Energy Conversion and Management 64 (2012) 482–498

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Design and analysis of speed-sensorless robust stochastic L_∞-induced observer for high-performance brushless DC motor drives with diminished torque ripple

S.A.KH. Mozaffari Niapour [a,*], M. Tabarraie [a], M.R. Feyzi [b]

[a] Private Research Laboratory, 51668 Tabriz, Iran
[b] Faculty of Electrical & Computer Engineering, University of Tabriz, 51664 Tabriz, Iran

ARTICLE INFO

Article history:
Received 17 January 2012
Accepted 11 May 2012
Available online 10 October 2012

Keywords:
L_∞-induced observer
Brushless DC motor
Sensorless control
High-performance drive
Torque ripple

ABSTRACT

This paper aims to present an analysis and design of a high-performance speed-sensorless control scheme for a three-phase brushless DC (BLDC) motor drive by means of a novel observer technique in the induced L_∞ norm setting, named robust stochastic L_∞-induced observer, with the purpose of reducing torque ripple and increasing system robustness. The proposed observer is used for estimating the phase-to-phase trapezoidal back-electromotive-force (back-EMF) for the BLDC motor merely via utilizing measured line stator currents and voltages in such a way that by estimating the back-EMF, position and speed of the rotor is readily obtained. In contrast to the conventional back-EMF sensing methods, this strategy of utilized drive requires no filtering of current and voltage; furthermore, it does not suffer from any sensitivity to switching noises. Owing to that high-speed operation is vital for a motor, the varying input voltage method is used for realizing the minimization of commutation-torque-ripple in a parallel way to the proposed method since drive performance intensely degrades in this mode. Apart from analytic investigation of the proposed method, two other types of observers, namely, the sliding-mode observer and Kalman filter are compared with the proposed method for the aim of determining steady-state accuracy, dynamic performance, parameter and noise sensitivity, low-speed-operation performance, and computational complexity. Finally, the proposed system has been simulated in different operating conditions of the BLDC motor by computer simulation, and the effects of the proposed speed-sensorless control scheme has been assessed by comparative studies and simulation results. Simulation results authenticate that the proposed method is of excellent robustness and high precision estimation in comparison with sliding-mode and Kalman filter methods under different operating conditions in spite of the existence of measurement noise and electric parameter uncertainty. Therefore, the proposed method with its strong robustness makes it possible for the drive to enable the motor to undergo a stable tensionless operation without facing any problem at high-and low-speeds.

1. Introduction

Brushless DC (BLDC) motor drives according to their applications require position sensors such as Hall-effect, resolver, or absolute encoder for accurate implementation of current commutation in stator windings and/or empowerment of appropriate desired control. However, installation of these sensors in the motor for meeting the control needs will make the motor-drive system encounter several problems. The main drawbacks are the increased cost and size of the motor, and a special arrangement needs to be made for mounting the sensors. Moreover, Hall sensors are temperature sensitive and hence the operation of the motor is limited, which could reduce the system reliability because of the extra components and wiring. Thus, considering the disadvantages mentioned above and powerful and economical accessibility of today's microprocessors, it is worthwhile to replace sensorless control methods with rotor speed- and position-sensor.

In the two recent decades, considerable efforts have been made for optimizing sensorless control techniques from the viewpoints of the BLDC motor drive [1–10]. In reference [1], the terminal voltage sensing method which is based on float phase voltage sensing with respect to virtual neutral point was originally proposed in order to detect zero-crossing point (ZCP) of the back-electromotive-force (back-EMF) waveform. However, when using techniques of chopping drive in this method, neutral point is no longer a standstill point and this point's potential varies between zero and dc-bus voltage. A compensation for the introduced phase delay of LPF in [2] has been reported by using frequency-independent phase shifter which can shift ZCP of input signal by a known phase delay. In [3], the direct back-EMF detection approach which is not in need of sensing or reconstructing motor neutral point and uses voltage

* Corresponding author. Tel./fax: +98 411 33 13962.
E-mail address: s.a.kh.mozaffari.niapour@gmail.com (S.A.KH. Mozaffari Niapour).

0196-8904/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2012.05.011

difference of unexcited phase and power ground of dc-link voltage for direct back-EMF information elicitation has been analyzed. In this method, sensing circuit can only operate during freewheeling period (off-time of PWM) with a minimum off-time 3 μs sampling which results in that the maximum duty cycle of PWM be lower than 100%. Another direct back-EMF detection approaches to extend duty cycle control from 5% to 95% has been proposed in [4] by means of measurement of line voltages without considering the back-EMF. Under an ideal assumption that there exists no freewheeling current in non-conducted phase, recently a simple position-sensorless technique for detecting the back-EMF ZCPs in [5] and starting of the motor in [6] are presented. This method emphasizes on the issue that by measuring difference of line voltages in the motor terminals, it will be possible to create amplified version of back-EMF in order to extend its ZCPs detection at lower speeds. Unfortunately, the considered assumptions in [5,6] methods cannot always come true; in fact, using these methods, there may be a possibility that freewheeling currents in non-conducted phase exist both during normal commutation period and during un-commutated period in such a way that their amplitude, duration, and location of effectivity can differ according to the type of switching method. In [7] a method based on proper PWM strategy (PWM-ON-PWM) is offered in order that overcome the disadvantages in [5,6]. Although by using this method can realize good motor performance over a much speed range, there is no wonder it results in a tiny variety in application of BLDC motor drives. In [8] a speed-independent new physical concept has been proposed to detect commutation instants by utilizing speed-independent position function. However, since this function depends on calculations of current derivatives, this method, firstly, requires digital implementation, and, secondly, due to the extreme sensitivity of the method mentioned to measurement noises and machine parameters, this issue inevitably leads to a disorder in the determination of commutation points.

Nevertheless, the strategies above-mentioned operate only in a bounded speed range and are considered to be among open-loop speed-sensorless methods, but observer-based methods are mainly considered to be among closed-loop speed-sensorless techniques which are more robust and are of high-accuracy with respect to uncertainty in parameters and disturbances. Therefore, observer-based drives for high-performance applications can be the best and safest choice. In [9], an extended Kalman filter (EKF) has been used for instantaneous estimation of system state variables and stator resistance by using line measured voltages and currents and utilizing complete model of the BLDC motor. Unfortunately, the most basic problem for EKF is that its robustness against parameter detuning is too weak. In addition, determining the values of noise covariance matrices is difficult in them, and as this method is based on having accurate knowledge of practical system noises, the parameters determined by simulation should still be adjusted in practical system which increases the inconveniences for EKF. In [10] a sliding-mode observer has been presented by means of the stator line voltages and currents and electrical motor model to estimate the phase-to-phase back-EMF of the BLDC motor. In this respect, it should be pointed that a continuous approximation has been used for switching sign function by applying sliding-mode observer to drive system in order to reduce chattering effect in the method mentioned, which results in that, on the one side, it reduces the accuracy of observer in estimating state variables, and, on the other side, the applied approximation is no longer effective in the reduction of chattering effect when a high-level noise exists in the system output.

The main aim of this paper is to develop a novel observer approach based on the stochastic L_∞-induced filter [11] which recently has been designed for state-multiplicative stochastic systems. This innovative observer is the first known study that extends state estimation to the case where the stochastic system contains a known input as well as input-dependent noise. Such an observer, which we refer to as the robust stochastic L_∞-induced observer, improves the robustness and accuracy of the conventional aforementioned methods for sensorless BLDC motor drives. The proposed method in comparison with Kalman filter has superiority from robustness point of view against parameter uncertainty although it has some more computational complexity than Kalman filter and requires adjusting more additional parameters. Furthermore, compared to sliding-mode approach, the proposed method not only excludes any chattering but also takes advantage of excellent robustness against external disturbance of course in turn of accepting more computational complexity and adjusting covariance matrices in addition to more additional tuning parameters. In this observer, apart from deterministic parameter uncertainties, stochastic uncertainties have been considered as well. Additionally, it has a more realistic viewpoint in comparison with the sliding-mode observer and Kalman filter because its estimation error variance or energy should not necessarily be minimized; rather, its peak value is bounded. The proposed observer has been designed for estimating phase-to-phase trapezoidal back-EMF of the BLDC motor by utilizing measured line voltages and currents so that rotor speed and position can easily be obtained by the back-EMF estimation. In order to overcome the big commutation-torque-ripple created under high-speed operation, the varying input voltage method has been utilized in parallel with the proposed method for reducing commutation-torque-ripple. Likewise, in this paper, basic principles of designing the proposed method has analytically been studied along with the two types of conventional observers, namely, the sliding-mode and Kalman filter methods. At the end, the proposed system has been simulated in different operating conditions of the BLDC motor by computer simulation, and the effects of proposed sensorless control method have been evaluated from five perspectives including steady-state accuracy, dynamic performance, parameter and noise sensitivity, low-speed-operation performance, and computational complexity via a comparative study of two conventional observers aforementioned.

2. Modeling of BLDC motor

General voltage equation of each BLDC motor active phase is obtained by means of Kirchhoff's voltage law as the following [8]:

$$v_x = Ri_x + \sum_{k=1}^{n} \frac{d\psi_{kx}(\theta, i_x)}{dt} \tag{1}$$

where v_x, R, i_x, and $\psi_{kx}(\theta,\ i_x)$ are active phase voltage, resistance, current, and total flux-linkage respectively, θ is rotor position, and n is number of motor phases. The flux-linkage in active phase includes both self and mutual flux-linkages. For a three-phase BLDC motor, the total flux-linkage of the phase a includes [8,12]

$$\psi_a = L_{aa}(\theta, i_a)i_a + L_{ab}(\theta, i_b)i_b + L_{ac}(\theta, i_c)i_c + \lambda_{ar}(\theta)_{-} \tag{2}$$

where first term represents self flux-linkage, second and third terms represent mutual flux-linkage between phase b and c and phase a, and the fourth term represents the flux-linkage of the permanent-magnet on the rotor. Supposing that the saturation effect to be negligible and the inductance variation dramatically to be small (L_d - $\approx L_q$), (2) can be expressed as follows:

$$\psi_a = L_{aa}i_a + L_{ab}i_b + L_{ac}i_c + \lambda_{ar}(\theta) \tag{3}$$

Substituting (3) into (1) and its extension for all three phases, we have