SENSORLESS DRIVE OF BRUSHLESS DC MOTOR BASED UPON WAVELET ANALYSIS

Murat YILMAZ
e-mail: mryilmaz@elk.itu.edu.tr

R. Nejat TUNCAY
e-mail: tuncay@elk.itu.edu.tr

Özgür ÜSTÜN
e-mail: ustun@elk.itu.edu.tr

Istanbul TechnicalUniversity, Faculty of Electrical & Electronics Engineering, Department of Electrical Engineering, 34469, Maslak, Istanbul, Turkey

Key words: Sensorless, Brushless DC, Wavelet, DSP,dSpace

ABSTRACT

This study tackles to develop a sensorless drive technique for brushless dc motors (BLDC) by using wavelet theory. Initially a BLDC motor with hall sensors is handled. The simulink model of the motor is established and the simulation performances are obtained. Then BLDC motor's PWM pulses are produced by DS2201 dSPACE digital signal processing (DSP) rapid control prototyping kit. The time domain input current and induced voltage waveforms are recorded. The wavelet analysis of these waveforms is obtained with an extra emphasis on commutation intervals. Finally an algorithm is developed to predict the commutation instants without any position sensor.

I. INTRODUCTION

Since permanent magnet brushless dc motors (BLDC) have higher specific torques; they are widely preferred in high quality drive applications. The electromagnetic structure of brushless dc motors (BLDC) is identical to synchronous machines but they have trapezoidal EMF waveforms. The reason why they called dc motor, is because of their well-known T=KI and E=Kω dc machine equations, where T= torque, I= current, E= induced voltage, ω= speed and K is a constant. With parallel to improvements in permanent magnet technologies, brushless dc motors are established as the most popular motors for cost-effective intelligent motion-control applications, such as appliances, electrical vehicles, mechatronic systems and etc.

The BLDC motors are driven by inverters, of which semiconductors are triggered in accordance with the signals coming from position sensors [1,2]. Optical encoders and Hall effect sensors are the more frequently used sensors. No doubt, these additional components increase the volume, weight and the cost, and reduce the reliability. In order to avoid these adverse effects, several sensorless drive techniques developed in the past.

In general, sensorless techniques base upon the use of back emf waveforms of the armature windings, that is a function of the position and the speed of the rotor. [3,4] For challenging applications, where accurate speed and position control is required, the microprocessors for controlling the motor may not be adequate. Then, digital signal processors become a must to meet the demand of those loads. Since programming procedure of DSPs are cumbersome; some techniques to avoid the programming are becoming popular. The rapid control prototyping technique is one of them. Nowadays it is more often used to avoid the tedious programming procedure of DSPs. In this technique the whole drive system, including detailed firing circuits, are modeled in Simulink and an interphase system (hardware/software) are used between the simulation model and DSP responsible for controlling the motor. This method facilitates to produce c codes of DSP directly from the computer model. In this study DS2201 dSPACE digital signal processing (DSP) rapid control prototyping interphase kit is utilized.

For trapezoidal EMF type of permanent magnet motors the excitation field in the gap is approximately constant with opposite polarities. The changes of the polarity occur at the nonmagnetic separation region between two opposite polarity magnets. In BLDC motor terms this region is called commutation region. Most of the sensorless schemes depend upon detecting the induced emf waveforms. However, as a result of Faraday's law the induced back emf is zero in magnets' constant flux region. Thus, only the commutation region can provide some information about the position of the magnets. Since detected emf is that of a motion, sensorless position definition becomes more difficult in lower speeds and most difficult at standstill.

The main objective of this paper is to implement the wavelet theory for developing a sensorless drive scheme for BLDC motors. Wavelet theory is widely used in image processing that enables to analyze non-stationary signals in time and frequency domain. Thus it is a useful tool to detect the peculiar properties of time varying signals. As it was pointed out above, induced emf has peculiar waveshape in commutation region and input current would carry the hidden properties of back emf and other signatures of rotor position. Application of wavelet theory would enable to detect these signatures and deduce the actual rotor position.

II. MATHEMATICAL MODEL OF BLDC MOTOR

In Figure 1 the mathematical model of BLDC motor drive system is shown. It consists of three phase winding resistances, inductances and back EMFs. The state-space equations of six-pulse operation of the system, including commutation intervals, are developed [5,6,7]. The State-Space Simulink model of the system, including a diode rectifier, an IGBT inverter and the motor, is shown in Figure 2. The simulation results for a constant load is presented in Figures 3, 4 and 5.

$$V = R \cdot i + L\frac{di}{dt} + e$$

$$e = 2NlrBw$$

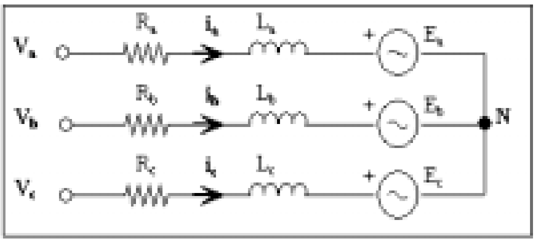


Figure2 Circuit model of armature winding

$$M_e = \frac{1}{\omega_r}\left(e_1(\theta_e)i_1 + e_2(\theta_e)i_2 + e_3(\theta_e)i_3\right)$$

$$M_e = \left(\frac{1}{2}i^2\frac{dL}{d\theta}\right) - \left(\frac{1}{2}B^2\frac{dR}{d\theta}\right) + \left(\frac{4N}{\pi}Brl\pi i\right)$$

$$\frac{d\omega_r}{dt} = \frac{1}{J}\{T_e - B\omega_r - T_L\}$$

$$\frac{d\theta_r}{dt} = \omega_r$$

$$\theta_e = p\theta_r$$

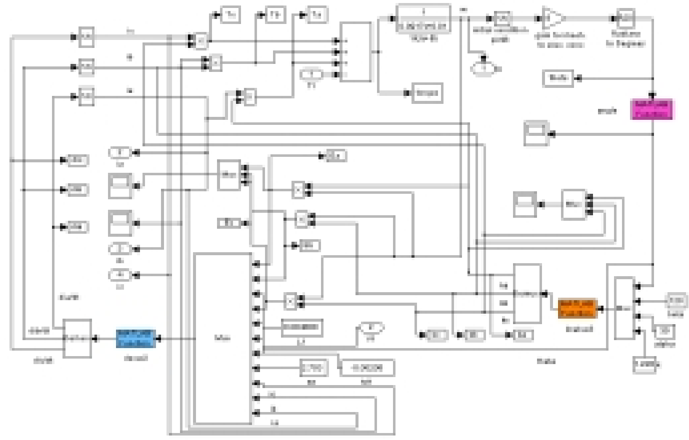


Figure 2. Simulink block diagram of BLDCmotor.

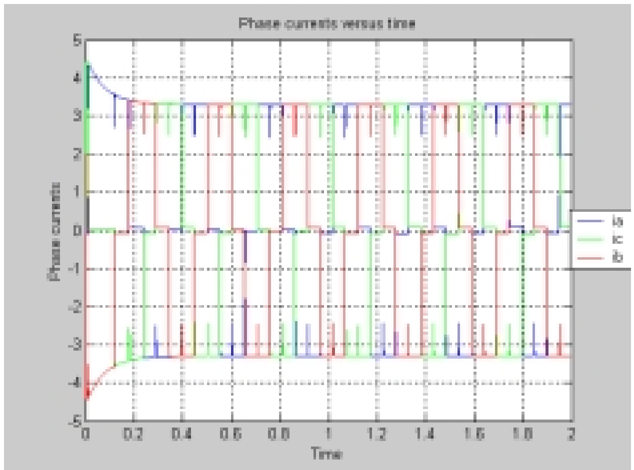


Figure 3. Phase currents versus time of BLDC motor.

III. SENSORLESS CONTROL METHODS OF BLDC MOTOR

It is known that permanent magnet brushless dc motors require detecting the relative position between magnets and windings. As it was stated above, avoiding position sensors is preferable.

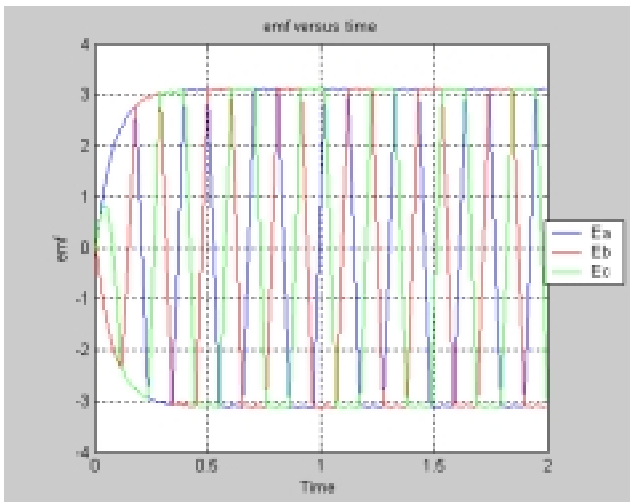


Figure 4. Emf versus time of BLDC motor.

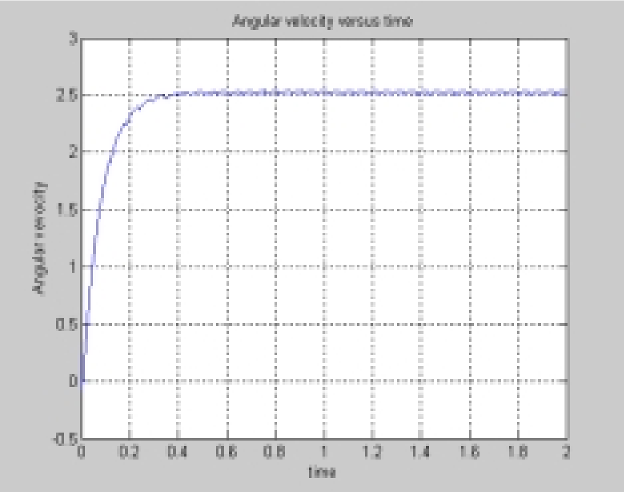


Figure 5. Angular velocity versus time of BLDC motor.

The literature survey yields that most of the recent studies about sensorless drive of BLDC motors concentrate on starting and low speed applications. In essence, all starting methods base is to excite any two phases and align the magnet and winding axes. Otherwise, direction of rotation would be coincidental. [8, 9, 10].

In some methods, armature winding is supplied with an increasing frequency in an open loop manner. Rotor speed is increased up to a certain level, at which a position information can be collected from motion emf voltage. In an other method for rotor alignment, a special PWM technique is used for inverter's switches. One other method is based on the sensing of phase inductances. Positions of magnets affect the flux distribution in the gap and core. Due to the nonuniformity of flux, saturation is not evenly distributed in the core. This causes slight variations in coil's inductances. Detection of inductances gives information about the relative position of magnets with respect to armature coils. One similar method claims that very good performance is achieved at starting with direct inductance measuring method.

Most popular method for getting rid of expensive position sensors and developing a sensorless control, is the measurement and analysis of back emfs [11,12]. This method is used in 60^0-commutation step scheme with two phases conducting at a time. Back emf of the idle third phase is measured and processed. Relative magnet positions and next commutation instants are defined accordingly. There are several sensorless control methods depending on back emf measurement. Detection and digital shifting of zero crossing points or analog shifting of zero crossing points is the main methods [13]. Another method is the measurement of indirect back emf measurement. For 180^0 commutation step scheme, there is no unexcited phase therefore back emf can not be directly measured. Luenberger type digital sensing is one of the indirect approaches. One of the frequently used indirect emf measurement methods is called the integration of induced voltage. This method is used for 60^0 operation. Unenergised phase voltage is sensed and time integration is taken to obtain the linkage flux as following.

$$\Psi = \int e(t)\, dt$$

In other words, this method depends on the sensing of flux linkage. Zero crossing of flux-linkage curve yields commutation instants. Another indirect method is the calculation of third harmonics of induced voltage. In three phase systems, due to trapezoidal waveforms and unbalances of induced voltages, the neutral point shifts and third harmonics occur. In order to detect third harmonics, an artificial neutral point is established in power electronic network by adding balanced three-phase resistors. The potential difference between artificial and real neutral point gives the instantaneous value of induced voltage of the idle phase, which is equal to the flat portion of the trapezoidal voltage. The major setback of this method is the very weak third harmonic voltage signals at low speeds.

Another sensorless control approach utilizes the observation of currents. In this method current is sensed continuously and inductance is computed. Since measurement and computation is a real time process, fast computation of inductance is one difficulty. Requirement of additional method for starting is another one. In one method the armature windings are supplied with high frequency low energy signals. In another, additional windings are inserted in. State observers are also among the methods of sensorless drive based upon the current sensing.

IV. BASICS OF WAVELET APPLICATION

Fourier theory widely used in the past for analyzing the periodical signals. In Fourier technique, signals are expressed as a combination of sinusoidal functions with different frequencies. Therefore, obtaining the frequency components of a signal is possible for stationary signals. For nonstationary signals, it is necessary to find the time variation of each frequency components.

Short Time Fourier Transformation Technique overcomes this setback. A signal is windowed with a window function and the product of the signal and window function is obtained, and then the Fourier transform of it is obtained. Demerits of this technique are the constant length of selected window function that causes resolution problems. As a definition, resolution is the amount of information in a signal. The relationship between time and frequency resolutions is expressed by Heisenberg uncertainty principle. In short-time Fourier transformation the time and frequency resolutions of a signal are equal. Since a single window is used, time-frequency resolution has a constant square shape [15,16].

In wavelet transform the frequency and time resolutions can be defined separately. There are windows with different width and hights, but the areas of them are equal. The width and height of the boxes represent the frequency and time resolutions respectively. Therefore for low frequency which means low height box the frequency resolution is high. When the width of boxes gets lower which means frequency gets higher; time resolution becomes higher since the height of the box is also increased.

In wavelet transformation the modulated window is shifted along with the signal and the spectrum is calculated for each position. This process is repeated many times for shorter or longer windows. As a result of this process, signal's time-frequency representations for various resolutions are developed. In wavelet technique, instead of time-frequency representations, the time-scale representations are used. The concept of scale is exactly the same as the maps. High scale is a larger picture with fewer details. In contrast, small scale shows the details. Moving from high scale to low scale means enlarging the figure's inner details. Scale is inversely proportional with frequency. A continuous wavelet transformation of a s *(t)* function with respect to $\psi(t)$ wavelet is defined as follows [17,18].

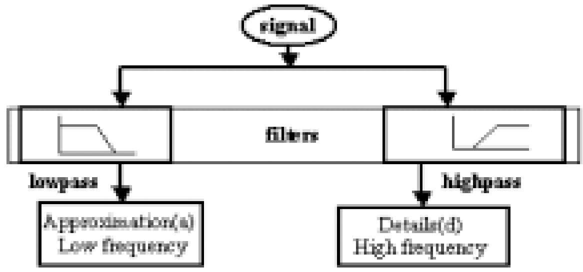
$$W(a,b)=\int_{-\infty}^{+\infty} s(t)\frac{1}{\sqrt{|a|}}\psi^{*}\left(\frac{t-b}{a}\right)dt$$

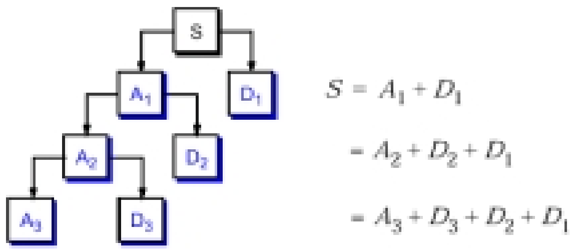
$$\psi_{a,b}(t)=\frac{1}{\sqrt{|a|}}\psi\left(\frac{t-b}{a}\right)$$

$$W(a,b)=\int_{-\infty}^{+\infty} s(t)\psi_{a,b}^{\ *}(t)dt$$

Where a is the scale and b is the translation. $\psi(t)$ mother wavelet leads to various $\psi ab(t)$ functions for different a and b values. The normalization factor $1/\sqrt{|a|}$ keeps the energy constant for every a and b values.

In continuous wavelet transformation, a scaled function is continuously shifted on the signal and the comparison between various position results is obtained. This process contains unnecessary terms and information that increases computation time. Discrete wavelet transformation produces enough information both in analyzing and synthesizing of the signal in shorter computation times. While discretizate wavelets, it is better to select the scale and position for a certain step. For example, a better analysis is achieved when scales and positions are selected as multiple orders of 2. The other method to do this is to use filters. For most of the signals, the bulk of the signal is represented in low frequency components and details are inside the high frequency components. In wavelet analysis too, filters are used to obtain the details. A low pass filter captures approximations and takes the low frequency and high scale components of the signal. A high pass filter however, corresponds to low scale and high frequency, and captures the details of a signal. While the resolution of a signal is varied with filtering, scaling is realized by using one of the following methods: upsampling, subsampling or down-sampling. Discrete-wavelet transformation and multi-resolution analysis is depicted in Figure 6. Selecting a most appropriate decoupling level is entirely depends on the signal and the experience.





$$S = A_j + \sum D_j$$

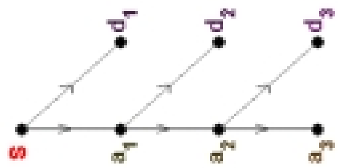


Figure 6. Discrete wavelet transformation and multi resolution wavelet analysis.

Wavelet analysis are used in various areas as; pattern recognition information systems and biomedical, feature extraction and trend detection in stock exchange, perfect reconstruction and video compression in communications. In electrical machines there are two Application areas seem to be emerging.. The first one is the noise, vibration, fault diagnostics and predictive maintenance of electrical machines[17,18]. The other area is the sensorless control of induction motors.

One of the work on sensorless control of induction motors uses the relationship between rotor current frequency and speed. In this work, stator current is analysed with wavelet technique and rotor current harmonics which are superimposed on stator current are decoupled and speed information are deduced. When wavelet technique is compared with others, it is seen that, the speed prediction is achieved easier and faster [19].

Another method for sensorless control of induction motors is to apply analytical wavelet transformation to stator current and achieve direct torque control. With this method, speed measurement for wider speed ranges in steady state and transient is possible. It is claimed that this method is much better for real time controlling of induction motors [20].

In this study, sensorless magnet position definition of BLDC motors are achieved by using multi-resolution decoupling technique of wavelets. Initially a hall-sensor equipped brushless dc motor has been driven through dSpace DS2201 digital signal processing kit. A simulation of this motor has been developed in Simuling and, hall sensor signals been utilised for producing required PWM waveforms for each phases of the motor. In the mean time, phase current and voltages have been recorded in time domain. These waveforms have been filtered by discrete wavelet technique. With low pass filters, approximations have been captured and the low frequency and high scale components of the current signal been obtained. Same procedure has been applied with high pass filter and, low scale and high frequency components have been captured and the details of a signal of low scale high frequency components have been obtained. The above procedure has been conducted on Matlab Wavelet Toolbox'. The obtained approximations and details have been used to reach the commutation instants of Brushless DC motors.

V. CONCLUSION

There has been various sensorless drive methods for Brushless DC (BLDC) motors. It is the first time the wavelet technique is applied to this type of motor, to detect the relative position of the magnets. A BLDC motor, that has hall position sensors, has driven through dSpace DSP kit and current and voltage waveforms have been recorded. Wavelet technique has applied on current and voltage waves. It has shown that wavelet analysis is a useful tool to develop an algorithm for sensorless drive of the brushless dc motors.

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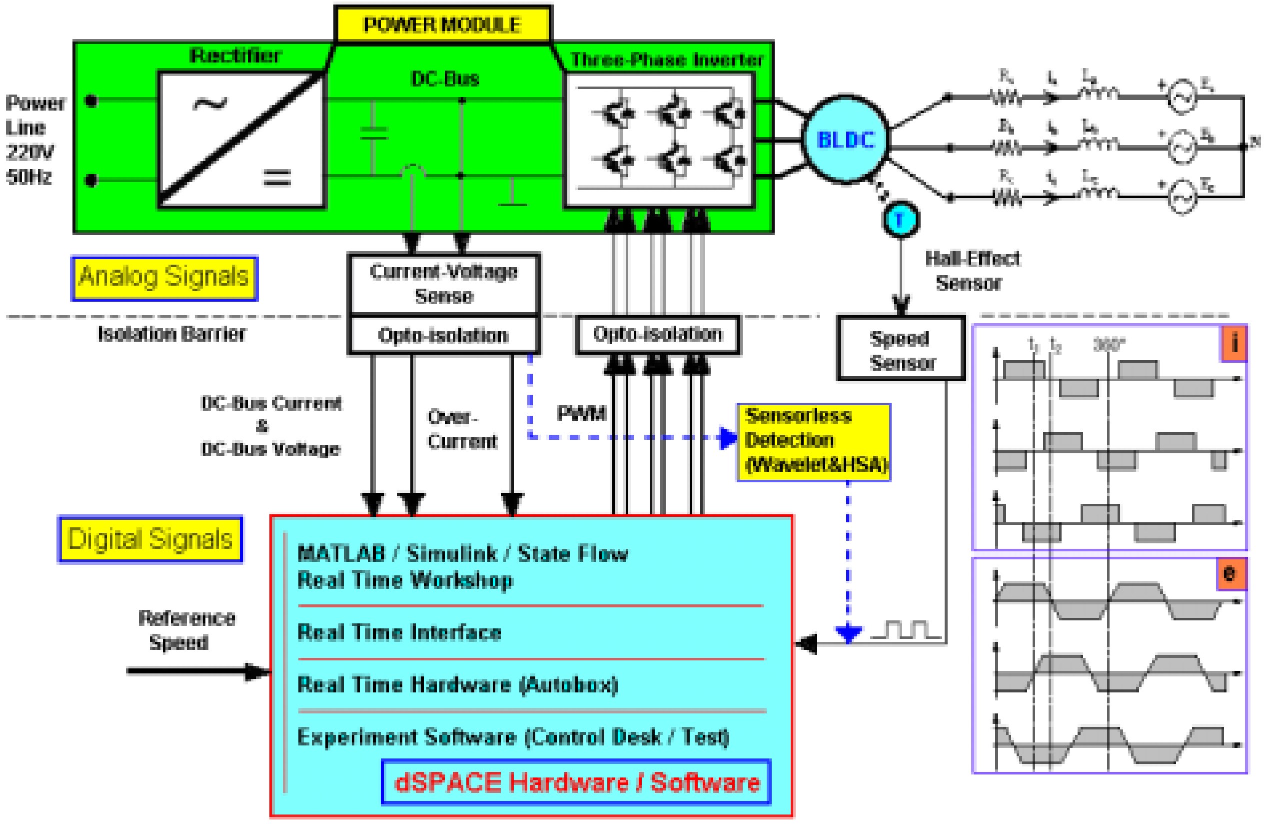

Figure 8. System control concept.