

# Simulation for High Speed Brushless Dc Motor Operating In a Low and High Speed Range Using A Novel Drive Method

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**Abstract** – a novel drive method, which is different from the traditional motor drive techniques, for high-speed brushless DC (BLDC) motor is proposed and verified by a series of experiments. It is well known that the BLDC motor can be driven by either pulse-width modulation (PWM) techniques with a constant dc-link voltage or pulse-amplitude modulation (PAM) techniques with an adjustable dc-link voltage. However, to our best knowledge, there is rare study providing a proper drive method for a high-speed BLDC motor with a large power over a wide speed range. Therefore, the detailed theoretical analysis comparison of the PWM control and the PAM control for high-speed BLDC motor is first given. Then, a conclusion that the PAM control is superior to the PWM control at high speed is obtained because of decreasing the commutation delay and high-frequency harmonic wave. Meanwhile, a new high-speed BLDC motor drive method based on the hybrid approach combining PWM and PAM is proposed. Finally, the feasibility and effectiveness of the performance analysis Comparison and the new drive method are verified by several experiments.

**Index Terms** – Brushless (BLDC) motor, commutation delay, drive method, high-speed, pulse-amplitude modulation (PAM).

## 1. INTRODUCTION

High-speed brushless DC (BLDC) motor, which is with the advantages of high efficiency, compactness, low cost, and maintenance compared with the traditional brush dc motor is getting more and more interest in industrial automation area, especially on blowers and compressors. Because the rotation speed of high-speed motor can reach up to tens of thousands revolutions per minute (r/min) due to the development of bearing technology [4], [5], a proper drive method to ensure low loss and high efficiency in a wide speed range is a critical issue.

Generally, the BLDC motor can be driven by either pulse width modulation (PWM) or pulse-amplitude modulation (PAM) techniques. However, it is well known that the inverter, which is applied to most of the BLDC motor drive systems, is

controlled by the PWM scheme for varying the voltage. Moreover, the PWM control is extensively used in high-power/low-power BLDC motor drives and the motor performance is decided by the commutation control techniques. The high-side power device is controlled by the PWM chopper signal every consecutive  $120^\circ$  in a fundamental period. Meanwhile, the low side of the same leg control signal is shifted by  $180^\circ$  without the PWM chopper signal, as compared to its high-side one, to clamp the related inverter output to the negative dc-link rail. The control signals for the other two legs are shifted by  $120^\circ$  and  $240^\circ$ , respectively. Unfortunately, the PWM techniques can induce serious current and torque ripples for the ironless stator motor that will tend to very low inductance. Moreover, the high-frequency and large-range current ripple will inevitably increase the copper and iron losses at high speed. The assessment of the aforementioned PWM techniques for the BLDC motor drives at low speed is given in [20]. The criteria for assessment include the drive circuit, reversal dc-link current, circulating current of the floating phase, and back electromotive force (back-EMF) detection.

In addition, the advantages and disadvantages of these PWM techniques for the BLDC motor drives are analyzed by several experimental results. A comprehensive analysis on the generated torque ripples of trapezoidal back-EMF due to the phase commutation in the six-switch three-phase inverter BLDC drives is proposed. The consultation that the PWM-ON Pattern achieves the smallest torque ripple due to the current commutation is also given. The performances of the PWM techniques at low speed are compared in the efficiency, reliability, torque ripple, EMC, and vibration through the theoretical analysis and simulation verification. It is shown that the PWM\_ON\_PWM method is superior to the other PWM methods. A novel PWM technique is introduced in to reduce the motor loss, but only suits for the motor with very small power.

In summary, the aforementioned studies are all based on the low-speed operations instead of the high-speed performance. Moreover, there are no detailed analyses about the performance improvement.

The PAM control is another popular control method for the BLDC motor. For PAM control, 120° commutation control, i.e., the so-called six-step mode is generally used and the dc-link voltage can be adjusted according to the error between the speed and its reference. It is shown that the PAM control is superior to the PWM control [23]. Due to the PWM period interruption caused by the commutation and limitation of the resolution of PWM generator, more torque ripple can be produced in the performance of PWM-controlled BLDC motor drives.

This phenomenon will become more serious when the motors work at high speed. Moreover, it will lead to high motor loss. But it does not give enough theoretical analysis. The advantages and disadvantages of PWM and PAM are assessed in using BLDC motor drives which are applied to the refrigerator. The result shows that the PAM control can provide higher efficiency than the PWM control. However, it only gives several low-power experimental results without any detailed analysis. A so-called PAM/PWM method is proposed to control the adjustable speed drives. The realization of PAM relies on a current source rectifier which adjusts the dc-link voltage. As compared to the Conventional PWM inverter with a constant dc-link voltage, this method can reduce the dc-link current ripples and prolong the lifetime of the capacitor effectively.

## 2. PROPOSED DRIVE METHOD

### 2.1. Drive Circuit Selection of High-Speed BLDC Motor

As analyzed above, the PAM control for the BLDC motor can provide less motor loss and higher efficiency than the PWM control at high speed. So the PAM control should be employed, especially at high speed. However, from the specification of the experimental BLDC motor as shown in Table I, it is interesting to find that the phase-winding resistance and the phase-winding inductance of high-speed BLDC motor are far smaller than those of the common low-speed BLDC motor. When the motor starts, the initial DC voltage of the three-phase inverter should be smaller enough to limit the startup current, as the back-EMF is too small to counteract a large dc voltage at the very low speed. Therefore, a suitable drive circuit should be first selected to reduce the initial dc voltage and guarantee the safe motor starting process. During the experimental process, the authors have tried three drive circuit structures to limit the startup current. the common drive circuit structure for the BLDC motor control. The dc voltage, i.e., the output voltage of the three-phase uncontrolled rectifier is more than 500 V. Though the three-phase inverter is controlled by the PWM scheme for reducing the voltage, the startup current is still far larger than

the Fig. 7. Drive circuit structure based on the dc–dc converter for the BLDC motor control. rated current. Moreover, the inverter cannot work anymore, as the protection circuit blocks the inverter due to the large current. So this common circuit structure is not employed. the drive circuit structure based on a front-end PWM-controlled dc–dc converter. A buck converter is taken to reduce the dc voltage of the three-phase inverter. Moreover, the motor starts normally.

Unfortunately, the buck converter increases the complexity mainly due to the dc inductance,  $LB$ , as marked. Let us assume that the working frequency of the buck converter is 6 kHz. As the rated power of the experimental motor is up to 100 kW, the normal dc current flowing through  $LB$  may be more than 250 A which will cause the bulky size and weight as shown in Fig. 7. Moreover, the bulky  $LB$  will increase the difficulty of the whole circuit layout design because the unreasonable layout will induce strong electromagnetic interference, which may affect the normal operation of high-speed and high-power BLDC motor. Finally, taking into account the subsequent PAM control and the disadvantages of the above-mentioned circuit structures, motor drive circuit as shown in Fig. 2 is employed in this paper. The front-end phase-controlled rectifier can provide an adjustable-link voltage to limit the startup current and achieve the PAM control, while the back-end three-phase inverter can achieve the commutation control.

### 2.2. Proposed Drive Method

In order to satisfy the commutation control of high-speed BLDC motor in a wide speed range and improve the motor efficiency, a hybrid drive method combining PWM and PAM is proposed. When the motor runs at low speed, the PWM controls adopted with a fixed dc-link voltage. With the motor accelerating, the back-EMF will increase with the speed. When the motor speed reaches a threshold value, i.e., the enough back-EMF can counteract the dc-link voltage, the PAM control works with an adjustable dc-link voltage. It should be noted that though the PAM control for the BLDC motor is superior to the PWM control, the PAM control is not employed in the whole speed range for the following two reasons.

The first one is that the larger dc-link voltage fluctuation of the rectifier limits its application at low and medium speed. Moreover, at low speed, it may be unable to produce a small enough dc voltage to achieve the PAM control due to small phase winding resistance and phase-winding inductance. Therefore, if we want to take the PAM control in a wide speed range, the range of dc-link voltage should be expanded at medium and Low speed. Meanwhile, a front-end PWM-controlled dc–dc converter shown in Fig. 7 is needed to produce such a low dc voltage. But the complexity of the system design is increased as explained above. The second one is that, to our best knowledge, the PWM control is the auxiliary drive method of high-speed BLDC motor, while the PAM

control is the main drive method, since the high speed region is the most common working range.

The aim of the PWM control is merely to guarantee that the high-speed motor can be accelerated to a high speed. Therefore, the operation time of the PWM control is far shorter than that of the PAM control, thus mitigating the disadvantage of the PWM control. However, both the two drive methods are indispensable. The transition process between PWM and PAM is achieved by a hysteresis comparator expressed as

$$\begin{aligned} \tau(n(k+1)) &= 1, \\ (n(k+1) > n+) &\tau(n(k)), \\ (n- \leq n(k+1) \leq n+) &, \\ (n(k+1) < n-) &(15) \end{aligned}$$

where  $\tau(n(k+1))$  is the  $(k+1)$ th hysteresis comparator output value,  $\tau(n(k))$  is the  $(k)$ th hysteresis comparator output value and  $n+$  and  $n-$  are the two endpoint speeds of the hysteresis comparator  $(k+1)$  is the  $(k+1)$ th calculated speed value, and  $(k)$  is the  $(k)$ th calculated speed value. The hysteresis loop schematic diagram is shown in Fig. 8. The region between  $n-$  and  $n+$  is defined as the transition region.

$$\text{If } \tau(n(k+1)) = 1$$

the PAM control mode will start to work, while if

$\tau(n(k+1)) = 0$ , the PWM control mode will start to work., we can obtain

$$\begin{aligned} u_{AN} &= Ri_A + Ldi_A/dt + e_A \\ u_{BN} &= Ri_B + Ldi_B/dt + e_B \\ u_{CN} &= Ri_C + Ldi_C/dt + e_C \end{aligned}$$

where  $u_{AN}$ ,  $u_{BN}$ , and  $u_{CN}$  are the three phase voltages. Let us assume that VT1 and VT6 are switched ON, i.e., phases A and B are conducted simultaneously with  $i_A = -i_B$  and  $i_C = 0$ . So the Equivalent circuit when VT1 and VT6 are switched ON. Experimental platform. (a) Control system. (b) Experimental motors. The line-to-line voltage can be obtained as

$$\begin{aligned} u_{d(0)} &= u_{AB} = 2Ri_A + 2Ldi_A/dt + e_{AB} \\ e_{AB} &= k_e \cdot \omega \end{aligned}$$

where  $u_{d(0)}$  is the initial voltage of the rectifier, i.e., the fixed dc-link voltage when the PWM control works, and  $k_e$  is the line-to-line back-EMF constant. Therefore, we can obtain the online result of  $n+$  by solving. In this paper,  $n+$  is about 10 000 r/min. Meanwhile,  $n-$  can be obtained as  $n- = n+ - \Delta n$  ( $\Delta n$  is the hysteresis width).

### 2.3. Calculation Principle for $\Delta n$

The motor torque balance equation of the BLDC motor can be obtained as

$$TM - TZ = J d\Omega/dt = 2\pi/60 J dn/dt$$

Where  $TM$  is the electromagnetic torque,  $TZ$  is the load torque  $J$  is the moment of inertia, and  $\Omega$  is the mechanical angular velocity of the motor.

Generally, for a BLDC motor,  $TM$  can be expressed as

$$\begin{aligned} TM &= (e_A i_A + e_B i_B + e_C i_C) / \Omega \\ &= 60(e_A i_A + e_B i_B + e_C i_C) / (2\pi n). \end{aligned}$$

Considering

$$i_A = -i_B, \text{ and } i_C = 0,$$

we can also obtain  $TM$  as

$$TM = 60i_A (u_{AB} - 2Ri_A - Ldi_A/dt) / (2\pi n).$$

It can be deduced from [29] that the commutation delay induced by the PWM control will lead to a serious torque ripple. So when the drive method transfers from the PWM control to the PAM control, a torque ripple,  $\Delta TM$ , will be introduced, and can be expressed as

$$TM + \Delta TM - TZ = J d\Omega/dt = 2\pi/60 J dn/dt$$

we can find that if  $\Delta TM > 0$ , the speed will increase, while if  $\Delta TM < 0$ , the speed will decrease. Unfortunately,  $TM$  is uncertain during the transition. It can be seen from Fig. 8 that when the speed reaches  $n+$ , if the speed is decelerating; the drive method may switch between the PAM control and the PWM control repetitiously which aggravates the current ripple.

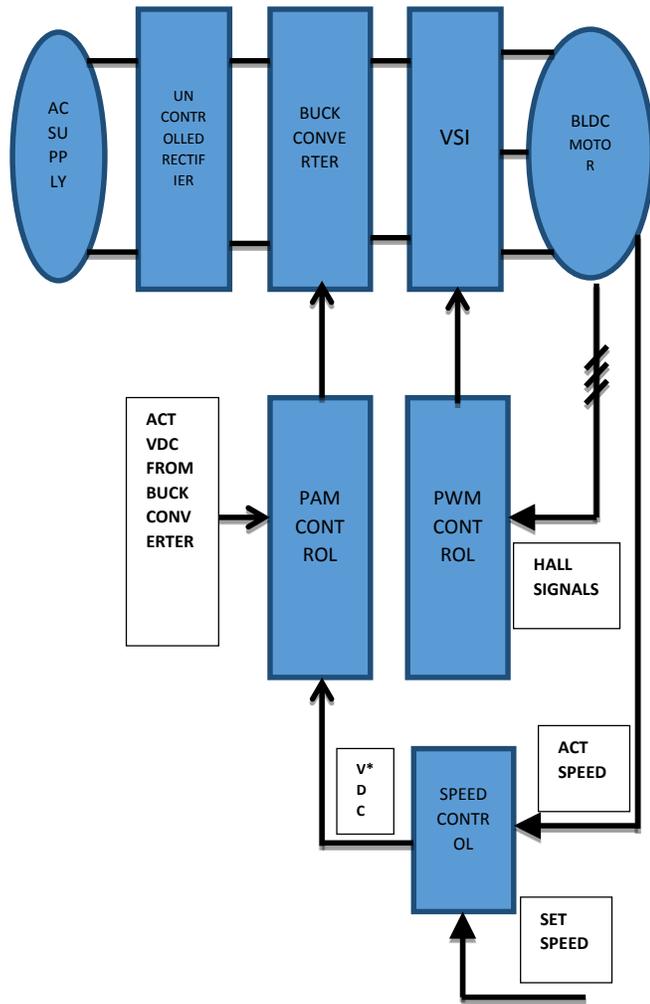
Therefore, a proper hysteresis width is critical to eliminate the unexpected repetitious switching. The proper hysteresis width is selected from many initial experiments, of which accelerate and decelerate the motor to pass the transition region with different hysteresis widths automatically, when the motor first runs. Once  $\Delta n$  is selected, it will be saved and does not need to be calculated in the subsequent experiments.

Considering,  $\Delta n$  can be obtained as

$$\begin{aligned} \Delta n &= \lambda \Delta t \cdot dn/dt + \lambda_1 \Delta n_1 = \lambda \Delta t \cdot 60/2\pi J \\ &\quad \times (TM + \Delta TM - TZ) + \lambda_1 \Delta n_1 \end{aligned}$$

where  $\lambda = 1.5-2$  is the experiential safety factor of the speed fluctuation during the transition,  $\Delta t = T_s/6$  is the commutation interval,  $TM$  is the electromagnetic torque that can be obtained from,  $\Delta TM = -(1-2)TZ$  is a experiential worst torque ripple that the motor can endure,  $\lambda_1 = 1.2-1.5$  is the experiential rate accuracy safety factor, and  $\Delta n_1 = (1-3\%)n+$  is the rate accuracy. In this paper,  $\Delta n$  is set 500 r/min.

3. BLOCK DIAGRAM OF PROPOSED SYSTEM



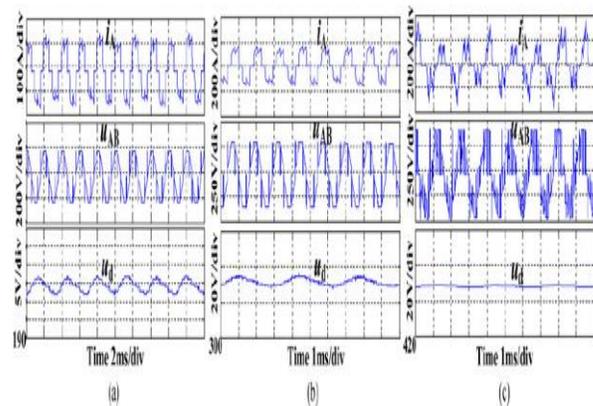
Block diagram of combining PAM and PWM control

3.1. Block Diagram Description

In order to satisfy the commutation control of high-speed BLDC motor in a wide speed range and improve the motor efficiency, a hybrid drives method combining PWM and PAM is proposed. When the motor runs at low speed, the PWM control is adopted with a fixed dc-link voltage. With the motor accelerating, the back-EMF will increase with the speed. When the motor speed reaches a threshold value, i.e., the enough back-EMF can counteract the dc-link voltage, the PAM control works with an adjustable dc-link voltage.

The experiment about the performance analysis comparison and the proposed drive method has been successfully implemented on the experimental high-speed magnetically suspended BLDC motor that coupled to a magnetically suspended generator by a flexible coupling. A variable resistance is taken as the load.

3.2. Commutation Delay Validation



Form of  $i_A$  and  $u_{AB}$  at 6000 r/min under PWM control with the dc voltage equal to 450 V, while Fig. (b) Shows that at 24 000 r/min under PWM control. As explained above, the PWM control will lead to a commutation Delay. Moreover, although this commutation delay can be neglected in a medium speed range, it has a significant influence on the phase current and the drive performance at high speed. When the speed is low as shown in Fig.(a), the commutation delay is inconspicuous. However, when the speed is high as shown in Fig. (b), the commutation delay is so obvious that  $i_A$  and  $u_{AB}$  are seriously distorted. It is well in accord with the operation given when the lagged commutation occurs. Fig. (c) Shows the operation at 24 000 r/min with PAM control. It can be seen that the commutation delay is eliminated and the distortion of  $i_A$  and  $u_{AB}$  is improved greatly.

3.3. Harmonic Content Validation

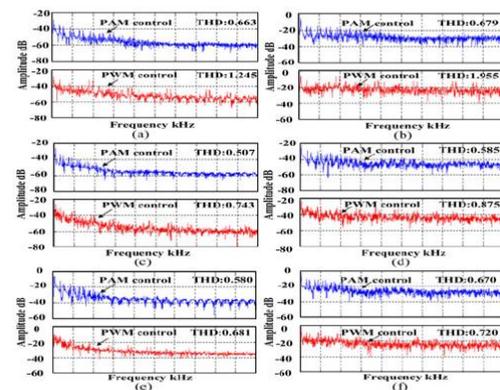


Fig Spectrum map of  $i_A$  and  $u_{AB}$  comparison between PAM control and PWM control at different speeds.

(b)  $u_{AB}$  at 12 000 r/min. (c)  $i_A$  at 20 000 r/min. (d)  $u_{AB}$  at 20 000 r/min.

(e)  $i_A$  at 24 000 r/min. (f)  $u_{AB}$  at 24 000 r/min

Fig. Shows the spectrum map comparison of  $i_A$  and  $u_{AB}$  between the PAM control and the PWM control at different speeds. Fig. (a) and (b) shows the spectrums at 12 000 r/min. We can see that the harmonic component under PWM control is larger than that under PAM control. The THD of  $i_A$  decreases from 1.245 to 0.663, while that of  $u_{AB}$  decreases from 1.955 to 0.679. Meanwhile, Fig. (c) and (d) shows the spectrums at 20 000 r/min. Also, the harmonic component under PWM control is serious.

We can also find from these four figures that when the PWM control is employed, the THD will decrease at high speed. To our best knowledge, this is because that the duty ratio can be maintained at higher level at high speed with the same generator load resistor. However, the improvement of THD is more insignificant than that under PAM control. Fig. (e) and (f) shows the spectrums at 24 000 r/min. Compared with the conditions at 12 000 and 20 000 r/min, the load is heavy due to the high speed. Nevertheless, the PAM control can still decrease the harmonic content greatly. In addition, it is noted that the THD under PAM control at 20 000 r/min is lower than that at 24 000 r/min. Therefore, for PAM control, the THD is not decreased with speed. The relationship between the THD and the speed under PAM control needs further research.

3.4. Motor Power Factor and Efficiency Validation

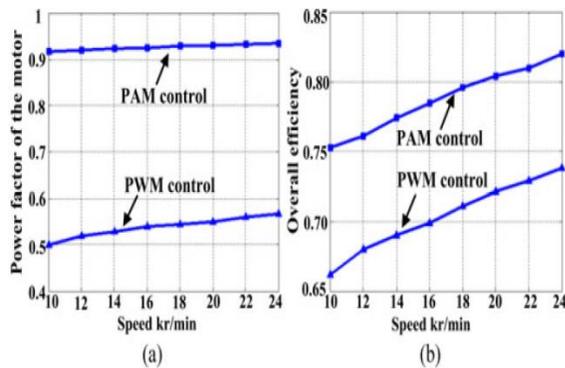
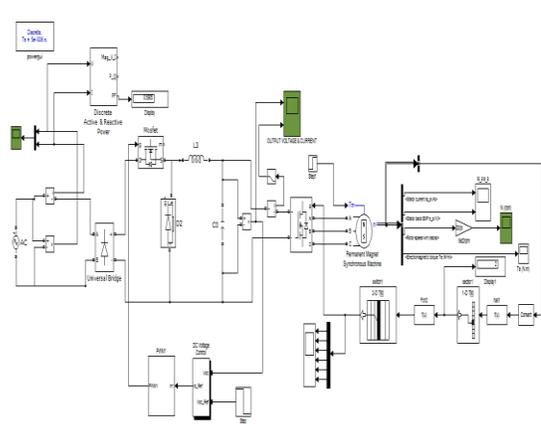


Fig Experimental comparisons of the motor power factor and the motor efficiency under PWM control and PAM control (a) Power factor (b) Overall efficiency.

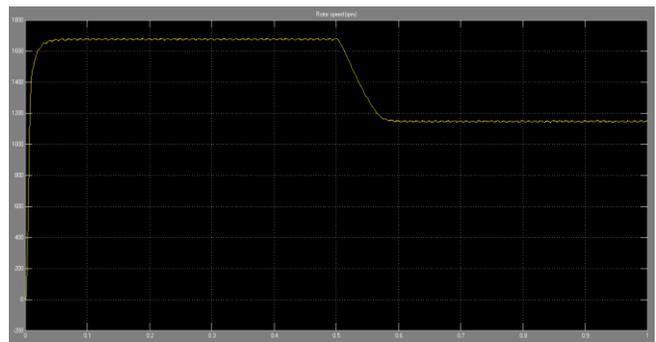
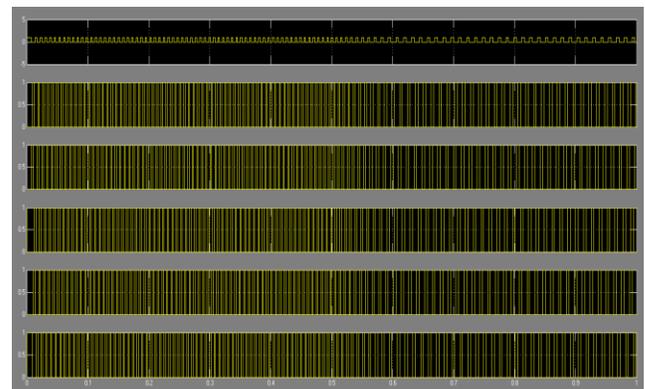
The experimental comparisons of the motor power factor and the motor overall efficiency under the two controls are shown in Fig. Fig. (a) shows the motor power factor. It can be seen that the power factor under PAM control is far higher than that under PWM control due to the less harmonic content and the smaller lag angle. Fig. (b) shows the motor overall efficiency comparison. In this paper, the overall efficiency is defined as the ratio of the generator’s output power to the phase-controlled rectifier’s input power. From Fig

We can see that the overall efficiency is improved under PAM control compared with that under PWM control at high speed, as the increased waveform quality reduces the motor loss and the harmonic content. The overall system loss consists of the motor loss (including the active motor loss and the passive generator loss),  $L1$ , the inverter loss,  $L2$ , the rectifier loss,  $L3$ , and the control system loss,  $L4$ .

4. Simulation Diagram Of High Speed Bldc Motor Operating In A Low And High Speed Range Using A Novel Drive Method



4.1. Simulation Output of Pwm Control



Simulation Output Of Pam Control

## 5. CONCLUSION

The detailed theoretical analysis comparison of the PWM control and the PAM control for high-speed BLDC motor is presented. The criteria for performance comparison include the commutation delay analysis, harmonic component analysis, and motor power factor analysis. Meanwhile, a new high-speed BLDC motor drive method is proposed. It has been shown that the PAM control is superior to the PWM control for providing good performance at high speed by several experiment results.

Unfortunately, the performance comparison between the PWM control and the PAM control at low speed cannot be provided due to the limited experimental condition. However, this disadvantage can be mitigated since the common work speed of the magnetically suspended motor in actual application is between 12000 and 35000 r/min.

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