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BLDC MOTOR CONTROL SYSTEMS ANALYSIS

Introduction

The use and performance of brushless direct current (BLDC) motors are significantly related to the electronic switching and control system that is required to operate these motors. Therefore, in the past, the use of BLDC motors was limited by the additional cost of the motor controller and its dependence on the control quality indicators and the complexity of the algorithms. Now the use of these motors is constantly increasing due to the evolution in the field of semiconductors and the rapid growth of computing capabilities of microprocessor systems and their reduction in their cost. This allows the implementation of compact devices with high performance while maintaining low costs.

BLDC motors have long been used in industrial applications such as electric drives, feed drives for CNC machines, industrial robots, extruder drives, etc. Due to such characteristics as compact size, constant mechanical torque, long service life, reduced weight, high speed range and the absence of sparks and noise, BLDC motors are successfully used in a wide range of applications.

The main areas of application of BLDC [1]: industry, automotive, HVAC systems, semiconductor industry, computer technology, home appliances, quadcopters and drones, robotics, medical industry, prosthetics.

In addition, the design features of BLDC motors, compared to other types of motors, allow for better heat dissipation, thus further expanding their application areas. A detailed overview of applications in these industries is given in article [1].

A brushless direct current (BLDC) motor is a synchronous AC motor with permanent magnets on the rotor (moving part) and windings on the stator (stationary part). The permanent magnets create the rotor flux, and the energized stator windings create the poles of the electromagnet.

The motor's work of converting electrical energy into mechanical energy is based on the attraction or repulsion between magnetic and electro-magnetic poles. In the simplified structure of a three-phase motor [2], shown in fig. 1, the process begins when current flows through one of the three stator windings and creates a magnetic pole that attracts the nearest permanent magnet of the opposite pole.

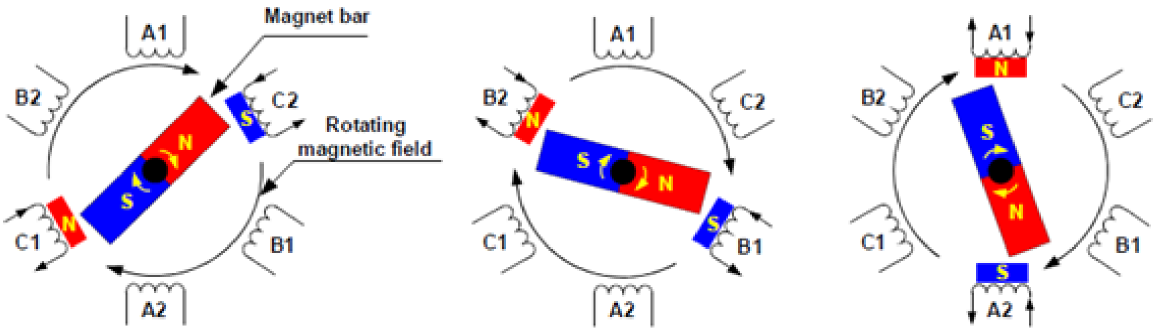

Fig. 1. Simplified diagram of a BLDC motor rotation

An important feature and characteristic of BLDC motor is the trapezoidal shape of the back EMF, which is created by a certain way of connecting the stator coils.

BLDC motor is a symmetrical three-phase system, where BEMF phase voltages are shifted by one third of field angle period ($2\pi/3$). BEMF voltage depends on rotor angle as shown in fig. 2.

This feature allows to implement very simple methods to control the motor with rectangular pulses. A BLDC motor with permanent magnets and trapezoidal back EMF then consumes rectangular currents.

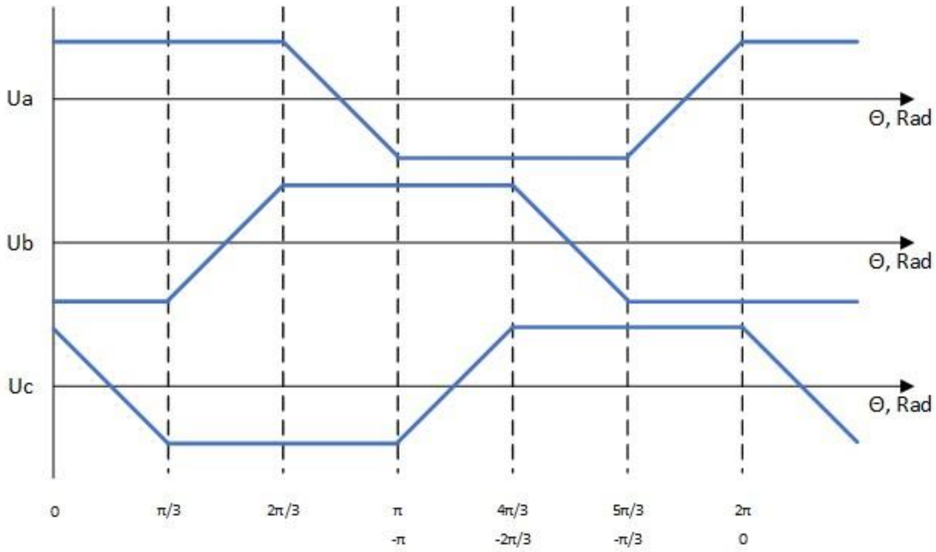

Fig. 2. BLDC motor phase Back EMF voltages

The line-to-line BEMF shape of the motor is calculated as the difference between phase voltages and this is shown in fig. 3.

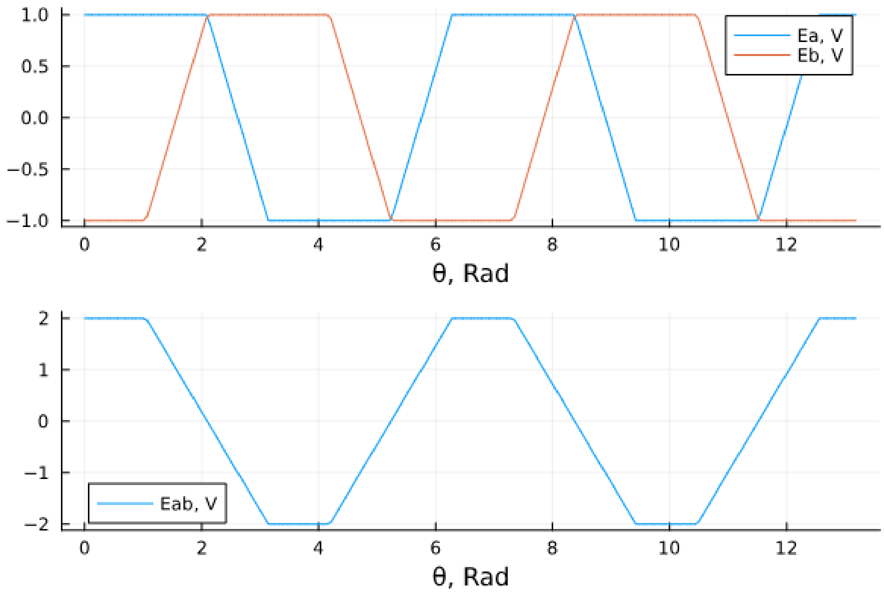

Fig. 3. BLDC motor line-to-line Back EMF voltage

In the classic motor design, the trapezoidal shape of the BEMF is determined by different coil connections and air gap distances. This winding configuration requires fewer windings compared to synchronous motors with a sinusoidal BEMF shape (PMSM motors) and, accordingly, BLDCs have a lower cost.

Real BLDC motors can have BEMF shape different from trapezoidal. It is smoother due to construction features and the influence of the stator resistance and inductance during rotor rotation. Example of BEMF shape of real motors is shown in fig. 4.

Some BLDC motors have BEMF close to sinusoidal shape; it makes them relatively close to PMSM motors. So, it is possible to use advanced control techniques developed for PMSM motors to control BLDC. In many cases, due to winding configuration or decreasing cost of the motor, its BEMF shape has significant differences from trapezoidal and sinusoidal.

BLDC motor simulation [3] shows that difference between the BEMF shape of the motor and shape of the stator voltage plays a significant role in forming motor currents under the load modes and reduces efficiency of the system. So, it is necessary to consider the BEMF shape in choosing the best control method for a given BLDC motor.

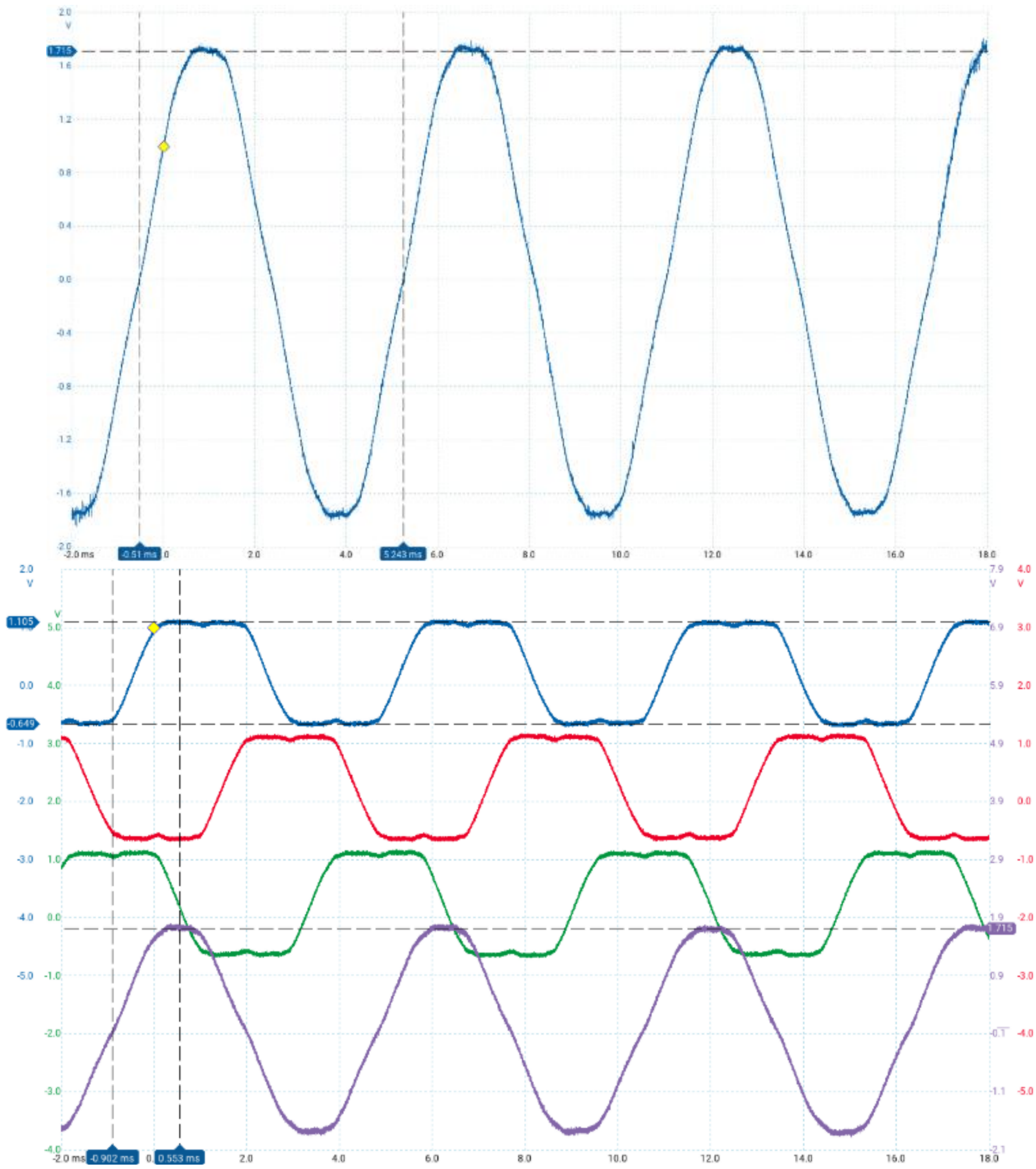

Fig. 4. Experimental Back EMF shapes of BLDC motors

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The aim of the article is to analyse generally used and latest methods of BLDC motor control to use these approaches in combine with developing prediction control system of the BLDC motor. Control methods analysed from point of stator voltage shapes passed to the motor from the power converter; methods of synchronisation with the rotor position and motor speed control techniques.

1. Power converter switching

To control the voltage and current in the windings of brushless DC motors, switching semiconductor electronic devices are generally used. The most common and universal power converter circuit for controlling BLDC motors is a three-phase bridge autonomous voltage inverter, the structure of which is shown in fig. 5.

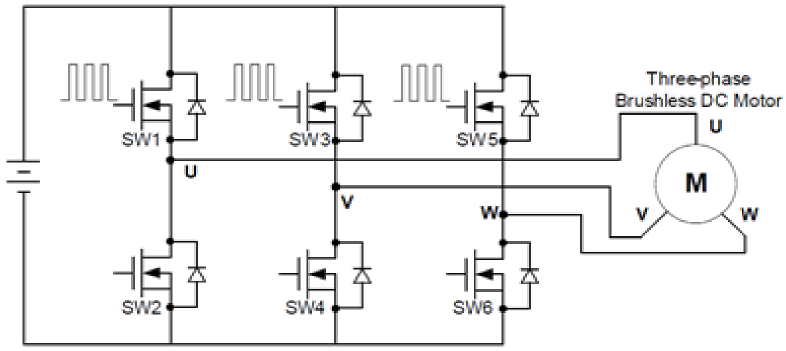

Fig. 5. Simplified circuit of 3-phase power inverter for BLDC motor control

The inverter circuit [4] uses fully controlled switches: FET or IGBT transistors that are turned off by the control circuit. Inverter is powered by a DC source.

3-phase inverter converts the DC voltage from a battery or a rectifier with a storage capacitor into a three-phase AC voltage with a sinusoidal or rectangular or other frequency-variable shape.

The main approaches to generate voltage for BLDC control motors are:

- autonomous voltage inverter in amplitude control
- 6-step commutation;
- sinusoidal 3-phase PWM;
- space Vector PWM;
- hysteresis control (relay switching).

First tree techniques generate different variations of rectangular AC voltage shape. They are used for simple and fast control applications such as fans, quadcopter motors and drones, where the motors have close to trapezoidal BEMF shape. In general, it is used to simplify control system and when exact BLDC motors.

In advanced control systems which use SVPWM inverter control it is possible to adopt output voltage to BEMF shape of the motor. Such systems will be reviewed later in the article These methods are reviewed in the next section.

2. Voltage shapes for motor control

2.1. Autonomous voltage inverter in amplitude control

This technique is classic form of the 3-phase inverter control and can be used to drive BLDC motor. The output voltage period is divided into six intervals. Each of the switches in the half-bridge is turned on for half the output frequency period. The diagrams of the operation of an autonomous voltage inverter in amplitude control mode are shown in fig. 6.

The linear voltage has a rectangular shape, its half-wave duration, the amplitude is full DC-link voltage. But the effective value of line-to-line voltage is 0.816 of DC-link voltage [4]. But such shape of stator voltage does not correspond to motor BEMF shape and simulation shows that motor currents lead to sufficient pulsations in the motor torque in steady state modes. Dependency of motor torque from 3-phase currents was simulated used setup from [3] and shown in fig. 7.

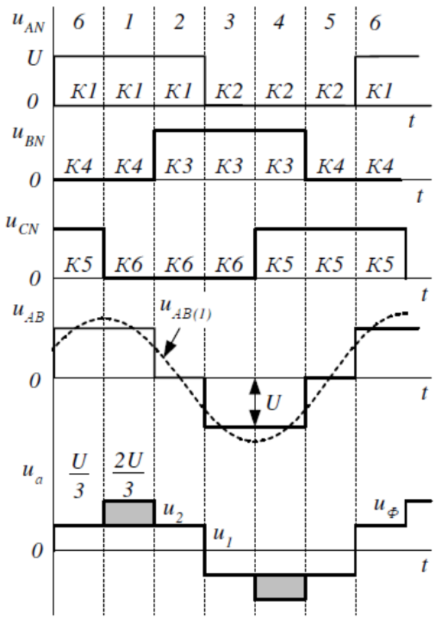

Fig. 6. Three-phase inverter operation with amplitude control

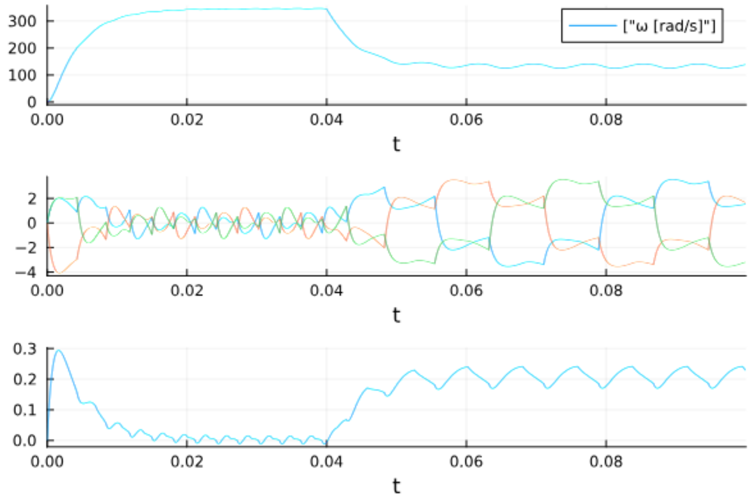

Fig. 7. Motor torque ripple

This sufficient disadvantage of simple amplitude control leads to the current and torque oscillations which cause speed disturbances. This control type is rarely used in practical applications.

2.2. 6-step commutation

This mode also known as 2-phase current injection. Trapezoidal commutation (also known as 6-Step commutation) follows the principle that current should flow in only two of the three phases at the same time. According to this method, a pulse with a width of 120 electrical degrees is applied to 2 phases of the motor and the third phase remains disconnected from the voltage source. This means that at the same moment one phase of the motor is connected to positive voltage, another phase is connected to 0 (GND) and third phase is left floating. All this three state generates by inverter half-bridges. Fig. 8 shows the control signals for inverter gates and output voltage at the one half-bridge (phase of inverter). Floating state (Hi-Z) it shown as half oh DC-link voltage. Separate control of the half-bridge keys required to create floating state – in this mode both FETs should be turned off (low level at the gate).

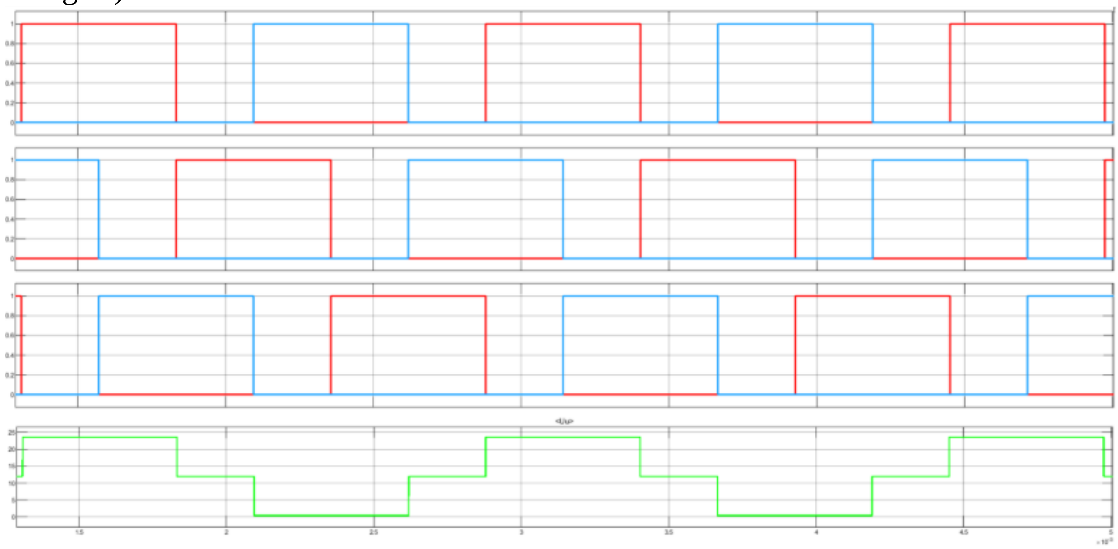

Fig. 8. 6-step commutation control signals

To change the voltage on the motor, PWM is used at the half-bridge inverter, which generates a positive voltage. The operation diagram is shown in fig. 9.

When a BLDC motor connected to inverter, the shape of the voltages at the inverter output changes because the rotating motor is a source of BEMF. At times when a phase remains disconnected from the voltage source, there is a back EMF of the motor phase on it.

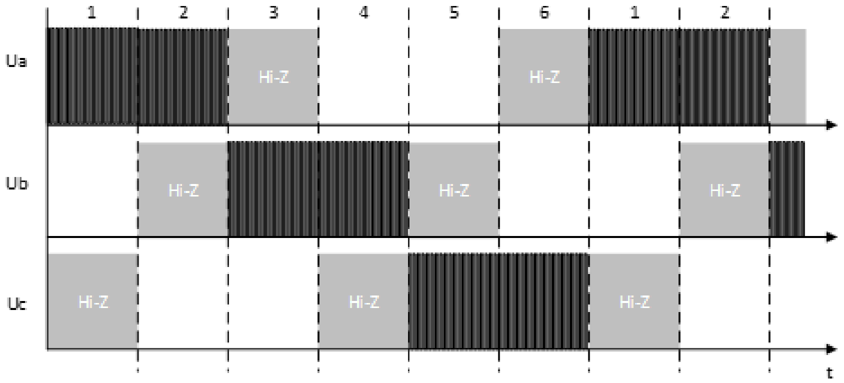

Fig. 9. Motor phase voltages in 6-step commutation mode with PWM voltage control

Motor phase and line-to-line voltages and motor current shown in fig. 10.

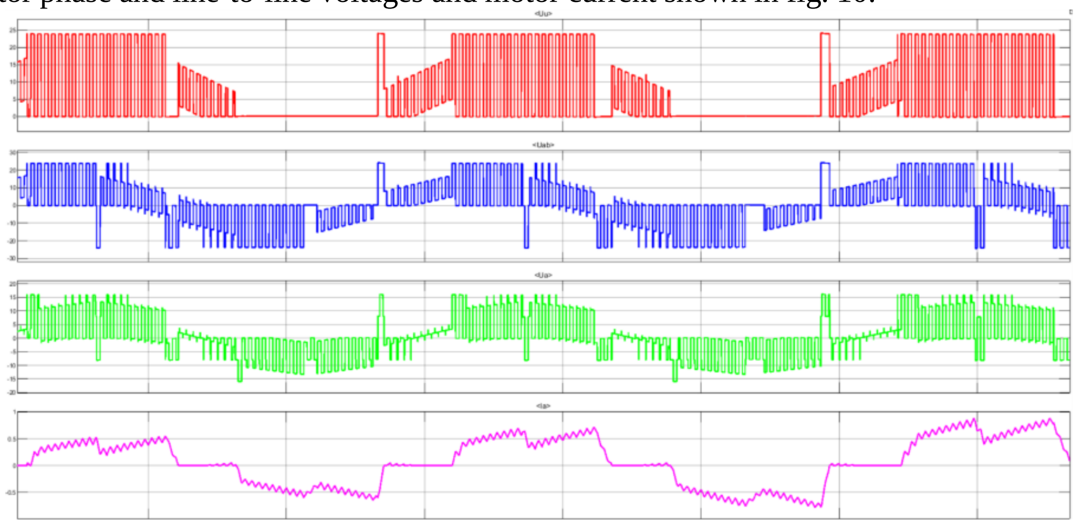

Fig. 10. Voltage and current diagrams of a BLDC motor with 6-step commutation

In this mode motor currents flows only through 2 phases, and this derives mostly linear shape of current and motor torque. One of the advantages of this technique – possibility to measure motor BEMF in real time at the phase which is left in Hi-Z state (floating).

Also, the shape of phase voltage is much closer to trapezoidal motor BEMF, and this mode delivers the minimal average torque required to rotate the load.

6-step commutation required synchronisation between inverter voltage and BEMF of the motor. The BEMF value should be synchronised with moments of current injection as shown in fig. 11.

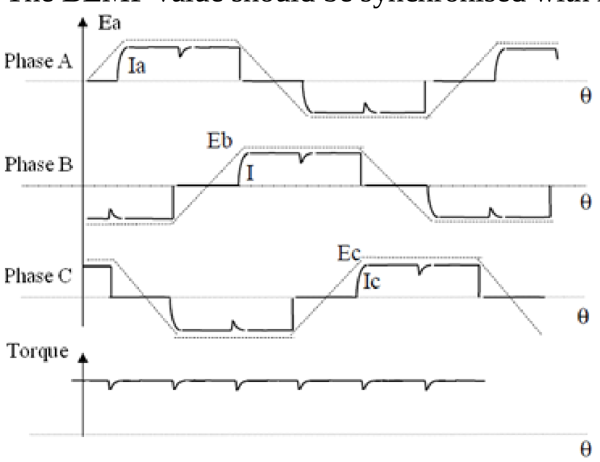

Fig. 11. BEMF and currents synchronization during 6-step commutation

The synchronisation techniques considered in more detail in the next section of article.

Disadvantage of this 6-step method is in sufficient torque cogging, when current switched from one phase to another. The torque and its ripples shown at bottom axis of fig. 11. At high loads also leads to sufficient commutation disturbances which can decrease EMI parameters of the system.

Also exists 12-step commutation methods that allow to form more than 6 output states which corresponds to more positions of the field flux vector. Theu are usualy used to increase motor rotation performance at the low speeds.

2.3. Sinusoidal 3-phase PWM (SPWM technique)

If the BLDC motor has a back EMF shape close to a sinusoidal one, the 6-step mode can be used for commutation, but in this case the next problems appear:

– torque consists of a fragment of a sine wave and is a combination of the trapezoidal current strategy and sinusoidal back EMF;

– the torque value is smaller.

In this case, the 3-phase sinusoidal voltage at the inverter output is used and the motor will create a constant torque without ripples.

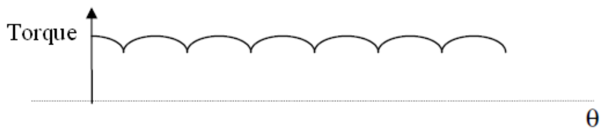

Fig. 12. Torque ripple in a sinusoidal motor controlled as BLDC

The most common for analogue and digital control systems is the method of formation based on reference signals [4] and the tabular method of voltage formation. These methods to control an autonomous voltage inverter to generate sine voltage have been significantly studied and have been used for a significant number of years, and therefore they will not be considered in detail in this review.

2.4. Space vector PWM (SVPWM)

This method of the 3-phase voltage generation allows to orient the instantaneous value of the voltage vector and its rotational speed in accordance with the required voltage frequency and magnitude in real time.

For the circuit of an autonomous voltage inverter (Fig. 5), there are eight possible discrete states of the power switches, and the output voltages of the inverter can be composed of these eight switch states.

The given voltage vector is formed during the PWM period from three consecutive states among which it is located at a given moment of time.

The diagram of the operation of this algorithm [5] is shown in fig. 13.

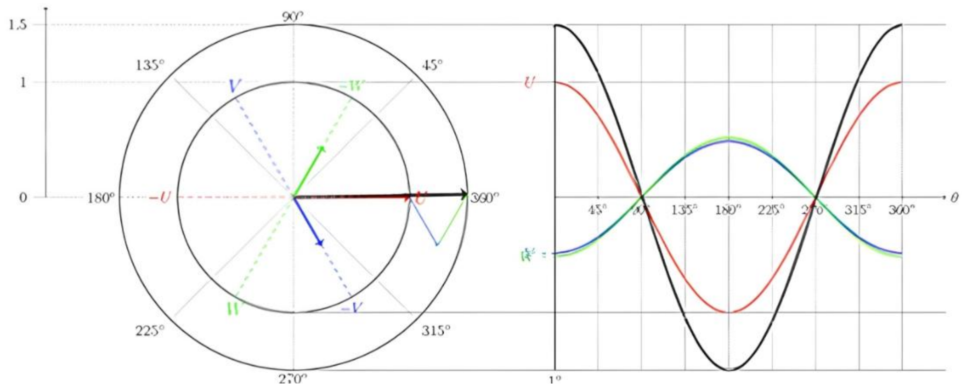

Fig. 13. Visualization of Space vector PWM generation

The advantages of this method are:

- fast control of the voltage vector, and thereby changing set the amplitude and frequency in real time;
- the ability to generate a constant voltage on the stator with any orientation
- easy integration into the motor vector control system
- posible to create non-sine voltage and adopt it to BEMF voltage shape of the motor

The disadvantages are relatively high requirements for the computing system and not full use of the inverter DC-link voltage. But the second disadvantage is neglecting by the compensation method by adding the third harmonic.

3. Rotor position measurement

While BLDC are synchronous AC motors, it is always necessary to adjust the position of the rotor with the voltages generated by the inverter, i.e. to sync control voltages with actual motor BEMF.

Therefore, information about the current position of the rotor is required.

Depends on the source of data about the rotor position, control methods and systems are divided into sensors position measurement and sensorless.

3.1. Hall-sensors control

Since most BLDC motors have a trapezoidal back EMF and the voltage waveform in these cases requires rectangular control signals, the most common position sensors are Hall effect sensors. The sensors are installed on the stationary stator of the motor and output a logic signal about the position opposite the south or north pole of the rotor magnet. For a three-phase BLDC motor, three Hall sensors are required to determine the rotor position.

Depends on the physical location of the Hall sensors on the stator, there are two types of sensor positioning: 60° phase shift and 120° phase shift. The combination of signals from the 3 sensors determines the exact sequence of commutation signals.

Fig. 14 shows the connection between Hall-sensors signals and motor BEMF for BLDC motor. Based on it the switching sequence for 3-phase inverter can be created. If 6-step commutation is used it is necessary to align current injection periods with BEMF which can be calculated from Hall sensor signals as shown in fig. 15 and in [2].

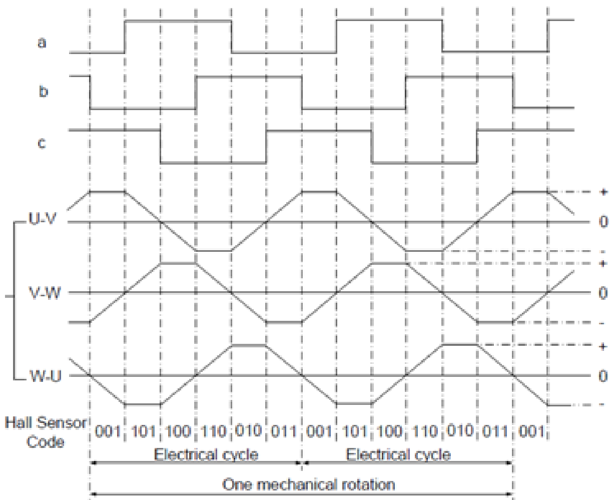

Fig. 14. Correlation of Hall sensor signals and BEMF signals

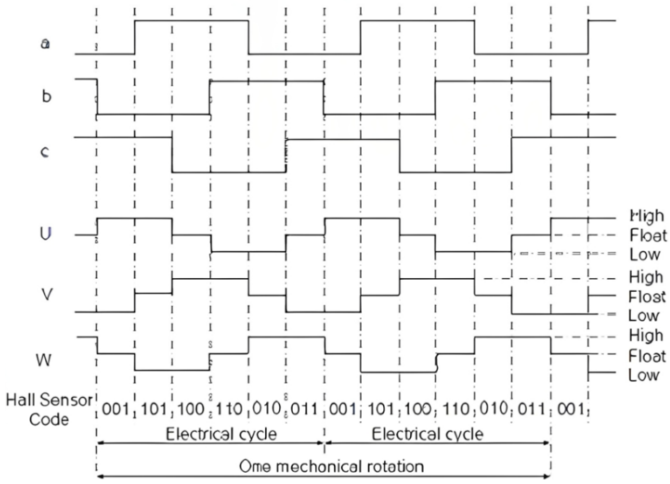

Fig. 15. Timing diagram of motor commutation using Hall sensors

For each 60° rotation angle, one of the Hall sensors changes its state. Six steps are required to complete a full electrical cycle. When the motor is running, the phase current switching is updated every 60°. For each step, one motor terminal is switched high, the other low, and the third remains floating (6-step commutation). Fig. 16 shows the block diagram of the motor control with Hall sensors and location correction system.

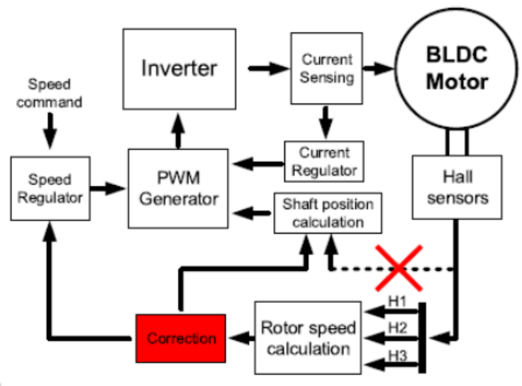

Fig. 16. Block diagram of the motor control with Hall sensors and location correction system

Controlling motors with Hall sensors provides high-quality motor control over the entire speed range and requires a simple, inexpensive control system that can be implemented without the use of a microprocessor.

However, when using cheap mass-produced motors, there is an error in the location of the Hall sensors. Signals from incorrectly shifted sensors lead to asymmetric operation of the inverter, which in turn leads to electromagnetic torque pulsation, an increase in the amplitude of the motor current and acoustic noise [6]. A higher current amplitude increases electrical losses, as well as electromagnetic interference, in addition to forcing manufacturers to use inverter transistors with a higher nominal current.

In [6] was proposed to correct the switching points based on the difference in the periods of the sensor output signal during motor rotation.

3.2. BLDC motor control w/o sensors

Hall sensors cannot be used in systems where the rotor is in a closed housing and requires minimal electrical inputs, or the system is designed to be as cheap as possible.

To obtain information about the rotor position, the following can be used:

– motor BEMF signals;
– rotor position estimation from motor current and voltage signals.

3.2.1. BEMF zero crossing measurement

When using back-EMF signals, the control system monitors the BEMF signals instead of the position determined by the Hall sensors [2] for signal switching. The relationship between the sensor output and the BEMF was 14 shown is used.

Common method for BLDC motor control w/o sensors is BEMF zero-crossing detection. As sensors are commonly used electronic comparators – to detect moment of BEMF zero cross. The sensor signal changes state when the polarity of the BEMF voltage changes from positive to negative or from negative to positive. The BEMF zero crossing provides accurate position data for switching.

Sensorless commutation significantly simplifies the design of the motor and its cost. The disadvantage of the system is that since BEMF is proportional to the speed of rotation, at low speeds the signal value is minimal and cannot be used for commutation. In such cases, the motor is forcibly accelerated to the minimum operating speed by forced rotation of the stator field, and the starting currents of the motor are increased even without load.

3.2.2. Rotor position estimation

With development computing power of motor controllers sensorless rotor position estimation became basic. In general, these techniques of estimation of the rotor position based on measurement motor currents and voltages (optionally) and calculation of actual rotor angle in real time. Basic block diagram of control system with motor angle observer given in [8] and shown in fig. 17.

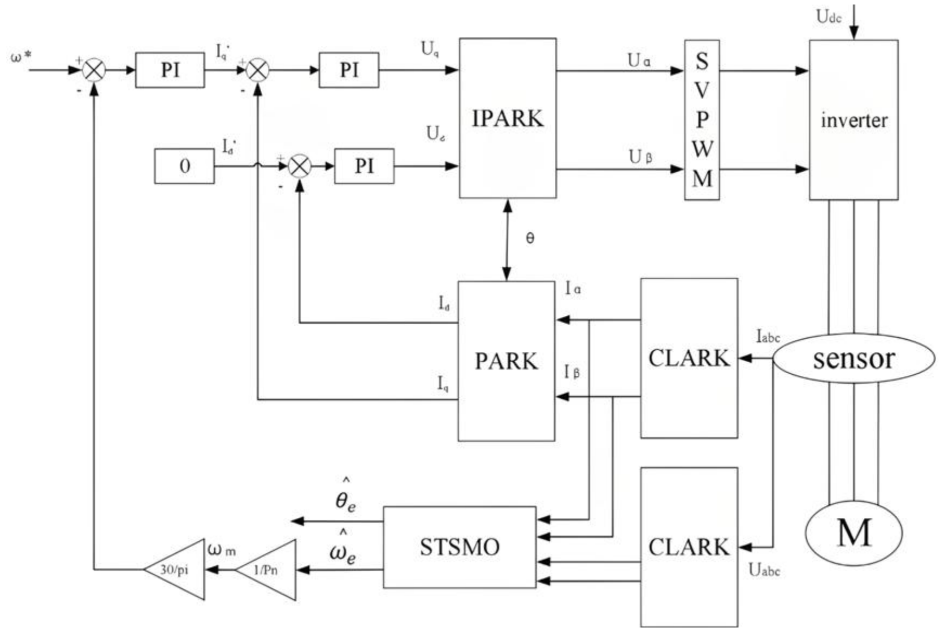

Fig. 17. Block diagram of the motor control with Hall sensors and location correction system

Control system uses information about angle, derived from observer for function of Park transformations, speed calculation, torque calculation and for calculation of SVPWM which is used in given control system to form 3-phase motor voltage.

Review and comparison of common techniques of BLDC angle estimation is given in [7]. The most common methods of motor angle estimation are: Flux linkage observers; BEMF observers; Sliding mode observers (SMO); Super-twisting SMO (ST SMO); Extended Kalman Filters (EKF);

Luenberger observers; Frequency-adaptive adaptive observers; Machine-parameters adaptive observers; PLL based angle observers.

Flux linkage observers are most simple from computational recourses and used for high-speed applications. They estimate rotor flux linkage using stator voltage and current measurements and don't include differential parts in model. However, they are sensitive to motor parameters accuracy and load conditions.

BEMF angle observers are Nonlinear-model-based observers and effective at medium and high speeds [7]. They estimate rotor position using BEMF induced in the stator windings, which directly correlates with rotor flux. Observer structure estimates the BEMF, which is then used to derive rotor angle with arctangent function. To improve range of speeds for BEMF observers one considered motor coils parameters (resistance and inductances) and calculates BEMF based on motor electrical model.

More robust solution is Sliding Mode Observer (SMO) - nonlinear state observer based on the principles of sliding mode control (SMC), designed to reconstruct unmeasured system states by enforcing a sliding condition on the estimation error dynamics. Common block diagram of the sliding mode observer shown in fig. 18.

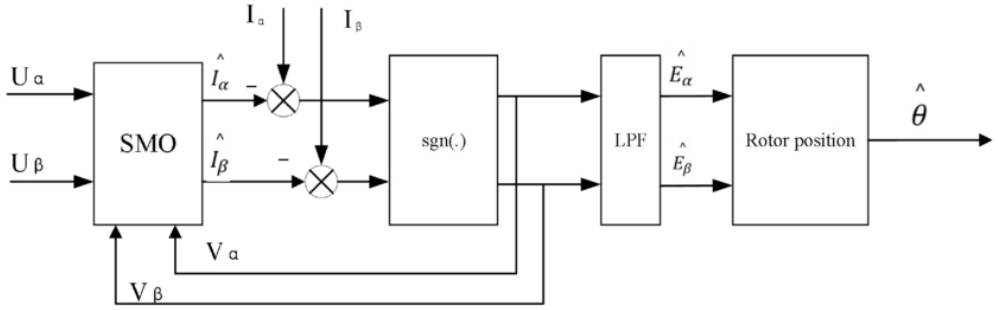

Fig. 18. Block diagram of Sliding Mode Observer

SMO is using internal simple motor model and compares its output signal with measured signal to create sliding condition. Mostly all simple observers are computationally efficient but fail at low speeds due to the diminishing back-EMF amplitude, which compromises observability. Open-loop I-f control is typically used for startup. To enlarge speed range are used more advanced estimations but with high computational complexity.

4. Motor speed control

Motor control systems mainly maintain speed because most applications require constant velocity under varying loads. Speed control ensures stable operation, energy efficiency, and process reliability, while torque control serves as a lower-level mechanism that supports speed regulation. In most industrial, automotive, and robotic applications, the output variable of interest is mechanical speed rather than torque or current. A review of various speed control methods is provided, including PID controllers, adaptive control, fuzzy systems, and others. The advantages and limitations of each method are investigated. As a result, an overview of the current state of research in this area is provided for further study of the prospects for the development and implementation of new BLDC motor speed control systems.

4.1. PID controller-based automatic control system

Proportional-integral control systems are the most widely used speed control technique for BLDCand all other types of motors. It can be easily implemented on analogue and digital components because it is well understood, simple and has been used in practice for a long time. Improving performance or reducing cost has been the subject of development for a long time.

The block diagram of a PID controller [9] is shown in fig. 19.

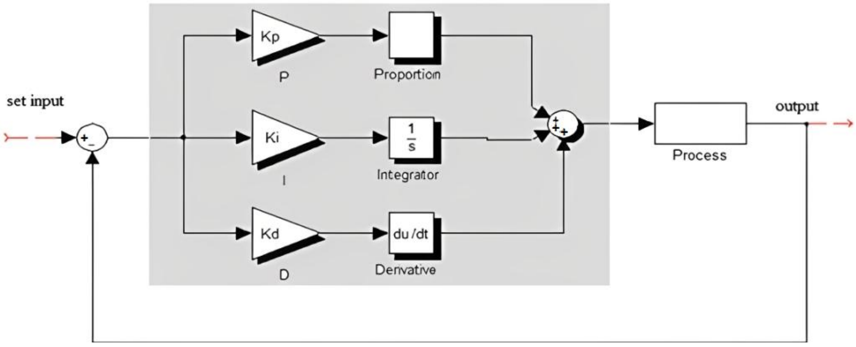

Fig. 19. Structure of the PID controller

Control systems using the PID controller are well studied and in the scientific community there is a huge amount of scientific research in this area, therefore, from the standpoint of scientific innovation, research in this area is not promising. But PID controllers are widespread as a component of more effective BLDC motor control systems.

For speed control of BLDC motors, the most common is the classic speed and current PI control in which the speed controller generates tasks for the motor current PI-controller (fig.20).

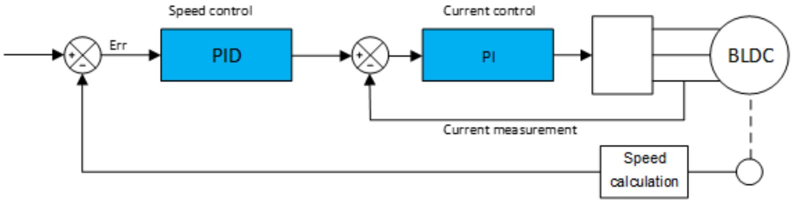

Fig. 20. 2-loop speed control system of a BLDC motor

The current regulator compensates the electrical component of the motor circuit and provides support for the motor torque, and the speed regulator compensates the mechanical component of the motor rotation with feedback.

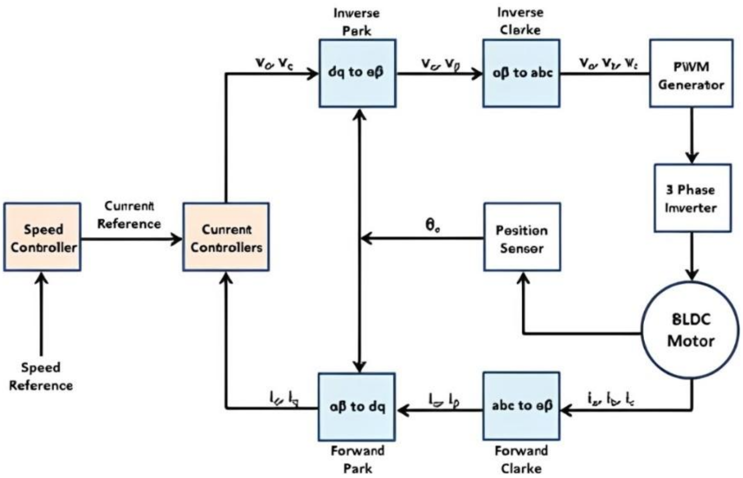

Fig. 21. Block diagram of BLDC vector control system

The current controller can be replaced by a hysteresis (relay) regulator, which increases the accuracy of current support and system dynamics, but may require high switching frequencies when working with low-power motors or high-speed motors.

The algorithm of a conventional PID regulator is simple, stable, easy to calculate parameters when the exact mathematical model of the system in differential equations is known. The disadvantage of implementing the system is that most industrial processes with varying degrees of nonlinearity, parameter variability and uncertainty of the mathematical model of the system. Setting the parameters of PID regulation is very complicated, so it is difficult to achieve stable regulation in field conditions and in actual production. Therefore, with the increase in the computing power of microprocessor systems and the emergence of high-speed parallel processing systems, classical PID control systems are replaced with more advanced control systems.

4.2. Field oriented control (FOC)

The most common control method for sensorless speed maintain of BLDC motors is 6-step trapezoidal control, which was described above. Although this method is easy to implement, it has several disadvantages, such as large torque ripple, high speed limitations, requirements for precise sensor positioning, speed ranges, and high noise levels.

The Field Oriented Control (FOC) methodology overcomes these limitations while providing increased efficiency by maximizing torque per unit current [11]. Accurate measurement of the rotor angular position is essential for the FOC algorithm and can be implemented in two ways. The first method is to use sensors, such as Hall effect sensors, to determine the rotor position, known as sensor-based FOC. This approach provides higher measurement accuracy, but is generally undesirable due to cost, installation issues, and limited application ranges. The second method, sensorless FOC, involves estimating the rotor position using state observers mentioned in 3.2.2 section. In this method, rotor position is estimated by measuring instantaneous motor parameters such as voltage and current and then mathematically calculating the rotor position vector. This eliminates the need for physical position sensors and requires only the use of motor current sensors, thus reducing cost and increasing reliability, albeit at lower levels of accuracy.

The principle of operation of the FOC algorithm is as follows. The three-phase power supply of the motor creates a rotating magnetic field of the stator. The permanent magnets in the rotor try to align themselves along this field, which leads to continuous rotation. The maximum torque is created when the fields are perpendicular. The FOC algorithm achieves this condition by dividing the stator field into two perpendicular components and then driving the component along the rotor field (without torque) to zero. The axes along and perpendicular to the rotor field are called the direct (d) and quadrature (q) axes, respectively. The adjustment of the stator field components is carried out using PID controllers that maintain the corresponding d and q components of the motor current.

Maintenance of reference speed is implemented by a speed PID controller that generates the motor torque command and affects the perpendicular component of the stator field.

Advantages of the method are [12] increased accuracy of maintaining speed in steady-state operation, minimal level of motor torque pulsations, low energy consumption. This method in combination with SVPWM allows to calculate instantaneous values of the motor voltage and adopts inverter output voltage to actual BEMF shape of the motor.

Disadvantages of this type of control include slow response to changes in load torque or set speed; relatively high computational cost of the algorithm; sensitivity to motor parameters used to calculate PID controllers of the FOC system.

4.3. Direct torque control (DTC)

The basic idea of Direct Torque Control (DTC) [13] is to select the appropriate stator voltage vector from eight possible inverter states to ensure that the stator flux linkage vector rotates as it produces the desired torque. The control system continuously measures the instantaneous values of:

- Motor torque – using a torque observer based on phase current data;
- Rotor position – using Hall sensors or using a rotor position observer.

Depends on the rotor position and the ratio of the reference and measured torque - the inverter voltage vector is selected, which increases or decreases the torque in the set direction (fig. 22).

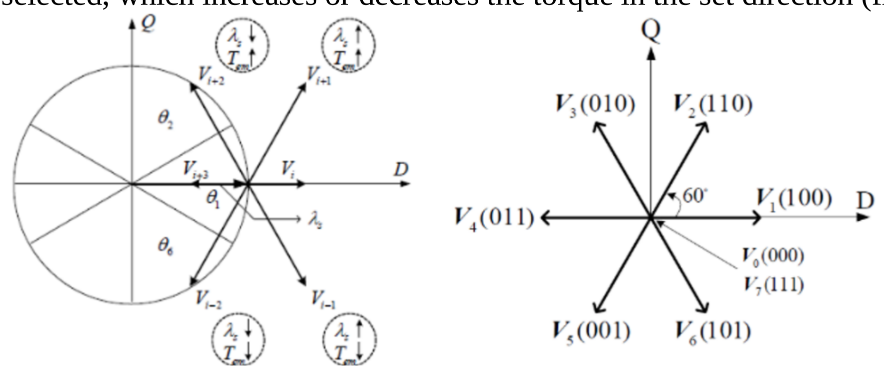

Fig. 22. Calculation of the inverter voltage vector depending on the current rotor position from 8 possible states

For this selection, a simple hysteresis switch is used as shown in the block diagram in fig. 23.

The advantages of this methodology are high accuracy of motor torque support, high dynamics of speed control and especially high speed of motor torque generation, which is limited only by the electrical motor constant.

Disadvantages are high computational complexity of the algorithm in sensorless control, requirement for small sampling times, reduced stability of speed support in sensorless motor control.

To improve the performance of sensorless torque measurement, a complex observer of motor parameters based on Sliding Mode Control (SMC) was proposed in [14]. In control systems, Sliding Mode is a nonlinear control method that changes the dynamics of a nonlinear system by applying an intermittent control signal (or, more precisely, a setpoint control signal), which causes the system to "slide" along the cross section of the normal behaviour of the system. The proposed Sliding Mode observer allows you to obtain the values of torque and speed simultaneously.

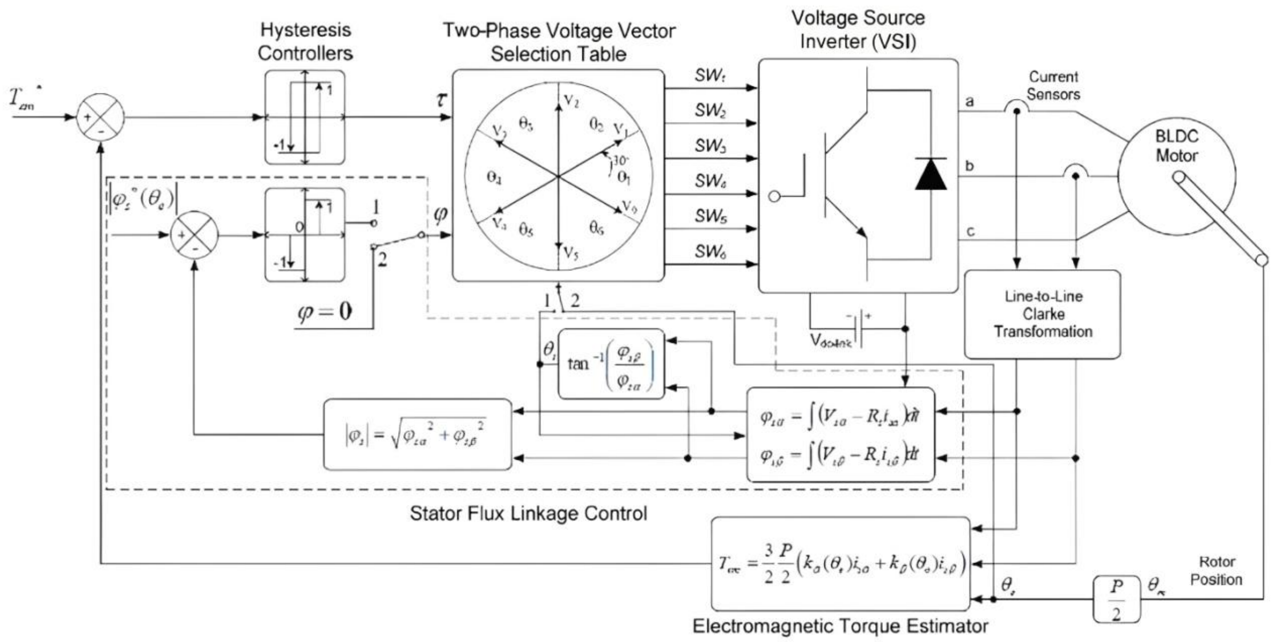

Fig. 23. DTC block diagram

To compensate for the shortcomings of DTC and FOC systems, a hybrid control system was proposed in [12] that combines the advantages of both systems. It uses an algorithm switch depending on the speed error as shown in fig.24.

4.3. Fuzzy logic controllers

In the applications of BLDC motor control, fuzzy logic systems are effectively used, while they have advantages in terms of calculation speed.

In the article [15], an adaptive control system with a fuzzy logic controller is proposed. The block diagram of the system is shown in fig. 25. The approach of combining a PID controller with a fuzzy logic controller is used in [16]. This allows one to improve the quality of regulation and the dynamics of the system by changing the controller coefficients in real time.

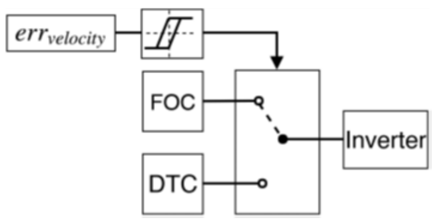

Fig. 24. Block diagram of a hybrid control system using DTC-FOC

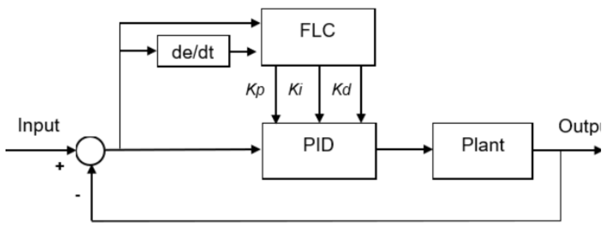

Fig. 25. Adaptive control system based on PID regulator with fuzzy logic controller

4.4. Model prediction control (MPC)

Predictive control or Model Predictive Control is one of the modern methods of dynamic systems control theory, based on prior knowledge of the dynamic characteristics of processes. The controller relies on an empirical model of the controlled process to predict its further behaviour, based on the previous values of state variables. With the increase in the computing power of microcontrollers, it becomes possible to apply predictive control methods for BLDC motors [17]. In addition to improving the parameters of the classical speed control structure (fig. 19), these systems allow direct control of the motor power and the use of the most economical motor operation mode by reducing reactive power to 0. The system structure of the BLDC predictive control system with power control is shown in fig. 25 and fig. 26.

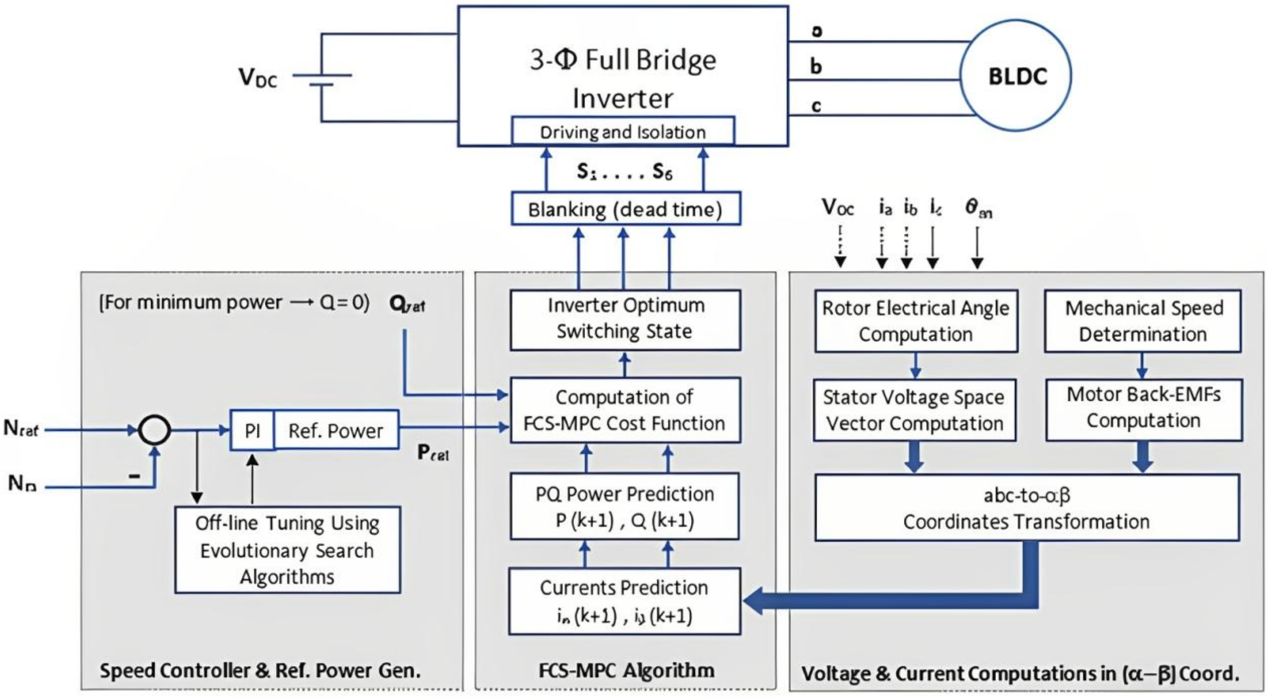

Fig. 25. Structure of a predictive control system with active power regulation

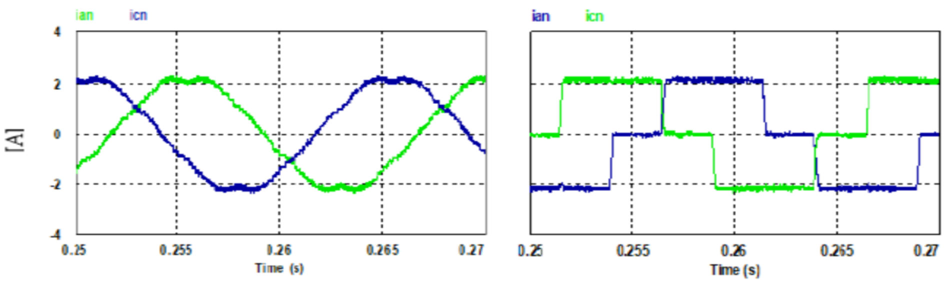

Fig. 26. Comparison of motor currents with reactive power reduction and current control

The disadvantage of the methodology is the significant computational cost and, accordingly, the limitation on maximum motor speeds

4.5. Adaptive control systems

With the development of the computing power of microcontrollers, so-called adaptive BLDC control methods are being introduced that can adapt to change the system according to unknown motor parameters or changing load parameters. Adaptive control methods for BLDC motors usually include complex algorithms and feedback mechanisms that constantly monitor the behaviour of the motor and adjust the control signals accordingly. These methods can use various sensors, such as Hall effect sensors or encoders, to provide feedback on the rotor position, speed and other relevant variables.

The control algorithms then use this feedback information to optimize the motor operation in real time, ensuring optimal performance under different conditions.

In [18], an adaptive controller is proposed that is used to compensate for the non-ideal shape of the BEMF of the motor, thereby improving the quality of speed regulation and minimizing losses during motor operation.

Adaptive systems allow to adjust the power consumed from the electrical network by jointly controlling the inverter for driving the BLDC motor and the power factor corrector [19].

4.6. Deep learning in BLDC motor control

With the creation of machine learning systems capable of working as part of embedded systems, it has become possible to use these flexible innovative algorithms for motor control.

When controlling the speed of a motor, a neural network can be used as a controller that includes all the functions of the control system and includes forward and inverse mathematical models of the system (just as a PID controller is an inverse function for the controlled system) [20]. The structure of such a system is given in fig. 27.

In addition to direct speed control, the neural network allows to implement optimization algorithms depending on the load and motor parameters changing. Also, in control systems, ANFIS (Adaptive Neuro Fuzzy Interference System) systems are used, which are a combination of neural networks and fuzzy logic systems [21, 22].

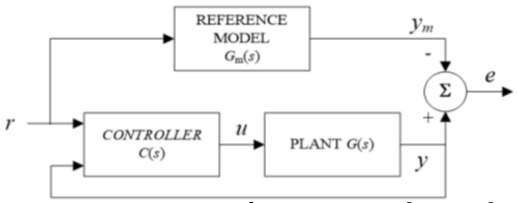

Fig. 27. Using ANN for motor speed control

An ANFIS controller is a neural model that operates on fuzzy logic values and adjusts itself through training. An example of such an adaptive controller [21] for motor speed control is given in fig. 28.

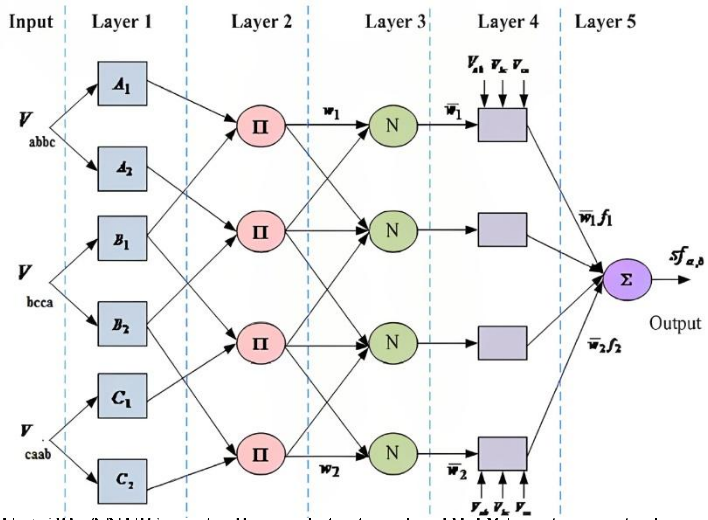

Fig. 28. ANFIS controller architecture for BLDC motor control

The main areas of application of neural networks in the field of BLDC control are:
- adjusting the motor speed depending on the load conditions, temperature and other;
- artificial neural networks (ANNs) can estimate the position and speed of the rotor without using physical sensors;
- improving the accuracy of back EMF estimation;
- adaptive controllers, reinforcement learning and fuzzy logic can improve the performance of speed control;
- optimizing the efficiency of the control system and extending the battery life;
- motor fault prediction, fault detection and diagnosis.

The disadvantages of the systems are high computational complexity and lack of training examples for training the network to handle dynamic operating modes. But using logic or FPGA based systems, where much easily to implement NN structures it is possible to create efficient and cheap BLDC motor control system.

Conclusions

Modern research focuses on the development of sensorless control methods, energy consumption optimization, enhancement of fault prediction algorithms, and improvement of the overall adaptability of systems to varying operating conditions. These directions play a key role in the advancement of electromobility and automated technologies, contributing to the creation of more efficient, reliable, and resilient electric drives.

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