This paper proposes a new control scheme for the implementation of a low-cost and high efficiency sensorless speed control IC for single-phase brushless dc (BLDC) fan motors. The proposed control scheme detects the zero-crossing-point (ZCP) of the measured back-EMF to generate commutation signals without Hall sensor. A current mode soft switching scheme is used to smooth the current spikes induced by the reduction of the back-EMF when the rotor is crossing the commutation boundary. An adaptive blanking time control strategy is used to adjust the time interval to ensure correct detection of the ZCP. An open-loop constant Ampere/Hertz ramping control scheme is developed for the startup control from zero speed and switching to sensorless mode once the ZCP is detected. The proposed sensorless control scheme has been verified by using computer simulation based on a developed single-phase BLDC fan motor model. Experimental verification of the proposed control scheme has been carried out by using digital implementation technique. Experimental results reveal the superior performance of the proposed control scheme.

Index Terms—single-phase brushless dc fan motor, sensorless control, adaptive blanking time control, soft commutation, soft start-up control, digital motor control IC.

I. INTRODUCTION

Single-phase brushless dc fan motors are widely used in nowadays personal computers and notebooks for thermal cooling [1]. The Hall sensor is usually used to provide feedback information of the magnetic rotor of the single-phase BLDC fan motor for proper commutation control. The Hall sensor IC requires a further installation procedure, sensitive to temperature variation, degraded in high temperature operating environment, and limits the power density of the fan motors. To lower the system installation cost, this Hall sensor is packaged with the driver IC as a component unit. However, this driver IC still needs extra components for operation settings and a PCB is required to be installed within the motor. To further reduce the cost, development of sensorless control techniques for the single-phase BLDC fan motor is required. Power density and efficiency are most important performance indices for high-performance fan motors [2]. A sensorless control IC can also eliminate the installation of the driver PCB within the motor housing package, this provides advantages of lower cost and motor with smaller size.

A general review of position-sensorless control of three-phase permanent-magnet machines has been given in [3]. However, these methods are not suitable for single-phase BLDC fan motors because of there is no unexcited winding for the detection of back-EMF voltage foe sensorless control. The single-phase BLDC fan motors have one important feature is the adoption of asymmetrical air gap to eliminate the zero-torque zone. This asymmetrical air gap complicates the generation of its electromagnetic torque and degrades its efficiency. High torque peaks are commonly found in single-phase BLDC motors. Different PWM driving schemes have been studied based on finite-element analysis (FEA) in [4] and it is suggested to insert a dead-zone into the driving signals to improve current waveforms and torque envelop. However, it did not provide more information about how to generate these driving signals.

A time-sharing method based on the concept of phase advance control of the PWM commutation signals has been developed in [5]. However, this method is based on the voltage mode control of the PWM signals and is sensitive to commutation noises during low-speed operation area. Current-mode control of the phase current can achieve better torque control performance of sensorless BLDC motors. A current mode control method with commutation tuning has been proposed in [6]. However, this method employed step current control without considering of practical flux distribution and the tuning algorithm is unsuitable for speed change control. To solve these problems and improve the motor efficiency over a wide speed control range, this paper proposes a new sensorless control method for the current-mode control of single-phase BLDC fan motors with a pre-defined modulation signal for the reduction of torque ripples to achieve best efficiency performance over a wide speed control range. The proposed scheme has been realized with DSP control software and compared with other control schemes. Experimental results reveal the superior performance of the proposed control scheme. The proposed control scheme can also be realized with specific digital control logic circuits and is suitable for the mixed-signal IC realization.

II. OPERATIONAL PRINCIPLE AND MODELING

Fig. 1 shows the photograph of a four-pole single-phase BLDC fan motor, its rotor structure, and the normalized measured flux linkage distribution. Modeling of a motor is a key step for the controller design. The asymmetrical air gap

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of the single-phase BLDC motor makes it difficult to obtain a small-signal mode for control loop analysis and design. The analysis and modeling of a single-phase BLDC motor with a bifilar winding and asymmetrical stator pole faces has been reported in [7]. The modeling method is based on the measured stator winding flux linkage with a derived state model of the developed electromagnetic torque. However, this nonlinear state model is unsuitable for practical design method in synthesis of the current mode controller.

The torque generation process is the essential characteristic of an electric machine. The torque generation of a single-phase BLDC motor is quite similar with a DC motor with permanent magnet stator. The alternating current applied to the phase winding of a single-phase one-winding BLDC motor just like the DC current applied to a PMDC motor, in which the mechanical commutator convert this DC current to an alternating current to the armature windings. However, due to its asymmetric rotor structure of the single-phase BLDC motor, its instantaneous torque becomes nonlinear and more complicated for design and control. The electromagnetic torque of a single-phase BLDC motor consists of two components: the cogging torque and the excitation torque. The cogging torque is generated by the magnetic-motive force (MMF) of the permanent magnet rotor functioning with the varied air-gap reluctance. The cogging torque is resulted by the motor design and should be kept to a minimum for smooth and efficient operation. The excitation torque is generated by the phase current functioning with the rotor MMF and can be controlled to achieve better torque responses.

The modeling of the excitation torque can be characterized by the rotor MMF distribution. A simplified dynamic model based on specified nonlinear element is proposed in [8] and is adopted to construct the small-signal model for current loop compensator design. The electrical equation of a single-phase BLDC motor can be described as

$$ V_{ab} = L_s \frac{di}{dt} + iR_s + V_{emf} \quad (1) $$

where $V_{ab}$ is the terminal voltage of winding, $R_s$ is the winding resistance, $L_s$ is the winding inductance, $i$ is the phase current, and $V_{emf}$ is the back-emf voltage. Fig. 2 shows the block diagram of the single-phase BLDC fan motor with nonlinear flux linkage distribution and load-torque characteristics. The flux distribution of the rotor MMF is used to characterize the generated torque and back-emf voltage. This model has been constructed and used for the simulation and design of the proposed sensorless current-mode control scheme.

**III. DIGITAL CURRENT MODE CONTROL**

Fig. 3 shows the proposed current-mode sensorless speed control scheme for single-phase BLDC fan motors used in applications to PC and NB cooling systems. High efficiency, low acoustic noises, and robust start-up control are fundamental requirements for these applications. The proposed controller includes a speed estimator for the detection of zero crossing of back-emf voltage and estimation of rotor speed, a speed controller to generate the desired current command for torque control, a current controller to generate the PWM control duties for the H-bridge PWM

Fig. 1. (a) Single-phase brushless dc fan motor, (b) rotor structure, and (c) normalized flux distribution.

Fig. 2. Block diagram of the single-phase BLDC fan motor with nonlinear flux linkage distribution and load-torque characteristics.

Fig. 3. Block diagram of the proposed sensorless speed control scheme.

Fig. 4. Block diagram of the digital current-mode control scheme.
During the switches pre-turn off period, the winding current is decreased to zero, the terminal voltage is equivalent to the back-EMF voltage and can be used for the detection of the commutation instant.

A synchronous sampling of the PWM switching signal has been used for the detection of the zero-crossing of the back-emf signal for sensorless commutation control. The proposed current-mode control scheme with DC-link feedforward control is illustrated in Fig. 4. A pre-defined flux distribution waveform has been used for the table look-up in modulation of the torque command and is synchronized with the sensorless commutation signal to generate the current command with an adjustable dead zone for the current mode controller.

To synthesize the digital current loop controller, small signal analysis of the current loop has been carried out. Fig. 5 shows the block diagram of the digital current control loop of the single-phase BLDC fan motor with a PWM switching amplifier. The analog design approach with loop gain fitting technique is adopted in the synthesis of the current loop controller to reach a bandwidth of 10% of its switching frequency. The analog controller is then transformer to the corresponding digital controller by using bilinear transform.

Fig. 6 shows the loop gain of the designed digital current control loop.

Verification of the designed digital current controller. Fig. 7 shows the incremental responses. It can be observed the rise time is about 190 μsec which corresponding to a bandwidth of 1.84 kHz for an approximation of an equivalent of a second-order linear system.

In order to improve the current response and overall efficiency, the motor phase current should be controlled in proportional to its back-emf voltage. The average output power converted by the motor can be expressed as

$$P_{av} = \frac{1}{2}(E_n I_1 \cos \phi_1 + E_2 I_2 \cos \phi_2 + E_3 I_3 \cos \phi_3 + \cdots)$$

where $E_n$, $I_n$ is the harmonic of back-EMF and phase current, respectively. In the conventional approach, the fan motor is under an open-loop PWM control scheme with commutation signal the synchronized with the Hall signal. However, current phase lag due to winding dynamics may result spiky current. Soft commutation with ramping controlled PWM duties can smooth these current spikes, however, they are still sensitive to parameter variations and operating points, and a time-consuming fine tuning process is required for different fan motors. To improve the efficiency of the fan motor drive, each back-EMF and phase current harmonic should be in phase, that is $\Phi_n$ should be zero.

There is only a single stator winding of a single-phase one-winding brushless DC fan motor and therefore, there is
no left floating winding for the detection of the back-emf voltage. In order to detect the back-emf voltage, we need to let the stator winding unexcited for a specified time interval. During the steady-state operation condition, a pre-defined blanking time can be inserted before the PWM on-period as illustrated in Fig. 8. Once the zero crossing point (ZCP) of the back-emf voltage is detected, it can be used as a synchronization signal for the commutation control of the phase current and a dead zone is inserted to generate a modulated phase current command as illustrated in Fig. 9. To ensure a correct detection of the ZCP, the dead-zone time interval is increased linearly with the torque command. The proposed digital current control scheme can control the phase current to be synchronized with a quasi-sinusoidal current reference with adaptive blanking time control.

II. START-UP CONTROL

A common problem associated with the sensorless motor drive is the start-up control performance [9, 10]. Without a stable start-up procedure, the motor may fail its start-up or running into a self-oscillation fault running mode. Most sensorless control methods are based on back-EMF, however, when motor is at standstill or low speed, the detection of ZCP of back-EMF voltage can be corrupted by switching noises or voltage induced by the spiky current of the free-wheeling diodes. To solve this problem, this paper developed a robust current-controlled start-up method based on motor cogging torque induced by the asymmetric air-gap.

Fig. 10 shows the proposed sensorless start-up procedure. It consists of three steps: alignment of the rotor, ramping current control for start-up, sensorless control to the target speed. The alignment of the rotor can result a same initial condition for the rotor. With a dc excited current, the rotor will align to its magnetic pole from a random initial position as shown in Fig. 11. A step exciting current for the rotor alignment may induce oscillations and results large variations of the settling time. A ramping exciting current can smooth its alignment and reduces the settling time. Fig. 12 shows the transient responses of the proposed sensorless start-up method. It can be observed the phase current starts up with a quasi-sinusoidal waveform, as the speed is increased, it will switched to the voltage mode control with soft commutation control.

Fig. 13 shows the experimental setup and Fig. 14 shows measured performances under different testing conditions. It can be observed that the single-phase motor can achieve smooth start-up responses under different target speed control. Fig. 15 shows the performance measures of the RMS values of phase current with different control schemes. It can be observed that the proposed current mode control with soft commutation control has achieved best performance within the full speed control range.
V. CONCLUSION

This paper has presented an innovative control scheme for the implementation of a low-cost and high efficiency sensorless speed control IC for single-phase brushless dc (BLDC) fan motors. The proposed control scheme detects the zero-crossing-point (ZCP) of the measured back-EMF to generate commutation signals without Hall sensor. Practical implementation issues of the digital current mode sensorless control scheme have been addressed. Experimental results show the proposed current mode control with soft commutation control has achieved best performance within the full speed control range.

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