New Reliable Sensorless Startup Strategy of Brushless DC Motor for Large Inertia System

Ming Lu[1,2], Lifu Yu[2] and Yaohua Li[1]
1 Key Laboratory of Power Electronics and Electric Drive, Institute of Electrical Engineering,
Chinese Academy of Sciences, Beijing, China
2 Beijing Institute of Control Engineering, Beijing, China
Email: luming@mail.iee.ac.cn

***Abstract*— A new reliable sensorless startup strategy of brushless DC (BLDC) motor is proposed to prevent long time integration commutation error specialized for large inertia load and to adapt large disturbance torque fluctuation. It includes four segments: orientation segment, I/f startup segment, observer startup segment and back EMF startup segment. Experimental results show that the proposed method could better adapt to large inertia systems with large disturbance torque fluctuation comparing with conventional methods.**

***Index Terms*— BLDC, sensorless startup, large inertia load, friction torque fluctuation.**

I. INTRODUCTION

During the past decades, sensorless control schemes for BLDC motor have been widely studied. Among the various sensorless control strategies for the BLDC motor, the sensorless control method based on the detection of zero crossing point (ZCP) of back electromotive force (EMF) has been widely used because of its maturity and simplicity[1]. However, the ZCP of the back EMF cannot be obtained when the BLDC motor is at standstill or operating at nearly zero speed. Therefore, a special starting method is required for smooth starting and reliable transfer to sensorless control.

So far, there are many kinds of starting methods for sensorless BLDC. Most of the starting methods are open-loop. In [2] the rotor is accelerated using V/f algorithm until the detection of the ZCP of the back-EMF is available. The control voltage and commutation frequency are increasing linearly during the starting time regardless of the real rotor position. In [3] I/f algorithm is used for starting, which consists in ramping the stator current frequency while the current reference is kept constant by the current controller, and the stator current frequency is obtained by integrating a reference speed. [4] proposed a open-loop method to compute commutation points of BLDC for large inertia system. During the starting, the motor current keeps constant and the commutation points are computed on line through the dynamics equation. An interpolation starting strategy is proposed according to the direct relation between the source voltage and the commutation instant in [5], but the starting process only lasts for the first 360 mechanical degrees. When the rotor is accelerated by open-loop method, “out of step” may occur because the stator windings are energized regardless of the actual rotor position. [6] proposed a close-loop method that adjusted on-line during the starting process according to the relationship between the characteristic of current response and commutation instant by fuzzy rules. [7] input the freewheel current error into a PI controller to correct the phase error. However, the close-loop methods need accurate current samplings and are more difficult to realize. In addition, the detection method based on motor inductance can obtain the position accurately but its application is restricted by the motor induction [8].

In large inertia system, the sensorless open-loop startup process of BLDC motor is much longer than the one in common system due to the limitation of the feasible driving torque. In addition, large friction torque fluctuation also results in commutation error. Under the influence of these two factors, the conventional startup methods are prone to be instable or even fail. During the long starting process, the conventional open-loop sensorless starting methods are prone to failed because their starting curves are linearized approximatively or have integration error as described in [2-3], [4] takes the long start process into consideration, but it do not ignore the friction torque fluctuation. [5] proposed an offline interpolation startup strategy to prevent integration commutation error. The starting curves is more accurate but the starting process is too short to adapt large inertia system and it also does not adapt to friction torque fluctuation. Close-loop methods [6-7] can be used in the long starting process system but their realizations are complicated and extremely accurate current sampling is needed.

In this paper, a new four segments startup strategy is proposed. It includes four segments: orientation segment, I/f startup segment, observer startup segment and back EMF startup segment. Section II presents the structure and commutation manner of BLDC driver, Section III introduces modified I/f startup strategy, section VI presents the four segments startup strategy in detail, section V compares the proposed strategy with the conventional strategy, section V gives the conclusion.

II. STRUCTURE AND COMMUTATION MANNER OF BLDC

The proposed startup strategy is based on a three phase BLDC motor driven by half-bridge driver which is

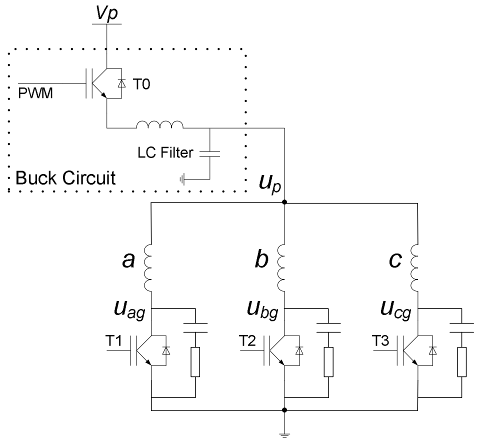

Fig. 1. Half-bridge driver with buck modulator

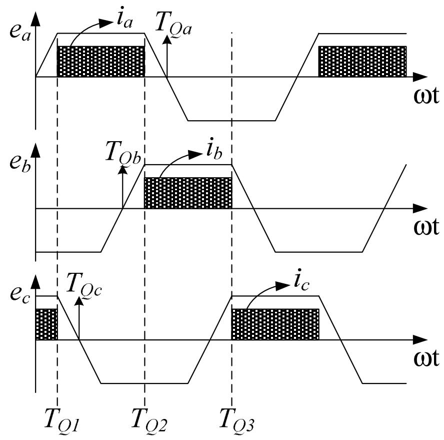

Fig. 2. Three-step commutation manner

shown in Fig.1. Here, a buck modulator is introduced to improve the performance of half-bridge driver. Four power devices T0-T3 are included in the driver circuit in total. T0, which is controlled by PWM signal in the buck modulator, is used to regulate the phase current. T1-T3 are all utilized for commutation. Three-step commutation manner is designed for half-bridge driver, the back EMF (e_a, e_b, and e_c), current (i_a, i_b, and i_c), ZCP (T_{Qa}, T_{Qb}, and T_{Qc}) and commuting points (T_{Q1}-T_{Q3}) are illustrated in Fig.2.

III. MODIFIED I/F STARTUP STRATEGY

Conventional V/f starting method and a modified I/f starting method are analysed in this section, and a simple comparison is made between them.

A. V/F Startup Strategy

From the dynamics equation of BLDC, we have

$$\sum T = T_e - T_f - T_l = J\frac{d\omega}{dt} \quad . \tag{1}$$

Here, T_f is disturbance torque, T_l is load torque, J is the moment of inertia. We can get the angle acceleration α:

$$\alpha = \frac{d\omega}{dt} = \frac{\sum T}{J}. \tag{2}$$

In V/f algorithm, the magnitude of motor voltage increases linearly. So the motor current, the ΣT and the angle acceleration α all increase linearly. Assuming T_f and T_l are constant during the starting process, T_0 is initial starting torque, $\triangle T_e$ is the torque increment with time t, we have Eq. (3),

$$\alpha = \frac{(T_0 + \Delta T_e \cdot t) - T_f - T_l}{J} = k_1 t + k_2, \tag{3}$$

where, $k_1 = \frac{\Delta T_{el}}{J}, k_2 = \frac{T_0 - T_f - T_l}{J}$.

By Eq.(4) we can get the relation between mechanical angle position θ and the starting time t:

$$\theta = \int_0^t \alpha \cdot t \cdot dt = \int_0^t (k_1 t + k_2) \cdot t \cdot dt = \frac{1}{3}k_1 t^3 + \frac{1}{2}k_2 t^2. \tag{4}$$

The commutation time t_k is the very time when the rotor angel position is at position θ_k. θ_k denotes the k times of 120 electrical degrees, k is sequence number of the commutation point, p is the number of pole-pairs of BLDC motor.

$$t_k = f(\theta_k) = f(\frac{2\pi}{3p}k), k = 1,2,3\cdots \tag{5}$$

It is difficult to obtain the commutation time t_k directly because solution process of Eq. (4) is complex. When the starting process is not very long in conventional application, the commutation time t_k can be given using linearized approximation, in case the starting process is longer, the linearized approximation would bring in big commutation error which may cause unsteadiness even starting failure.

B. Modified I/F Startup Strategy

In I/f startup strategy, current is kept constant and commutation time is computed according to equation of motion.

The motor current is kept constant by the current controller, so ΣT and the angle acceleration α are all constant if we assume T_f and T_l are constant during the starting process. We can get the relationship between the mechanical angle position θ and the starting time t directly in Eq. (7) and the commutation time t_k easily by Eq.(8), the commutation time t_k only relates with variable k.

$$\theta = \int_0^t \alpha \cdot t \cdot dt = \frac{1}{2}\alpha \cdot t^2. \tag{7}$$

$$t_k = \sqrt{\frac{2\theta_k}{\alpha}} = \sqrt{\frac{4\pi k}{3p\alpha}} = \sqrt{k} \cdot \sqrt{\frac{4\pi J}{3p\sum T}}, k = 1,2,3\cdots \tag{8}$$

It is obvious that commutation time t_k can be obtained more accurately and easily using I/f algorithm than V/f algorithm. From Eq.(8) we could compute the commutation time t_k directly, but the extraction operation $\sqrt{k}$ is difficult in circuit realization by either hardware or software. Considering that the square operation is much more easily to realize than extraction operation in circuit design, we utilize equation (9) to compute the commutation time t_k,

$$t_k^{\ 2} = k \cdot \frac{4\pi J}{3p\sum T} = k \cdot C_0, k = 1,2,3\cdots, C_0 = \frac{4\pi J}{3p\sum T}. \tag{9}$$

Here, C_0 is constant because the rotor is accelerated by constant motor current and constant torque ΣT. It is easy and accurate to obtain the commutation time t_k by comparing t_k^2 with kC_0.

C. Comparison

Experiments are designed to compare position sensors startup, I/f startup and V/f startup. The simulation parameters are shown in Table I. The position sensors starting method utilizes position sensor for commutation. The proposed I/f starting method obtains the time of commutation points by e Eq.(9). Both of the two methods control the motor current to be 1A during the starting process. In the V/f starting method, we use linearized function to draw up ideal commutation points.

In addition, the influence of friction torque and load torque are taken into account, we add a 0~0.0125Nm random disturbance torque into the simulation model which is 0~12.5% of the maximum electric torque.

TABLE I
SIMULATION PARAMETERS

Phase	*Pole*	*Back EMF Coefficient*	*Torque Coefficient*	*moment of inertia*
3	8	0.1 V/(rad/s)	0.1 Nm/A	2 kgm^2

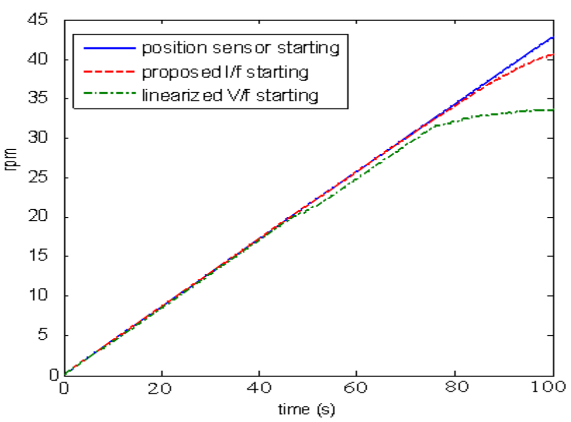

Fig. 3. Speed curves for different starting method

Simulation results are shown in Fig.3. The speed curve of position sensor starting method gives a reference for starting method design. By comparison, it is obvious that the starting process of the proposed I/f starting method is smoother than the one of linearized V/f method. The linearized V/f starting method is prone to failed if the startup process is longer.

IV. FOUR SEGMENT STARTUP STRATEGY

With the friction torque fluctuation being larger, I/f startup will be instable even fail because it assumes disturbance torque to be constant. A speed observer is designed utilizing the current and voltage of BLDC motor driver circuit, and the commutation time can be obtained from the motor speed. The observer startup strategy can be self-adapting to adjust the commutation time, it is more adaptive for large friction torque fluctuation.

A. Align the Motor

The commutation is achieved by changing the control voltage vector orderly. As shown in Fig.4, there are three voltage vectors V1-V3 for three-step commutation and

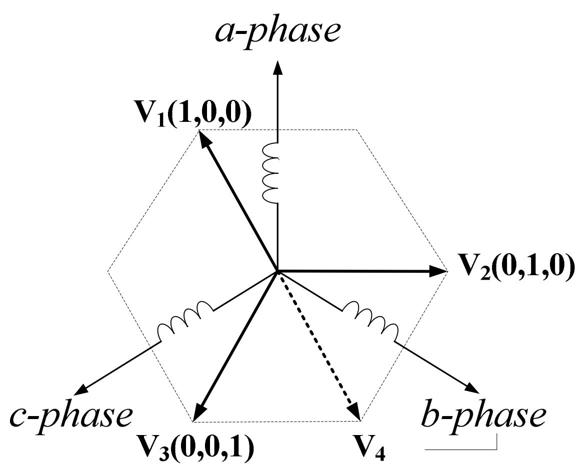

Fig. 4. Voltage vectors for three-step commutation

the phase angle between two adjacent voltage vectors is 120 electrical degrees.

The first step for sensorless starting is to align the rotor at a known position. The conventional one-step aligning method cannot work when there is neither more nor less than 180 electrical degrees between the energized voltage vector and the initial rotor position. To ensure the rotor can be aligned to the specified position reliably, we introduce two-step aligning method. For example, voltage vector V1 is energized first, and then the rotor will align to vector V1 except the case when the initial rotor position is at vector V4. The rotor position is V1 or V4 after the first step. Then voltage vector V2 is energized, and the rotor will align to the position V2 reliably.

B. I/F Startup

Modified I/f startup strategy is utilized here, the commutation points are computed by Eq.(9). Here, I/f startup only lasts for short time when the speed observer is ready.

C. Observer Startup

A speed observer is designed based on the half-bridge driver illustrated in Fig.1. From the electric equation of BLDC, we have

$$u_p = L \cdot di_x / dt + ri_x + k_v \omega_m . \quad (10)$$

Here, u_p is control voltage modulated by buck modulator. i_x is current for phase x, ω_m is the mechanical rotor speed, and k_v is the back EMF coefficient. x could be any one of the phase a, b, and c. r and L are the resistance and self-inductance of the three phases.

There is a low pass LC filter in the buck modulator, so u_p is smooth without high frequency component. Similarly, we force phase current i_x to be filtered by a low pass filter, then i_x becomes smooth and Ldi_x/dt is small enough to ignore. Under these circumstances, the mechanical rotor speed can be observed as follows,

$$\omega_m = (u_p - ri) / k_v . \quad (11)$$

From ω_m, we can get the commutation time interval t_{in},

$$t_{in} = \frac{2\pi}{\omega_m \cdot p \cdot 3} = \frac{2\pi \cdot k_v}{3 \cdot p \cdot (u_p - ri_x)} . \quad (12)$$

Here, p is the number of pole-pairs of the BLDC motor.

During the observer startup segment, the startup process has the ability of self regulation. t_{in} is related with observed ω_m, if the startup process is favorable, t_{in} becomes shorter with ω_m increasing. Else, if the startup process is unfavorable, such as encountering large disturbance torque fluctuation and resulting in ω_m coming down, t_{in} can regulate itself longer to adapt ω_m decreasing. So, the observer startup segment is applicative and reliable under the conditions of long time open loop startup process and large disturbance torque fluctuation.

D. Switch to Senorless Control

When the back EMF of BLDC motor is big enough for sensorless position detection, open-loop starting should switch to sensorless control mode. Before switching to sensorless control mode, we must make sure the phase error is enough small between the open-loop commutation points and the detected commutation points, or else, switching process may cause unsteadiness. Once the back EMF detection is ready, we should compare and gradually minish the phase error until the phase error is within the range that we can accept.

V. SIMULATION

Parameters of the simulation are the same as section III. Three experiments are built:

1) Four segment startup strategy: after orientation and a 50 seconds I/f startup process, observer startup switches over, when the back EMF is big enough for detection at 450 seconds, back EMF startup works.

2) I/f startup strategy: after orientation and I/f startup is utilized until the back EMF is big enough.

3) senor startup: position senor is used during the startup, it is the reference for the comparison.

During the startup, the influence of disturbance torque is taken into account. We add a 0.0125~0.0625Nm random disturbance torque into the simulation model which is 12.5%~62.5% of the maximum electric torque.

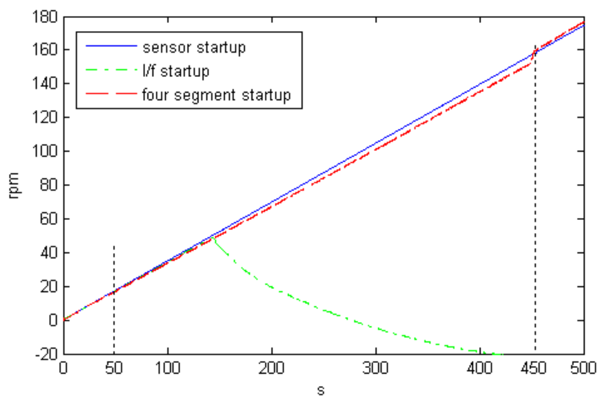

Fig. 5. speed curves of four segment startup strategy

Simulation result is shown in Fig.5. The I/f startup strategy is failed after 150s under the condition of a large friction torque fluctuation. The proposed four segment startup strategy can endure large friction torque fluctuation and starts up successfully. The motor speed increased slower than the one utilizing senor startup because of the limited speed observer precision.

VI. CONCLUSIONS

In conventional V/f starting method, the commutation time is difficult to obtain directly and accurately especially in large inertia systems. A modified I/f starting method is proposed to solve this problem, the commutation time is computed on line directly, but it cannot adapt to the large disturbance torque fluctuation. So, a new reliable four segment startup strategy is proposed. Speed observer segment is added to regulate the commutation time interval with the ability of self-adaption. Simulation results demonstrate the proposed four segment startup strategy for BLDC motor can achieve reliable startup for large inertia load with large disturbance torque fluctuation.

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