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An ultra-high speed motor driver with hybrid modulations

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Abstract: An ultra-high speed motor driver with hybrid modulations is proposed in this paper. The speed range of a spindle motor is more wider and trends to ultra-high, but the traditional driver which provides either sinusoidal pulse width modulation or six-step modulation could not support so wide speed range. Normally, the variable voltage variable frequency control is used to support different type motors, then, SPWM is chosen in low speed range drivers and six-step is picked in high speed application. In this paper, the hybrid modulation driver with adjustable DC bus voltage is proposed, and the modulation could be selected for different motor and speed by users. For lower switching power loss, the six-step modulation is better when ultra-high speed application. For low speed range, the trapezoidal PWM is used to replace the SPWM for the reduction of switching power loss. The experimental results show the performance of proposed driver.

Keywords: Ultra-high Speed, Trapezoidal modulation, Hybrid Modulation

1 INTRODUCTION

In most applications, an inverter is the popular solution to driver motors, such as electric vehicles, appliances, machine tool and so on. As the applications increasing, there are many researches studied the control method to enhance the performance of system, and got good improvement [1-3]. But they didn't discuss the ultra-high speed case. As the speed variation is wider, the range of the fundamental frequency supported by inverter is more extensive. These years, it is extended to 300,000 rpm, even to 500,000 rpm. The traditional modulation method, sinusoidal pulse width modulation (SPWM), is considered to implement ultra-speed inverter [4-6], but the switching frequency of power switches are requested to support 20-times higher than the frequency of the sinusoidal, then the material cost will rise and the switching power loss will also up. Another solution is six-step modulation with variable DC bus voltage [7], nevertheless, the current includes big harmonic distortion, and which will cause torque ripple. The other modulation strategies are also discussed: Third harmonic injection modulation could improve the modulation ratio, and it could get the same line to line voltage of motor driven by the lower DC bus voltage[8], but the switching power loss is still the same like SPWM. With variable DC bus voltage, the trapezoidal modulation is used to perform similar modulation ratio effect, but to reduce about 66% of switching power loss [9-11]. A series of the current harmonic distortion are analysis for different kinds of trapezoidal modulation in [11]. Author proposed the hybrid modulation strategy for such kind of wide speed rage [12], with the variable DC bus voltage, the trapezoidal modulation is applied for the low speed range to reduce torque ripple, but the six-step modulation is used to lower the switching power loss when running in high speed range. The simulation results of every modulation method in different speed show the strategy is workable. A hybrid modulation driver for ultra-high speed spindle motors is proposed in this paper, the hybrid modulation strategy will detail, and the driver hardware structure will be described. Finally, the THD of motor current in the experimental results will show the hardware and the modulation method of the proposed driver feasible and valuable.

2 THE MODULATION STRATEGY

2.1 SPWM, third harmonic injection modulation, an d Trapezoidal modulation

The SPWM is a standard and popular modulation method, and the power switch turn-on/-off intervals of three phases are proportional to the voltage of a three phase sinusoidal waveform. If the switching frequency is fast enough, the line current of motor will be also sinusoidal, and the motor rotates smoothly. However, the switching power is proportional to switching frequency. On the other hand, due to property of a power switch, the dead-time is necessary when switching, and it will induce torque ripple. The THD is increasing when the fundamental frequency of sinusoidal waveform is getting higher. So, the fundamental frequency supported by SPWM is limited.

To get higher phase voltage in the same DC bus voltage, the third harmonic injection modulation is proposed [8]. It means the same performance of motor could be driven lower DC bus voltage, and the cost of power switch device is also lower. In other words, the third harmonic injection modulation could improve the modulation ratio. If the original phase voltage is $V_{bus}\bullet\sin(2\pi f)$, the third harmonic with 1/6 amplitude is injected. Then the phase voltage is shown in (1), and VXN3 (X is U, V and W) denotes the phase voltage with third harmonic injection. The phase to phase voltage with third harmonic injection (ex: VUN) is as same as original sinusoidal waveform. As shown in Fig.1, the dash line is the original sinusoid and the dot line is sinusoid with third harmonic, the amplitude of the latter is about 86.5% of the former, but it could perform the same line to line voltage effect in three phase power source.

$$
\begin{aligned}
V_{UN3} &= V_{bus}\cdot\sin(2\pi f)+\frac{V_{bus}}{6}\sin(3\cdot 2\pi f)\\
V_{VN3} &= V_{bus}\cdot\sin(2\pi f+2\pi/3)+\frac{V_{bus}}{6}\sin(3\cdot(2\pi f+2\pi/3))\\
&= V_{bus}\cdot\sin(2\pi f+2\pi/3)+\frac{V_{bus}}{6}\sin(3\cdot 2\pi f)\\
V_{WN3} &= V_{bus}\cdot\sin(2\pi f-2\pi/3)+\frac{V_{bus}}{6}\sin(3\cdot(2\pi f-2\pi/3))\\
&= V_{bus}\cdot\sin(2\pi f-2\pi/3)+\frac{V_{bus}}{6}\sin(3\cdot 2\pi f)
\end{aligned}
\quad (1)
$$

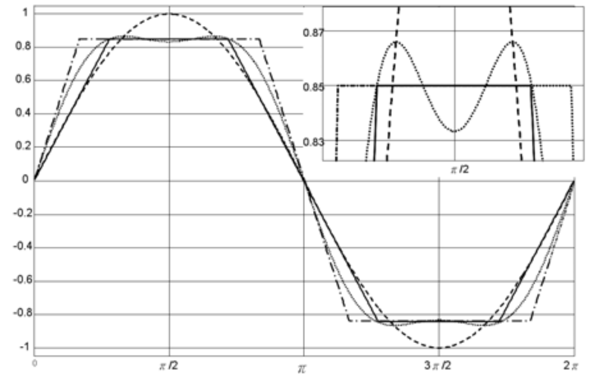


Fig. 1. The comparison of the sinusoid (60Hz), sinusoid with third harmonic and two trapezoids, and the partial zoon-in

From the Fig. 1, the sinusoid with third harmonic approximates to the trapezoids, specifically around the peak portion. Obviously, if the system hardware could provide a variable DC bus voltage and keep the output in a same voltage, the trapezoid is a good choice to approach the sinusoid with third harmonic. The reason is that there is not switching power loss when the output keeps in high or low base voltage. Two trapezoids are shown in Fig. 1, the slops of trapezoids are different. The fig. 2 shows the FFT analysis results of the sinusoid with third harmonic and trapezoids, 'x' denotes the frequency components of the former, then 'o' and '*' indicate the latter's'. The frequency analyses of three waves look similar.

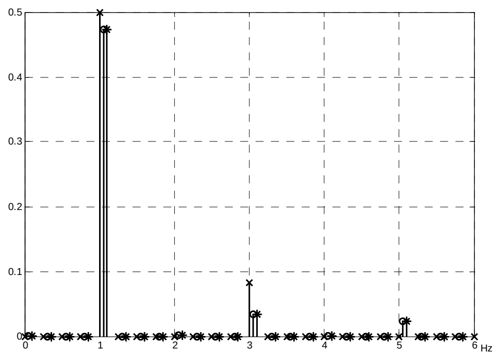


Fig. 2. The FFT analysis results of the sinusoid with th ird harmonic and trapezoids (Note: To identify, the 'o' and '*' are right shifted)

To get high modulation ratio, the sinusoid could be replaced with the sinusoid with third harmonic. And, to reduce the power switching loss, the sinusoid with third harmonic could be replaced by trapezoid with variable DC bus. However, due to the dead-time request of a power switch, a trapezoid is not suitable for ultra high speed.

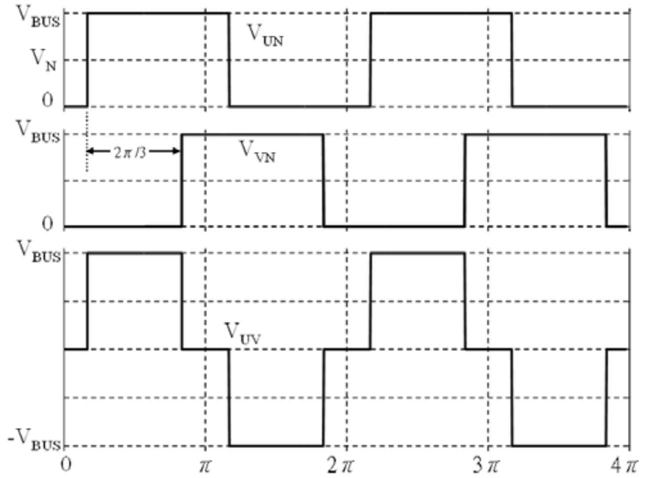


Fig. 3. The six-step modulation and the line-to-line voltage

2.2 Six-step modulation

The Six-step modulation is applied to driver motor in ultra high speed. For three phase driver, every phase is connected to DC bus or ground for a half of a cycle, and the time interval is 1/3 cycle, 2π/3. The phase voltage is shown in Fig. 3. If the fundamental frequency is very high, the phase current will be quasi-sinusoid due to the low pass filter effect of the resister and Inductor (RL) in static coil. This method will introduce bigger harmonic distortion in low speed, but switching power loss is lower than above modulations due to less switching.

2.3 The modulation strategy

To design an ultra-high speed motor driver and lower switching power loss, a hybrid modulation driver is proposed in [12]. The effect is verified by simulation, from THD comparison of the different speed with variable modulation methods. The driver is designed to supply the adjustable voltage of DC Bus, and then a motor is driven by the six-step modulation in high speed range and handled by trapezoidal modulation in lower speed.

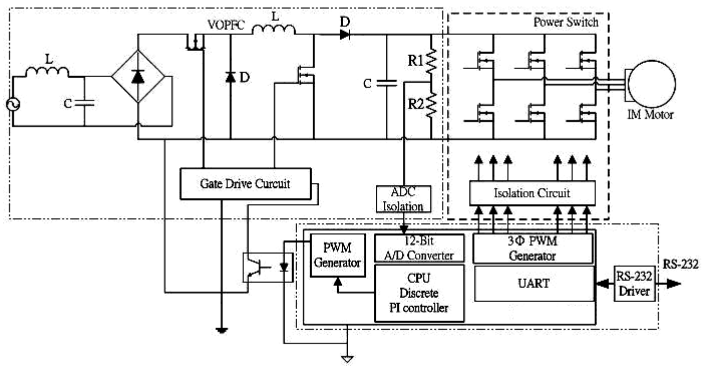


Fig. 4. The system block diagram of the experimental hardware

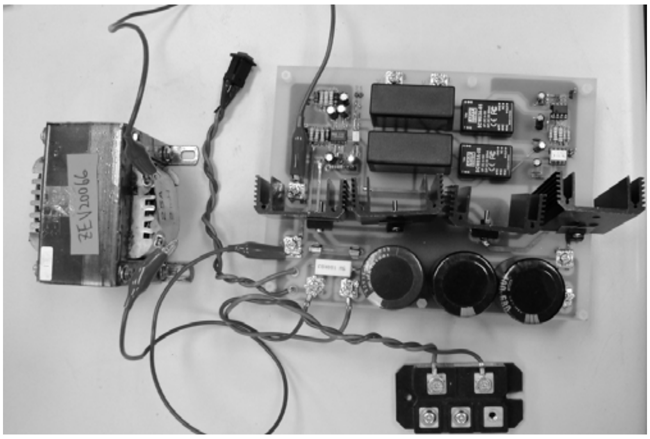
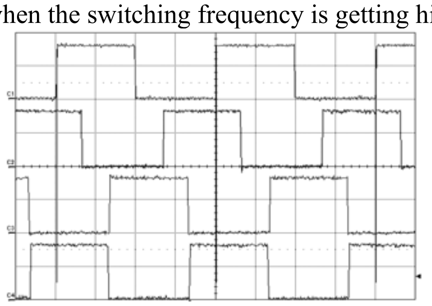


Fig. 5. The photo of the experimental hardware

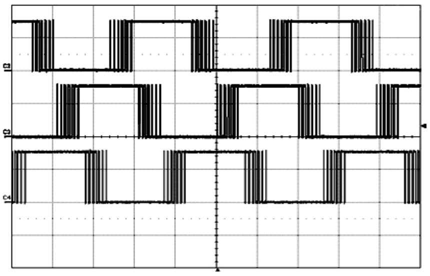
3 EXPERIMENT

3.1 The hardware system

The block diagram and photo of the hardware system are shown respectively in Fig. 4 and Fig. 5, it includes three blocks: the variable output DC bus voltage control block, the power switch block, and control block. To provide a variable voltage, a variable output power factor correction structure is considered, however, only the buck function is used in the experiment. The power switch block is used to perform modulation, and the six switches belong to three legs to supply three phase power. The other block is the control system block, and the controller could be the TI TMS320F28x35 DSP or Renesas RX600 MCU. Note, only the VOPFC block and power switch block are shown in Fig. 5. To prevent shoot through current, the dead time is necessary when switching, both of controllers support the automatic dead time generation function in the build-in PWM peripheral block. However, the dead time will cause the distortion for motor voltage and current, this distortion is worse when the switching frequency is getting higher.

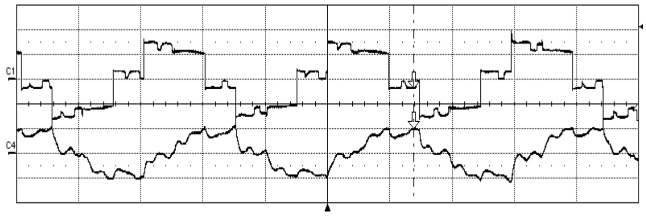


(a)

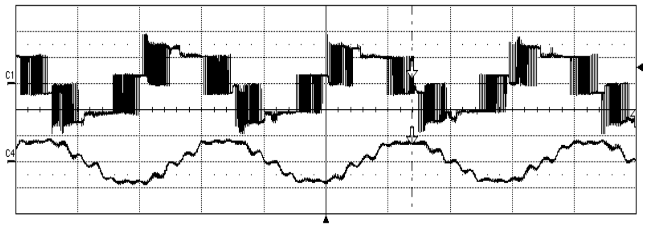


(b)

Fig. 6. The phase voltage of three phases for (a) the six-step modulation and (b) the trapezoidal modulation



(a)



(b)

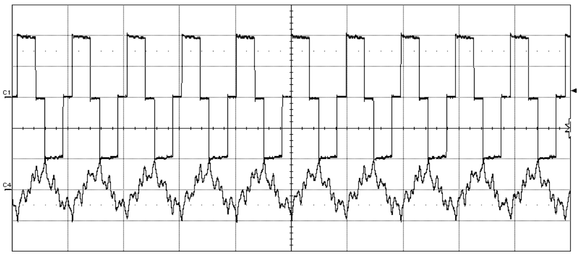
Fig. 7. The line-to-line voltage and phase current run in 10k rpm for (a) the six-step modulation and (b) the trapezoidal modulation

3.2. Experimental results

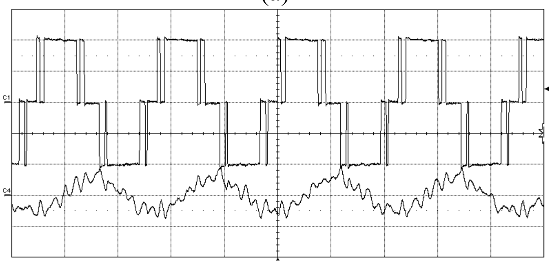
In low speed, the phase voltage of three phases for the six-step modulation and trapezoidal modulation are shown in Fig. 6 (a) and Fig. 6 (b) respectively. Every phase voltage of the six-step modulation is constructed from a 50% duty square-wave, what changes between variable DC bus voltage and ground. To simplify program, the original trapezoid is the dash dot line shown in the Fig. 1, waveform is formed with two straight line segments of 120 degree, one segment is connected to the variable DC bus voltage, and the other is turned to ground. The phase voltage between two segments is the PWM base and the duty is proportional to the slope. However, when motors run in ultra-high speed, due to the dead-time limitation, only the six-step modulation could be performed.

Next, the low speed (10k rpm) experimental results of the line to line voltage and line current for the six-step modulation and trapezoidal modulation are shown in Fig. 7 (a) and Fig. 7 (b) respectively. The current waveform of latter is more similar to sinusoid than formers. Then, the experimental results in middle speed (130k rpm) are shown in Fig. 8, and the two current waveforms are not different. And, for high speed (here is the 300k rpm), the experimental current of the six-step modulation is shown in Fig. 9, the current looks more like sinusoid than the current in low speed. Although only the six-step modulation could be applied in ultra-high speed range, it is more suitable for higher speed.

To compare the effect of two modulation method, the THDs of the motor current are measured and shown in Fig. 10. In low speed, the THD of the trapezoidal modulation is lower than the six-step modulation's, and it means former is more suitable to implement. As the speed is increasing, the THD is getting higher. However, the THD of the six-step modulation will reduce when over 130k rpm, it shows that the six-step could be used to driver in ultra-high speed. Note, due to instrument issue, the vertical-axle scale of Fig. 10 is skipped.



(a)



(b)

Fig. 8. The line-to-line voltage and phase current run in 130k rpm driven by (a) the six-step modulation and (b) the trapezoidal modulation

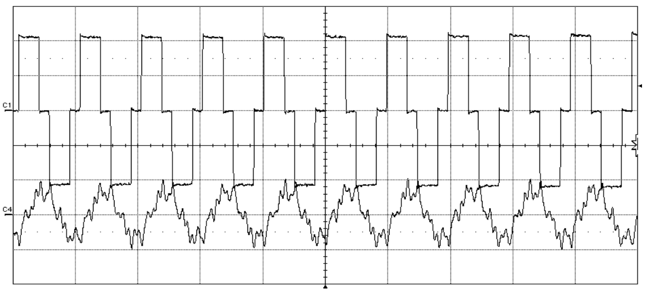


Fig. 9. The line-to-line voltage and phase current run in 300k rpm driven by the six-step modulation

4 CONCLUSION

An ultra-high speed motor driver with hybrid modulations is proposed in this paper. Due to dead-time limitation and reduction of switching power loss, the six-step modulation is considered to driver motor in ultra-high speed range. But in low speed range, the trapezoidal modulation is implemented into the driver, for the similar THD but lower DC bus voltage. Depended on the property of a motor, for different speed, the modulation method could be selected to provide better driver current and lower torque ripper.

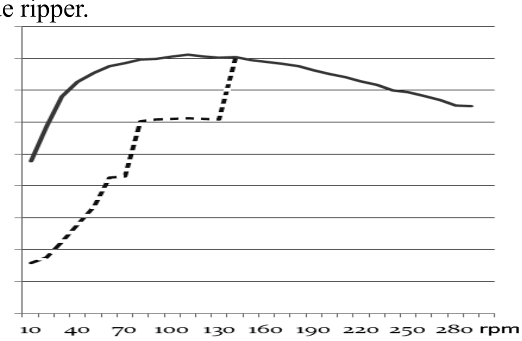


Fig. 10. The THD comparison between the six-step modulation (solid) and the trapezoidal modulation

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