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Direct Torque Control of Brushless DC Drives With Reduced Torque Ripple

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***Abstract*—The application of direct torque control (DTC) to brushless ac drives has been investigated extensively. This paper describes its application to brushless dc drives, and highlights the essential differences in its implementation, as regards torque estimation and the representation of the inverter voltage space vectors. Simulated and experimental results are presented, and it is shown that, compared with conventional current control, DTC results in reduced torque ripple and a faster dynamic response.**

***Index Terms*—Brushless dc (BLDC) drives, direct torque control (DTC), permanent-magnet motor.**

I. Introduction

THE permanent magnet brushless ac (BLAC) and brushless dc (BLDC) drives [1], [2] are used extensively for many applications, ranging from servos to traction drives. They differ primarily in their current and back-electromotive-force (EMF) waveforms. In a BLAC drive, the phase current is controlled by a pulsewidth-modulation (PWM) inverter to have a sinusoidal waveform and vector control is often employed, while in a BLDC drive, the PWM phase current has an essentially rectangular waveform. In theory, a permanent magnet brushless motor with any back-EMF waveform can be operated in either BLAC or BLDC mode, although, in practice, it is desirable for a BLAC motor to have a sinusoidal back-EMF waveform and BLDC motor to have a trapezoidal back-EMF waveform in order to minimize the torque ripple and maximize the efficiency and torque capability. A sinusoidal back-EMF waveform can be obtained by skewing the stator slots and/or rotor magnets, employing a distributed stator winding, shaping the magnets, or employing a sinusoidal magnetization distribution. BLDC motors often employ concentrated windings [2], since these result in shorter end windings, which is conducive to a high efficiency and torque density. Further, while BLAC drives require a precision rotor position sensor, such as encoder, BLDC drives only require discrete position sensors, such as Hall devices [1], [2]. Therefore, in general, BLDC drives are relatively low cost. This paper focuses on the control of such BLDC drives.

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Generally, BLDC drives employ current control, which essentially assumes that the torque is proportional to the phase current. Since, in practice, the relationship is nonlinear, various current control strategies have been adopted to minimize torque pulsations, by employing pre-optimized waveforms for the reference current, for example. Such an optimal current excitation scheme was proposed in [3], which resulted in minimal copper loss and ripple-free torque from a BLDC drive. However, it was based on the d–q axes transformation, and could not respond to rapid torque changes. A current controller which estimated the electromagnetic torque from the rate of change of coenergy was described in [4]. However, in its implementation to a BLDC drive, the estimated torque was obtained from a lookup table, and the control algorithm did not directly involve flux control. An instantaneous torque controller based on variable structure control in the d–q reference frame was proposed in [5]–[7]. However, although experimental results showed that it was effective in reducing torque ripple, it was only applicable to three-phase BLDC operating in the 180° conduction mode, and not to the more usual 120° conduction mode. In [8], electromagnetic torque pulsations were reduced with a torque controller in which the torque was estimated from the product of the instantaneous back-EMF and current. However, the winding resistance was neglected and the inverter output voltage had to be calculated, which assumed that the back-EMF waveform was known. The real-time estimation of the back EMF, using the model reference adaptive method, was reported in [9], which also employed a variable-structure torque controller with space-vector PWM. However, it was only applied to a three-phase BLAC drive, and resulted in a relatively complex relationship between the output voltage in the q axis and the torque error.

Direct torque control (DTC) was originally developed for induction machine drives [10], [11], and directly controls the flux linkage and electromagnetic torque, considering the electrical machine, the power electronic inverter, and the control strategy at the system level. A relationship is established between the torque, the flux and the optimal inverter switching so as to achieve a fast torque response. It exhibits better dynamic performance than conventional control methods, such as vector control, is less sensitive to parameter variations, and is simpler to implement. DTC has been successfully applied to induction machines [10], [11], and, more recently, to BLAC machines [12], [13].

This paper considers the application of direct torque control, to a three-phase BLDC drive operating in the 120° conduction mode (i.e. two phases conducting) to achieve instantaneous