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Modelling and Simulation of a Brushless Motor DC for Electric Power Steering Assistance

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Abstract

This paper presents an approach to develop a brushless DC motor to assist an electric power steering. Optimal design for electric power steering system implies the adequate selection of topology, technology, sizes and control algorithm. This paper briefly describes the electric power steering system structure, the most used topologies of electric power steering and the advantages of using brushless DC motors for electric power steering assistance. An electric power steering architecture is proposed. The method of design the brushless DC motor for this electric power steering is presented. Design of the brushless DC motor was based on the analysis of the requirements of the EPS systems, analysis of the control methods, modelling and simulation in MATLAB/SIMULINK. Simulation for six various conditions are presented and analysed for optimal sizing of the electric motor. An experimental model of the designed motor has been manufactured for validation.

Keywords: Simulation analysis, Brushless motor, Electric Power Steering, Permanent magnets, Optimal Design, Control methods

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1. Introduction

In recent years, brushless DC motors (BLDCs) have started to be used frequently in many applications in automotive industry, such as electric vehicles drive systems, electric power steering, air conditioner, engine cooling, etc.

Joanne Goh's analyses on the evolution of the market share for different electric motors used in the automotive industry, for the 2016–2021 time frame, highlight that the growth rate of BLDCs sales is higher than that of DC brushed motors and stepper motors [1], [13].

The global brushless DC motor market size is expected to reach over $ 15.000 million in 2021, from about $ 12,000 million in 2016.

The steering system is one of the most important and complex system installed on a vehicle. Steering system provides the directional change in the movement of an automobile. This system converts the rotation of the steering wheel into angular movement of the front wheels to control the direction of the vehicle motion.

In recent developments, in automotive industry, the trend is that electrical power steering (EPS) replaces the hydraulic power steering (HPS). EPS offers several advantages over conventional HPS, such as improved fuel economy (because the electric motor is driven only when the steering wheel is turned), elimination of hydraulic fluid and eliminates many components such as the pump, hoses, fluid, drive belt and pulley. For this reason, electric steering systems tend to be smaller and lighter than hydraulic systems [2], [3].

One of the main parts of the EPS is the electric motor, typically a BLDC motor, which replace the hydraulic actuation mechanism to develop the required steering torque.

Many research and technical papers on the EPS system and BLDC motors have been published, relating to basic principle and control algorithms and strategies, method for operating the brushless electric motors, permanent magnets, inverters for actuating brushless motors, BLDC rotor position control method [2]-[6]. Various EPS systems were modelled and analysed. Most articles refer to column type EPS [7]-[9], [23]-[25].

However, the topic is still of interest, in order to improve and optimize the BLDC motors and EPS systems performances.

Current research areas are:

- improvement of manufacturing materials and technologies;
- power electronic drivers;
- feedback sensors;

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- control techniques;
- hardware and software solutions development;
- sizes, efficiency, quality and reliability of EPS systems improvement.

The main components of an EPS are:

- Torque sensor, which measures the effort being applied by the driver to the steering wheel;
- Electric Control Unit (ECU), which calculates the necessary assist torque, considering the driving situation;
- Electric Motor, which assists the steering force of the driver according to the speed and steering condition of the car;
- Rotational angle sensor;
- Vehicle speed sensor;
- Reduction gear, which input the necessary power assist to the steering mechanism.

A block diagram showing all these components is shown in Figure 1.

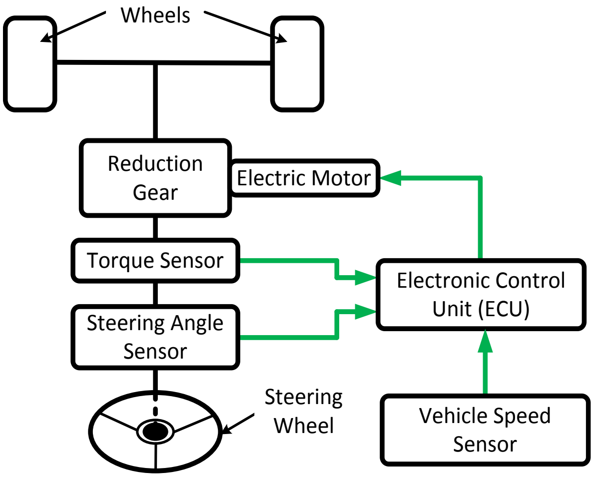

Figure 1. Electric power steering-block diagram

Optimal design for electric power steering system implies the optimal selection of topology, technology, sizes and control algorithm.

In this paper, we present some considerations regarding the design of a BLDC motor for electric power steering applications and an electric power steering architecture. The design of the BLDC motor was based on the analysis of the requirements of the EPS systems, analysis of the control methods, modelling and simulation in MATLAB/SIMULINK. An experimental model of designed motor has been manufactured for validation.

2. Electric power assisted steering systems for automobiles

EPS systems amplify the driver's steering responses to make steering easier. The most important functional requirements of all types of EPS systems are:

- Safe operation in all driving situations;
- The steering mechanism should be accurate, easy to handle and should provide directional stability;
- High dynamic response characteristics in the most varied driving situations;
- A sufficient level of steering assist for the driver in the case of intensive actuation forces, for example, parking manoeuvres.
- Minimum transmission of shock from road surface and minimal noise during steering manoeuvres;
- Accurate control of steering torque and angle.

As we mentioned above, one of the main parts of the EPS is the electric motor, typically a BLDC motor.

Depending on the position of the electric motor in the construction of the steering system and the transmission mechanism there are several basic types of EPS [11], [12]:

- Column type EPS (C-EPS): the power assist unit, controller and torque sensor are attached to the steering column. It is suitable for small vehicles.
- Pinion type EPS (P-EPS): the power assist unit is attached to the steering gear's pinion shaft. The power assist unit is outside the vehicle's passenger compartment, allowing assist torque to be significantly increased without causing more interior noise. It is also suitable for small vehicles.
- Rack parallel type EPS (R-EPS): the power assist unit is attached to the steering gear rack. Its high reduction gear ratio enables very low inertia. It can be applied to mid and full-sized vehicles.
- Rack direct drive type (DR-EPS): the steering gear rack and power assist unit form a single unit, enabling low friction and inertia.
- Dual Pinion EPS (DP-EPS): the power assist mechanism is located away from the steering axis, vibrations from the motor are controlled and system has high rigidity and superior dynamic performance.

In principle, the operation of the electric motor is the same: when the steering wheel turns, the torque sensor detects the torque that the steering wheel produces and transmits an analogue or digital signal to the ECU of the steering system. The ECU processes the received information, calculates the necessary assist torque, considering the driving situation (using system-internal and external information, such as the vehicle speed) and controls the electric motor correspondingly. The torque produced by the steering wheel and assist torque is converted into an actuation force by a pinion on the steering rack and transmitted to the wheel unit via the tie rod.

Choosing the EPS topology, component sizes and the control algorithm are a complex process, integrated general optimal design being desired for the vehicle.

3. Proposed solution for electric power steering system

In order to establish the constructive solution of EPS system, the following key elements were analysed: electric motor; ECU, steering mechanism.

Basic requirements for the electric motor used for EPS system assist are [13], [14]:

- start quickly;
- bidirectional operation;
- high reliability and security;
- high torque density;
- moment of inertia small;

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- very good dynamics;
- minimum weight and size;
- good thermal and acoustic behaviour;
- energy efficiency;
- good servo performance;
- robustness and low price.

Usually, for EPS system constructions brushed or brushless DC motors are used.

The first EPS system in a series manufactured vehicle, used in 1993 by Honda for Acura NSX, was equipped with a brushed DC motor. The presence of brushes limits its performance especially at higher speeds, and the sparks may cause safety and electromagnetic interference (EMI) problem [14].

BLDC motor is a type of permanent magnet synchronous motor (PMSM), which does not operate using brushes. It uses the electronically controlled commutation system to produce rotational torque by changing phase currents depending on the rotor position.

Figure 2 provides a diagram of the operation mode of a 3-phase BLDC motor in an EPS [22].

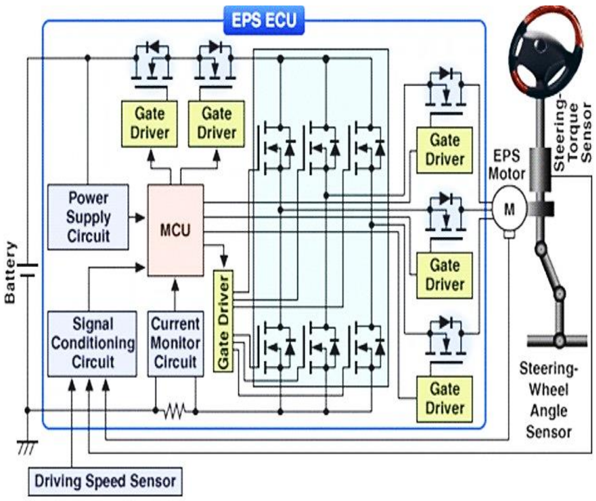

Figure 2. Diagram of an electronic control unit (ECU) of a 3-phase BLDC motor in an EPS

Three separate pairs of MOSFETs are used to drive the phases of the motor. BLDC motors have many advantages over DC brushed motors. The main advantages of replacing the brushed DC motor with BLDC motors are: high power efficiency, high dynamic response, less noise, less maintenance, no arc is generated during operation, longer life compared to DC motors, higher torque / volume ratio and higher speed range [15], [16], [26].

There are also some disadvantages such as the possibility of irreversible demagnetization of the magnets in overloading, high temperature conditions, higher design complexity [14].

The motor drive and control system are one of the key elements in EPS operation. There are many ways to control and drive the BLDC motors. Among them, there are voltage control methods such as space vector modulation (SVM) and six step modulation [17]. To establish the BLDC motor control strategy, we analysed the following methods: space vector pulse width modulation (SVPWM) and six step control.

SVPWM is the most widely used switching algorithm for three-phase inverter used for BLDC motors [18]-[20].

SVPWM is a modulation technique for generating a fundamental sine wave that provides a higher voltage to the motor, lower total harmonic distortion, better power factor, less switching losses at high frequencies and controls the number of short pulses in the pulse width modulation (PWM) waveform. The SVPWM control method involves the sector identification, switching-time calculation, switching-vector determination and the use of a "feedback".

Figure 3 shows the solution developed by Icpe for the control of an electric motor using the SVPWM algorithm.

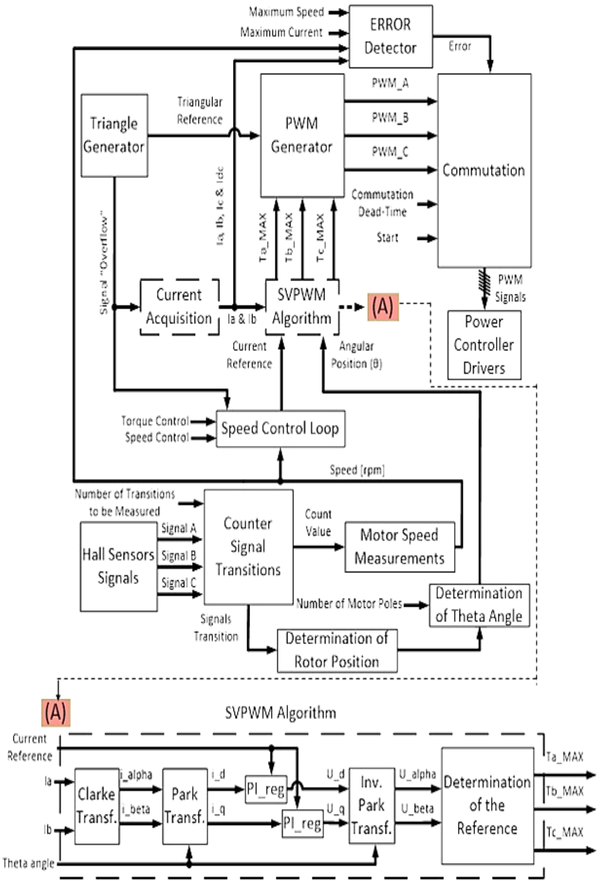

Figure 3. Space vector pulse width modulation control system

The main advantage of this method is the accuracy of the electric motor control. In addition, the time response of the entire system is short.

The control algorithm of the electric motor is based on the accuracy measurement of the theta angle (rotor position) generated by the feedback of the used sensors but also on the accuracy of motor's electric currents acquisition. If three Hall sensors are used, the determination of the rotor position has a reduced accuracy (the errors that occur are mainly given by the position of the Hall sensors on the PCB, but also by the magnets placed on rotor). In order to increase accuracy and improve the control of the electric motor, can be added more Hall sensors or encoders, but the price of the entire system increases significantly.

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The six step control technique is based on sensing the rotor position, in order to keep stator and rotor flux positions synchronous, by using three Hall sensors which are embedded into the motor drive, a closed loop control system and PWM inverters.

The six step control technique can be obtained using low-cost components. The main advantages of this control method are the simplicity of the control algorithm and the small number of components needed to achieve a precise control. As the control based on SVPWM technique, the control in 6 pulses is based on the accuracy of the electric currents of the motor acquisition but also on the speed measurement. In the case of SVPWM, the accuracy of the speed is considered critical with a significant impact on the functionality of the whole system if no suitable filters are used.

Figure 4 presents a control system based on six step technique developed by Icpe.

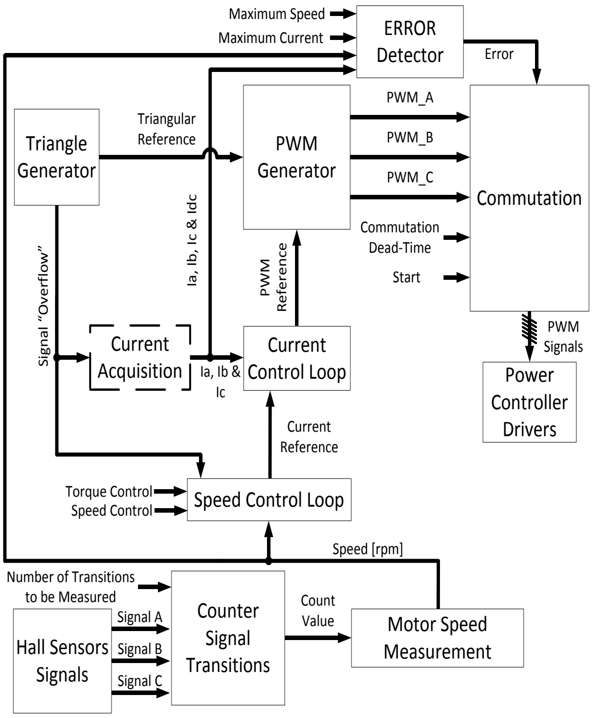

Figure 4. The six step control system for electric motor

In order to obtain a precise control of the motor using only Hall sensors, has been considered a control method which involves the measurement of Hall signal transitions over a set period of time. In addition, the speed error is substantially reduced when a transmission ratio is used.

Based on the two control methods analysed, the six step control method was used to simulate and develop the BLDC motor for power steering with rack-direct drive type mechanism because:

- the entire power steering system must be reliable and contain as few components as possible;
- the power steering system must have a low price;
- the power steering system must have control based on 3 Hall sensors;
- the transmission ratio reduces speed error;
- the control based on SVPWM is more precise, it realizes a control of the electric motor without inducing vibrations, but it is much more complex and requires a higher computing power compared to the control based on 6 pulses;
- the response time of the power steering system based on the six step motor control is sufficiently small, according to the simulation results presented in the present paper.

Based on the analysis of the functional and constructive requirements of EPS, was proposed the constructive solution.

The proposed construction has the advantage of a compact structure and smaller size compared to the axially parallel or dual pinion EPS architectures.

Other advantages of the proposed EPS system are:

- high efficiency and reliability;
- possibility of being used in the vehicles that adopt the concept "drive by wire";
- brushless DC motor has a simplified manufacturing process and it does not require periodic maintenance;
- simplicity of six pulses control system for BLDC motor and the small number of necessary components, with direct impact on the price of the whole system.

In Figure 5 is presented the cinematic scheme of proposed solution.

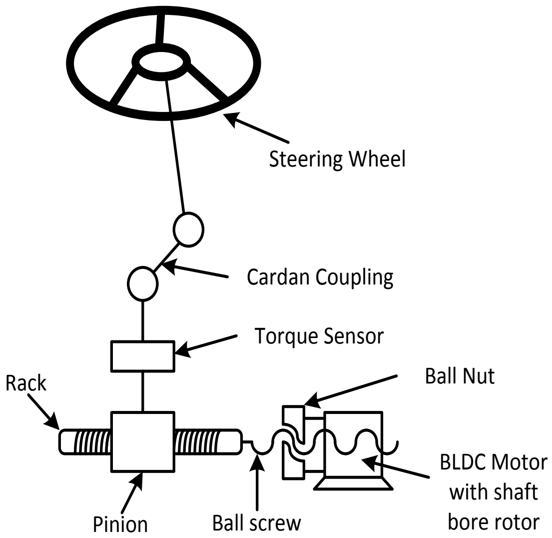

Figure 5. Cinematic scheme of the designed solution

The rotor of the electric motor is seated on the ball screw nut. The electric motor acts the steering rack by the ball screw. The electric motor must provide a high torque because the system includes only one transmission stage.

4. Structure and preliminary determination of the motor parameters

BLDC motors exist in different configurations. Due to its efficiency and low torque ripple the most common type is the three phase motor.

The topology of performed BLDC motor is presented in Figure 6.

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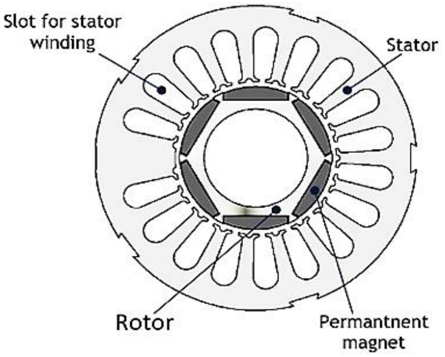

Figure 6. Topology of Designed motor

The stator of the motor consists of stacked steel laminations with 18 slots axially cut along the inner periphery for windings.

The slots are tapered semi-closed type. For these shapes of the slots the air gap characteristics are better compared to open type slots.

On the periphery of the rotor are incorporated 6 permanent magnets. The permanent magnets are placed in the grooves of the outer periphery of the rotor. This construction provides robustness and uniform cylindrical rotor surface.

The BLDC motor is controlled using a three phases semiconductor bridge. To identify the rotor position, 3 Hall sensors are used for providing proper commutation sequence. Based on the rotor position, the power devices are commutated sequentially every 60 °.

The preliminary determination of the motor parameters was performed by calculation. The calculations are made for a small vehicle, type 67’ VW Beetle, which was converted into an electric vehicle.

$$M_{SW} = D_{SW} \cdot F_{SW} = 0{,}2 \cdot 70 = 14 \; [\mathrm{Nm}] \qquad (1)$$

$$R_p = \frac{L_R/N_{SW}}{2\pi} = \frac{0{,}15/2{,}5}{2\pi} = 0{,}0095 \; [\mathrm{m}] \qquad (2)$$

$$F_R = \frac{M_{SW}}{R_p} = \frac{14}{0{,}0095} = 1466 \; [N] \qquad (3)$$

$$R_{EN} = \frac{p}{2\pi} = \frac{0{,}01}{2\pi} = 0{,}00159 \; [m] \qquad (4)$$

$$T_M = \frac{R_{EN} \cdot F_R}{\eta_N} = \frac{0{,}00159 \cdot 1466}{0{,}9} = 2{,}592 [Nm] \qquad (5)$$

$$v_R = n_{maxSW} \cdot R_p \cdot 2\pi = 1 \cdot 0{,}0095 \cdot 2\pi = 0{,}06 [m/s] \qquad (6)$$

$$n_M = \frac{v_R[m/s]}{p[m]} \cdot 60 = \frac{0.06}{0.01} \cdot 60 = 360 [rpm] \qquad (7)$$

where:

MSW = Steering wheel torque [Nm];
DSW = Steering wheel diameter [m];
FSW = Steering wheel force [N];
Rp = Pinion radius [m];
Lr = Rack stroke [m];
NSw= Number of turns of the steering wheel;
FR = Rack force [N];
REN = The equivalent radius of the ball nut [m];
p = Ball screw pitch [m];
TM= Required torque of the motor [Nm];
ηN = Ball nut efficiency;
vR = Linear rack speed [m/s];
nmaxSW = Maximum speed of the steering wheel rpm];
nM = Motor speed [rpm].

5. Simulation and discussion

BLDC motor control system analysis is considered a difficult process. An important role before the practical implementation of such a system belongs to the simulation process.

In order to build up the complete drive model and determine the optimal parameters of the BLDC motor we used MATLAB/SIMULINK graphical modelling and simulation tool.

The BLDC motor and its control system were developed based on the functional equations and the transfer functions.

The simulations were performed for a motor with the parameters presented in Table 1.

Table 1. Parameters of the BLDC motor

Symbol	Description	Value	Unit
f	Frequency of the triangular signal	15	kHz
R	Stator phase winding resistance	30	mΩ
L	Winding inductance	123	μH
K_e	Back EMF coefficient	3,59	Vpk/krpm
F_f	Friction torque	0,1	Nm
J	Motor inertia	0,00018	kg·m^2
n_p	Number of pole pairs	3	
U	Supply DC voltage	12	V
T	Simulation time	0,2 or 0,4	sec.
ΔT	Simulation sample time	1	μs

The variables that can be controlled for driving the BLDC motor are speed, torque and phase currents. The control scheme can be made in open-loop or closed-loop.

Two simulation models have been developed for open-loop and close-loop control strategy.

Open-loop control is a simple control system which does not use feedback to determine if the output has achieved the intended goal of the input. The key advantages of this control system are:

- Simplicity in designing the control system;
- Lower cost.

In open-loop control of BLDC motor, the speed can be controlled through the control of voltage. The BLDCM motor is driven by the PWM pulses which are given as inputs to the base port of the IGBT three phase inverter.

The closed-loop techniques are used for high accuracy control system. The closed-loop control adjusts the control inputs by the feedback of the outputs. The purpose of closed-loop control is to monitor the dynamic behaviour of the motor by means of appropriate feedback. The most interested features in the closed-loop control system response are settling time, overshoot, steady-state error and response time [21].

In Figure 7, the general block scheme used to perform the closed-loop control of the electric motor, based on six pulses method, is presented.

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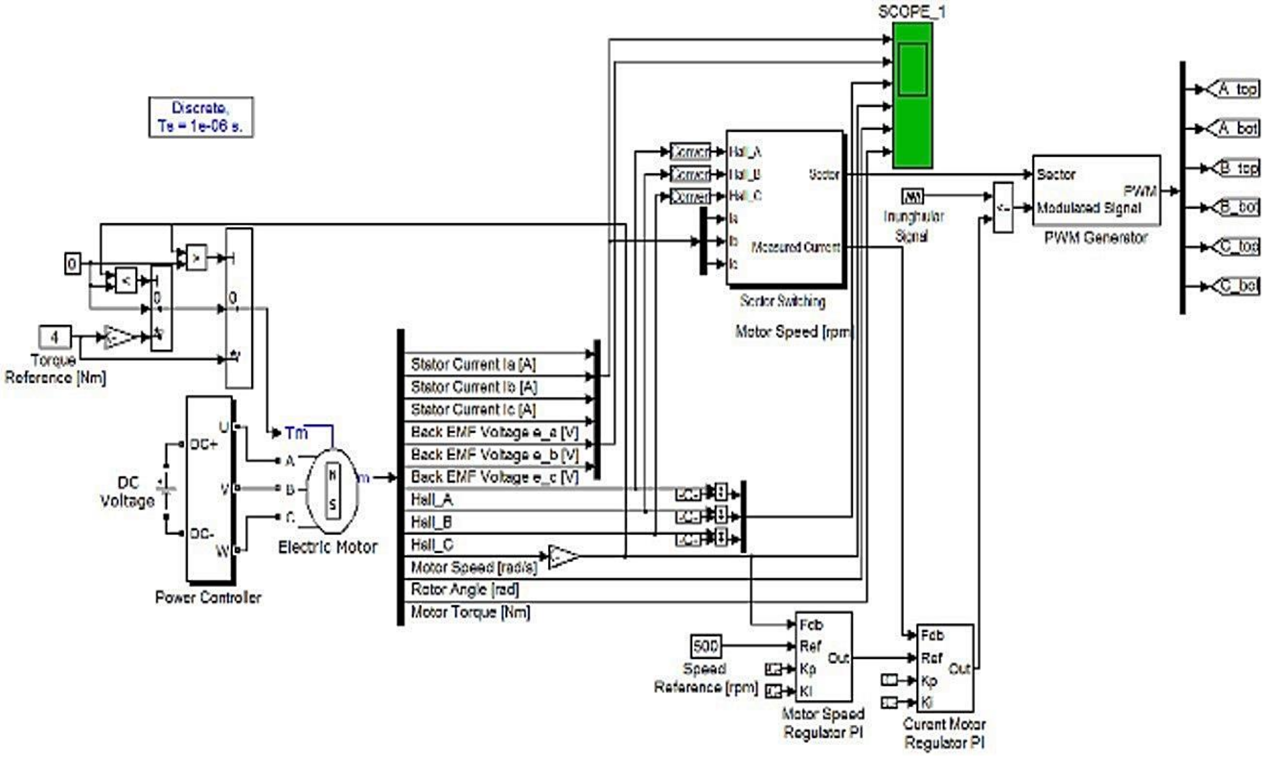

Figure 7. Simulation model of closed–loop control for the BLDC motor (MATLAB/SIMULINK)

The MATLAB/Simulink model of the proposed controller for 3-phase brushless DC motor, according to Figure 7, consists of the following main blocks:

- The DC voltage source (a constant DC voltage source which provide 12V to driver circuit);
- Torque calculation module;
- Power converter;
- BLDC motor;
- Hall-effect sensors block;
- Speed controller;
- Current controller;
- PWM generator.

All these blocks were modelled and integrated using the MATLAB/ Simulink platform and specialised toolboxes, for simulation the dynamic behaviour of the BLDC motor.

The power converter is a three phase inverter for electrical commutation. The inverter block in simulation model consists of three pairs of power semiconductor switches (IGBTs), arranged in a bridge structure similar to the MOSFETs pairs in Figure 2, to implement the commutation logic and output the phase-to-phase voltage and power the BLDC motor.

In order to control the direction of the motor rotation it is necessary to know the relationship of the six inverter switches state and the Hall sensor position.

The motor speed controller required to take a signal representing the demand speed and to drive the motor at that speed. The speed is controlled using a proportional and integral (PI) controller. The actual speed of the motor is compared with the reference speed and the speed error is processed in PI speed controller.

The output of the speed controller is fed as an input to the PI current regulator which generates the three phase reference currents to control the duty cycle of PWM generator. PMW generator generates a PWM signal and controls current in the BLDC motor.

The winding currents i_a, i_b and i_c are compared with the reference currents from PI current regulator and the switching commands are generated to drive the inverter devices.

The magnitude of the reference current is determined by using reference torque according to equation (8):

$$i_{ref} = \frac{T_{ref}}{K_T} \qquad (8)$$

where Kt is the torque constant.

Simulations were performed for various conditions according Table 2.

Table 2. Control simulation conditions

Simulation	Simulation conditions
Open loop control	
1	- Unitary (fixed) PWM duty cycle - Imposed task: a torque of 4 Nm - Simulation time: 0,2 sec.
Closed loop control	
2	- Variable PWM duty cycle - Control in closed-loop with imposed reference current of 50 A - Imposed task: Constant speed of 10 rad/sec. - Simulation time: 0,4 sec.
3	- Variable PWM duty cycle - Control in closed-loop with imposed speed of 200 rpm - Imposed task: constant torque of 2 Nm

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4	- Variable PWM duty cycle - Control in closed-loop with imposed speed of 200 rpm - Imposed task: constant torque of 4 Nm
5	- Variable PWM duty cycle - Control in closed-loop with imposed speed of 500 rpm - Imposed task: constant torque of 2 Nm
6	- Variable PWM duty cycle - Control in closed-loop with imposed speed of 500 rpm - Imposed task: constant torque of 4 Nm

After running the simulations, current and back EMF voltage waveforms, speed and torque diagrams and Hall signals were recorded and analysed. During simulations the direction of rotation is kept clockwise (CW).

First simulation was performed for open-loop control configuration and unitary PWM duty cycle. Imposed task was a torque of 4 Nm.

Figure 8 shows the Simulink diagrams of speed and torque results in open-loop control configuration.

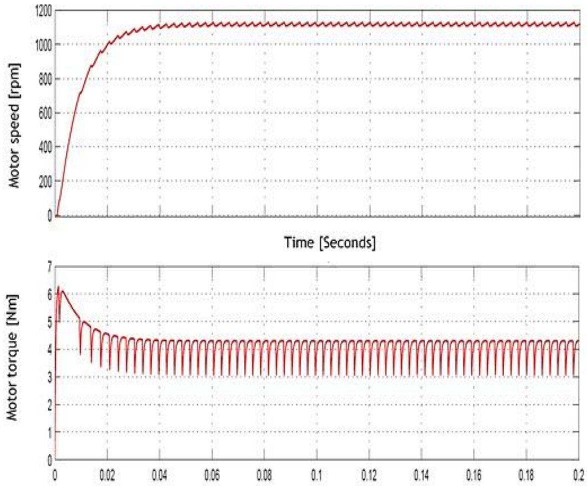

Figure 8. Waveforms of speed and torque in open loop control of BLDC motor (for an imposed torque of 4 Nm) (MATLAB/SIMULINK)

In this Figure, X axis represents the time in seconds (s) and Y axis represents the rotor speed (rpm), respectively the motor torque value (Nm).

Results of first simulation show that the current is positive when the back EMF is positive, and the current is negative when the back EMF is negative and produces the unidirectional torque. Stator currents have a maximum value of 126 A and the back EMF voltage has a maximum value of 2 V.

From the Figure 8, it is observed that in about 0,07 s the rotor runs at a quasi-constant speed of 1118 rpm. The load torque of 4 Nm is obtained after acceleration period. However, a significant torque ripple exists, due to current ripple, EMF waveform imperfection and phase current commutation.

The groups of simulations 2…6 (see Table 2, *supra*) are made with closed-loop speed control, to solve the problems of speed and torque regulation observed during the simulation of open-loop speed control.

The current control is achieved by PI controller PWM signals with varying duty rates. After acceleration period, the speed remains constant at a desired speed. The simulations were performed for different imposed values of current speed and torque, according to Table 2.

The results of second simulation show that:

- The imposed speed of 95,5 rpm is constant.
- A torque of 1,7 Nm is obtained in 0,12 msec.; the torque waveform shows small values of the torque ripple.
- The currents in stator have a maximum value of 50 A; the current control is achieved by PI controller and PWM signals with varying duty rates.
- Back EMF voltage has a maximum value of 0,17 V.

In the third simulation, analysis of current, back EMF voltage and Hall signals waveforms, speed and torque diagrams shows that:

- Imposed speed of 200 rpm is obtained after acceleration period of 3,2 msec.
- During the acceleration period a maximum torque of 6 Nm is reached; the torque becomes 2,1 Nm, constant, after the acceleration period.
- The maximum values of the currents in the stator windings are 61 A.
- The maximum back EMF voltages is 0,359 V.

In the fourth simulation, the imposed speed is also 200 rpm, but required torque is 4 Nm.

The simulation results show that:

- Imposed speed is obtained in 3,5 msec.
- During the acceleration period a maximum torque of 6,2 Nm is reached; the torque becomes 4 Nm, constant, after the acceleration period.
- The maximum currents in stator is 120 A.
- The maximum back EMF voltages is 0,359 V.

The analysis of the stator windings current, back EMF voltages, rotor speed and motor torque diagrams, obtained in the fifth simulation, shows that:

- The imposed speed of 500 rpm is obtained after acceleration period of 5 msec.
- A maximum torque of 6 Nm is obtained during the acceleration period and then, a torque of 2 Nm at the constant speed.
- The maximum value of currents in stator are 61 A.
- The maximum value of back EMF voltages is 2,2 V.

In Figure 9, the diagrams of current in stator windings, back EMF voltages, rotor speed and motor torque obtained in the sixth simulation are presented.

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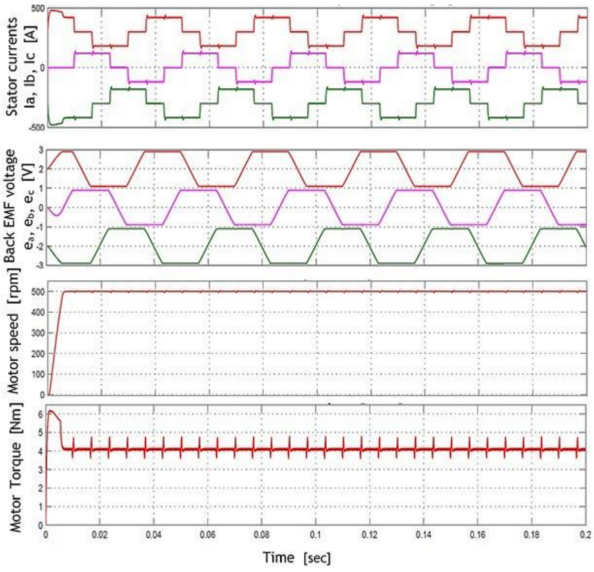

Figure 9. Stator currents, back EMF voltage, motor speed and motor torque in the sixth simulation (MATLAB/SIMULINK)

Diagrams from Figure 9 show that:

- The reference speed of 500 rpm is obtained in 6 msec.
- A maximum torque of 6,2 Nm is obtained during the acceleration period and then a torque of 4 Nm at the constant speed.
- The maximum value of currents in the stator windings are 120 A.
- The maximum value of the back EMF voltages is 0,9 V.

To equip an EPS system with a BLDC motor onto a vehicle, the motor torque ripple needs to be minimized.

The results of the simulations show that by using closed-loops for speed and current control with PI regulator the torque ripple is reduced comparative with open-loop drive.

Based on the mathematical calculations and analysis of simulation results, following parameters of BLDC motor and EPS system were established:

- Motor type: BLDC;
- Control algorithm: six pulse control;
- Torque: 4 Nm;
- Rated speed: 500 rpm;
- The constructive solution of the power steering mechanism: direct assistance;
- Step of the ball screw: 10 mm;
- Ball screw displacement range: 150 mm.

6. Conclusions

Brushless motors are recommended to be used in EPS systems. They have the capability of developing high torque with good speed response. The Brushless DC motors has high efficiency, high torque, low maintenance, less noise and low volume.

In this paper we presented a compact model of the EPS, assisted by a BLDC motor coaxial with steering rack.

The motor of the EPS has the following main requirements:

- Good speed response;
- High torque with relative low speed;
- Low noise, good mechanical properties;
- Easy to control;
- Small size, light weight, as much as possible to save space and reduce weight.

For the design and construction of the BLDC motor for the EPS system, shown in Figure 8, we have taken into account all these requirements.

The preliminary determination of the electric motor parameters was determined by calculation.

In order to optimize the parameters, a group of 6 simulations was developed in the MATLAB/SIMULINK platform, for various conditions.

The analysis of the simulation results showed that a constant torque of 4 Nm, with minimum torque ripple, can be obtained in an interval of 6 ms, at a constant rotor speed of 500 rpm, controlled in a closed loop control system by varying duty rates of PWM signals.

The experimental model of the BLDC motor will be tested on a specialized stand at Icpe.

The results obtained after the tests will be compared with the results obtained by simulation.

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Full Probabilistic Characteristics of Power Losses in the Electrical Power System Branches

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Abstract

Stable operation of the electrical power system (EPS) is one of the main issues considered in the power industry. Current levels of electricity consumption lead to the need to increase the generated capacity, repeatedly converting and complicating the original circuit. In addition to this, given the current trend towards the use of renewable energy sources (RES), more and more uncertainties are added, that are difficult to predict. Events in the EPS, and especially in the case of RES, are deterministic, i.e. random. This leads to the fact that it is difficult to fully assess the EPS stability and the possible power loss. It is also difficult to determine the amount of permissible power generated by RES, which will not lead to subsequent mode violations. The purpose of this article is to test the developed SIBD method for obtaining the full probabilistic characteristics of power losses in each branch. This method, unlike the Monte Carlo methods, does not use a random sample of initial data, but completely covers the studied functional dependence (FD). The method is used to obtain the probability distribution laws (PDLs) of power losses in transmission lines based on unmodified IEEE 30-Bus and IEEE 14-Bus systems and their examination. These laws are necessary for further determination of the optimal EPS operating modes, to solve the problem of determining the optimal RES installation, the required amount of renewable generated energy in a non-deterministic way.

Keywords: probability density function, random variable, quantity, electric power system, power losses.

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1. Introduction

During recent years, ensuring the EPS secure planning has become an important issue along with its development. There is currently a great demand for electricity all over the world, but production is not enough to meet demand. Due to this, the penetration of RES into the EPS has expanded. In future, a large share of the energy [1] will be generated with wind power plants (WPPs) and other RES, such as solar power cells. As a result, more and more uncertainties are introduced which makes power system uncontrolled.

This is due to the fact, that the system normally has a classical “vertically-operated” power system there is only a “small” number of large centralized generators dispatchable, i.e. controllable to meet the demand. However, in the “horizontally-operated” power system, the DG units in the “active” distribution networks are practically non-dispatchable [2].

The Distribution network operators (DNO’S) are liable for retaining the reliability and efficiency of EPS. Thus, for optimal energy systems operation with minimal power losses and fluctuations, as well as the ability to install RES, it is necessary to determine a strict and adequate method to eliminate the uncertainties associated with these problems.

To find the magnitude of change in power loss, it is necessary to determine all possible losses that can flow through the transmission line of interest to research, as well as the total losses throughout the system. Therefore, it is necessary to determine in a non-deterministic form [3] how the power loss is distributed over the network, in order to their possible connection with installations for the active generation of electricity from RES, not in random (deterministic cases), but in a whole set of states.

The main problem is that obtaining the probabilistic characteristics by standard statistical methods has no full solution [4]. It is necessary to make a full assessment of the probabilistic characteristics of the EPS, including power losses, in order to understand the entire range of processes in the network. In this regard, the method of selection of interval boundaries of input and output data (SIBD) is proposed, and its application for obtaining probabilistic characteristics of electrical quantities and their imbalances.

2. The Literature Review

Obtaining the cumulative distribution function (CDF) and probability density function (PDF) of multi-dimensional FD, as well as probabilities of a FD assuming values from the multidimensional domain, in its

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