A Low-power Sensorless Inverter Controller of Brushless DC Motors

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***Abstract*— A low-power sensorless inverter controller is designed for brushless DC (BLDC) motors without using any Hall sensor. A back-EMF (back-electromotive force) estimation method is adopted to detect the commutation moment for rotation control of the brushless DC motors. The position of the rotor can be precisely estimated by measuring the back-EMF as well as the zero-crossing points. The proposed controller is low power and low cost because of not using expensive power consuming Hall sensors. The proposed sensorless inverter controller is integrated in a standard mixed-signal single-poly, and six metal 0.18-μm CMOS process.**

***Keywords*—sensorless, brushless, motor, low-power, inverter, BLDC.**

I. INTRODUCTION

Power requirements of large motors in home appliances dictate the overall power consumption of a house, e.g., air conditionings, washing machines, refrigerators, and water pumps. The BLDC motors probably are the most widely-used motors in these applications, [1], [2]. The conventional controls of motors are quite simple: either ON or OFF. However, such a simplicity will result in lots of collateral damages, e.g., high power dissipation, large noise, large harmonics, and heat problems. If the motors are driven by inverters, e.g., air conditionings, they are no longer controlled by a simple switch to be turned on or off. On the contrary, the rotation speed and the direction of the motors will be automatically adjusted by certain well-developed algorithms such that the temperature will be kept stable, and the power consumption is reduced. Hence, by adopting inverters, not only is the motor power saved, the noise, harmonics, and heat problems are also expected to be resolved.

The development of such a motor inverter controller IC is particularly important to the widely used DC motors in home appliances as shown in Fig. 1. Although advanced microprocessors with high computing capability and execution speed are used in motor control [3], certain interface ICs are still required in the set-up of these motor control systems [4]. The target controller IC is composed of an 8-bit MCU, a PWM (pulse width modulation), a zero crossing detector, an ADC (analog-to-digital controller) [1], and a residue amplifier (RA). Meanwhile, the position and the speed of the rotor can be detected and estimated by back-EMF [5] without using Hall sensor nor any encoders. Notably, when the rotation is about to be reversed, the detection of the rotor position becomes extremely critical. The features of the controller IC is particularly suitable for the control of the brushless DC motors.

II. DESIGN OF THE SENSORLESS INVERTER CONTROLLER

Fig. 2 shows the block diagram of a brushless DC motor control system using the proposed sensorless inverter controller. The description of each subcircuit is given in the following text.

A. 8-bit Microcontroller

Regarding the development of modern motor control systems, most of the central processing units are implemented by the digital signal processors (DSP). Although DSPs possess higher speed and precision than general-purpose microprocessors, they suffer from the overhead of area, cost and large power consumption. Considering low power consumption and low cost, we need to develop a special-purpose 8-bit motor controller with a power saving control unit (PSCU), to accomplish low power, low cost and high precision [2].

We propose an 8051-compatible microcontroller with a power-saving algorithm based upon feedback signals from the zero-crossing detector and the ADC in this work. Fig. 3 shows the hierarchical block diagram of the 8-bit motor controller.

B. PWM Generator

In traditional PWM generator designs, every output channel has its own registers to store the parameters that produce waveforms. In motor control systems, six channels have six groups of registers to generate the required voltage waveforms. However, PWM signals applied to the motor control system have an interdependent relationship among the control signals. Then, the output of six signals can be simplified with a single group of registers to reduce area cost [6] as well as power consumption. Fig. 4 shows the function of PWM generator. The inputs are the system clock and the reference clock of the

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rotational speed. The period of the output PWM signals will follow the reference clock's period. Therefore, we can control the output PWM signals frequency and consequently control the rotational speed of the brushless motor. The control flow of this part is implemented in the PSCU by a standard ASIC design flow.

C. Zero-Crossing Detector

A low power comparator circuit is employed in this work to implement the zero-crossing detector whose power consumption is less than 0.84 mW. The schematic is shown in Fig 5. Table I shows the characteristics of the comparator. The slowest transfer time is 58.0 ns which is far more than enough to carry out the zero-crossing detection.

D. Analog-to-Digital Converter

Since the speed estimation algorithm is executed in the microcontroller, an ADC is needed to convert the analog non-excited phase back-EMF signals to digital signals. In order to reduce the power consumption of ADC, we adopt the charge-redistribution successive approximation (SA) architecture [7] in this work, as shown in Fig. 6. A binary search through all possible quantization levels is performed to obtain the final digital value. In order to avoid the drastically increased area of the binary-weighted capacitor array due to the higher resolution of SA ADC, a 6-bit binary-weighted capacitor array and a 4-bit resistor string DAC are combined to construct the 10-bit DAC. Additionally, a four-stage comparator is utilized such that the input voltage difference is amplified stage by stage. Thus, the input equivalent capacitor of the comparator can be reduced so that the matching of the binary-weighted capacitor array is ensured.

E. Residue Amplifier

It is obvious that RA has to carry out an accurate estimation of the voltage difference between the neutral voltage and the average of the voltages on the three phase windings [8]. In other words, it must estimate the non-excited back-EMF. The detailed circuit is shown in Fig. 7.

$$V_{out} = V_{natural} - \frac{1}{3} \cdot (V_a + V_b + V_c), \tag{1}$$

where $V_{natural}$ is the neutral voltage, V_a, V_b, V_c denotes the terminal voltages of the three phase windings, V_{out} is the output of the OPA.

Although Cheng et al. proposed an RA design in [8] basing on a capacitive reset gain amplifier [7], the operational amplifier (OPA) therein drastically affects the overall performance, including speed and noise immunity. For instance, the common-mode voltage, Vcm, which is coupled to the minus input of the OPA might be vulnerable to the power supply noise or the vibration of the motor. An additional CMFB (common-mode feedback) circuit and a bandgap bias, thus might be needed to regulate the Vcm. What is worse that such an extra feedback loop might introduce an extra low-frequency pole to deteriorate the speed performance and the DC gain. Meanwhile, the detailed schematic as well as the analysis in the prior works were never studied and explored.

Referring to Fig. 7, the architecture of the proposed RA is revealed. Notably, the minus input of the OPA is permanently ground due to two simple thoughts : First, since the speed of the BLDC motor (≈KHz) is far less than switching speed of MOS transistors (≈MHz), the noise in the high-frequency is unlikely to contaminate the low-frequency band of the motors, the CMFB and bandgap bias can be removed without causing any noise problem. Second, the poles introduced by the extra feedback loop can be avoided. By a similar thought, the offset voltage compensation biases are no longer needed. Therefore, the overall cost will be drastically reduced. In short, the RA can be modified to be the cost-effective design as shown in Fig. 7.

III. IMPLEMENTATION AND SIMULATION

The function of the proposed sensorless inverter controller is verified on FPGA with discrete components. In order to evaluate the power consumption and reduce the area, the proposed design is further implemented by a standard and full-custom 0.18-μm single-poly and six metal CMOS technology to verify the power consumption. Fig. 8 shows the layout of the inverter controller. Fig. 9 shows the off-chip driver and a test connector which we can measure the output signal of our design. Fig. 10, 11, 12, respectively, show that the output of the zero-crossing detector closely matches with the ideal signal of the Hall sensor given different rotation speeds. Therefore, Hall sensors of the motor will no longer be required in inverter control systems.

IV. CONCLUSION

We have proposed a low-power sensorless inverter controller for brushless DC motors to attain low power consumption and low cost, but still maintain the high precision operation. The proposed design would relax the load of the motor engineers to develop motor products.

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	Propagation delay (ns)			
	Raising edge		Falling edge	
V-	Fastest	Slowest	Fastest	Slowest
0.825 V	18.2	28.8	27.0	58.0
1.650 V	23.6	40.4	19.1	35.4
2.475 V	29.6	50.2	15.8	31.0

TABLE I

ZERO-CROSSING DETECTOR TRANSFER TIME

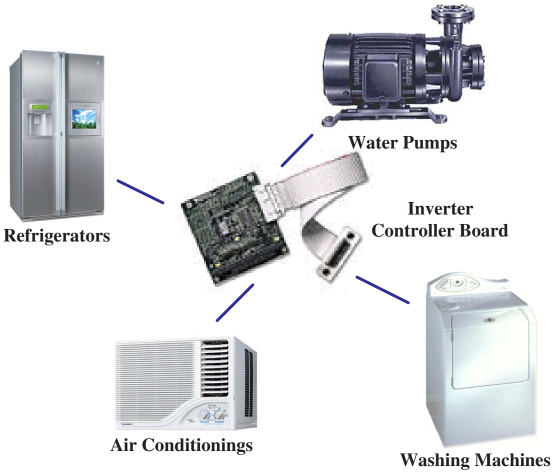


Fig. 1. Applications of the sensorless inverter controller

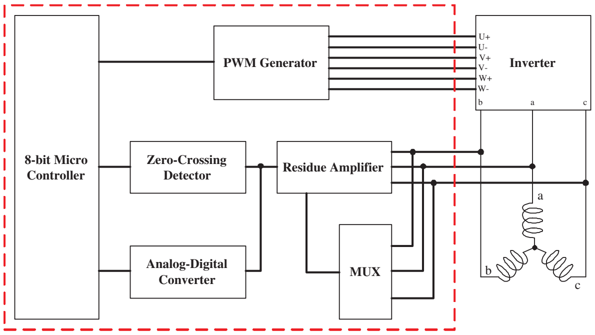


Fig. 2. Block diagram of a brushless DC motor control system with the proposed sensorless inverter controller

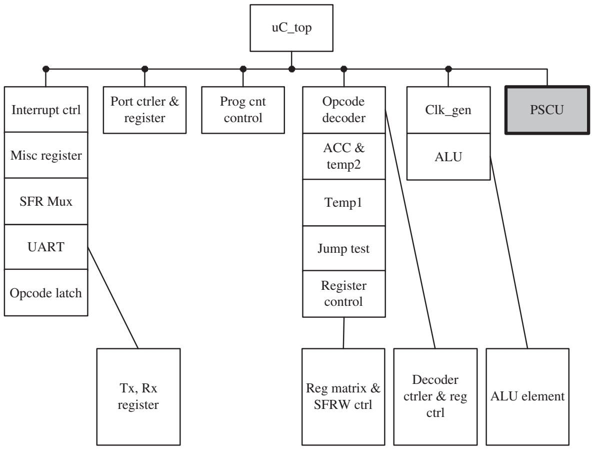


Fig. 3. Block diagram of the 8-bit motor controller

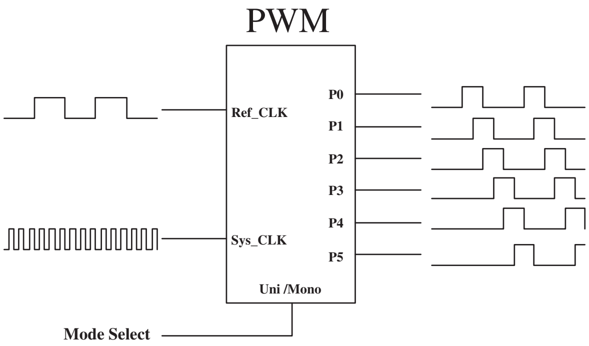


Fig. 4. Function of PWM generator

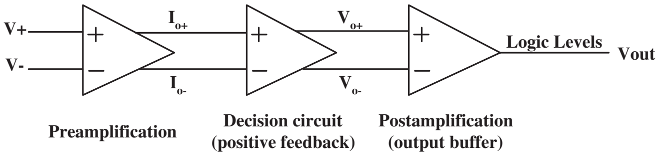


Fig. 5. Schematic of the zero-crossing detector

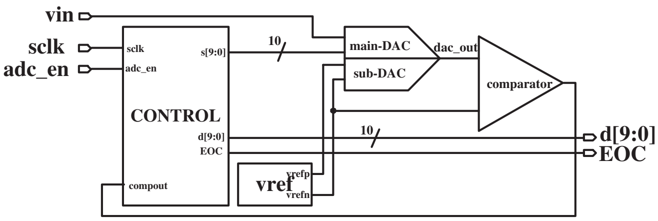


Fig. 6. Architecture of charge-redistribution successive approximation ADC

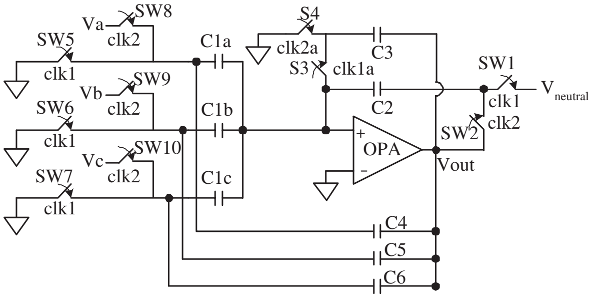


Fig. 7. Schematic of the residue amplifier

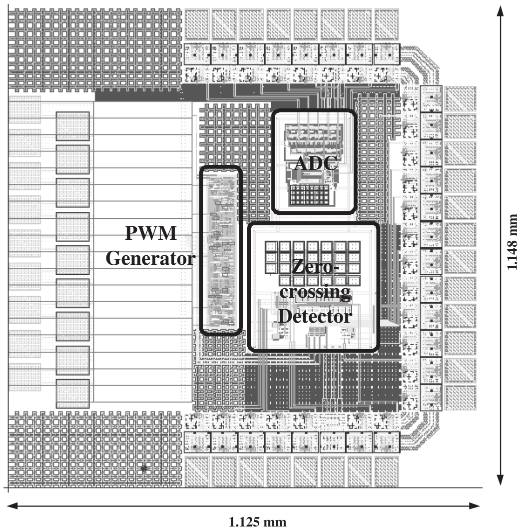


Fig. 8. Layout of the inverter controller without 8-bit MCU

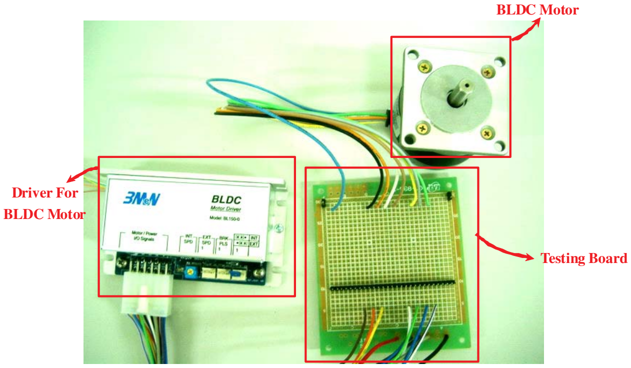
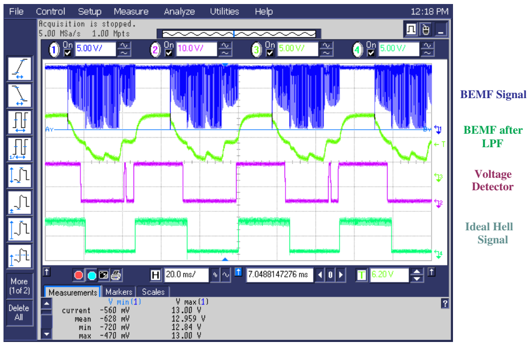
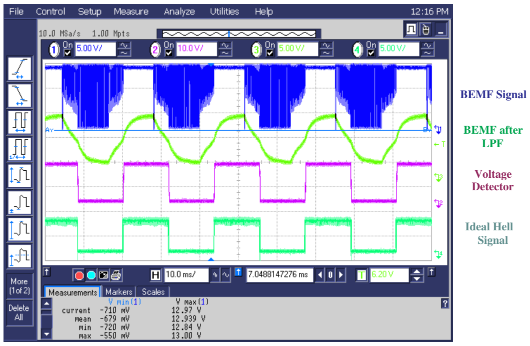


Fig. 9. Off-chip driver and the connector



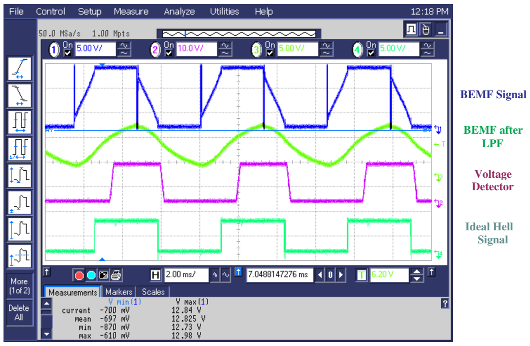
```
           V min(1)        V max(1)
current  -560 mV          13.00 V
   mean  -628 mV          12.959 V
    min  -720 mV          12.84 V
    max  -470 mV          13.00 V
```

Fig. 10. Output of the design (rotation speed = 300-rpm)



```
           V min(1)        V max(1)
current  -710 mV          12.97 V
   mean  -679 mV          12.939 V
    min  -720 mV          12.84 V
    max  -550 mV          13.00 V
```

Fig. 11. Output of the design (rotation speed = 1500-rpm)



```
           V min(1)        V max(1)
current  -700 mV          12.84 V
   mean  -697 mV          12.825 V
    min  -870 mV          12.73 V
    max  -610 mV          12.98 V
```

Fig. 12. Output of the design (rotation speed = 4500-rpm)