MICROSTEPPING CONTROL OF STEPPER MOTORS WITH DATA INTERPOLATION AND DIRECT VOLTAGE CONTROL

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Abstract

This paper presents a novel approach for microstepping control of a low-power stepper motor (SM) for an automotive dashboard instrument application with a direct connection of a low-cost microprocessor. The microstepping operation of the SM is very important to indicating instrument applications, for example, meters for fuel, battery, speed, oil, and engine revolution. The proposed system uses pulse-width modulated output and digital output pins of a microprocessor for low-cost implementation. In order to perform a smooth positioning operation for an indicator application, a simple low-pass filter (LPF) and modified sine data table are introduced.

The modified sine data table is produced by injected harmonics to reduce the low-frequency harmonics of the SM phase voltage. Also proposed are the S-curve function for the smooth position reference and the amplitude control of the motor phase voltage depending on motor acceleration and deceleration speeds. The S-curve function provides a smooth response while maintaining high acceleration. The proposed voltage amplitude controller can change the motor phase voltage according to the motor speed to compensate the back-electromotive force (EMF) at high speed and to reduce the torque ripple in the low-speed region. The proposed system is implemented with a low-cost, 8-bit microprocessor without any external memory and power devices. The effectiveness of the proposed control scheme is empirically verified by a practical automotive dashboard instrument system.

Introduction

The SM is widely used in an open-loop position control system for its inherent stepping-position operation characteristics without any feedback loop [1-3]. Today, low-power and small-size SMs are extensively adapted as indicating instruments on the dashboards of automotive vehicles [4-6]. In an indicating instrument system, the SM controller should perform positioning smoothly. In order to achieve smooth positioning, a microstepping mode using a pulse-width modulation (PWM) approach is an excellent choice [3], [7-9]. Some applications use the multi-phase SM for smooth operation; however, the drive system of the multi-phase SM is more complex than a conventional two-phase one [10-15]. In this paper, a low-cost dashboard indicating system is developed using a low-power SM which is directly connected to a microprocessor.

The proposed system uses the PWM output and the digital output pin of a microprocessor for each motor phase winding. The phase current can flow from the PWM pin to the digital pin during the positive voltage region, and it can flow in the opposite direction from the high active digital pin to the PWM pin in the negative voltage region.

In order to perform smooth positioning, a simple LPF and a modified sine data table are introduced to reduce the low-frequency harmonics of the motor phase voltage. The modified sine data table is produced by injected harmonics to reduce the harmonics of the motor phase voltage. Further proposed in this paper are the S-curve function for smooth position reference and amplitude control of phase voltage in connection with acceleration and deceleration. The S-curve function can generate the position reference with respect to the measured frequency for smooth indication with the SM.

The voltage amplitude controller can produce enough phase voltage to compensate for the back-EMF when the motor operates with high speed in the fast acceleration and deceleration region. Similarly, the amplitude of the phase voltage is decreased to reduce the torque ripple in the low acceleration and deceleration region from the low speed and low back-EMF of the motor.

The proposed system is designed with a low-cost, 8-bit microprocessor without any external memory and power device. The effectiveness of the proposed control scheme is verified with a practical automobile dashboard system. The experimental results show the smooth positioning of the dashboard indicator system.

Conventional Microstepping Operation

Figure 1(a) shows a conventional H-bridge circuit for an SM and its bipolar switching method for the microstepping operation. Different from the conventional full-step and half-step operation modes, the microstepping operation can indicate the precise rotating angle, using sinusoidal phase voltage with PWM technology, as shown in Figure 1(b).

The output torque of the SM can be derived by the phase current and vector summation of each phase torque [7]. The phase current equation can be summarized as follows:

$$i_{as} = I_m \cdot \cos\theta_e \qquad (1)$$
$$i_{bs} = I_m \cdot \sin\theta_e$$

where, i_{as} and i_{bs} are phase currents of phase A and phase B. I_m denotes the current per phase. θ_e is the electrical position of an SM.

The resulting torque generated by the corresponding phases is derived by

$$T_{ma} = K_T \cdot I_m \cdot \cos\theta_e \qquad (2)$$
$$T_{mb} = K_T \cdot I_m \cdot \sin\theta_e$$

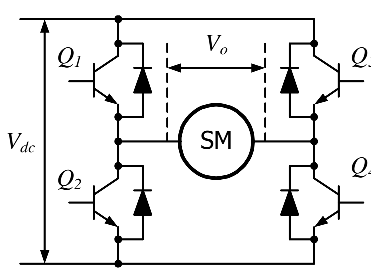
where K_T is the torque constant of the motor [7].

The total torque of the motor can be derived by the vector summation of the torque phases as follows:

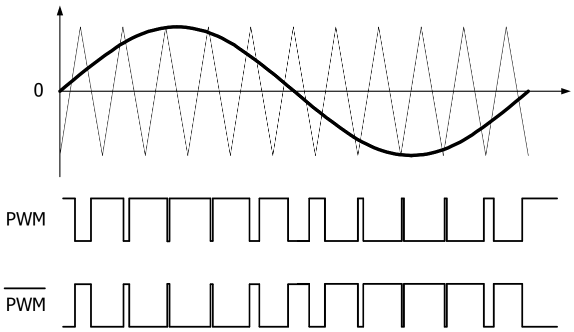
$$(3)\, T_m = \sqrt{\left(T_{ma}^2 + T_{mb}^2\right)} = K_T \cdot I_m$$

In order to produce sinusoidal phase voltage and phase current, the conventional methods use a complex digital-to-analog converter (DAC) and a comparator circuit for PWM switching. The phase current is limited for stable operation.

In this paper, a simple microstepping operation scheme for the SM is directly connected to a low-cost microprocessor, and a passive LPF is introduced and applied to a dashboard indicator. The proposed scheme uses a simple modified sine table for reduction of low-frequency harmonics.



(a) H-bridge circuit per phase of a SM



(b) Bipolar switching for microstepping operation

Figure 1. H-bridge circuit and bipolar switching for microstepping operation

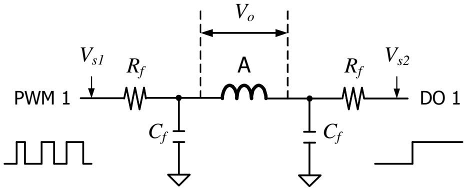
Proposed Direct Microstepping Operation(2)

PWM and Digital Output with a Passive Filter

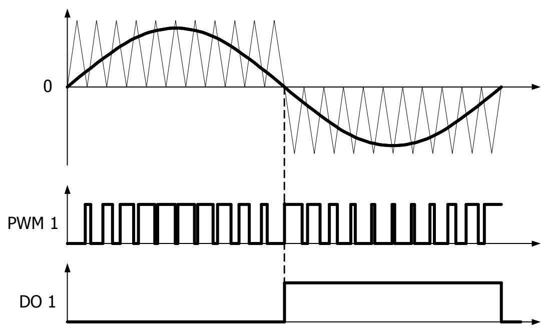
Also presented here is a direct microstepping operation scheme using PWM and the digital output of a low-cost microprocessor is proposed. In the front-end of the phase winding, a simple passive LPF is connected to reduce current ripple from PWM switching. The SM is designed for low-power consumption operating at 5V. The phase current is under 20mA, so the motor can be directly operated by the microprocessor output pin without an H-bridge converter or amplifier.

Figure 2(a) shows the passive LPF circuits for each phase and pin connection between the microprocessor and the SM. In Figure 2(b), ‘PWM 1’ and ‘DO 1’ are output pins of the microprocessor. In the positive voltage region, phase current can be generated by the ‘Low’ output of the digital pin and positive PWM output as shown in Figure 2(b). In the negative voltage region, phase current can be generated by the ‘High’ output of the digital pin and the negative PWM output.

The pulse duty ratio is controlled by the sine table according to the reference position of the SM and amplitude gain according to acceleration and deceleration. The digital output signal is changed according to the reference position. The digital output is kept at the ‘Low’ signal for 0 to 180 electrical degrees, and ‘High’ signal for 180 to 360 electrical degrees.



(a) Passive filter and pin connection per phase



(b) Signal output of PWM and digital output for sinusoidal waveform

Figure 2. The proposed phase connection and signal waveforms

The phase current flows from the PWM pin to the digital pin in the positive region, and flows from the digital pin to the PWM pin in the negative region. In the positive region from 0 to 180 electrical degrees, the terminal and phase voltages can be derived without the filter as follows:

$$\begin{aligned} V_{s1} &= d \cdot V_{cc} \\ V_{s2} &= 0 \\ V_o &= V_{s1} - V_{s2} = d \cdot V_{cc} \end{aligned} \tag{4}$$

where d is the duty ratio of the PWM and V_{cc} is the control voltage of the microprocessor.

In the negative region, from 180 to 360 electrical degrees, the terminal and phase voltages can be derived as follows:

$$\begin{aligned} V_{s1} &= (1-d) \cdot V_{cc} \\ V_{s2} &= V_{cc} \\ V_o &= V_{s1} - V_{s2} = -d \cdot V_{cc} \end{aligned} \tag{5}$$

From these relationships, the phase voltage can be controlled by the PWM duty ratio.

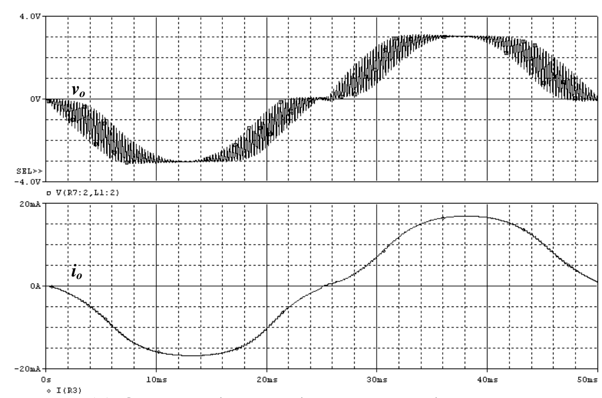
In order to supply a sinusoidal phase voltage, the internal memory of the microprocessor is used for the sine table. Figure 3(a) shows the output phase voltage and current with the passive LPF in conventional 8-bit PWM data.

As shown in Figure 3(b), the conventional sine data produces low-frequency harmonics in phase voltage and current, such as 3rd and 5th harmonics. The switching harmonics has a high-frequency component which slightly affects the position error. But, the low-frequency harmonics can produce an additional position error in the microstepping operation. In order to reduce the low-frequency harmonics, a modified sine table for 8-bit PWM signal is used. The modified sine table is generated with an additional harmonic injection to reduce the 3rd and 5th harmonic frequencies in the output voltage and current as follows:

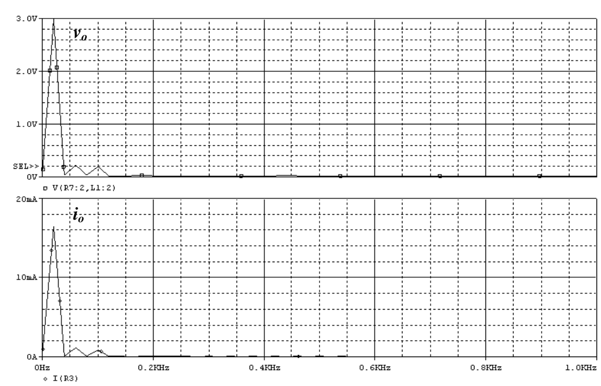
$$PWM[\theta] = 128 \cdot \sin(\theta) + a \cdot \sin(3\theta) + b \cdot \sin(5\theta) \tag{6}$$

where a and b are the injected harmonic coefficients of the 3rd and 5th harmonic frequencies, and where 6 and 4 are used for a and b respectively.

Figure 4(a) shows reduced low-frequency harmonics in the phase voltage and current with modified sine data. By comparison with Figure 3, the modified sine data with injected harmonics can reject the low-frequency harmonics. This pure sinusoidal phase current can produce a constant torque in any position.

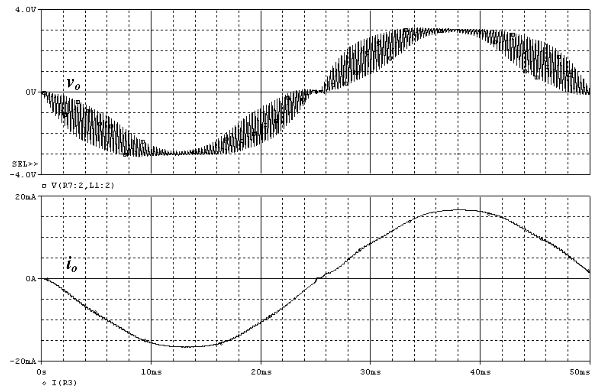


(a) Output voltage and current per phase

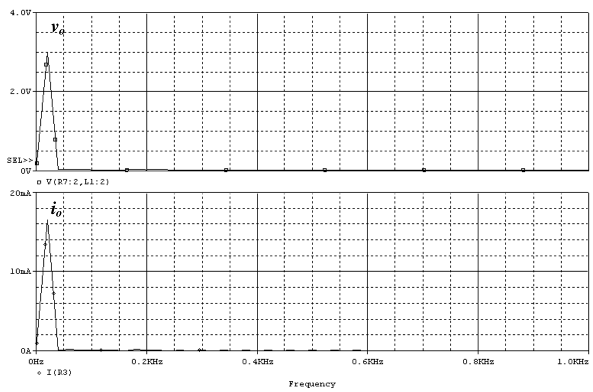


(b) FFT analysis of output voltage and current

Figure 3. Output characteristics of a conventional sine table



(a) Output voltage and current per phase



(b) FFT analysis of output voltage and current

Figure 4. Output characteristics of the modified sine table

Voltage Controller

Smooth torque control is essential in order to reduce the vibration of an indicator. In a conventional open-loop position controller of an SM, simple acceleration and deceleration curves are used without any current control. The conventional method is very simple, but the same torque at a different speed can cause indicator vibration.

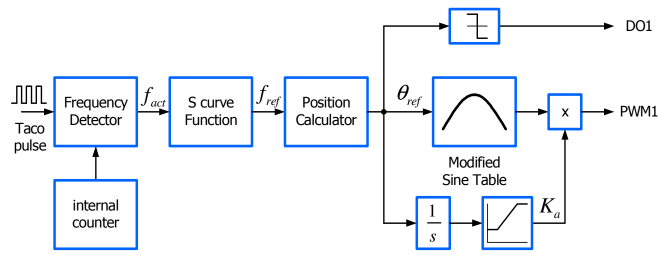
In this paper, a simple voltage control scheme to adjust the output torque of an SM according to motor speed is proposed. The variable voltage can change the phase current and output torque. The practical voltage controller is implemented by a PWM duty ratio control in order to change the PWM duty cycle by the position and motor speed and is given by

$$D = K_a \cdot \mathrm{PWM}[\theta_{ref}] \qquad (7)$$

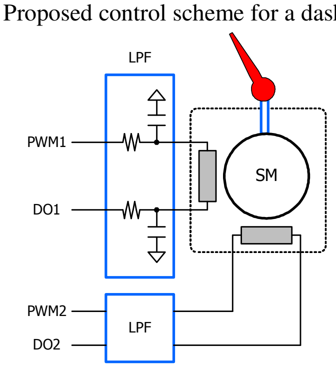
where D is the duty ratio of the PWM data. PWM[θ_{ref}] is the PWM data determined according to the reference position as described in equation (6). K_a is the proportional gain according to the motor speed and is lower than 1 as follows:

$$K_a = \lim(\,\omega_{ref} / \omega_{base}\,) \qquad (8)$$

Figure 5(a) shows the proposed control scheme for the dashboard indicator. In order to reduce the indicating vibration, the phase voltage is controlled in relation to acceleration and deceleration. K_a, shown in Figure 5(b), denotes the amplitude gain of the PWM data according to the acceleration of the position reference. During fast acceleration, the amplitude gain is increased and the duty ratio of the PWM can be increased to increase the phase voltage.



(a) Proposed control scheme for a dashboard indicator



(b) SM connection

Figure 5. The proposed control scheme of a dashboard indicator using a low-power SM

For fast acceleration, the speed and the back-EMF of the SM should be increased with respect to the motor speed. In order to compensate the back-EMF in relation to increasing speed, phase voltage should be increased. In the proposed control scheme, the amplitude gain can control the phase voltage according to the motor speed. If the acceleration is decreased, the amplitude gain is decreased to decrease the phase voltage.

Experimental Results

In order to verify the proposed control scheme, an experimental test setup was implemented. A digital controller was designed using the ATmega16 8-bit microprocessor from ATMEL Corporation. The practical indicating instrument consists of one SM for indication and a 4-digit liquid-crystal display (LCD) for user display. The SM was directly connected to the PWM output and digital output pins of the ATmega16 with a simple passive LPF for each phase. The SM has an internal gear train with a ratio of 180:1, and the mechanical accuracy is 0.3° per step. Figure 6 shows the implemented experimental test setup for the proposed control scheme.

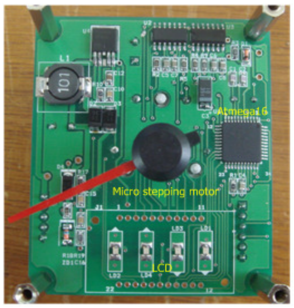
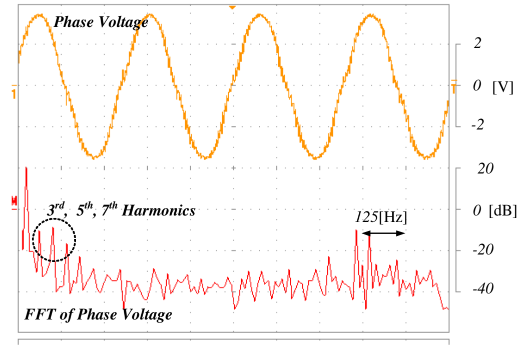


Figure 6. Experimental system

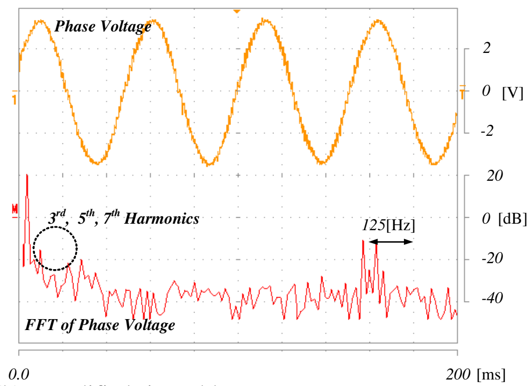
Figure 7 shows the phase voltage and the fast Fourier transformation (FFT) analysis of the SM under test with respect to the conventional sine and the modified sine data to reduce the low-frequency harmonics. As shown in Figure 7, the modified sine data can reduce the low-frequency harmonics with injected harmonics.

Figure 8 shows the experimental results at a 100Hz input frequency according to both sine tables. The measured frequency, the S-curve position reference, and the motor phase voltages are displayed in Figure 8. The amplitude of the phase voltage is fixed. The phase voltage waveform has low-frequency harmonics with the conventional sine table, as shown in Figure 8(a). However, the waveforms of the phase A and B voltages were closer to sinusoidal with the modified sine table without low-frequency harmonics, as shown in Figure 8(b).

Figure 9 shows the experimental results of the proposed control scheme at 100Hz and 300Hz input frequencies. The amplitudes of the phase voltages were changed by acceleration and deceleration. Compared with Figure 8(b) with a constant phase voltage, the amplitude of the phase voltage was not constant and the value was controlled by the speed, as shown in Figure 9. The low-phase voltage in the low-speed region reduces the phase current and the output torque. This is because the load torque of the indicator needle was almost the same, but the practical torque depends on the acceleration and deceleration torque. This variable phase voltage according to acceleration and deceleration can reduce the indicating vibration of the SM.

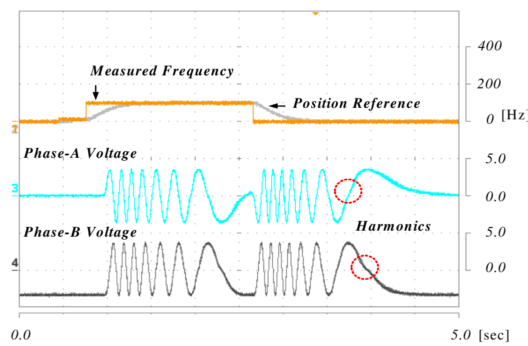


(a) Conventional sine table

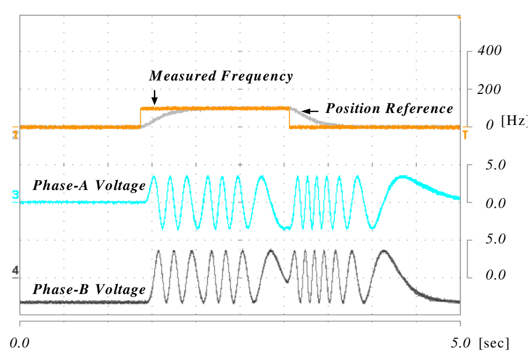


(b) Modified sine table

Figure 7. The phase voltage and FFT analysis

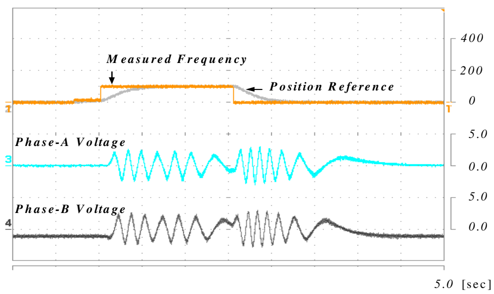


(a) Conventional sine table

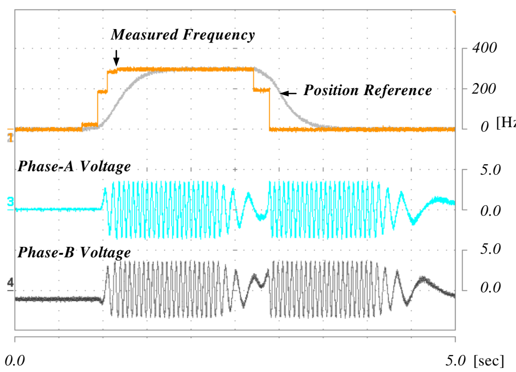


(b) Modified sine table

Figure 8. Experimental results at 100Hz input



(a) At 100Hz input



(b) At 300Hz input

Figure 9. Experimental results of the proposed control scheme with two different input frequencies

Conclusions

This paper presents a microstepping operation of an SM which was connected directly to a microprocessor for an automotive dashboard indicator application. In order to implement smooth indicating, the modified sine data table with a simple LPF was used. The FFT analysis showed that the modified sine data can reduce the low-frequency harmonics significantly. In addition, an internal S-curve function for producing a smooth reference position from a detected input frequency was designed.

The amplitude of the phase voltage was controlled by the acceleration and deceleration of the reference position to reduce the indicating vibration. In the proposed control scheme, the amplitude of the phase voltage could be easily controlled by the amplitude gain, and the gain changes the actual duty ratio of the PWM data from the sine table.

The proposed system uses a PWM and digital output pins for each phase, allowing any low-cost microprocessor to be used for the dashboard indicator application. From the experimental results, the proposed system does a good job of controlling the SM with regard to the input frequency that eliminates low-frequency vibration.

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