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Synopsis of the Speed Control Methods of Electric Drives with BLDC Motor

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Abstract: The use of BLDC motor has had rapid growth in various applications, in all areas of use of electromechanical systems. This has come as a result of not only the advantages, that have the BLDC motor compared to other types of electric machines of alternating and direct current, but also the possibility of using all control methods to ensure safe and high-precision work, which have given it a very large advantage in adapting it to perform a variety of tasks. Electronic control of BLDC motor gives it the advantage of being suitable for control schemes, starting with the ones with sensors, to determine the position of the rotor, to sensorless methods, from traditional control methods PI, PID and up to advanced and intelligent control methods, or in the production of controllers as integrated circuits, for specific commercial purposes. This advantage makes possible for the motor to be selected for different functions, be flexible and adaptable. BLDC motor control can be accomplished with or without sensor methods. The advantage of sensorless control methods is the realization of the required quality indicators at the lowest cost. But the disadvantage of BLDC control methods without sensors is that it needs a control algorithm and more complex electronic circuits. The purpose of this paper is to examine the different methods of BLDC motor control with sensor and without sensor, to point out the advantages and disadvantages of each, as well as to recommend the field of application of each of these methods. Based on the literature review all of these control methods for electrical transmissions with BLDC motor, will be briefly reviewed in this paper.

Keywords: BLDC motor, Control methods, Sensorless methods, İntelligent control, Advanced control

Introduction

One of the most important issues today is the saving of electricity and reduction of green gases emission. Initially this will be required by the end-users that consume it more. According to the world electricity consumption statistics, electric motors consume 46% of the total electricity consumption (Waide et. al., 2011).

Saving electricity is associated with increasing the efficiency of electric drives. This is made possible by using higher energy efficiency motors on newer electrical drives or replacing them with higher energy efficiency motors on older drives. Using the static converters for control of the electrical drivers, creates the good conditions to control the speed, position or torque of the motors. On the other hand, high efficiency electrical motors have less electrical losses, are more robust and increase the performance of the motors. (Splahiu et. al., 2008; Miller, 1989). On the table 1 there are given advantages of BLDC motors, taken in study on the paper.This paper presents some of the BLDC motor control methods as well as their advantages and disadvantages.

Table 1. Advantages of BLDC motors (Splahiu et. al., 2008; Miller, 1989).

Advantages of BLDC motors	The reason about these Advantages
Small size Motors	The using of modern permanent magnet makes that BLDC motors to have the smaller size compare to the induction motors.
High efficiency motors	The permanent magnet in the rotor reduces the core losses in comparison with induction motor (AC) and there are no losses in brushes compare of direct current motor with brushes (DC).
Higher speeds	There are no brushes to limit the speed, smaller size, lower inertia. BLDC motors are designed to work with high speed up to 100000 rpm. This motor has losses for low speed.
Low maintenances	Brushes privation, this means that motors don`t need replacement, inspections, or maintenances.
Fast dynamic response	Lower rotor inertia in comparison with the DC and Induction motors.
Lower interference, radio frequency interference, RFI	Eliminations of brushes
Linear mechanical characteristic, speed versus torque.	The internal feedback of the rotor position is the reason of the linear mechanical characteristic of BLDC motors.
High starting torque	The internal feedback of the rotor position creates the possibility of a higher starting torque compared to induction motors with open loop
Speed control	Electronic commutation can be used to control the speed, without increasing the cost of the electrical drive.
Good thermal condition	The element which generates the thermal energy is the stator, that is in the outer part of the motor. compared to DC motor, which has the stator in the inner part of the motor.
More control possibility as induction motors.	Due to linear mechanical characteristic, pole design, and feedback of the rotor position, there are good conditions for better speed and position control.

Applications

The use of BLDC motor has had rapid growth in various applications, in all areas of use of electromechanical systems. The applications of BLDC motor are presented in the table 2

Table 2. The application of BLDC motors. (Xia, 2012)

The field of applications	Equipment
Hybrid and electric autos	Air conditioning, wiper glasses, air bags, electrical doors, control of the seats, fuel pump control, electronic steering control, engine control
Industry	In the industry of robots and manipulators, in the textile machineries, printed machinery, woodworking machinery, paper industry machinery, food industry machines, packaging machines, machinery manufacturing of plastics etc.
Office Equipment	To drive the main shaft of the hard disc, to drive the optic disc and floppy disc. The blower of the computer, Digital Camera, Lesser Printer, Photocopy
Household appliances	Vacuum cleaner, air conditioning, refrigerator, DVD, cd players, camera
Medicine	Respiratory equipment, medical analyzer
Aerospace	High-speed centrifugal pumps, robotic arm control, gyroscope control, high-speed cameras

Method

Based on the requirements of various electromechanical systems, regarding the accuracy, quality of different dynamics during work, in order to meet all the requirements of load, the control method for the BLDC motor is also selected, sometimes combinations of different control methods can also be used to take advantage of the positive sides of each.

In general, if the electromechanical system operates under conditions of immutability of the internal parameters of the motor, with constant load, and when there are no speed control requirements, traditional speed control methods give satisfactory results. In this case the system is seen and treated as a linear system and studied and designed according to well-studied methods. The most commonly used regulators in industrial applications are PI, PD, PID. In case the system is in the conditions of changing the motor parameters, of a change in wide load limits and has high demands on the accuracy of the technological process, then it is presented as a nonlinear

system and its mathematical model is expressed through state equations. The most used methods in this case will be Estimation based methods, Sliding mode Observer, MRAS, Extended Kalman Filter, etc.. (Xia, 2012). Of course each method has its limitations and performance enhancement and optimization of system operation is achieved using intelligent methods where, Fuzzy based control, sliding mode control, neuro-network control, genetic algorithm etc. are included. Intelligent methods do not need a mathematical model of the system, because they are distinguished by their property of analyzing, learning off and on line and finding the optimal solution in each case, when working conditions change (Xia, 2012).

The field of use of the wide range of control methods, provides indicators of high performance of BLDC motor control systems. The control problem is to monitor the state of the system and bring it to the desired state. The initial state of the system must match the desired initial state. While other states must follow the desired state every moment with zero error without endless action but certainly after a transitional process. The tasks included in the BLDC motor control system are: switching the motor through the inverter, providing the pulse to turn the transistor on or off through the PWM strategy. Detection of rotor position using sensors, or sensorless methods. Various control methods are used to improve the performance of electrical drives.

One of the indicators of electrical drives performance is the dynamic output response of the system expressed by the output signal as a function of time. In control systems, the output signal as a function of time is given through two components, the transient response and the continuous response. Sometimes specifications can be added, such as sensitivity from variation of parameters, stability, disturbances, cost, etc. (Kuo, 1975).

Figure 1 shows the typical transient response of the electrical drives and its main indicators.

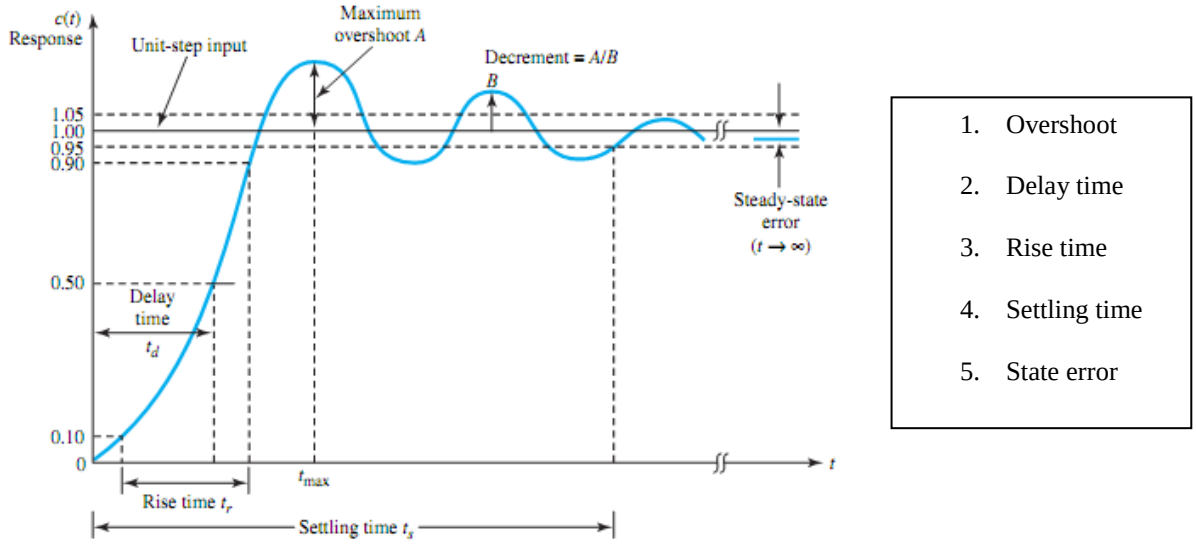

Figure 1. Transient response of the system (Kuo, 1975)

Sensor and Sensorless Control Method

The BLDC motor unlike other motors does not feed the winding phases continuously, but feeds them sequentially according to the rotor position. Depending on the position of the rotor poles it is determined which phase of the coil should be fed and how long. Therefore, different methods have been developed to determine the position of the rotor, two of the most important are as follows:

The method of direct detection of the rotor position, which is realized with sensors and is called the traditional method. Sensors can be the Hall effect sensor, optical encoder, resolver, etc. Methods of indirect detection of rotor position, which are realized by methods without sensors. This is based on an algorithm, which measures the value of voltage or current in the motor (Miller, 1989). Of all the rotor position detection methods, the motor back EMF method is the most elaborate method, which has been used since the beginning of the sensorless method and continues to be used successfully today.

On the table 3 are presented advantages and disadvantages of sensor and sensorless methods, and in the table 4 advantages and disadvantages of detection methods of rotor position. (Xia, 2012; Loreta et. al., 2018)

Table 3. Advantages and disadvantages of sensor and sensorless methods (Xia, 2012; Gamazo-Real et. al., 2010; Loreta et. al., 2018)

Methods	Advantages	Disadvantages
With sensor	Simple schemes	It increases the motor volume, they have higher costs, it causes magnetic interference. They are affected by temperature and humidity and so the accuracy drops. It is difficult to assemble. A small displacement reduces process performance.
Without sensor (sensorless)	Low cost, The motor size decreases, the performance increases.	Requirements for control algorithms. The complexity of electronic circuits increases.

Table 4. Advantages and disadvantages of detection methods of rotor position (Xia, 2012; Gamazo-Real et. al., 2010)

Detection methods of rotor position	Advantages	Disadvantages
Terminal voltage sensing method	It is widely used for low-cost industrial applications such as fans, pumps, compressors that do not require frequent speed variation. They are also used in work tools with very high speed, due to their light weight and small size for the same power.	It needs a position sensor, which can be eliminated by taking the value of back EMF through this method.
Back -EMF integration method	Switching the motor in delay or phase progress is done by adjusting the voltage Vth, and is not sensitive to the switching signal. It reduces sensitivity to switching noises and automatic adjustment of the inverter connection.	There are accumulated integration errors and the threshold setting problem. Problems in the accuracy of back EMF at low speeds.
Third-harmonic back-EMF method	Simplicity in implementation, low sensitivity to noise, wide speed range, small phase delays, compared to the first method. Signal detection at low speeds is possible because the frequency is three times higher. It is used in a range (100–6,000 rpm)	Continuous accumulation of noise signal error at low speeds, errors are made during the integration process, which will cause inaccurate switching.
Freewheeling diode method	High sensitivity, wide adjustment range. It outperforms the previous methods for low speed.	There is error around the zero point of back EMF as well as other methods. Six independent sources are needed in the additional detection circuit which complicates the application. So the detection circuit is a bit complicated and costly expensive.

Traditional Control Methods

In general, if the system operates under conditions of invariability of the internal parameters of the motor, or with constant load, the traditional methods give satisfactory results. In this case the system is seen and treated as a linear system and the selection of the controller and its parameters in such a way that the transient response meets the specified design requirements. On the table 5 are presented advantages and disadvantages of traditional controllers (Kuo, 1975).

Table 5. Advantages and disadvantages of traditional controllers (Kuo, 1975).

Traditional controllers	Advantages	Disadvantages
PD	It is a predictive control. It gives with precision the effect of the required compensation of the error in the stabilized state. It reduces overshoot and increase time of the transient process.	It has an effect on the steady state error only if the error changes with respect to time. If it is constant, then this adjustment does not affect it.
PI	It improves steady state error and damping.	There is a greater growth time and greater set time of the transient process. So, the system is slower.
PID	Overshoot approximately is equal to the PI regulator, Shorter duration. Error in the stabilized state is zero.	

PWM Strategy

In controlling systems with the sensorless method, signal processing and impulse input for switching inverter transistors based on the PWM control strategy, is most useful. Some of the techniques based on this strategy are listed in the table 6, (Xia, 2012; Spahiu, 2009; Gamazo-Real et. al., 2010).

Table 6. Advantages and disadvantages of PWM strategy in sensorless control (Xia, 2012; Spahiu, 2009; Gamazo-Real et. al., 2010).

PWM strategy in sensorless control	Advantages	Disadvantages
PWM technique for low speed and voltage	With signal amplification and offset voltage adjustment, the speed range of the motor, that can use this technique, is greatly expanded. (50-2500) rpm	Difficulty in detecting back EMF, due to its very small values. An amplifier is used as the preliminary circuit to adjust the offset voltage and amplify the signal near the zero-crossing point.
PWM technique for high speed and voltage	With the reduction of the motor time constant due to the voltage and high-speed technique, it is successfully used for speeds up to -30000 rpm.	Difficulty of connection in time, frequency of connection disconnections very large. Additional elements, such as resistors and diodes, are used to reduce the time constant and avoid errors leading to erroneous detection due to delays, as well as diodes to block the passage of current to additional resistors.
PWM technique for low power applications	Significantly reduces the voltage drop caused by the connection of the resistor to the power circuit, the load current, compared to the positive voltage drop of the diode. Power consumption and heat loss are significantly reduced.	The problem in these schemes is to reduce power consumption and losses, which are reduced by the way of command and control and the addition of a resistor in the power circuit.
Direct current control (Hysterezis current control)	In order for the phase currents to be as close as possible to the reference currents the regulator bands need to be as narrow as possible. Reducing the hysteresis, the regulator band increases the switching frequency. Better performance than PWM technique.	The cost of static converter component increases and also the losses in it from increasing the frequency due to the reduction of the regulator band. The hysteresis regulator band takes 5% of the reference currents. Variable frequency compared to the PWM technique, which has a constant frequency.

Advanced Control Method

In traditional control of BLDC motor drives, the mathematical model of the system must be known. The closer this model is to the real one, the better its performance indicators are. But again, in the mathematical equations of the model there are inaccuracies which are divided into two major groups:

1. The inaccuracies that include the difficulty of recognizing the parameters of the model, or even changing them during load operation.
2. The inaccuracy of mathematical model presentation, and non-modellable dynamics.

The sliding mode is a control method that ensures that quality requirements are met even in the presence of inaccuracies, because it finds a control law capable of adapting. In table 7 are presented advantages and limitations of advance control methods (Xia, 2012; Gamazo-Real et. al., 2010).

Intelligent Control Methods

The intelligent control system combines the techniques of the field of artificial intelligence, with those of control engineering to design autonomous systems which can understand, reason, plan, learn and act in an intelligent way. Such a system must be able to achieve the desired consistent behavior in conditions of uncertainty, with regard to the plant model, with unpredictable changes in the environment, uncertainties, incomplete, incorrect, unreliable information of the sensor and improper functioning of the actors.

The intelligent control system has several subsystems. The perceptual subsystem that collects information from the plant and the environment, and processes it in a form suitable for recognition by the subsystem. Under the recognition system associated with the decision-making process under conditions of uncertainty. Key activities include reasoning, strategic planning, learning. The operating subsystem uses signals from the recognition

subsystem in order to operate the plant in certain desired states. If the action of the actor or sensor fails, then the intelligent control system is available and is able to reconfigure its control strategy. In table 8 are presented Advantages and problems of intelligent control methods (Xia, 2012).

Table 7. Advantages and limitations of advanced control methods (Xia, 2012; Gamazo-Real et. al., 2010; Zhixun et. al., 2018; Lenine et. al., 2007; Nicosia et. al., 1984; Sugimoto et. al.; 1987).

Advanced control methods	Advantages	Limitations
Estimation and model- based method	Simplicity of design is the biggest advantage of using the observer. It can evaluate all measurable states or not in the system model	
Applications	PMSM, BLDC, etc.	
Sliding- mode observer (SMO) DTC techniques	It is very efficient in assessing the conditions of the system, it is robust against the variation of parameters and concerns including measurement noises. Also with the introduction of DTC Technical, an optimal performance is achieved even in the area of low speeds, because the change in the value of the stator resistance can be taken into account. These bugs are solved through the DTC space vector modulation scheme, which uses a constant frequency switching.	This method applied in practice has the problem of high voltage values given by the power supply and stress caused on static power converters. To improve the control performance, we can use digital observer. However, hysteresis-based DTC methods have some serious drawbacks: High torque pulse, flow pulse, inverter switching variable frequency. Great time for calculations.
Applications	Position control in induction motor uses FPGA, which has implemented sensorless SMO for PMSM drives. It is robust and has a high performance. BLDC motor.	
Extended Kalman Filter (EKF)	Rotor position and speed can be estimated with sufficient accuracy in both steady and dynamic states Achieves a rapid convergence.	Intensive calculations
Applications	The BLDC motor without position and speed sensors has attracted wide attention. Extended Kalman filter will be employed to estimate the motor state variables by only using measurements of the stator line voltage and current. When applying the extended Kalman filter, it is necessary to solve some specific problems related to the voltage and current waveforms of the BLDC motor. EKF will be designed and implemented for the estimation of speed and rotor position of BLDC motor, so the motor could run at low speed with reasonable accuracy.	
Model Reference Adaptive System (MRAS)	It is also used in cases of estimating the resistance value of the stator and rotor when the sensorless control system is in the transient state, such as operating under a wide variation of the load moment or the change in the speed command. The scheme of an active power MRAS is based on the identification of rotor resistance, the evaluation of which is effective, over a wide range of variations and can be applied in real time Field Oriented Control (FOC).	One of the advantages is the high speed of adaptation. It is relatively easy to be implemented in a quick adaptation for a large application area.
Applications	For some problems concerning the control of multifunctional manipulators (industrial robots) with high-speed continuous movements, highly interconnected and non-linear, whose model is known, approaches based on the Model Reference Adaptive System (MRAS) method of control are possible and useful. A generalized MRAS control assures the convergence to a suitable reference model for a class of processes. Model reference adaptive systems (MRAS) are used to identifies the secondary resistance under any load and any speed in induction motor, also in BLDC motor.	

Results and Discussion

What control methods are used for the BLDC motor? It's a question that seeks for an answer for anyone starting to study the BLDC motor and its control. Confusion increases with the number of methods used. The paper tends to make a summary of control methods, advantages, disadvantages of each, as well as a brief information on their use without indicating what is the principle on which each method is based. From the literature review it is shown that for BLDC motor can be used all kinds of control methods from those with sensors to methods without sensors, from traditional methods to intelligent ones. This means that any kind of performance we want through the BLDC motor can be provided, as we can switch from one method to another that compensates for

the shortcomings of the former.From the methods based on the correct mathematical model of the motor, to methods that even allow inaccuracies of the model to those that do not need a mathematical model at all.

Table 8. Advantages and problems of intelligent control methods (Xia, 2012; Gamazo-Real et. al., 2010; Levine, 2010; Singh et. al., 2015; de Barras Ruano, 1992; Wang et. al. 2003).

Intellıgent Control	Advantages	Problems
Fuzzy logic Control	Requires less calculation, good reasoning skills, It has good durability and adaptability.	There is no ability for new rules, and very poor learning skills
Applications	Automobile and other vehicle subsystems, such as automatic transmissions, ABS and cruise control, Air conditioners; Cameras; Digital image processing, Rice cookers; Dishwashers; Elevators; Washing machines and other home appliances; Pattern recognition in Remote Sensing; Hydrometeor classification algorithms for polarimetric weather radar; Fuzzy logic has also been incorporated into some microcontrollers and microprocesors.	
Artificial Neural-Network Control	It has very good ability to solve structured uncertainty and system concerns. It learns very well. The ability to perform arbitrary nonlinear mappings. Allowing traditional control schemes to be extended to the control of nonlinear plants. This can be done without the need for detailed knowledge of the plant. The ability to create arbitrary decision regions means that they have the potential to be applied to fault detection problems. The use of ANNs is the duty of control managers, deciding which control algorithm to employ based on current operational conditions.	Requires more computing capacity and more memory space, but lacks good reasoning skills. .
Applications	Robots are nonlinear, complicated structures. Robotics was one of the first fields where ANNs were applied. It is still one of the most active areas for applications of artificial neural networks. ANNs have also been applied to sensor failure detection and diagnosis. The use of neural networks, in the three different capacities of identifiers, pattern recognizers and controllers, to detect, classify and recover from faults in control systems. Neural networks can also provide, significant fault tolerance, since damage to a few weights need not significantly impair the overall performance.	
Genetic Algorithm	Can optimize online and offline settings to get a better performance out of control.	Requires longer computation time and more memory space
Applications	GAs is applied in many different areas, such as signal processing, game playing, robotics, image segmentation, scheduling and control engineering. Application of GAs in Control Engineering, PID Control, Optimal Control, Robust Control, System Identification, Online Adaptive Identification and Control.	

Conclusion

The BLDC motor is the motor with with the highest increase in propagation in various applications because it provides very good and excellent properties, such as linear mechanical characteristic, lower losses, higher torque density and higher power density, noiseless operation, etc. The feature that has always attracted attention is the very high efficiency compared to other AC and DC motors of the same power. Experimentally tested and as written in the literature reference, the BLDC motor has a less moment of inertia than the IM motor. Its impact appears to be on the dynamic response with smaller starting currents, shorter stabilization time and faster stopping. For this reason the BLDC motor is more suitable especially in variable speed electric drives. Using this motor brings a higher performance.

On the other hand, electronic schemes greatly influence the use of control methods. For BLDC motors sensor methods or sensorless control methods, traditional methods, advanced methods and intelligent methods can be used. But a combination of methods can be realized not only of the same nature, but also of different natures to take benifits of the advantages of each of them, such as traditional method with intelligent method, etc. The type of control method is selected according to the requirements that must be met by the electric transmission with BLDC motor.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

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