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BLDC MOTOR SIMULATION MODEL WITH CONFIGURABLE BEMF IN JULIA

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ABSTRACT *Modern technologies in the field of electrical engineering and automation require constant improvement and development. One of the key aspects of this development is the use of brushless permanent magnet (BLDC) motors. BLDC motor control methods play a key role in ensuring the efficiency and reliability of their operation. Until recently, simulation of these motors was a complex task, requiring excessive costs for computation resources, equipment and software. An important task in the development of motor control systems is the development and use of motor models. In modern motor control systems, modeling is used not only in the development process - the motor model can be an integral part of the control system, according to which control signals are calculated in real time. Processes in motors are described by systems of differential equations, and there are many methods for numerically solving these systems. The vast majority of these systems are built into relatively complex automatic design systems, and modeling control systems requires a significant amount of computing resources and studying the specifics of these systems. The search for an effective tool for modeling the motor and the control system should also take into account its availability for the scientific community and developers from the point of view of software ownership.The article presents the simulation model of a BLDC motor with simplified DC and full 3-phase electrical parts. The presented model describes the motor directly in the differential equations and allows you to quickly simulate processes in the motor and their changes under the influence of external variable parameters. The described model was created using programming language Julia perfected for mathematical calculations. Model allows to simulate motor operation under Variable voltage and load. The part of the model that generates external disturbances and control signals allows to simulate various forms of 3-phase voltage without complicating with external components or generators. The article presents the motor control results from 3-phase voltage and an autonomous voltage inverter.*
Keywords: *BLDC motor; model; simulation; differential equations; back EMF; 3-phase voltage; Julia programming language*

МОДЕЛЮВАННЯ BLDC МОТОРУ ІЗ ЗАДАВАННЯМ ЗВОРОТНЬОЇ ЕРС І ВИКОРИСТАННЯМ JULIA

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АНОТАЦІЯ *Сучасні технології в сфері електротехніки та автоматизації вимагають постійного вдосконалення та розвитку. Одним із ключових аспектів цього розвитку є використання безколекторних постійних магнітних (BLDC) моторів. Ці мотори знайшли широке застосування у різних галузях, включаючи автомобільну промисловість, промислову автоматизацію, медичні пристрої та багато інших. Методи керування BLDC моторами відіграють ключову роль у забезпеченні ефективності та надійності їх роботи. До недавнього часу контроль цих моторів був складним завданням, що вимагає великих витрат на спеціалізоване обладнання та програмне забезпечення. Однак, завдяки постійному розвитку технологій, сьогоднішні методи керування стали більш доступними та ефективними. Важливою задачею при розробці систем керування моторами є розробка й використання моделей мотору. В сучасних системах керування моторами моделювання використовується не лише у процесі розробки - модель мотору може бути складовою частиною системи керування за якою обчилсюються сигнали керування у режимі реального часу. Процеси у моторах описуються системами диференційних рівнянь й існує багато методів чисельного вирішення даних рівнянь. Переважна більшість даних систем вбудована у відносно складні системи автоматичного проектування а моделювання систем керування потребує суттєвої кількості обчислювальних ресурсів й вивчення специфіки даних систем. Пошук ефективного інструмента для моделюванння мотору й системи керування має враховувати також його доступність для наукової спільноти й розробників с точки зору пропрієтарності програмного забеспечення.У статті представлено імітаційну модель електродвигуна BLDC зі спрощеним постійним струмом і повною 3-фазною електричною частиною. Наведена модель створена з використанням мови програмування Julia, вдосконаленої для математичних розрахунків. Наведена модель описує мотор безпосередньо на мові диференційних рівнянь й дозволяє швидко моделювати процеси у моторі та їх зміни під впливом зовнішніх змінних параметрів. Модель дозволяє моделювати роботу двигуна під змінною напругою та навантаженням, а також реалізовано керування від 3-фазного інвертора.*
Ключові слова: *BLDC двигун; модель; моделювання; диференціальні рівняння; зворотна ЕРС; 3-фазна напруга; Мова програмування Julia*

Introduction

The use of BLDC motors offers many advantages [1], the main ones of which are high constant torque, high mechanical power density and a wide speed range. 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) [2]. Permanent magnets create the rotor flux, and the energized stator windings create the poles of the electromagnet. The rotor magnets are attracted by the stator electromagnetic field, which is created by the sequence of currents in the stator windings. This sequence, given by the voltage on the windings, creates and maintains a rotating electromagnetic field. In BLDC motors, the mechanical switching used in brushed DC motors is replaced by an electronic switch controlled by an electronic system. This feature allows to increase reliability, significantly increase the service life, and reduce maintenance costs (due to the absence of brush erosion and the need to replace them). Fig. 1 shows a simplified cross-section of a three-phase BLDC motor [2].

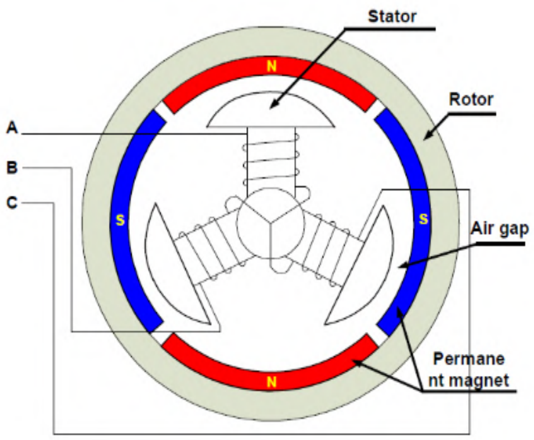

Fig. 1 - Simplified design of a BLDC motor

The rotor has permanent magnets that form 2 pairs of magnetic poles and surround the stator, which has three windings.

An important feature and characteristic of BLDC [3] is the trapezoidal shape of the back EMF, which is created by a certain way of connecting the stator coils. BEMF voltage depends on rotor angle as shown on Fig. 2.

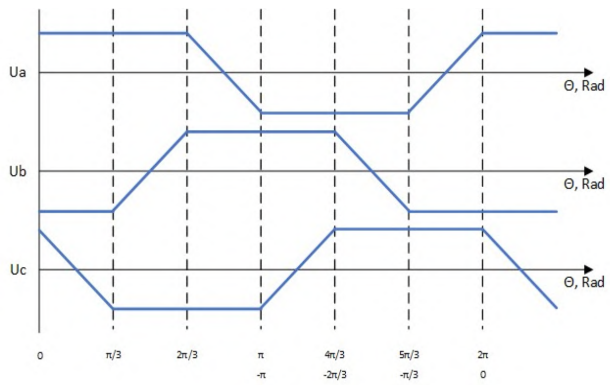

Fig. 2 - Back EMF shape of a BLDC motor

A BLDC motor with permanent magnets and trapezoidal back EMF consumes rectangular stator currents. 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.

The chosen classical model of BLDC motor consists of 2 parts: electrical and mechanical models. The electrical model reflects the conversion of the voltage on the motor into current and torque of the motor. Mechanical model simulates motor rotational mass and motor torque conversion to the rotation motion.

The aim of the article

The aim of the article is to present the development of a motor model with the ability to change the shape of the EMF, motor parameters and external voltage and load torque change laws. Further the model will be used to design a predictive control system for BLDC motors.

The main part

1. Simple electrical motor model

To control the voltage and current in the windings of brushless DC motors, switching semiconductor 3-phase converters are used that controls the voltage and current, and thus ensure the rotation of the motor.

The equivalent circuit for the motor average current [4] and for steady state operation [5] can be represented as shown in Fig. 3.

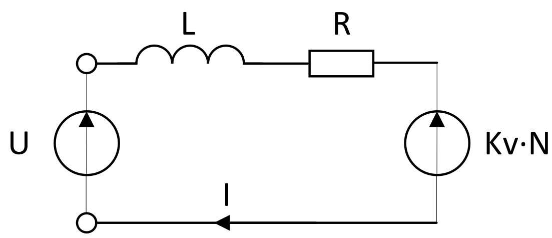

Fig. 3 - Electrical circuit diagram of a BLDC motor at a constant frequency

The motor current (I) for a trapezoidal voltage can be reduced to a constant current like a DC motor. The motor current is directly proportional to the motor torque and its definition allows us to move on to the mechanical part of the motor model. The equation for the motor current can be derived by composing the voltage and back EMF source equations for the circuit shown in Fig. 3 using Kirchhoff's 2nd law:

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$$L\frac{dI}{dt}+RI=U-\ \omega\cdot C_W,\qquad (1)$$

where I – motor current, t – time, which is the argument of the system, L – motor winding inductance, R– motor winding electrical resistance, C_w – motor speed constant, U – voltage applied to the motor. It is used to change the motors' speed.

In this model the back EMF is simply represented as linear function of the motor speed and acts as DC motor BEMF. This model is simplified DC motor model. BLDC motors are close to DC motors except for commutation with power converter and this allows to simulate motor operation using one voltage parameter.

Solving the differential equation (1) with the fixed motor parameters gives an increasing current shape that, after changing, is limited by the motor resistance and the difference between the voltage source and the back EMF.

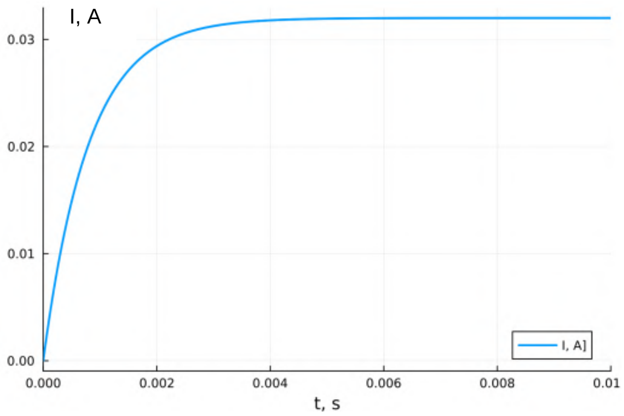

Fig. 4 – Motor current at constant voltage and motor speed

The dependence of the torque Tm(t) on the motor current I(t) in time is given by the equation:

$$Mm(t) = Cm\ I(t),\qquad (2)$$

where Cm - is the motor torque constant.

The electric motor torque (Me) for a trapezoidal motor voltage is directly proportional to the motor current.

2. Motor mechanical model

A model of the mechanical part of the motor, represented by a rotating mass model. This model is described by Newton's 2nd law. For rotational motion, the rotor position is found by the differential equation:

$$J\frac{d^2\theta^2}{dt^2}+\beta\frac{d\theta}{dt}=Mm(t)-Me(t),\qquad (3)$$

where θ – motor rotation angle, t – time, which is the argument of the system, β – coefficient of viscous friction and is a constant value, Me(t) – external load torque, Mm(t) – motor torque that affects the rotation speed. It has a directly proportional dependence on the motor current I.

Considering that the target function for regulation is the angular velocity ω=dθ/dt and if the load torque, we can compose a system of equations on the motor speed:

$$\begin{cases}\frac{d\theta}{dt}=\omega(t)\\ J\frac{d\omega}{dt}==Mm(t)-Me(t)-\beta\omega\end{cases}\qquad (4)$$

With a constant external load and small values of the viscous friction coefficient β (which occurs in practice), the solution of the equation gives a linear change in the motor speed depending on the torque value:

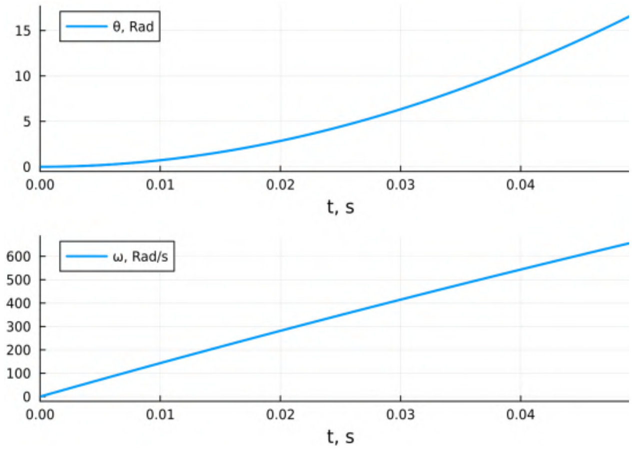

Fig. 5– Mechanical part of the motor model at constant motor torque and load without the influence of the motor's EMF

To complete the motor model, it is necessary to:

– substitute the motor torque calculated from the electrical model and equation (2)
– substitute the motor speed value calculated from the mechanical model into the electrical model

Thus, we obtain a complete motor model described by a system of differential equations:

$$\begin{cases}L\frac{dI}{dt}+RI=U-\ C_W\omega(t)\\ J\frac{d\omega}{dt}=Mm(t)-Me(t)-\beta\omega(t)\\ \frac{d\theta}{dt}=\omega(t)\end{cases}\qquad (5)$$

The solution of the system of equations gives the transient process of the motor speed depending on the voltage supply over time and the constant load.

To control a BLDC motor, a 3-phase bridge power converter is needed to convert the DC voltage (Ud) 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.

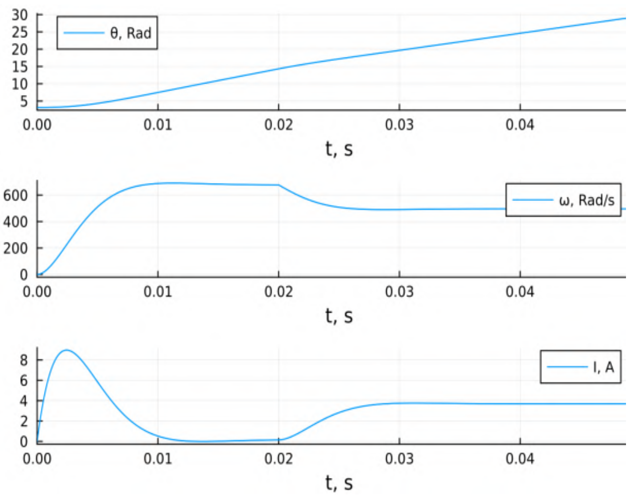

Fig. 6 – Motor acceleration and load calculated using a system of equations (4)

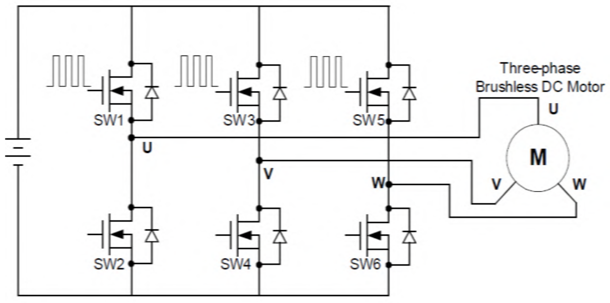

Fig. 7 - diagram of a converter for controlling a BLDC motor

For example, when power converter forms phases commutation automatically depends on the rotor angle, then speed will depend on the voltage level. In basic 2-phase injection mode (also known as 6-step commutation) motor control algorithm the motor voltage creates using PWM like shown in Fig. 8.

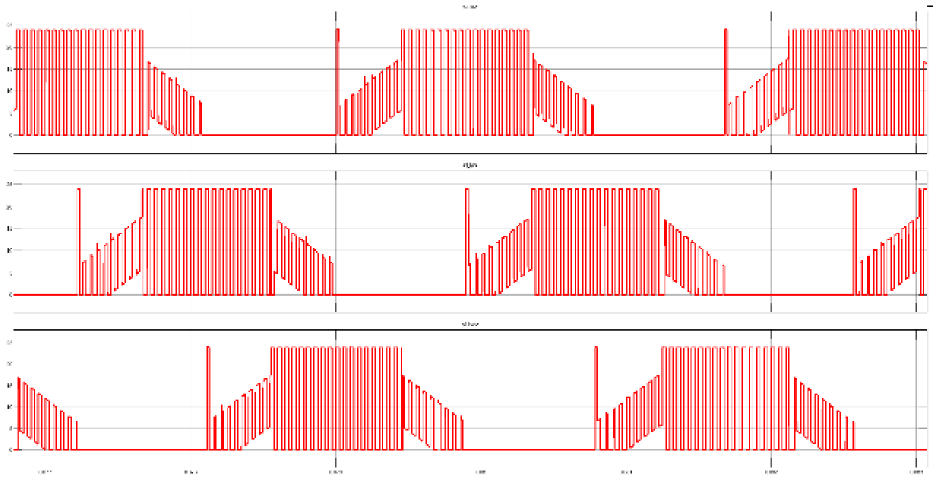

Fig. 8 - Voltage diagrams at the output of the 3-phase power converter with 6-step commutation

Also, it is possible to use DC-DC converter at the input of the three-phase inverter. The model uses this approach at the first development stage.

The solution of the system of equations (4) is sufficient for motor simulation since the control system independently provides motor commutation and only the voltage value needs to be generated.

Motor voltage U in this case can pe calculated according to classic equation:

$$U = D \cdot Ud, \qquad (6)$$

where D – PWM duty cycle, Ud – Voltage in power converter input DC-link.

This value can be used as input voltage value for the system of equations (5).

3. Three-phase motor electrical model with BEMF shape simulation

3.1 Configurable Back EMF model

Most BLDC motors have 3-phase windings connection. A simple equivalent electrical circuit is shown in Fig. 9.

The electrical equation for each phase voltage can be composed like the equation (1):

$$U_a = L\frac{dI}{dt} + RI + E_a \qquad (7)$$

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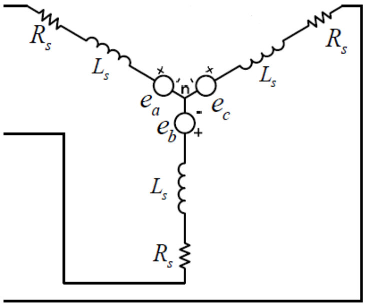

Fig. 9 – Electric equivalent circuit of a 3-phase BLDC motor

Back EMF voltages *(Ea, Eb, Ec)* in each phase depend not only on motor speed but also from the rotor electrical angle [6]:

$$E_a = \omega(t) \cdot C_W \cdot F(\theta). \quad (8)$$

Back EMF in motor phases is shifted to 120 electrical degrees between each other.

$$E_b = \omega(t) \cdot C_W \cdot F(\theta - \tfrac{2\pi}{3}). \quad (9)$$

$$E_c = \omega(t) \cdot C_W \cdot F(\theta - \tfrac{4\pi}{3}). \quad (10)$$

The function F(θ) can specify a different shape of the BEMF according to the motor configuration. As mentioned - an important feature and characteristic of BLDC is the trapezoidal shape of the back EMF. Such shape can be specified as proposed in [7] using a trapezoid with unit amplitude shown at Fig. 10. Trapezoidal F(θ) can be simulated using piecewise functions.

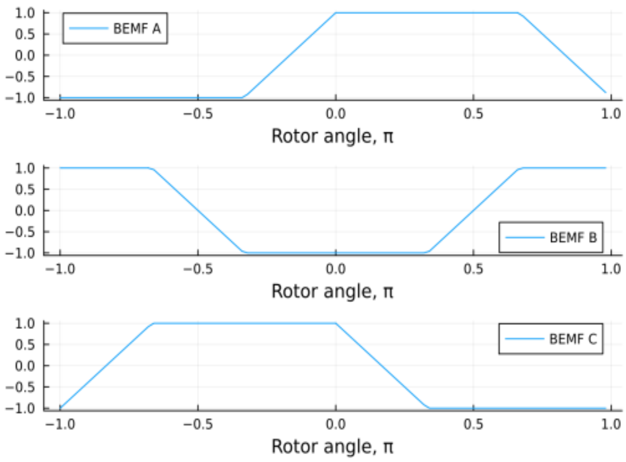

Fig. 10 – Trapezoidal BEMF shape

Also using F(θ), any BEMF shape can be implemented.

There are different representations of the supply voltages for 3-phase motors. While the 3-phase system the sum of phase and line voltages equals zero - the common practice is to reduce the number of voltage values from 3 to 2. There are 2 main approaches to do this. First of them is to use DQ-representation [8]. Second is the use only two line voltages [9] and this method was chosen while model will be used to work with inverter model and it is output line-to line voltages to the motor.

Also, while most BLDC motors don't have neutral points, physically only line voltage can be applied to the motor. To find the motor currents and further the motor torques it is necessary to compose the equation of the motor currents depending on the line voltages on the motor [10]. Since in a symmetrical 3-phase system the sum of the line voltages is zero, it is sufficient to use the values of the two line voltages (Uab Ubc). Using equation (6-9) it is possible to derive the differential equation for the currents depending on the two line voltages as given in [9], as follows:

$$L\frac{di_a}{dt} = \frac{1}{3L}(2U_{ab} + U_{bc} - 3Ri_a + \frac{C_m}{2}\omega(-2Fa + Fb + Fc), (11)$$

$$L\frac{di_b}{dt} = \frac{1}{3L}(-U_{ab} + U_{bc} - 3Ri_b + \frac{C_m}{2}\omega(Fa - 2Fb + Fc), (12)$$

$$\frac{dia}{dt} = -\frac{dib}{dt} - \frac{dic}{dt}, \quad (13)$$

where Fa Fb Fc – functions that specifies shape of the BEMF depends on rotor angle θ:

$$Fa = F(\theta);\ \ Fb = F\left(\theta - \frac{2\pi}{3}\right);\ Fc = F(\theta - \frac{4\pi}{3}). \quad (14)$$

Input functions for equations (9) are line voltages (Uab Ubc) which allows to calculate motor currents and then motor torque can be calculated to be used as input in the mechanical model.

3.2 Motor torque calculations

Total motor torque consists of torque output of each phase. Phase torque depends on current and connected to BEMF shape [6,9] and can be calculated using same trapezoidal dependency F(θ).

$$M_a = C_m \cdot I_a(t) \cdot F(\theta) \quad (15)$$

$$M_b = C_m \cdot I_b(t) \cdot F(\theta - \tfrac{2\pi}{3}) \quad (16)$$

$$M_c = C_m \cdot I_c(t) \cdot F(\theta - \tfrac{4\pi}{3}) \quad (17)$$

Total motor torque:

$$M_m = M_a + M_b + M_c. \quad (18)$$

According to this

$$M_m = C_m(I_a \cdot F(\theta) + I_b \cdot F\left(\theta - \frac{2\pi}{3}\right) + I_c \cdot F(\theta - \frac{4\pi}{3}) \quad (19)$$

This expression can be used to calculate the instantaneous value of the motor torque for known values of the phase current and the actual rotor angle.

3.3 Three-phase BLDC motor model

Full system of equations for BLDC motor model can be derived from (5) by replacement currents and torque equations with equations (11-13) and calculating motor torque (Mm) using expression (19):

$$\frac{d\theta}{dt} = \omega$$

$$J\frac{d\omega}{dt} = Mm - Me - \beta\omega$$

$$L\frac{di_a}{dt} = \frac{1}{3L}\left(2U_{ab}(t) + U_{bc}(t) - 3Ri_a + \frac{C_m}{2}\omega(-2Fa + Fb + Fc\right)$$

$$L\frac{di_b}{dt} = \frac{1}{3L}\left(-U_{ab}(t) + U_{bc}(t) - 3Ri_b + \frac{C_m}{2}\omega(Fa - 2Fb + Fc\right)$$

$$\frac{di_a}{dt} = -\frac{di_b}{dt} - \frac{di_c}{dt}$$

System of equations can be solved using Julia programming language [11] and embedded tool for solving the differential equations - DifferentialEquations.jl package [12].

Motor model is simply described in the Julia function. In Julia, the function is the first-class citizen and this allows to specify an arbitrary form of the variable supply voltage depending on the rotor angle. Since in real motors the supply voltages generated by the control system often depend on the rotor angle - they are calculated in the motor function to have access to the instantaneous rotor angle. The line-to-line motor voltage functions are used in a derived system of equations (11-13) and are specified in the variables.

To solve differential equations numerically, it is required to define a problem type by giving it the system of equations, the initial condition, and the timespan to solve over. The external torque (Me) is defined in the problem as external parameter and can be given as the constant or function over time.

Solving the ordinary differential equations problem gives the angle, speed and currents values for given voltage and external torque expressions.

Discussion

The simulation was done for the different shapes of the linear voltages on the motor. The effective value of the voltage on the motor does not change in time. At the time point 0.05 s, a constant load (Mext) is applied to the motor (Heaviside step function).

1. Sinusoidal voltage simulation

Three phase sinusoidal voltage applied to the motor. The phase shift of the voltage coincides with the phase shift of the back EMF as shown below.

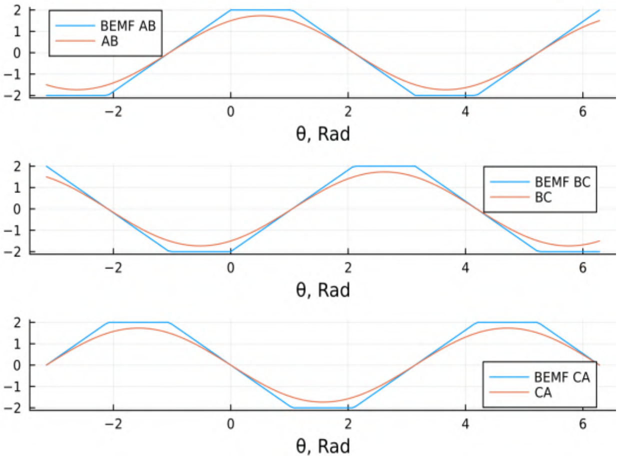

Fig. 10 - sinusoidal voltage vs BEMF

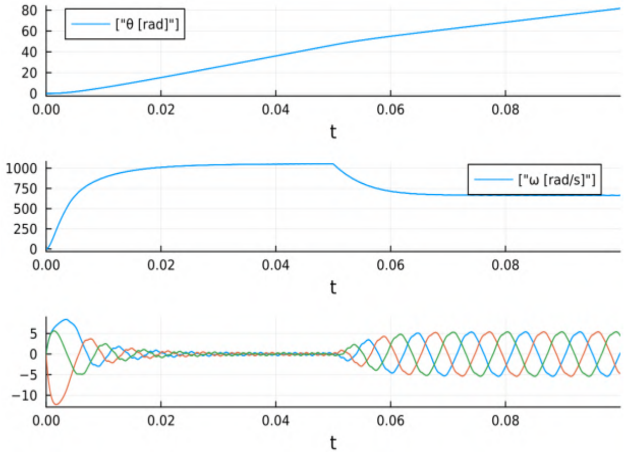

Fig. 11 – Motor acceleration and load calculated using a system of equations.
(Motor currents are shown in bottom plot: blue – Ia, A, red – Ib, A, green – Ic, A)

The graph shows the acceleration of the motor and the deceleration of the speed when an external load moment is applied. Currents are high at the start of the motor and under applied load.

2. Voltage of a 3-phase autonomous inverter simulation

Voltage of a 3-phase autonomous inverter. The 3-phase autonomous voltage inverter with amplitude control [13] can be used to control the motor. The diagrams of the linear voltage at the inverter output are shown in the Fig. 12.

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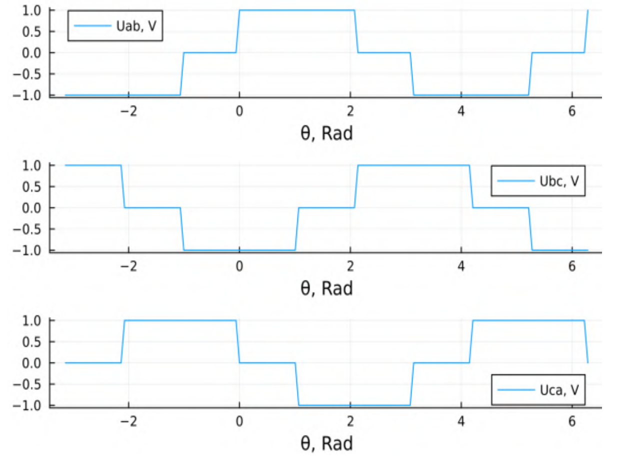

Fig. 12 – 3-phase autonomous inverter output voltages

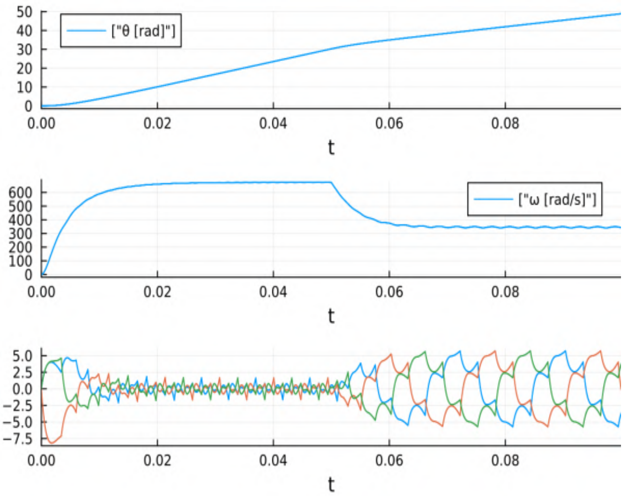

Fig. 13 – Motor acceleration and load with control from autonomous inverter.
(Motor currents are shown in bottom plot:
blue – Ia, A, red – Ib, A, green – Ic, A)

The Fig. 13 shows the presence of speed and torque ripples with this type of control and lover speed due to limitations on RMS voltage value.

As were mentioned in section 3 – the 2-phase injection mode is most simple and common BLDC motor control technic. This voltage form method was not simulated in this research. This method has time intervals with floating state at the output of half-bridges and for now research is focused on how to simulate this floating state. Also motor voltage can be simulated using voltage vectors as described in [14] and this approach also will be researched to simulate 2-phase injection control mode.

Conclusions

The developed BLDC motor model allows to simulate motor operation with different shapes of the 3-phase supply voltages and use free powerful simulation language Julia. Motor operation under sine and square 3-phase voltage is simulated. Derived motor angle and speed functions are close to real motor operation waveforms with same motor parameters. This model will be used in the latest research of the BLDC motor predictive control system and for development of the inverse model which will allow us to predict motor voltage by required speed.

Also, the next research lies in the development of the program model of power converter. An issue for now is simulation of the floating state at the output of the inverter.

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