CHAPTER 1

INTRODUCTION

1.1 Motivation

Large portion of electrical energy production in developed countries is consumed for ventilation and air conditioning in commercial and residential areas [1-3] and for similar applications in the industrial sphere. Also it is well-known that adjustable speed drives (ASD) can be used in these fields to achieve great energy saving effect for partial loads by lowering motor speeds. On the other hand, permanent-magnet brushless dc (PMBLDC) motors have been used in wide applications for their benefits of easy speed controllability and long life time expectation. Moreover, by using high energy product magnets, such as neodymium-iron-boron (NdFeB), a PMBLDCM can provide rather high power density, high torque and high efficiency [4-6]. In fact, due to the necessity of small volume and weight, PMBLDCM are now replacing rapidly the traditional induction motors for variable frequency control of air conditioning units and compressors. However, the resulting mechanical noise due to the torque ripples of the PMBLDCM remains to be further improved without increasing too much extra cost. Therefore, in this dissertation, a new phase-locked loop (PLL) adjustable speed controller for PMBLDC motors is proposed to further improve the dynamic response of the controller and reduce the drive cost.

1.2 Literature Survey

By adopting PMBLDC motors for ASD applications, there remains two problems to be concerned, namely the reduction of mechanical vibration noise and the implementation cost. For the first problem, although various methods have been proposed to improve the robustness or enhance the load disturbance rejection [7-9], the PLL control can provide more accurate speed regulating control of motor [10-16]. In fact, the more accurate speed regulation comes from the better current loop control. Hence, the torque ripples are reduced simultaneously to reduce the mechanical vibration noise. However, unlike applying to control signal synchronization [17-18], stable implementation of the PLL control for adjustable speed motor drives is rather difficult to achieve due to the large motor inertia. Hence, most existing PLL motor speed controllers are mainly implemented for constant speed control [10-14]. In [15] a proportional control mode is used for transient response and another phase-locked loop is then used to control the motor at a fixed speed. Although this scheme can achieve stable transient response and high steady state accuracy for adjustable speed drives, the controller requires to switch between two operation modes. In other words, if the two modes can be further integrated to provide a smooth and automatic transition, then the dynamic response can also be improved.

Next, the hardware implementation cost of the PMBLDC motors drives are needed to be considered. In the PMBLDC motor drive, the current sensing method which senses the motor stator current for the drive control circuit dominates the partial cost of the drive implementation. There are many current sensing methods which have been proposed to do the effort of cost reduction. Normally, the Galvanic isolated current sensors such as Hall-effect current sensors [7], [19-21], are more popularly used to measure the intensity of the magnetic field generated by the phase current. Usually two Hall-effect current sensors are required to be mounted on the output lines of the inverter. They may be occupying more than 20% cost of the drivers. These Hall-effect current sensors with field-based current sensing scheme can effectively sense current signals but are quite expensive and too hulky to be integrated into the control chip. Another scheme, like IR2175 as shown in

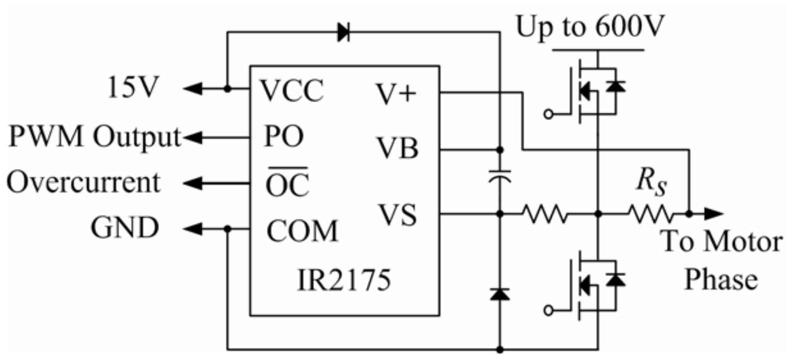

Fig. 1.1 Circuit diagram of the linear current sensing IC, IR2175, for the motor phase current sensing.

Fig. 1.1, is developed by International Rectifier Company [22]. This component senses the motor phase current through an external shunt resistor and converts the sensed signal from analog to digital, then transfers the signal to the low side. Also the high voltage isolation technology is adopted in this chip to ensure the high bandwidth signal processing. The output signal is a digital pulse-width-modulation (PWM) form which can eliminate additional A/D input interface for the IR2175. This sensing scheme can also provide Galvanic isolated phase current signal for the control circuit. But, due to requiring special high voltage isolation technology for implementation, it is too complicated, expensive and hard for further control circuit integration. Although intelligent power module [23] or integrated pilot current sensing module are proposed by the T. M. Jahns et al. [24-34] to act as the power switch which provides the conducting current signals while power switch of the inverter is turned ON. These integrated pilot current sensors are integrated directly with the gate driving circuits of the power switches to reduce the cost and size of inverters. However, by using this current sensing scheme, as all of the power switches of the inverter are turned OFF, portion of the stator current signal will be lost because the conducting

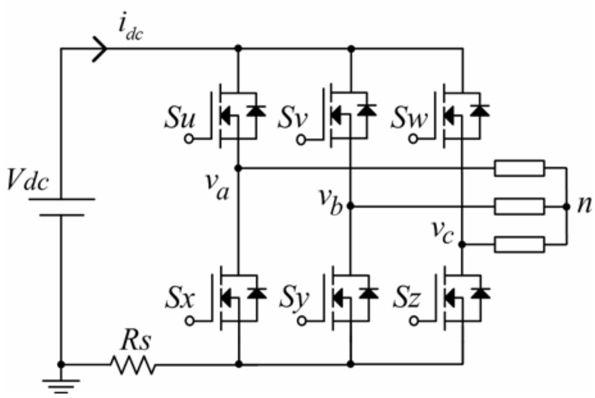

Fig. 1.2 The dc-link current sensing method for the motor phase current sensing.

current is flowing through the body diode of the inverter power switches. There are many current reconstruction or estimation methods which have been proposed [23-34] to compensate this drawback. However, due to complicated reconstruction algorithm, they are still not feasible for practical applications. On the other hand, references [35-41] provide a simple current sensing scheme for PMBLDC motor drives as shown in Fig. 1.2. In Fig. 1.2 one can see that, in addition to the power switches, a shunt resistor is connected between the bottom power switches and the common ground. The phase current signal is obtained by measuring the voltage drop of the shunt resistor. The merit of this sensing scheme is simple, cost saving for reducing the number of current sensors and elimination of potential load imbalances caused by unequal gains of the output terminal current sensors [41]. The resulting measured signal of the PMBLDC motor current is available while the windings of the PMBLDC motor are powered by the inverter at the ON time of the switches (operated under active mode), or the power is regenerated by the PMBLDC motor while the power switches of the inverter are OFF (operated under regenerative mode). But, portion of the PMBLDC motor current signal may be lost while the upper or lower switches of the inverter are turned ON which isolates the PMBLDC motor current flow from the dc-link voltage source (operated under freewheeling mode). Therefore, the measured current signal of this sensing scheme can be applied for over current protection of the power switches of the inverter, but it is hard to be applied to the torque loop current control. Besides, according to the control strategy [38], the voltage across the phase windings will alternate between positive and negative dc-link voltages. This will cause higher energy circulation in machine and result in a small reduction in efficiency and creating higher torque ripples which is now a well-known fact as can be seen in [19]. Hence, in this dissertation a PWM control strategy which includes both the two operational modes, namely, active mode and regenerative mode, as [19] and an additional mode, namely freewheeling mode is proposed to avoid the energy circulation and reduce the torque ripples. Also in this dissertation a novel equivalent armature current sensing, synthesizing and controlling scheme is first proposed which is implemented by using programmable logic devices (PLDs) [42-44] to integrate with the PWM control of the switches to achieve complete motor current information as well as to avoid the energy circulation and reduce size, weight and cost. Then, a simple and cheap PLL assisted adjustable speed controller is proposed for PMBLDC motor drives to achieve both the merits of cost saving and acoustic noise reduction.

1.3 Contributions of the Dissertation

Basically, the main contributions of this dissertation can be summarized as follows :

First, an equivalent dc brush motor model for the concerned three-phase PMBLDC motors has been proposed to simplify greatly the drive control and make the low cost system integration feasible.

Second, a novel tri-mode control and synthesis scheme of the equivalent armature current for the PMBLDC motor has been proposed. The major contributions of the proposed current sensing, synthesizing and controlling scheme are as below:

(a) Compared with the conventional Hall-effect sensing method, the proposed equivalent armature current sensing technique is more simple, compact, cheap and easy for chip implementation.

(b) Compared with the intelligent power module sensing method which senses the motor current through the power switches of the inverter, the proposed current sensing technique is rather simple and can obtain complete information of the motor currents for torque ripple control.

(c) The proposed tri-mode current control strategy can effectively eliminate high energy circulation in machine and reduce the torque ripples.

Third, a novel phase-locked loop assisted adjustable speed controller for PMBLDC motor drives is proposed. The major advantages of the proposed PLL adjustable speed controller are as below:

(a) A PLL assisted adjustable speed control strategy is proposed to achieve fast transient response and high speed control accuracy.

(b) Comparison with the existing PLL motor speed controllers which are implemented for constant speed control, the proposed PLL assisted speed controller can automatically lock the system speed while the system speed is changed.

(c) Mathematic approximation model of the phase frequency detector is derived which is helpful in closed loop analyses of the proposed control system.

(d) Closed form expressions of k_P and k_I parameters are derived to rendering the design of the proposed control rather easy.

(e) Design criteria of the controller parameters have been proposed to guarantee the stability of the proposed control system.

Fourth, the novel current controller is implemented by using programmable logic devices (PLDs) to integrate with the PWM control of the switches to achieve complete motor current signal as well as to avoid the energy circulation and reduce size, weight and cost. A prototype of the proposed controller is constructed and is applied to an industrial blower testing system which is driven by a self-designed PMBLDC motor to verify the feasibility of the proposed controller. The experimental results of the testing system are summarized as below:

(a) The experimental result of the nonzero current magnitude waveforms of the equivalent armature current are quite uniform and can closely track the constant current command $i_s(t)$ except at the commutation instants.

(b) The proposed controller can effectively suppress the commutation electromagnetic torque ripples automatically through forcing $|di_b/dt| \cong |di_c/dt|$ during the phase current transition interval for both low and high speed conditions.

(c) Under steady state, the motor speed pulse train (f_r) can indeed track the speed command pulse train (f_s) without speed error.

(d) Under transient conditions, the proposed drive system can provide rather smooth responses electrically and mechanically.

(e) The proposed drive system can effectively save the power consumption by 20% at rated speed and reduce the total volume and weight by 30% and 57% respectively compared with the traditional three-phase induction motor driving blower.

1.4 Outline of the Contents

The contents of this dissertation can be outlined as follows:

In chapter 2, the mathematical model of the conventional dc brush motors as well as the PMBLDC motors are reviewed in advance as a basis. Then the mathematical model of the proposed equivalent dc brush motor for the concerned three-phase PMBLDC motors is proposed for the drive control. From the derived model, one can see that the electromagnetic torque of the PMBLDC motor is proportional to the magnitude of the equivalent armature current of the PMBLDC motor. This linear relationship makes the instantaneous control of the PMBLDC motor become more easy and convenient by properly regulating the motor equivalent armature currents.

Therefore, in chapter 3, a novel low cost equivalent armature current sensing and synthesizing scheme is proposed. The proposed technique can provide the complete information of the phase current and is integrated sophisticatedly with the PWM control of the inverter switches. Moreover, a tri-mode control strategy of the PMBLDC motor is also introduced to avoid the energy circulation in machine and effectively suppresses the commutation electromagnetic torque ripples automatically.

In chapter 4, in order to hold in the advantages of fast dynamic response, no limitation of speed lock range and high speed control accuracy, a PI type PLL assisted adjustable speed controller is proposed. In section 4.2, the control strategy of the proposed speed controller is described. In section 4.3, the closed form expression of parameters k_P and

k_I of the PI controller is deduced by using a robust internal reference model control method. Also the stability analyses of the proposed closed-loop speed controlled system are made in the last section.

In chapter 5, the prototype of the proposed controller is constructed. Also by applying the proposed PLL assisted adjustable speed controller and a self-designed PMBLDC motor to an industrial blower, some experiments are made to validate the feasibility of the proposed control.

Finally, some conclusions are offered in the last chapter.