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Digital fixed-frequency hysteresis current control of a BLDC motor applied for aerospace electrically powered actuators

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Abstract In the conventional cascade control structure of aerospace electrically powered actuators, the current (or electromagnetic torque) loop plays a critical role in realizing a rapid response for a digitally controlled BrushLess Direct Current (BLDC) motor. Hysteresis Current Control (HCC) is an effective method in improving the performance of current control for a BLDC motor. Nevertheless, the varying modulating frequency in the traditional HCC causes severe problems on the safety of power devices and the electromagnetic compatibility design. A triangular carrier-based fixed-frequency HCC strategy is expanded by relaxing the constraints on the rising and descending rates of the winding current to advance the capability of HCC to realize fixed-frequency modulation in the steady state. Based on that, a new flexible-bound-size quasi-fixed-frequency HCC is proposed, and the range feasible to realize fixed-frequency modulation control can cover the entire running process in the steady state. Meanwhile, a corresponding digital control strategy is designed, and four digitalization rules are proposed to extend the capacity to achieve fixed-frequency modulation control to the unsteady working state, that is, a novel fixed-frequency modulation is realized. Simulation and experimental results prove the effectiveness of this improved fixed-frequency HCC strategy.

1. Introduction

Safer, cheaper, and greener technologies are important initiatives for the future of air transport. In response to these needs, the aerospace industry is searching for an innovation (incremental or disruptive) in safety-critical actuation systems.[1] Recently, significant interest is given toward "more electric air-

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craft" even "all electric aircraft".[2,3] The trend is to increase the usage of power-by-wire electrical actuators: electro-hydrostatic actuators and electro-mechanical actuators.[4] These actuators are projected to replace the conventional hydraulic servo actuators. From the power-to-weight ratio viewpoint, the high performance (significant efficiency and torque/power density)[5] and maturity improvements of the robust design for permanent magnet BrushLess Direct Current (BLDC) motor and their power drive electronics make electrically supplied actuators increasingly attractive.[6,7] However, alternative solutions need to be studied for BLDC motor control to ensure the required dynamic performance of an actuator under a wide range of in-flight maneuvers. The current loop is an innermost control loop in the control of a motor drive electronics, and its control strategy has a dramatic effect on the performance of a motor-driven device.[8] Thus, the study of a high-performance current control strategy has been an issue amid studies of motor control.[9]

In practical applications, the triangular-carrier-based Pulse Width Modulation (PWM) is adopted as a common method in current modulation, and a certain upper controller, such as a PID controller, a sliding mode controller, a predictive controller, and so on, is used to control the current quantitatively.[10–13] In these current control strategies, the dynamic response of the current controller can be effectively improved through increasing the frequencies of current sampling and PWM carrier. However, because the current is not controlled directly and an updating delay of the PWM carrier duty cycle exists, the actual winding current can easily exceed its upper limit confined by the power device capability due to an extremely high rising rate of current. Efforts have been done to solve this problem. For instance, Zhang et al. proposed a feed-forward control method combined with a dual current sampling and dual PWM duty ratio update scheme in Ref. 14 to decrease the time delay caused by a digital control system. In Ref. 15, twofold of current sampling and duty cycle updating were performed in a single carrier period, which decreased the updating delay to half of that in traditional PWM. Nevertheless, the disadvantage of these PWM-based current control strategies has not been overcome fundamentally.

Hysteresis Current Control (HCC)[16] is an alternative to achieve high-performance current control. In HCC, the control target is the bus current instead of the bus voltage, which overcomes the inherent disadvantage of PWM-based current control strategies. In addition, the simple structure, rapid response speed, inherent overcurrent protection function, lower switching losses, and excellent control stability of this strategy constitute the merits of HCC.[17,18] When HCC is applied to a current control loop, stability can also be achieved, although the outer speed control loop has a high control gain. Hence, HCC is fairly suitable for applications with high dynamical response. However, in traditional HCC, the switching frequency of a power device (namely, the modulating frequency) varies with a change of the system working state, which causes a severe electromagnetic compatibility problem and may result in an excessive switching frequency that will damage the power device; this disadvantage hinders the spread and application of HCC.[19,20]

Extensive work has been conducted to overcome the disadvantages of HCC. The use of a flexible hysteresis band size is a common way to achieve a fixed modulating frequency.[21–27]. In these HCCs, the hysteresis band size is calculated in each switching period in real time according to transient system state variables. However, this calculation is computationally expensive and suffers from stability problems.[25] Meanwhile, other ways exist. In Ref. 28, to realize a fixed-frequency modulation, the hysteresis band is removed, and the switch-on and switch-off times are determined using the predicted reference current, system behavior, and past time within a predefined switching period. Comparing the real-time current with the hysteresis bounds to determine the switching signal at a fixed frequency is another way to reach the target,[29] and if the hysteresis band size is set as zero, this current control strategy becomes similar to the bang-bang control.[30] Nevertheless, this strategy has the same problem concerning the sampling interval as that in PWM-based current control strategies. The triangular carrier-based fixed-frequency HCC strategy is a new way to obtain the fixed modulating frequency.[31,32] In this strategy, the triangular carrier technology and HCC are combined, and by tuning the amplitude of the carrier and the hysteresis band size, only a pair of switching signals is guaranteed to occur during a carrier period. However, strict constraints on the rising and descending rates of winding current are observed, and these constraints are usually ineffective in the unsteady state.

In this paper, a flexible-bound-size quasi-fixed-frequency HCC based on the triangular carrier-based fixed-frequency HCC is proposed to tackle the problem of traditional HCC. The digitalization of the proposed HCC is conducted to expand its feasible range to the entire running process. This paper is organized as follows. In the second section, the mathematical model of a BLDC motor using a PWM_ON modulation mode is constructed. In the third section, the triangular carrier-based fixed-frequency HCC is studied, and the new method is applied to analyze constraints to realize a fixed-frequency modulation control. In the fourth section, based on the results obtained in the third section, a new flexible-bound-size fixed-frequency HCC feasible during the entire running process is proposed, and the process of obtaining the flexible bound size is analyzed. In the fifth section, simulations and experiments are conducted to verify the effectiveness of the newly proposed digital fixed-frequency HCC. Finally, conclusions are made in the last section.

2. Modelling of a BLDC motor

In this paper, a Y-shaped BLDC motor is used as the research target. This motor is driven by a three-phase inverter controlled using six steps for commutation, in which only two phases conduct current at any time; for each phase, the conducting interval is 120 electrical degrees. For the modulation of conducting current, a PWM_ON modulation mode is used to produce switching signals for power electronic devices. Specifically, assumptions are made as follows:

(1) The three-phase windings are perfectly symmetrical.
(2) The back-ElectroMotive Force (back-EMF) is a trapezoidal wave of 120 electrical degrees.
(3) The stator core is unsaturated.

In addition, the armature reaction, eddy current, hysteresis loss, and cogging effect are neglected. The simplified circuit diagram of the BLDC motor and the three-arm power drive

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