IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 11, Issue 1 Ver. IV (Jan. – Feb. 2016), PP 19-25
www.iosrjournals.org

Sensorless Control of Brushless DC motors and H_∞ Control Theory Applications - A Literature Review

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Abstract : *This paper reviews the recent developments in the field of sensorless control of Brushless Direct Current motors. Moreover a survey of application of H_∞ control theory for robust control, considering the uncertainties like modeling errors and external disturbances in various motors and systems has been carried out. This provides a deeper insight into the recent developments and future scope in the robust control of sensorless BLDC motors to mitigate the effects of parametric uncertainties and unmodeled dynamics.*

Keywords - *BLDC motor, Disturbance, H_∞ control, Robust, Sensorless control.*

I. Introduction

Brushless Direct Current motors (BLDCM) exhibit tremendous advantages such as elimination of sparking, better speed verses torque characteristics, noiseless operation, higher speed ranges, better service life, rugged construction, etc. This finds applications in day to day life such as household products, military, aerospace, industrial automation and so on. A lot of research work is being carried out in proper commutation of windings, improvement in speed variation, reduction of torque ripples and response time and stability of the motor under disturbances as well as uncertainties.

When the stator phases in a BLDCM are energised, a flux is generated in the stator which interacts with the rotor magnetic flux. Maximum torque is produced when the angle between stator and rotor flux is 90 degrees. Therefore, it is important to know the position of rotor in order to ensure alignment of stator flux close to 90 degrees. There are two ways of rotor position sensing in a BLDCM, which are by use of sensors [1] and by sensorless methods. Position sensorless control technology attracts increasing research interest because it saves cost, space, maintenance, etc. and has become one of the most promising trends of BLDCM control system.

Rotor position sensing by various sensorless techniques has been proposed in the literature which include inductance and flux measurement method, back emf detection, estimation and observer based models. Usually, there exist nonlinearities and perturbations in mechanical control objects. The modelling of these parameters for control design is difficult. Even though they are modelled, control system design and adjustment of parameters with a conventional controller like PID are difficult and tuning requires more work and consumes time. Robust control is concerned with the problem of designing control systems when there is uncertainty about the model of the system to be controlled or when there are external disturbances influencing the behaviour of the system. The modern approach to design controllers which are robust against model uncertainties is provided by the H_∞ control theory.

This paper presents the research efforts carried out by various researchers in this field starting from the year 1991 which is being basically categorised based on sensorless BLDC motor control and various applications of H_∞ control theory.

II. Research Efforts On Rotor Position Sensing By Sensorless Techniques

Obtaining rotor position information from electrical measurements without any position sensor is the technique used in a permanent magnet brushless sensorless drive. Various existing technologies that are being adopted in the sensorless control of BLDC motors are shown in Fig. 1. The control methods of BLDC motor which include types of PWM techniques used, various methods for rotor position detection, initial rotor position detection, recent advances in the position sensorless control of BLDC motors and the expected future research works to provide insight in sensorless drive techniques along with their benefits have been reviewed in the literature [2]-[5]. The research efforts carried out on the three basic types of sensorless control schemes that are found in the literature are described below.

2.1 Research Efforts on Position Estimation Using Inductance And Flux Measurements

The inductance of a phase which includes both self and mutual inductances and hence the flux linkage, varies with the rotor position. The flux linkage is calculated using measured voltages and currents as per equations (1)

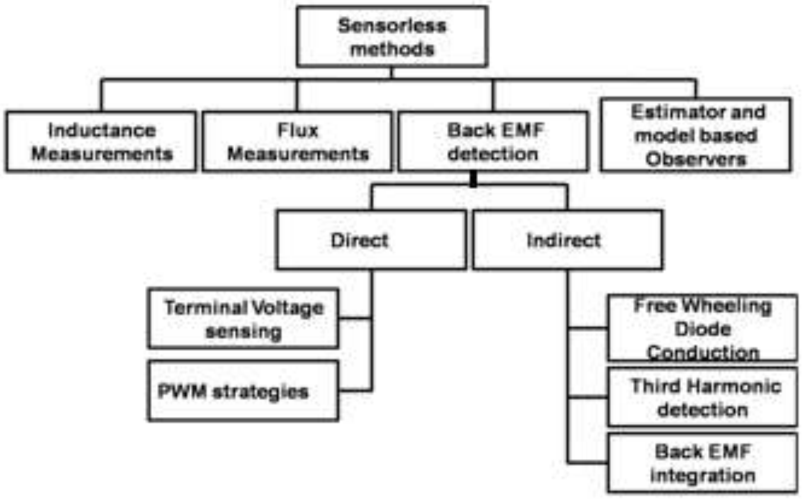

Fig. 1 Various existing technologies in the sensorless control of BLDC motors

$$L = \lambda/i \qquad (1)$$

$$v = iR + L\,di/dt + d\lambda(\theta)/dt \qquad (2)$$

& (2), where L is self inductance, λ represents flux linkage due to permanent magnet attached to the rotor which is a function of rotor position (θ), *i* is current and *v* represents voltage. From the initial position, machine parameters, and the flux linkages' relationship to rotor position, the rotor position can be estimated. Since flux linkage is independent of speed, it is used to detect the rotor position at low speeds.

A flux linkage function which is speed independent has been defined to control BLDC motors at low speed operations [6]. Detection of ZCP of BEMF from the rotor position where the rotor reaches the equally self-inductance position has been proposed [7]. This method does not depend on the BEMF, and so it can be operated at very low speeds but torque ripple is bigger than that in the conventional method. Salih Baris Ozturk *et al.* [8] investigated the position-sensorless direct torque and indirect flux control of BLDC motor by estimating the electrical rotor position using winding inductance and stationary reference frame stator flux linkages and currents. Though this method is speed independent it has a drawback of significant estimation error at low speed.

2.2 Research Efforts on BEMF Detection

In this method, the zero crossing of trapezoidal BEMF induced in the stator winding by the movement of a permanent magnet rotor is used to detect the rotor position. When one of the BEMF signals crosses zero, the controller should change the supply to the phases by appropriate switching whereby the process of commutation is achieved. The BEMF detection methods are classified into direct and indirect detection.

Direct BEMF Detection usually uses a hardware low pass filter or software detecting method to filter out the noise signal. Since direct BEMF sensing scheme requires minimum PWM "off" time to sample the BEMF signal, the duty cycle cannot attain 100%. A method has been projected to detect the motor BEMF during PWM "off" time at start-up and low speed, and during PWM "on" time at high speed, thereby the duty cycle is extended to 100% [9] .

Zicheng Li *et al*. [10] proposed line-to-line BEMF calculation for sensorless BLDC Motor Drives and demonstrated that the zero-crossing of line-to-line BEMF is actual commutation instant. This method detects the rotor position over a wide speed range not only at steady state but also at transient state. This scheme is simple to implement without the need to sense or reconstruct the motor neutral, and good motor performance is achieved from near zero to high speed when compared with the traditional BEMF method. Ming Lu *et al*. [11] put forward two methods. The first method is terminal voltage detection for half-bridge driver which extracts the true BEMF ZCP by detecting voltage difference between the terminal voltage of the floating phase and the control voltage modulated by buck modulator. Compared to neutral point, the control voltage modulated by buck modulator is stable during PWM switching. The second one is line voltage detection for half-bridge driver by detecting ZCP of line voltage between two floating phases.

Another method to detect ZCP of BEMF is from the line voltage difference [12]. The correct commutation instants are delayed by 30 degrees from the zero crossing of BEMF. This method eliminates common node noise and need for neutral. But the induced EMF deviates from the trapezoidal wave shape due to slot ripples. Since the ZCP of BEMF difference is exactly the same as the ZCP of the terminal voltage difference, it is also used as commutation signal directly without phase compensation [13]. The commutation instants (duration of commutation) are also calculated by deriving the sum of the terminal voltages of the motor [14]. This method is robust across variations in stator resistance due to changes in temperature or frequency. The knowledge of initial position of rotor is not required.

In the ***Indirect BEMF Detection*** method detection of position information on the basis of the conducting state of the free wheeling diodes connected in anti parallel with power transistors has been suggested in the literature as it is a result of BEMFs produced in the motor windings. [15], [16]. The third harmonic BEMF is used to detect position as the zero crossings of the third harmonic component occur at 60 electrical degrees which is exactly at every desired current commutation instant [17]. It keeps a constant phase relationship with the rotor flux for any speed and load condition. BEMF mapping with six-step control has also been presented [18] as all commutation instances corresponding to 30 electrical degrees at various speeds can precisely be calculated using a single known reference slope and a BEMF point considered at the same speed.

2.3 Research Efforts on Estimation and Model Based Observers

Various strategies that are used in the speed control of different types of motors based on estimators and model based observers are shown in Fig. 2.

SMC is a nonlinear control method that changes the dynamics of a nonlinear system by application of a discontinuous signal, thereby forcing the system to slide along a cross section of the system's normal behaviour. A hybrid rotor position self-sensing approach for full speed range by combining stator core saturation method and SMO method has been developed [19]. The initial rotor position is detected by magnetic saturation characteristic of the core. The sign function is replaced by saturation function which reduces chattering problem associated with SMO. The application of PISMC techniques have been studied in the literature for controlling the rotor position of Permanent Magnet DC motor drive system [20]. A speed component in the BEMF observer gain has been introduced to modify the sliding mode observer, which eliminates multiple zeroes at low speeds and phase shift at higher speeds [21].

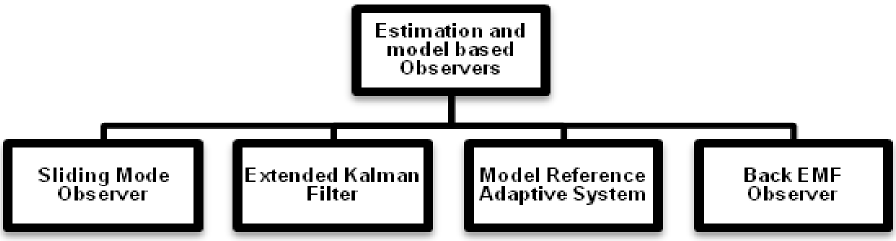

Fig. 2 Strategies used in the speed control of motors based on estimators and model based observers

EKF is an optimal recursive estimation algorithm for nonlinear systems that are disturbed by random noise. It is recursive because the processing of measurements is done in real time. It uses a two step algorithm in which the first step is to project both recent state estimate and error covariance estimate to compute a predicted state estimate at present time. The second step is to correct predicted state estimate by incorporating recent process measurements to generate an updated state estimate. Dhaouadi R *et al.* [22] designed the extended Kalman filter for the on-line estimation of the speed and rotor position by using measurements of the motor voltages and currents of a PMSM without a position sensor. The online estimation of speed and rotor position of the BLDCM based on the application of the EKF have been presented to improve the maximum steady-state error between reference and actual motor speed which is 1% over a speed range from 5% to 100% of the rated value. [23]-[25]. The advantages of EKF are easy usage, proper working in practical estimation problems and computational efficiency. It has demerits such as less responsive to systems with considerable non-linearities, differentiable measurement and dynamic model functions, low estimation accuracy at lower speeds, intensive computation, high degree of dependence on the motor's parameter and requirement of proper initialization.

MRAS estimator creates a closed loop controller with parameters that can be updated based on the error between the output of the system and reference model to change the response of the system. An indirect-rotor-field-oriented-control scheme has been proposed for sensorless speed control of a PMSM where the rotor-flux position is estimated by direct integration of the estimated rotor speed and the stator resistance [26]. The rotor-flux speed and magnitude are estimated adaptively using stable MRAS estimators. The inaccuracy of the low speed estimation is mainly because of the divided voltage of the stator resistor. At high speeds, the inaccuracy of BEMF constant *ke* is the main reason. A speed estimation algorithm has been projected based on MRAS to correct the speed error estimated from BEMF considering the voltage compensation of the stator resistor at low speeds [27]. The attracting feature of MRAS method is its desired closed loop performance. Its structural limitation is that the tuned system, to which it converges under a model matching design rule, may not have an acceptable level of robust stability or an acceptable sensitivity function.

Various ***BEMF Observer*** methods are found in the literature for real-time estimation of the rotor position and speed. Tae-Sung Kim *et al.* [28] offered a method in which trapezoidal BEMF is modeled as an unknown input and the proposed unknown input observer estimates line-to-line BEMF in real time to detect the rotor position over full speed range. The commutation functions for mode conversions have been defined which serve the purpose of hall sensors. A novel BEMF observer which could estimate phase BEMFs that rely only on DC voltage and phase currents of motor and has only one inertia element to simplify the structure of traditional back-EMF observers for the improvement of response time and robustness of the system [29] has been proposed. Cassio Luciano Baratieri *et al.* [30] used a new BLDCM dynamic model expressed in a synchronous reference frame with BEMF vectors. Since the electromagnetic torque under nonsinusoidal orientation is proportional to the q-axis stator current, the torque ripple is minimized with highly nonsinusoidal back-EMF. A new BEMF difference detection method based on a disturbance observer structure which can detect the BEMF as well as BEMF difference signal has been designed to improve the performance at low speed range as the information of rotor position is calculated independently of the rotor speed [31].

III. H_∞ Control And Research Efforts On Its Applications To Motors And Other Systems

Controller design by H_∞ optimization involves the minimization of the peak magnitude of a suitable closed-loop system function. The desired responsiveness and noise-suppression properties of the controller are achieved by assigning appropriate weights to the plant transfer function in the frequency domain. The generalized version of standard problem of H_∞ optimization as applied to a plant is shown in Fig. 3. The plant *G (s)* has two inputs and two outputs. The signal *w* is an external input, and represents driving signals that generate disturbances, measurement noise, and reference inputs. The signal *u* is the control input. The output *z* is control error, and ideally should be zero. The output *y* is the observed output and is available for feedback.

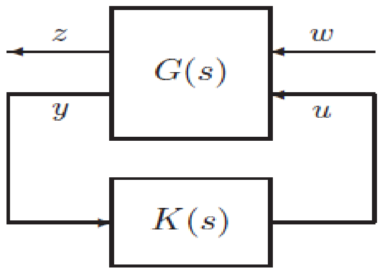

Fig. 3 Standard Problem of H_∞ optimization

H_∞ control problem is to find a controller *K(s)*, based on the information in *y* that generates a control signal *u* which counteracts the influence of *w* on *z*, thereby minimizing the closed-loop norm from *w* to *z*. Even though robustness to modeling uncertainties is one of the most important motivations for the H_∞ control problem, it can also be applied to the disturbance rejection problem.

H_∞ control theory has been widely used in the speed control of various motors including Permanent magnet DC motor, PMSM, SRM and BLDC motor. This theory has also found its applications in active magnetic bearing position control, vertical aircraft control, electric vehicles etc.

H_∞ control theory has been applied to ***Permanent Magnet DC motor*** speed control system to get a controller which acts effectively with the control object including uncertainties and modeling inaccuracy. The modeling inaccuracy which is the difference between the model and the reality is achieved by defining the uncertainty for selected parameters [32], [33]. H_∞ controller for electric vehicle actuated by permanent magnet DC motor has been applied to stabilize the system by minimizing the error between charging current and its reference in the presence of large perturbations in the load rotational inertia and variations in terminal voltage of the battery [34]. A. Ahuja *et al.* [35] proposed an approach that poses the design problem as a controller for DC motor speed control with a mixed sensitivity H_∞ method. Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) are adopted to solve the optimization problem of finding the optimal controller.

H_∞ tracking controller has been used to compensate external disturbances in the current loop [36], [37] for ***PMSM Servo System*** and to control speed during load changing [38], [39] of Permanent Magnet Linear Synchronous motor. H. ZANG *et al.* [37] nominated a robust H_∞ controller based on genetic algorithm optimization of space vector control model of ***PMSM*** to improve the speed of tracking performance. A control technique has been identified to track the position of the rotor from the speed performance of ***SRM*** [40] and the optimal transfer function matrix weight is obtained by genetic algorithm (GA) [41].

In practical applications one of the major problems lies in selecting suitable weighting functions that incorporate both stability and performance requirements. A novel method has been put forward for the selection of weighting functions in H_∞ mixed sensitivity design to control the percentage overshoot directly of ***a vertical take-off aircraft*** [42]. This provides explicit formulae for typical plants with complicated cases which serve the control engineers a good starting point. The robust stabilization of ***Active Magnetic Bearings*** has been addressed by appropriate selection of the free parameters in the robust controller [43]. The parameter uncertainty in the system and the unmodeled dynamics are included in the disturbance. Robust control of current-controlled active magnetic bearing system using H_∞ controller has also been developed [44]. An algorithm for the synthesis of robust H_∞ controller with a novel automatic weight selection has been proposed [45] and a novel weight selection algorithm using DSP processor has been developed for the automatic synthesis of H_∞ controllers [46].

Thirusakthimurugan. P in his thesis [47] proposed a robust control scheme of ***Permanent magnet BLDC motor*** which included a cascade control structure to generalized predictive control (GPC). A novel robust stochastic H_∞ deconvolution filter for sensorless BLDC motor drives has been proposed to improve the robustness and dynamic performance in a vast speed range [48]. This deconvolution filter contains a known input, a state input and a disturbance. The proposed observer is used to estimate phase-to-phase trapezoidal BEMF dynamic of the BLDC motor by utilizing actual line voltages and currents in order to obtain rotor speed and position.

IV. Discussions

To summarize, a comparative study of existing methods has been conducted and consolidated as explained below. With inductance measurements, the rotor position detection at low speeds is better, but the torque ripple is high. There is a significant estimation error with flux measurements. With direct BEMF detection method, it is easy to detect the ZCP of the phase BEMF indirectly by utilizing the terminal voltage since the neutral point required to extract BEMF directly is not offered in the manufacturing process of a motor. Moreover it is learned that terminal voltage detection method has higher detection precision than line voltage detection method, while the latter one is simple to realize. But the drawback is the speed range is narrow and also due to a phase shift of 30° there is a position error at transient state.

The advantage of indirect BEMF detection methods is that the requirement of a small amount of filtering as they are noise free and since third harmonic signal can be detected and processed at low speeds, starting of motor is superior. Moreover, there is no need to access stator neutral. But the back emf is distorted thereby location of precise commutation signal is difficult at low speeds. The most serious drawback of indirect back emf technique by freewheeling diode conduction method is the requirement of six additional isolated power supplies for the comparator circuitry to detect current flowing in each freewheeling diode.

Although estimator and model based observers are complex, real time estimation is possible. Though the rotor position at low and high speeds is detected by SMO it has the drawbacks of chattering problem and multiple zero crossings in BEMF which leads to improper commutation at low speed. PISMC exhibits better performance with higher precision and better robustness to plant imprecision and external disturbances than PID controllers. With EKF, sensorless drive is not achieved as the estimation accuracy decreases at lower speeds.

The line to line back emf observer provides estimation of rotor speed in real time with precise control and obtains a precise commutation pulse even in transient state as well as in steady state without any additional circuits. A BEMF difference detection method based on a disturbance observer improves the performance at low speeds.

H_∞ control theory has been used to compensate disturbances such as parametric uncertainties and unmodeled dynamics in the speed and current control of motors. It is learned that suitable selection of weight functions of H_∞ controller improves starting characteristics when the initial position of the rotor is much nearer its equilibrium position.

V. Conclusion And Future Scope

A review of various sensorless techniques used in BLDC motor control has been presented in this paper along with their merits and demerits in detail in order to have a clear understanding. The use of sensorless techniques reduces the size, maintenance, and cost.

But most of the control techniques applied in the literature are based on the assumption of accuracy of the model and parametric certainty, whereas the actual system deviates from the model and uncertainties are unavoidable. The parametric uncertainties and unmodeled dynamics dealt in various works and their mitigations with H_∞ control have been discussed in detail. The studies based on optimization of selection of weighting function which leads to the stability and performance requirements have also been considered. In general, an attempt is made to have an overview on the application of H_∞ control strategies which mitigate the effects of uncertainties and disturbances in various motors. This study leads to the future scope of effective, robust control of sensorless BLDC motor.

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