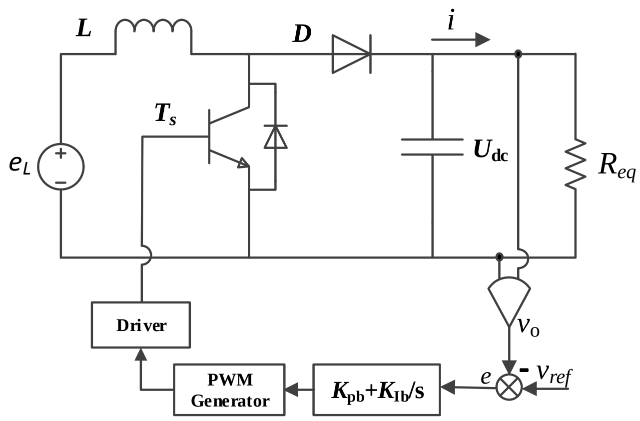


Fig. 6 Equivalent circuit diagram of the braking method at low speed.

The voltage source e_L is the line-to-line back EMF. The inductor *L* is the line-to-line winding inductor. T_S is the active controllable switch, which could be T2, T4 or T6. *D* are the free-wheeling diodes according to T_S. *C* is the DC-bus capacitor. In order to reduce the voltage ripple, the capacitance of *C* should be as large as possible. The PI controller could be expressed as $K_{Pb}+K_{Ib}S$. Where K_{Pb} is the proportional coefficient and K_{Ib} is the integral coefficients.

Therefore, U_{dc} could be maintained at a given reference value by using the equivalent boost converter with voltage closed-loop control. Meanwhile, the switch S2 is also used to regulate the current. The efficiency of conversion from kinetic energy to thermal energy is significantly improved at low speed, which shortens the whole braking process.

4. Experiments

4.1 Experiment setup

The proposed braking method is applied on the self-developed magnetically levitated 2 TMP. Fig. 7 shows that it consists of a testing TMP, a backup pump, a temperature 3 meter, a braking resistor and a digital controller, which is used to drive and brake the 4 TMP. The parameters of the experimental high speed PM motor of the TMP are shown 5 in Table 2.

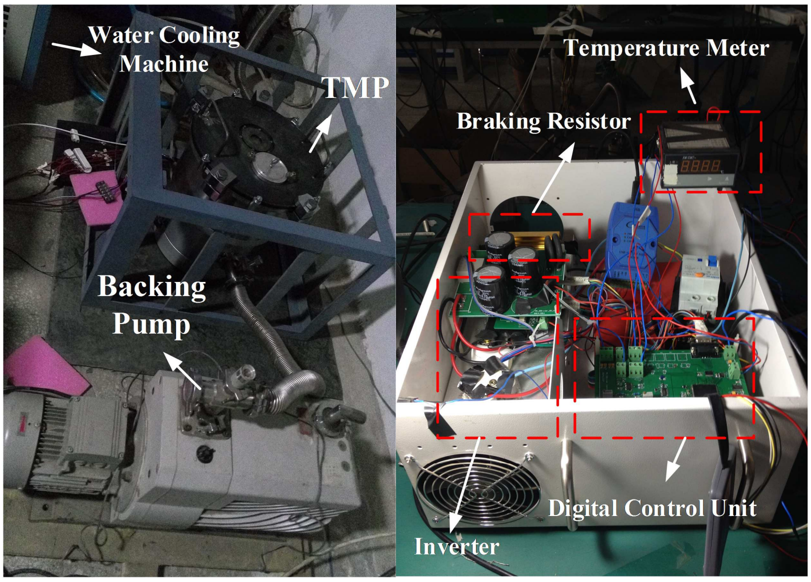


Fig. 7 The experimental TMP platform.

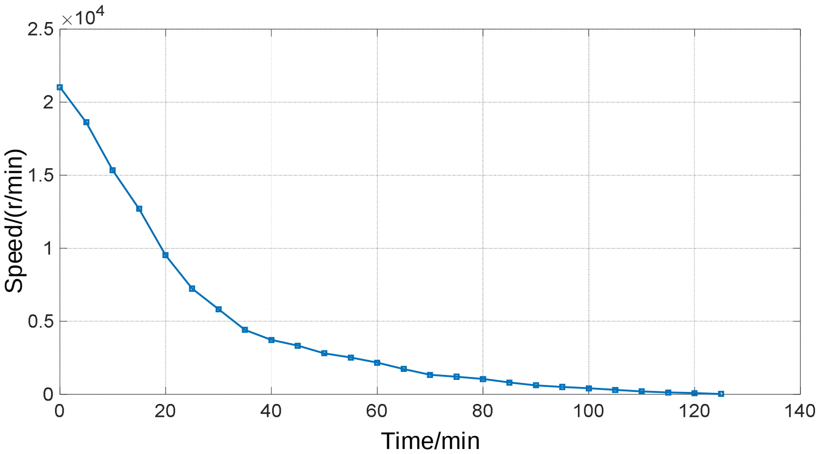
Table 2 High speed PM motor parameters

Motor Parameters	Value
Rated Power (W)	1400
Rated dc voltage (V)	100
Rated speed (r/min)	21000
Phase resistor (Ω)	0.28
Phase Inductance (H)	0.24×10^{-3}
Rotor speed (r/min)	21000
Number of pole pairs	1

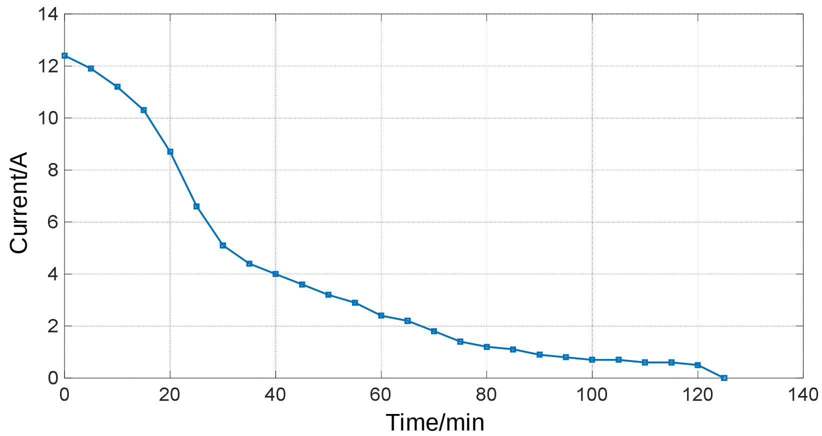
Line-to-line back EMF constant (V(r/min))	0.0033
Moment of inertia ($kg{\cdot}m^2$)	0.002139

5.2 Experiment of the traditional braking method

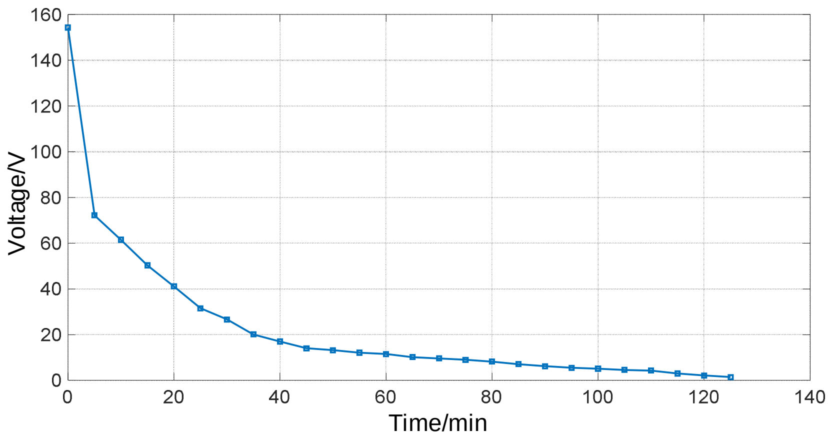
The TMP is driven by the high-speed PM motor to the rated speed 21000r/min firstly. Then, the TMP starts to decelerate with the traditional brake method. Since the braking process and the motor driving process dose not affect each other, this braking method could be applied on the high-speed PM motors driven by the square currents and sinusoidal currents. During the braking process, the motor speed, the brake current flown through the power resistor, the DC-bus voltage and the TMP stator temperature are recorded every 5 minutes. The experimental results are shown in Fig. 8.



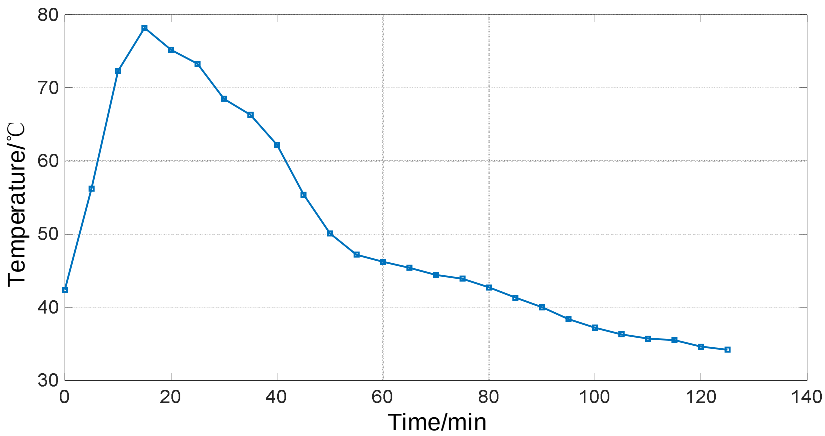
a) Rotor speed with traditional braking method



b) Motor current with traditional braking method



c) DC-bus voltage with traditional braking method



d) Stator temperature with traditional braking method

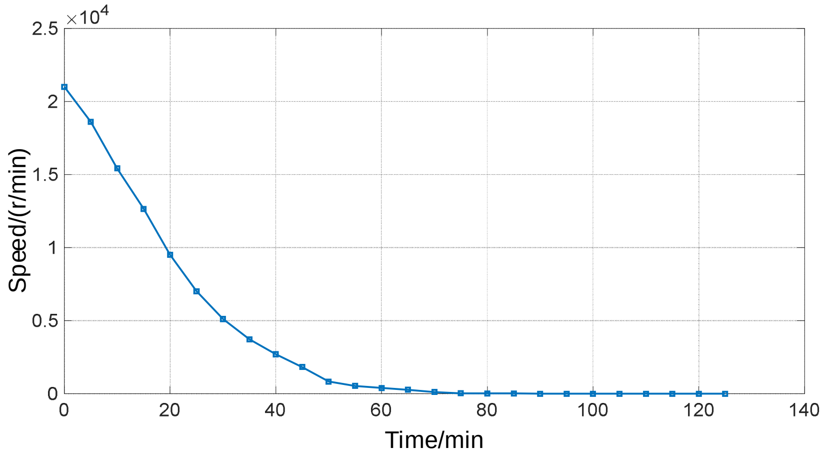
Fig. 8 Experimental results with the traditional braking method.

With the traditional braking method, the TMP decelerates from 21000r/min to 6000r/min quickly at the first 50 minutes with high braking current. However, since the DC-bus voltage value is proportional to the TMP speed with non-controllable rectification, the braking current decreases sharply in the low speed range. In this case, the whole braking process lasts about 117min.

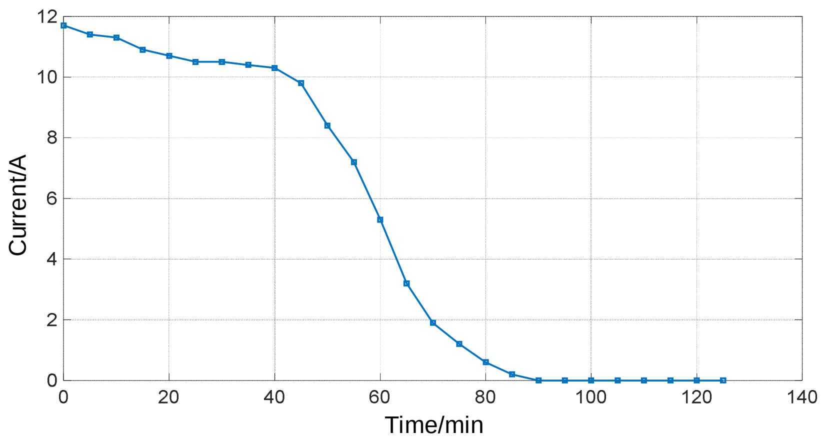
The temperature is also shown in Fig. 8 d). Because there is no temperature closed-loop control, the stator temperature rises to about 80℃ temporarily, then it drops quickly as the braking current decreases. At last, it stays around 34℃ .

5.2 Experiment of the proposed braking method

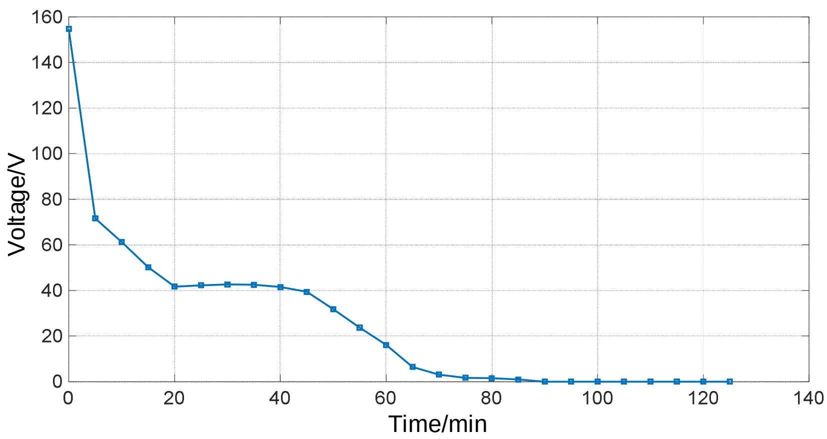
The proposed braking method is also tested and the experimental results are depicted in Fig. 9. In the high speed range, the typical braking method with non-controllable rectification is used. The results show that the motor decelerates quickly comparing to the traditional method. The braking current maintains at a high value even in low speed range. The whole braking process last about 86 minutes which is much shorter than the traditional method. From Fig. 9 c), the DC-bus voltage value decreases firstly, then it is kept around 42V with the active controllable rectification method, which is proposed in Section III. Besides, with the temperature closed-loop control, the stator temperature is controlled at about 78℃ for about 47 minutes which is longer than the traditional braking method. The water cooling of the TMP can be fully used.



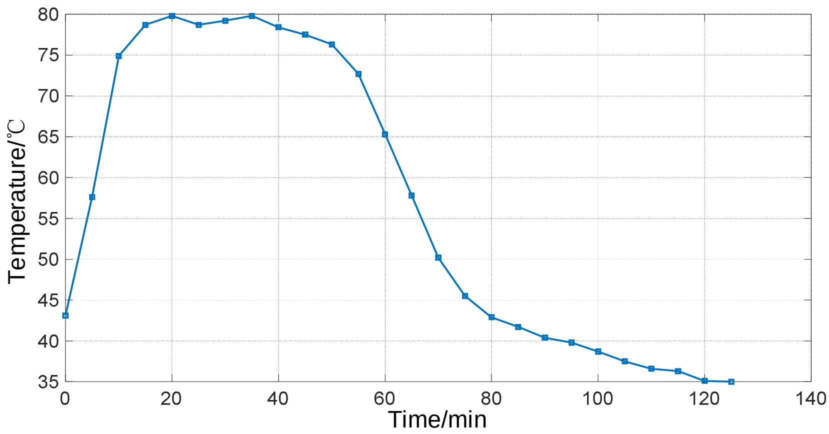
a) Rotor speed with proposed braking method



b) Motor current with proposed braking method



c) DC-bus voltage with proposed braking method



d) Stator temperature with proposed braking method

Fig. 9 Experimental results with the traditional braking method.

6. Conclusion

This paper proposes an improved braking method of TMP. The following conclusions are obtained through the analysis and experiments.

1) With no air friction, the TMP braking process lasts much longer than that of the traditional high speed motor in the air using the traditional braking method. The operating efficiency of the TMP could be improved by shortening the braking process.
2) Comparing with the traditional braking method, the proposed method could reduce the braking time via increasing the braking current with the active controllable rectification in the low speed range.
3) In the braking process, the kinetic energy is converted to heat power and dissipated by a power resistor. With some specific control methods, the kinetic power could also be used to provide the appropriate voltage supply for the control system, which will make better use of the energy. Therefore, it will be studied in the future.

Acknowledgements

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Highlights:

1. The traditional braking method based on the non-controllable rectification of the magnetically levitated turbo-molecular pump is analyzed.
2. An improved braking method is proposed to reduce the braking time by increasing the braking current with active controllable rectification method in the low speed range.
3. The temperature closed-loop control is also introduced to make full use of the water cooling machinery.