DTC CONTROL OF BLAC AND BLDC MOTORS FOR PURE ELECTRIC VEHICLES

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ABSTRACT

While creating an industrial system which has an electric motor, the designers should to be think over not only control method but also motor type to create successful and efficiency system. If created system is an electric vehicle, designers have two powerful candidates as traction motor: Brushless AC (BLAC) or Brushless DC (BLDC) motors. In this study, a comparative performance investigation and evaluation are presented between direct torque controlled (DTC) Brushless AC and Brushless DC motors which have been considered as traction motor on electric vehicles. In addition, a short review to BLAC and BLDC motor technology is also included. The basics of the DTC method are presented and small-scale pure electric vehicle model is created and integrated to the motor control model. The BLAC and BLDC motors modeled as having the same electrical parameters and simulated with same control model parameters in order to make fair comparison. The simulation studies have proved that DTC controlled BLAC and BLDC motors have closer performances as vehicle traction motor, and both motor types can be allowed as a good candidate for pure electric vehicles applications.

KEYWORDS

Direct Torque Control, Brushless motors, Electric Vehicle, Vector Control

1. INTRODUCTION

When the humanity faced with the reality about unsustainable fossil fuel sources and also environmental issues like global warming, a new research route was defined in all major sciences: to produce energy with same source again and again. So, it was called as Renewable Energy. Unfortunately, energy nightmare is not only about producing renewable energy side but also in usage of produced green energy side. If you attend to shift energy dependence on fossil energy to electric energy, you have to convert all fossil fuel based – internal combustion (IC) motors to the electric motors. Many statistical reports show that the researches about energy production and consumption have to focus on electric vehicles (EVs). United States Environmental Protection Agency (EPA) reports that the U.S. gets most of his energy from fossil fuels, which include coal, petroleum, and natural gas. Moreover, transportation sector that includes personal and good transportation, accounted for the %28 percent of energy use [1]. Another report of the EPA shows that percent of the U.S. transportation sector consumption is about 95% based on fossil fuels [2].

Over the last decades, it can be seen that automakers have focused on EVs or hybrid vehicles (HEVs) for personal transportation in short distances. Due to limitations on energy storage, and also fast charge needs, EVs still have very limited ranges. However, researches about increase the range and decrease the charging time of the EVs still going on. Beside, chose of the optimum motor type and driver is vitally important for an EV.

DOI : 10.5121/ijics.2016.6302

In the mid-20th century, the availability of high energy density permanent magnets (PMs) and developments in power switching technologies led the development of PM motors[3]. Two typical classifications of permanent magnet synchronous motors (PMSMs) have been presented in literature by scholars according to shape of the induced emf (also known as back emf). One is called as brushless AC (BLAC) which has a sinusoidal-wave back-emf and the other is brushless DC (BLDC) motor which has a trapezoid-wave/square-wave back-emf. A BLDC motor can be defined as a electronic commutated self synchronous rotary motor, where the rotor contains permanent magnet with rotor position sensors. [4] But, it's obvious that same definition can be easily used for the BLAC motors. So far, there has not been a unified standard about the classification or definition of the BLDC motors or BLAC motors.

The main question that should be asked about the PMSM is "Why are the PM motors happening more and more popular with every past day?" A PMSM incorporates starting characteristic of serious excitation DC motors and speed-torque characteristic of shunt excitation DC motor. Furthermore, the PMSMs have structural advantages of conventional brushless AC motors [4].

The PMSMs have great advantages like high efficiency, simple structure, high power densities, high starting torque, wide speed ranges, linear torque and speed characteristics, low maintenance and works in any condition. Due to absence of mechanical brushes and commutator, PMSMs can be acceptable as best choice for high performance drive applications [5]. Hence, it has been preferred motor type in many fields such as robotics, vehicle propulsion, aerospace, industrial control, machine tools, etc.

2. DRIVE SYSTEM ON PMSM

AC drive systems can be grouped under two major heading – induction drive systems and synchronous drive systems. Not far, about 3 decades ago, the induction drive systems almost monopolized the whole market, but with the advent of high magnetic permanent magnets, synchronous drive systems, include the PM brushless motors, are becoming popular [6].

A BLDC motor is designed to be supplied with a trapezoidal shape current while a BLAC with sinusoidal as can be seen in Figure [7]

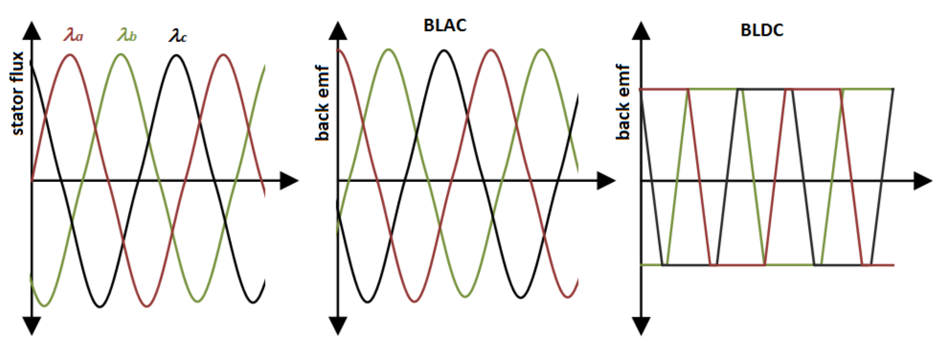

Figure 1. Stator flux and back-emf forms of BLAC and BLDC motors

The PM-BLAC motor fed by sinusoidal AC sources and produces an essentially constant torque, or so-called smooth torque. On the other hand, the PM-BLDC motor fed by rectangular or trapezoidal AC waves and has a significant torque pulsation. However, due to interaction between a rectangular field and a rectangular current, the BLDC motors can produce higher torque than the BLAC motor.

Torque ripples issue is major problem for the many kind of systems, include EVs. The torque ripples causes torsional vibration and also acoustic noise. Due to vibration systems, mechanical parts of the system can be damage, even all system can be breakout [8]. For many years, reduction of the torque ripples in motor control systems have been major research subject and many kind of methods have been proposed by scholars and engineers to overcome this problem.

Direct torque control (DTC) is the name of reliable and energy efficiency vector control method. Although the DTC was originally proposed for asynchronous motors by Takahashi in 1986[9], over the years, it has been applied for various motor type such as linear motor, reluctance motor and also PM motors [10-12]. Conventional DTC scheme for AC motors is given in Figure 2.

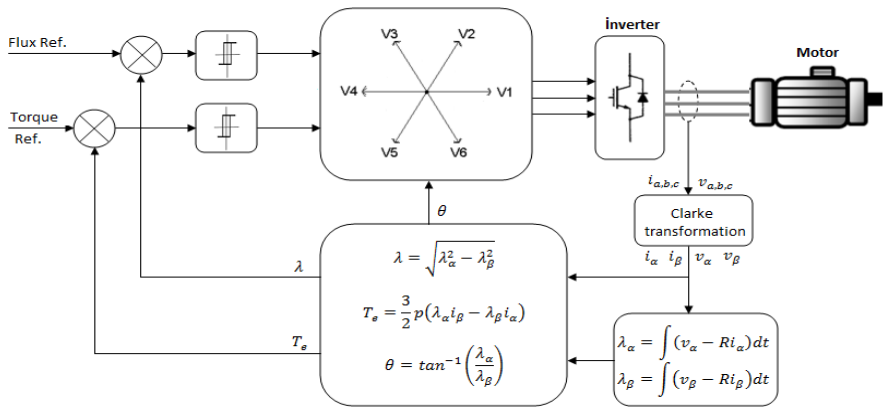

Figure 2. DTC scheme for AC motors

Another vector control method which can be preferred in high performance control of motors is field oriented control (FOC). Almost half a century ago, the FOC method was also firstly proposed for asynchronous motors [13], but today, the FOC has been completely developed and it has been implemented for many motor types such as PM motors. FOC scheme for AC motors is given in Figure 3.

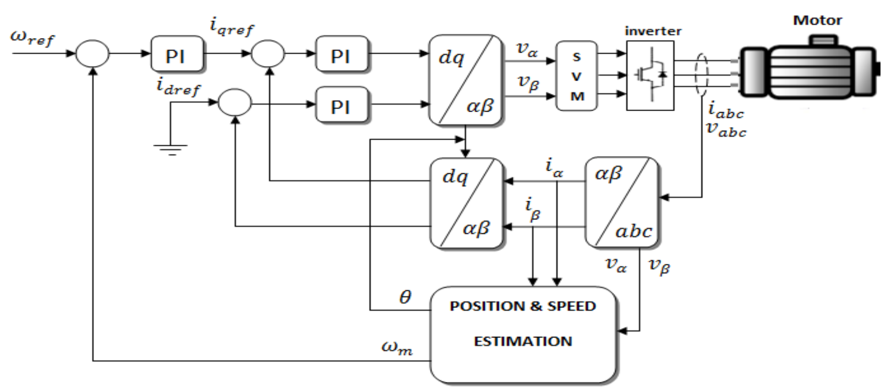

Figure 3. FOC scheme for AC motors

Over the last 40 years, many articles have been published about FOC and DTC of different motor types. However, few articles have focus on similarities or differences of between these methods. [14-17]

Some main structural advantages of the DTC can be listed as follows;

- Does not require current regulator
- Does not require PWM modulator
- Does not require rotor position measurement
- Does not require complex coordinate transformation
- Less parameter depended

To summarize, it can be pointed out that the DTC has simple structure when compared the FOC. On the other hand, the DTC method has some disadvantages and most important differences against to the FOC is high torque ripples.

In [16], the authors presented comparative analysis between two control methods for PMSMs. Advantages and disadvantages of the both methods were compared and discussed. Moreover, simulation based tests were performed for different working conditions. The authors claimed that the DTC had fast dynamic response while the FOC had better torque response and when selecting control method application requirements should be considered.

In another paper [17] the FOC and the DTC controlled PMSM was compared and discussed in detail. As a result, the authors claimed that there were no meaning differences in the main characteristics of the motor for both control method.

A comparisons between the FOC and the DTC controlled PMSMs had also been presented in [15] by numerical simulations. The paper supports almost same the claims with [16]. In other words, numerical simulations proved that the FOC was better on overall torque performance and the DTC had faster dynamic responses.

Similar studies have been realized for induction motors and similar results to the PMSMs have obtained.

3. MODELLING OF EVS

Small-Scale Electric Vehicles (SSEV) are used in personal transportation for short distances. The SSEVs are powered by only battery packs and they only driven by electric motors-pure electric vehicle (PEV)- such as bicycles, scooters, skateboards, toy cars, rail cars, watercraft, forklifts, golf cars, and city cars, etc. The synchronous motors with PM–(BLAC/BLDC) are leading choice for vehicle propulsion in EVs due to advantages that mentioned earlier sections [18].

The acting forces on the vehicle are shown in Figure 4.

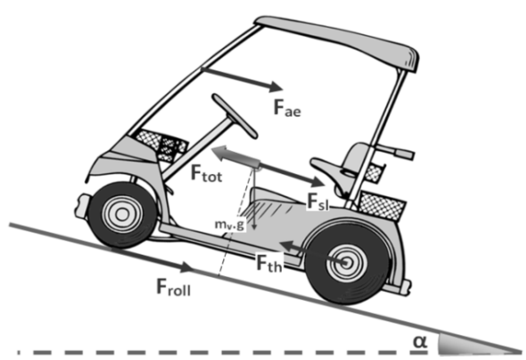

Figure 4. The acting forces on the vehicle

The inertia force is neglected to simplify the model, than, motion equation of the vehicle can be written from the equilibrium of forces as:

$$F_{tot} = F_{th} - F_{roll} - F_{ae} \mp F_{sl} \quad (16)$$

Where; F_{tot} is the total force on the vehicle, F_{th} is the thrust force, F_{roll} is the rolling force, F_{ae} is the aerodynamic force and F_{sl} is the slope force.

The thrust force is the tractive force generated by the electric motor. The F_{roll} is the rolling resistance force and it describes friction losses that produced by the tire at the surface with the roadway. The F_{roll} depends on the coefficient of rolling friction between the tire and the road, C_{roll}, and the vertical component of the vehicle weight. The vertical component of the vehicle weight can be calculated with vehicle mass, m_v, the gravitational acceleration, g, and road slope angle, α. The equation for the rolling force can be given as;

$$F_{roll} = C_{roll}.m_v.g.\cos\left(\frac{\alpha\pi}{180^{\circ}}\right) \quad (17)$$

C_{roll} is named as rolling resistance coefficient and, in practice, it is a function of vehicle speed, tire pressure, external temperature, etc[19].

The aerodynamic resistance is modeled as:

$$F_{ae} = \frac{1}{2}.\rho_{air}.A_f.C_d.v_v^2 \quad (18)$$

where ρ_{air} is the air density, A_f is the vehicle frontal area, C_d is the aerodynamic drag coefficient and v_v is the vehicle speed. The force due to road slope depends on the mass of the vehicle, m_v, road angle in degrees, α, and gravitational acceleration, g. The equation for the slope force can be given as;

$$F_{sl} = m_v.g.\sin\left(\frac{\alpha\pi}{180^{\circ}}\right) \quad (19)$$

The sign of the F_{sl} changes with the road slope angle. If road slope angle is positive (uphill mode), F_{sl} is positive. It means, F_{sl} force opposes the thrust force and slowing down the vehicle. Otherwise, if road slope angle is negative (downhill mode), F_{sl} is negative. It means, F_{sl} force facilitates the thrust force and accelerates the vehicle.

The DTC method is very useful and appropriate for EVs due to its great advantages such as; Controlling torque directly, Simple structure and easy applicable, Low parameter sensitivity [20].

To compare of the BLAC and BLDC traction motor performances on the DTC controlled system, Matlab/Simulink models of the controller has been created. Small-scale EV model has also included to model to obtain reference torque parameter for the DTC system. Figure 5 shows Small-scale EV Simulink model.

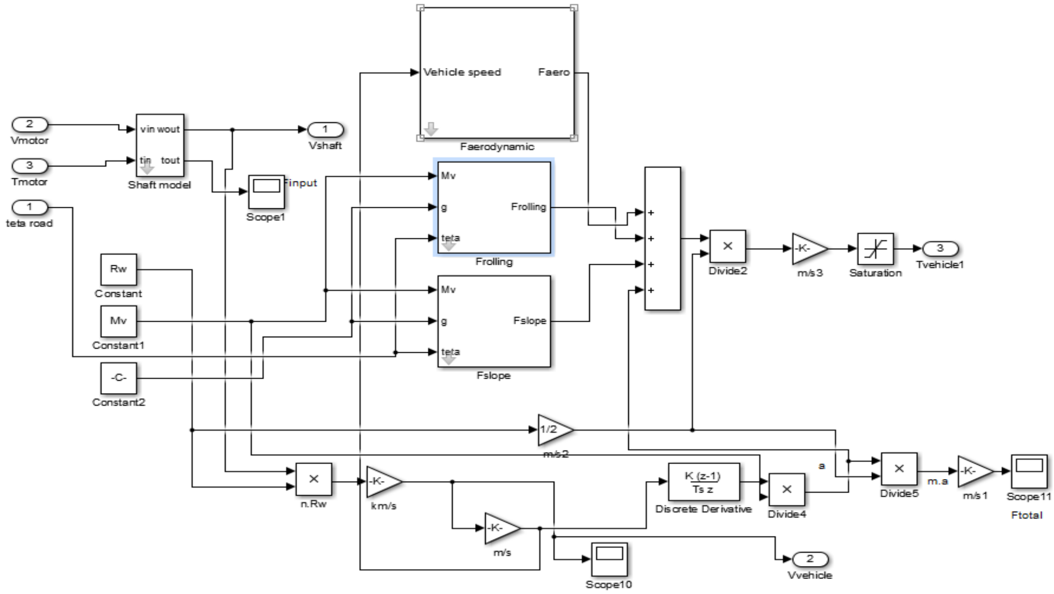

Figure 5. Simulink block diagram of EV

In simulations, BLAC and BLDC driven EV is accelerated to 0-2000 rpm motor speed, and the torque reference value is produced by EV model. Road angle is 0° between 0–1 sec. and 30° between 1–2 sec. The Matlab/Simulink block diagram of the DTC model for BLDC motor is given in Figure 6.

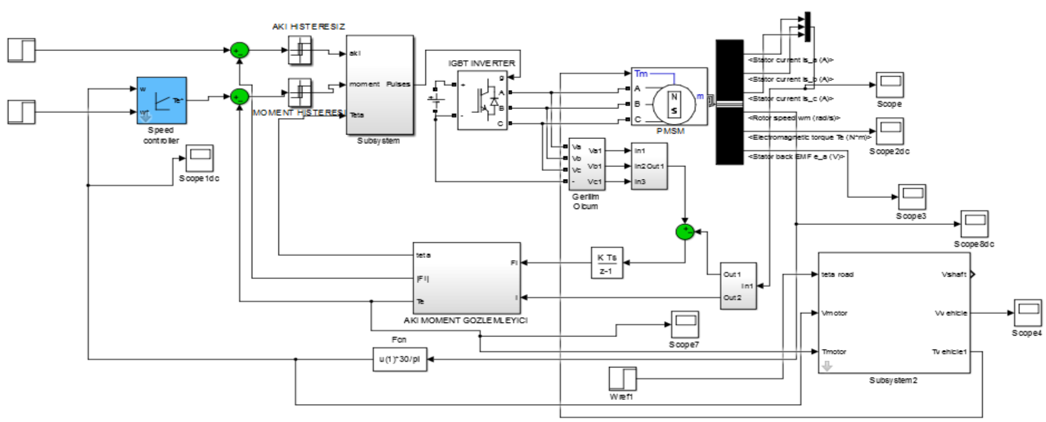

Figure 6. Simulink block diagram of BLDC-DTC

The model and vehicle parameters which have been used in simulation as follows: Vehicle mass: 100kg, wheel radious: 0.4 m, Ratio of shaft: 1/10, BLAC/BLDC stator resistance: 0.4578 ohm, BLAC inductances (d-q): 0.003173 H-0.003507 H, Bus voltage of inverter: 300V, Flux reference:0.22 Wb, Flux Hysteresis band:±0.01, Torque hysteresis band: ±0.1. The speed (in rad/s) and the torque responses of the motors and vehicle are presented in Figure 7 – Figure 10.

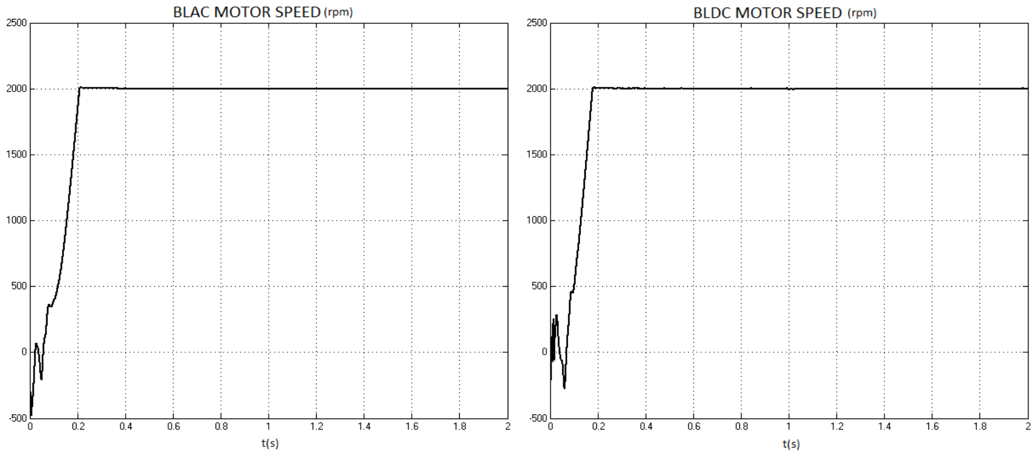

Figure 7. Overview of speed responses of the motors

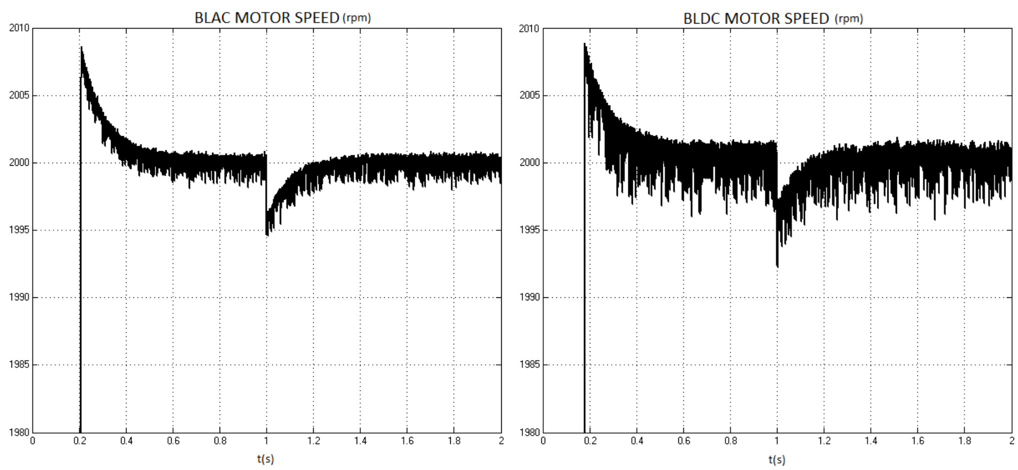

Figure 8. Zoomed view of speed responses of the motors

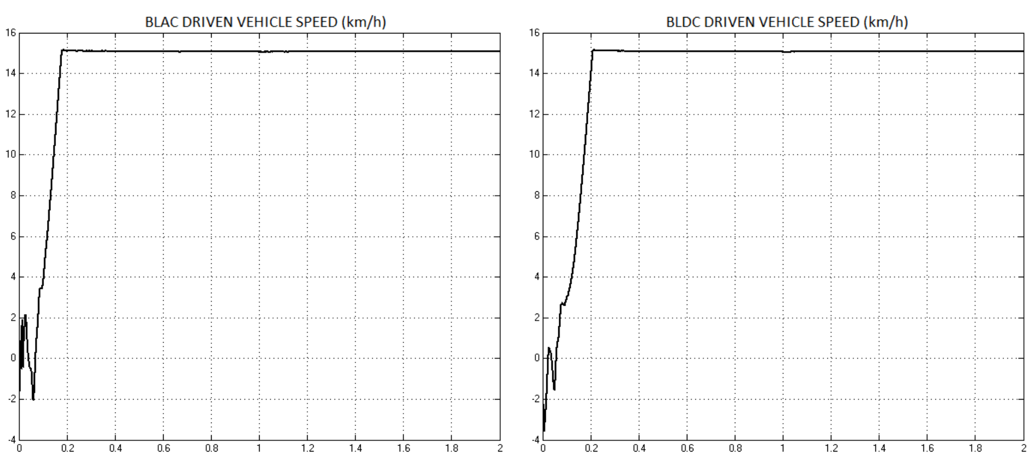

Figure 9. Overview of speed responses of the vehicle

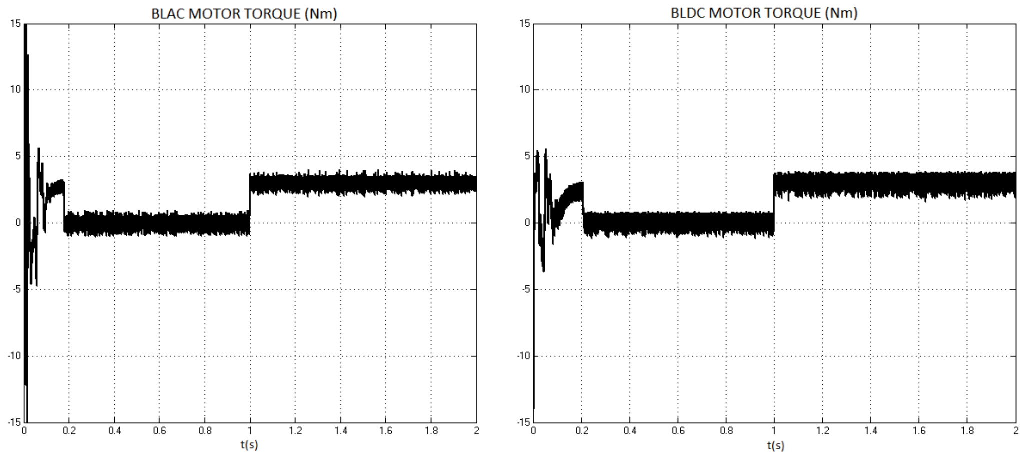

Figure 10. Overview of torque responses of the motors

When the speed and torque curves of the motor are compared, it can be clearly seen that motor performances are pretty close to each other for both motor types. However, the BLAC motor speed and torque responses have better performance than the BLDC motor due to fewer ripples. The simulation studies prove that the DTC method is very appropriate for the BLAC and the BLDC motors and vehicle designers/engineers can choice one of the two considering other physical or economical parameters.

4. CONCLUSION

Brushless AC and brushless DC motors are getting more and more popular every past day due to their well-known advantages like maintenance-free structures, height mass-power ratio, silent works, etc. In parallel, the BLAC and BLDC motors are indispensable motor types for electric vehicle traction systems. This paper aims to present a fair comparison between the BLAC and the BLDC motors for vehicle traction systems. For this purpose, direct torque controlled BLAC and BLDC motors have been modeled and simulated. The simulation studies show that both motors can be applicable for electric vehicle with DTC method. The speed and torque performances of the motors are pretty closer. So, it means, when brushless synchronous motor selection is necessary for electric vehicles or similar industrial system, some other physical or economical factors should be taken into consideration.

ACKNOWLEDGEMENTS

Thanks to Cankırı Karatekin University because of their valuable contributions to this paper. This research was funded by a grant (No. MF050315B15) from the Research Council of Cankırı Karatekin University. This research was performed in cooperation with the Institution.

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