# A Comparative Study of Different BLDC Motor Construction Types Used in Automotive Industry under Specific Command Strategies

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***Abstract*** **– The automotive industry future focus is based on the construction of hybrid and fully electric vehicles, with the trend towards autonomous driving. Different electric drive subsystems from the structure of these electric vehicles are aiming to achieve a higher efficiency, which is why permanent magnet synchronous machines of either BLDC / PMSM type are currently being used as main actuators in their construction. These types of electrical machines are known in the literature as having sufficient power density and efficiency to meet the criteria and requirements of the automotive building industry. That's why an important area of interest is the construction and the control topology specific to these electrical machines. Based on these considerations, the paper purpose is to present a comparative study regarding different constructive types concepts of BLDC electrical machines and different control methods related to them. In order to validate the theoretical aspects of this study, two distinct ways of modelling and simulation were used in parallel: the first method is based on FEM (Finite Element Method) analysis and the second analytical method uses the MATLAB / Simulink software package.**

***Keywords – Automotive, BLDC, PMSM, FEM, Control***

## I. INTRODUCTION

Automotive industry has strong actual trends towards the development of hybrid and full electric cars. By taking into account that the actual power supply batteries that are used on these vehicles have a limited energy supply capability, it is necessary for the electrical and electronic load systems connected to them to present low power losses and implicitly high efficiency. The main consumer of electricityare the drive systems that include electric motors, so it is imperative to use and develop electric machines that meet the most demanding criteria in terms of efficiency and reliability. Currently, the most widely used electric machines in this field area are Brushless Direct Current Motor (BLDC) and Permanent Magnet Synchronous Motor (PMSM), due to their features such ashigh reliability, efficiency and power density. Some drawbacks may bealso mentioned, such as the need for advanced control methods compared to other types of motors.

### *A. Paper Purpose*

Based on these considerations, the paper purpose is to present a comparative study regarding two different constructive types concepts of BLDC electrical machines and different control methods related to them. In order to validate the theoretical aspects of this study, two distinct ways of modelling and simulation were used in parallel: the first method is based on FEM (Finite Element Method) analysis and the second analytical method uses the MATLAB / Simulink software package.

Among the original contributions of this work, we can mention:

- Designing, modelling and simulation by using finite element (FEM) of special constructive structures of BLDC / PMSM electrical machines suitable for the automotive industry;
- Modelling and simulation of equivalent models of these previously developed BLDC / PMSM electric motors in MATLAB / Simulink working environment;
- Modelling and simulation of a specific control system able to drive these electric machines in different operating conditions.

## II. ANALYTICAL MODEL OF BLDC / PMSM WITH THREE STATOR PHASES (A,B,C)

This section presents a brief overview of the basic mathematical equations that were used for the implementation of the analytical BLDC / PMSM model.

In the development of the mathematical model of BLDC / PMSM with three phases, some simplified considerations were made: the structure of the stator yoke and field coil phase windings is symmetrical, anisotropy of the material, saturation of the iron core, Hysteresis and Eddy currents losses are equated by a general cumulative efficiency factor.

### *A. Voltage Equations in Static Reference System*

The stator phase voltage equations for the three phase system may be expressed in static frame reference as [1]:

$$
\begin{cases}
u_A(t) = R_A \cdot i_A(t) + \overbrace{L_A(t)\cdot\frac{di_A(t)}{dt}}^{\frac{d\psi_{sA}(t)}{dt} = \overbrace{\frac{\partial\psi_{sA}(i_A)}{\partial i_A}\cdot\frac{\partial i_A}{\partial t}}^{\frac{\partial\psi_{sA}(i_A)}{\partial t}}} \overbrace{-\omega_e\cdot\psi_{PM-A}\cdot\sin(\theta_e)}^{e_{PM-A}(\theta_e,\omega_e) = \overbrace{\frac{\partial\psi_{PM-A}(\theta_e)}{\partial\theta_e}\cdot\overbrace{\frac{\partial\theta_e}{\partial t}}^{\omega_e(t)}}^{\frac{d\psi_{PM-A}(t)}{dt} = \frac{\partial\psi_{PM-A}(\theta_e)}{\partial t}}} \\
u_B(t) = R_B \cdot i_B(t) + \overbrace{L_B(t)\cdot\frac{di_B(t)}{dt}}^{\frac{d\psi_{sB}(t)}{dt} = \overbrace{\frac{\partial\psi_{sB}(i_B)}{\partial i_B}\cdot\frac{\partial i_B}{\partial t}}^{\frac{\partial\psi_{sB}(i_B)}{\partial t}}} \overbrace{-\omega_e\cdot\psi_{PM-B}\cdot\sin\left(\theta_e - \frac{2\cdot\pi}{3}\right)}^{e_{PM-B}(\theta_e,\omega_e) = \overbrace{\frac{\partial\psi_{PM-B}(\theta_e)}{\partial\theta_e}\cdot\overbrace{\frac{\partial\theta_e}{\partial t}}^{\omega_e(t)}}^{\frac{d\psi_{PM-B}(t)}{dt} = \frac{\partial\psi_{PM-B}(\theta_e)}{\partial t}}} \\
u_C(t) = R_C \cdot i_C(t) + \overbrace{L_C(t)\cdot\frac{di_C(t)}{dt}}^{\frac{d\psi_{sC}(t)}{dt} = \overbrace{\frac{\partial\psi_{sC}(i_C)}{\partial i_C}\cdot\frac{\partial i_C}{\partial t}}^{\frac{\partial\psi_{sC}(i_C)}{\partial t}}} \overbrace{-\omega_e\cdot\psi_{PM-C}\cdot\sin\left(\theta_e + \frac{2\cdot\pi}{3}\right)}^{e_{PM-C}(\theta_e,\omega_e) = \overbrace{\frac{\partial\psi_{PM-C}(\theta_e)}{\partial\theta_e}\cdot\overbrace{\frac{\partial\theta_e}{\partial t}}^{\omega_e(t)}}^{\frac{d\psi_{PM-C}(t)}{dt} = \frac{\partial\psi_{PM-C}(\theta_e)}{\partial t}}}
\end{cases}
\tag{1}
$$

where the following notations were used:

$j = A, B, C$ stator phase index; $u_j(t)$ = instantaneous stator phase $j$ voltage [V]; $R_j$= self electric resistance of stator phase $j$winding [Ω];$i_j(t)$ = instantaneous stator phase $j$current [A];$\psi_{sj}(t)$ = instantaneous stator magnetic field produced by inductance and current flowing through stator phase winding $j$ [Wb] or [Vs]; $L_j(ij)$ =instantaneous self inductance of stator phase $j$, depending only on the stator phase current value [H];$\psi_{PM-j}(t)$ = instantaneous magnetic field (component) of rotor permanent magnets (PM) which traverses ferromagnetic core of stator phase $j$ [Wb]; $\omega_e(t)$= instantaneous electrical angular velocity [rad/s];$e_{PM-j}(t) = e_j(t)$ = instantaneous electromotive force component dependent only on PM magnetic flux variation with angular velocity [V].

### *B. Electromagnetic Torque in Static Reference System*

The electromagnetic torque developed by the BLDC / PMSMcan be analytically expressed in three phase static frame reference, as [1]:

$$
T_e(t) = \sum_{j=A}^{C} T_{ej}(t) = \sum_{j=A}^{C} \frac{e_j(t)\cdot i_j(t)}{\omega_m(t)} \Leftrightarrow
$$

$$
\Leftrightarrow T_e(t) = \frac{e_A(t)\cdot i_A(t) + e_B(t)\cdot i_B(t) + e_C(t)\cdot i_C(t)}{\omega_m(t)} \Leftrightarrow
$$

$$
T_e(t) = -p\cdot\Psi_{PM}\cdot\begin{bmatrix} sin(\theta_e)\cdot i_A(t) + sin\left(\theta_e - \frac{2\cdot\pi}{3}\right)\cdot i_B(t) \\ + sin\left(\theta_e + \frac{2\cdot\pi}{3}\right)\cdot i_C(t)\end{bmatrix}
\tag{2}
$$

where the following notations were used:

$T_{ej}(t)$= instantaneous electromagnetic torque component developed by phase $j$ [Nm];$T_e(t)$= total instantaneous electromagnetic torque developed by BLDC / PMSM [Nm]; $p$ = number of pole pairs [-];$\Psi_{PM}$ = total magnetic field of the rotor permanent magnets (PM) which traverses the ferromagnetic core of the stator [Wb]; $\theta_e(t)$ = instantaneous electrical position angle [rad].

### *C. Equation of Motion (General Form)*

The equation of movement can be expressed as [1]:

$$
\overbrace{T_e(t)}^{\text{Electromagnetic Torque}} = \overbrace{J\cdot\frac{d\omega_m(t)}{dt}}^{\text{Inertial Torque}} + \overbrace{\beta\cdot\omega_m(t) + sign(\omega_m)\cdot T_C}^{\text{Friction Torque}} + \overbrace{T_L(t)}^{\text{Load Torque}}
\tag{3}
$$

where the following notations have been used:

$T_e(t)$ = total instantaneous electromagnetic torque developed by BLDC / PMSM [Nm]; $J$ = moment of inertia [kg m2];$\beta$ = viscous friction coefficient [-];$T_C$ = Coulomb friction torque [Nm]; $T_L(t)$ = load torque [Nm].

## III. FINITE ELEMENT METHOD (FEM) MODEL

This section provides an outlook to the designand structure of two BLDC motor models developed by using finite element method (FEM) analysis.

The first proposed BLDC motor modeltopology presents a symmetrical structure provided with 9 stator slots and 10 rotor poles. The ferromagnetic circuit of the stator is made from standard FeSi material. The armature of the rotor is made from standard FeSi material, while the permanent magnets (PMs) are composed of rare-earth neodymium (NdFeB) type material and are disposed at the surface, as can be seen in Fig. 1. The saturation of the ferromagnetic material can be interpreted through the colour spectrum legend attached in the left side of the figure, as: dark blue colour represents a weak magnetization of the material (magnetic flux density $B$ is about 0.1T), whilelight yellow represents a strong magnetization (magnetic induction is about 2.2T). The magnetic field lines are closing through the rotor, airgap and statorarmaturesas can be seen in figure 1.

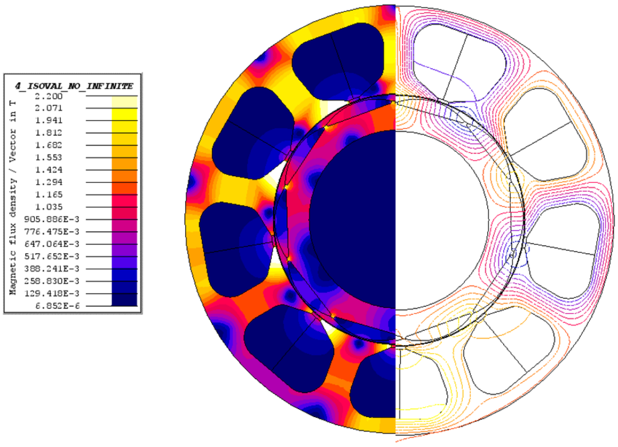


*Fig. 1. BLDC motor with 9 stator slots and 10 rotor poles*

The second proposed BLDC motor modeltopology presents a symmetrical structure provided with 12 stator slots and 10 rotor poles,as can be seen in Fig. 2. The stator and rotor armature and PMs materials are the same as for the first case previously presented. The interpretation of the figure can be made in a similar manner.

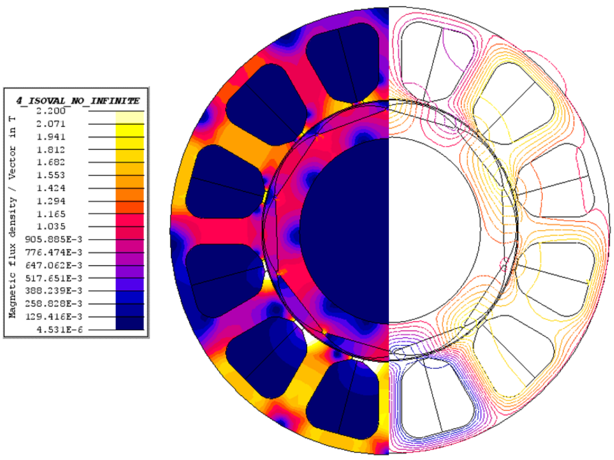


*Fig. 2. BLDC motor with 12 stator slots and 10 rotor poles*

## IV. MATLAB / SIMULINK MODEL

This section provides an outlook to the MATLAB / Simulink motor control and equivalent BLDC motor models used for different simulation tests purposes.

The overview of the Simulink scheme that was implemented for testing through simulation various control possibilities in normal mode operation can be seen in Fig. 3.

A brief description of the Simulink model is as follows: blocks 1, 2 and 3 implement the desired control algorithm, blocks 4 and 5 implement the equivalent physical power inverter with semiconductor devices (switches), block 6 implements the BLDC motor model, while block number 7 implements the loading machine.

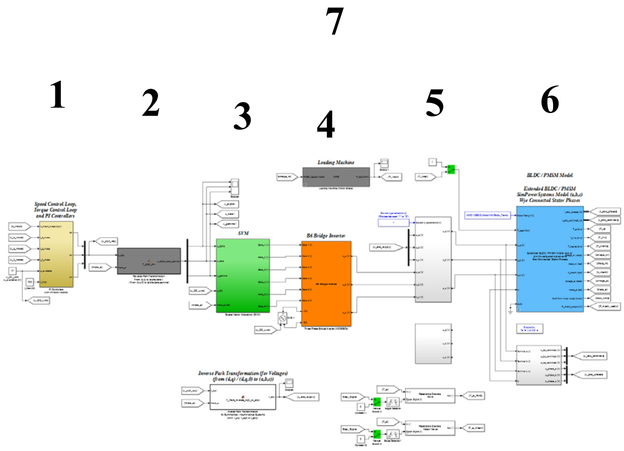


*Fig. 3. Simulink model overview (motor control and BLDC)*

The block number 1 contains three PI current controllers provided with anti-windup clamping circuit (for the *d*-, *q*- and *0*- axis respectively) as in [2]. For the simulation tests the *0*- axis current controller was deactivated. In block 2 is implemented the reverse Park transform (from $(d,q,0)$ to $(\alpha,\beta,\gamma)$) for asymmetrical / unbalanced systems [2]. The SVM algorithm for normal mode operation is modeled inside block number 3 [3]. The SVM blockprovides the corresponding gate signals to the transistors from the B6 power bridge inverter (modeled with SimPowerSystems library blocks) which is implemented in block 4. A source type selection can be made through block number 5 between the pulse width modulated (PWM) signals provided by the B6 bridge inverter and an ideal sinusoidal voltage waveform obtained by using the inverse Park transformation directly from the PI current regulators block. The equivalent BLDC motor model calibrated with the same parameters as those obtained from previously presented FEM analysis is implemented in block 6. To provide some similar conditions as for an equivalent test bench, a motor braking (loading) machine was modeled inside block number 7.Different simulation test scenarios were considered, both for the FEM and Simulink results comparisons and also for further motor control and motor behaviour investigations purposes that will be presented in the following chapters.

## V. SIMULATION RESULTS COMPARISONS: FEM / SIMULINK

This section provides acomparison overview between the FEM analysis and MATLAB / Simulink results obtained by using equivalent BLDC models. For this purpose, three different simulation tests were considered:

- first scenario to determine the resulting BEMFs when no currents are present in the stator windings (open windings case, BLDC is not electrically supplied) and the rotor is mechanically drive by the external loading machine at a constant speed (of 1000 rpm);

- second scenario to determine the *maximum electromagnetic torque developed* by BLDC motor when high (40A) DC currents are imposed in stator windings and rotor is mechanically drive by external loading machine at low constant speed (100 rpm);
- third scenario to determine the *developed electromagnetic torque* when sinusoidal waveform currents (55A) are imposed in the stator windings and the rotor is mechanically drive by the loading machine at a constant speed (of 1000 rpm).

The first simulation test scenariois shown in figure 4and presents the comparison results between FEM and Simulink analysis for the first BLDC motor model with 9 stator slots and 10 rotor poles.

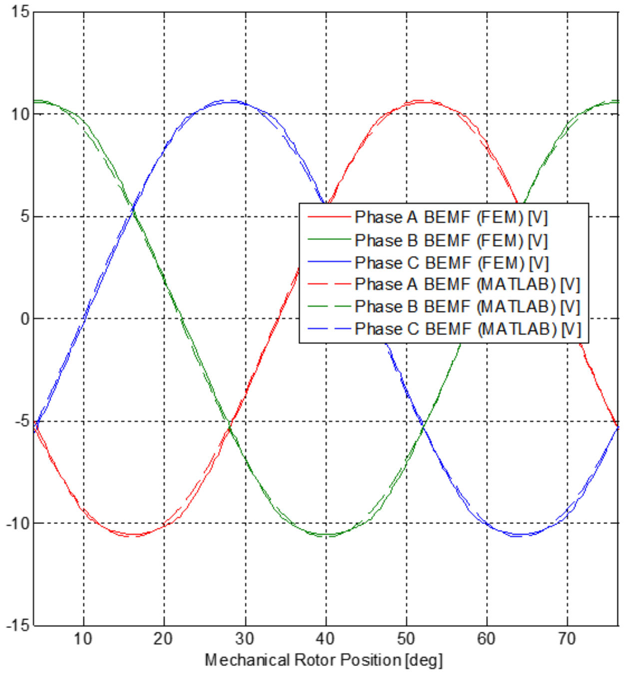


*Fig. 4. BEMFs at 1000 rpm (one full electrical rotation of the rotor) for BLDC 9 Slots 10 Poles*

A similar simulation test case (as last described) is shown in figure 5, but for the second BLDC model.

The second simulation test scenario is shown in figure 6andpresents the electromagnetic torque developed by the BLDC with 9 stator slots and 10 rotor poles when DC currents of 40A, -20A and -20A respectively are imposed in the stator windings with rotor being externally rotated.

A similar simulation test case (as previously described) is shown in figure 7, but for the second BLDC motor model with 12 stator slots and 10 rotor poles.

The third simulation test scenario is shown in figure 8 and presents the electromagnetic torque developed by the BLDC motor with 9 stator slots and 10 rotor poles when sinusoidal currents of 55 A amplitude and 83.3 Hz frequency are imposed in the stator windings with rotor being externally drive at a mechanical speed of 1000 rpm.

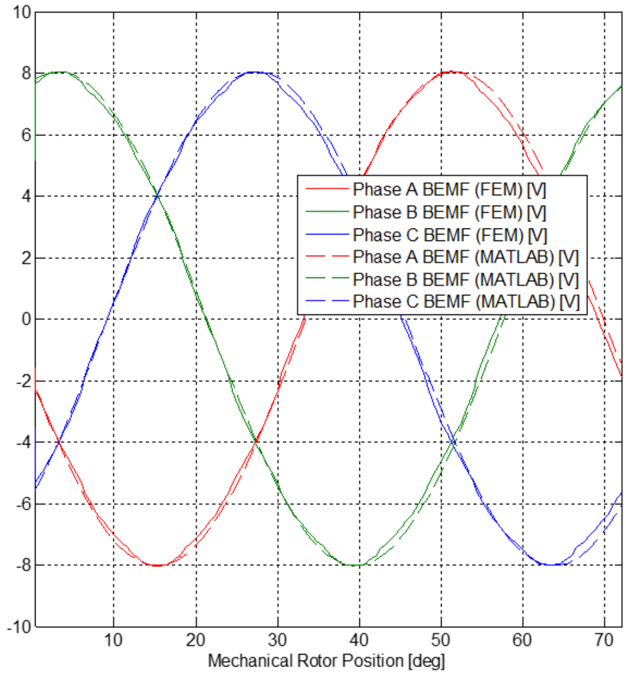


*Fig. 5. BEMFs at 1000 rpm (one full electrical rotation of the rotor) for BLDC 12 Slots 10 Poles*

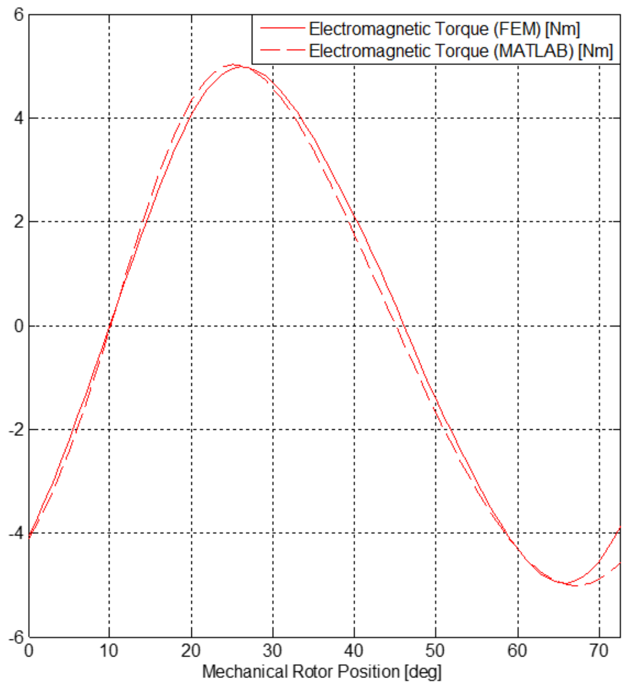


*Fig. 6. Maximum Torque at 1000 rpm and 40 A DC phase currents (one full electrical rotation) for BLDC 9 Slots 10 Poles*

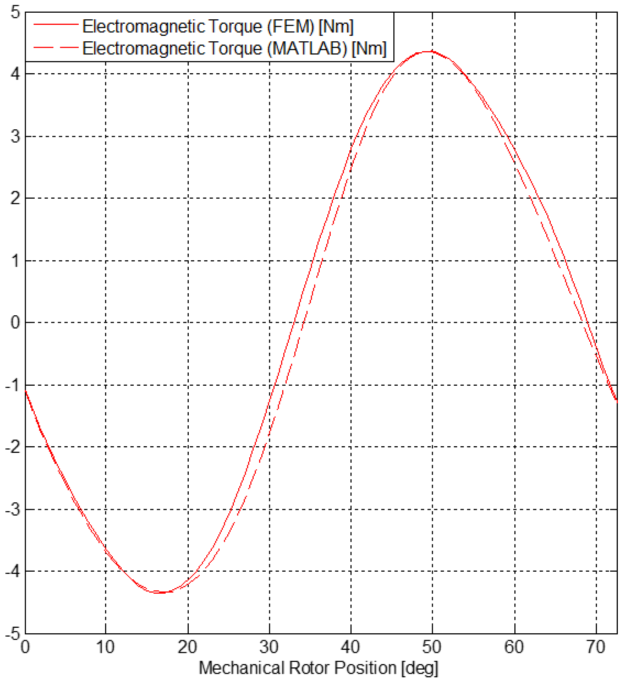


*Fig. 7. Maximum Torque at 1000 rpm and 40 A DC phase currents (one full electrical rotation) for BLDC 12Slots 10Poles*

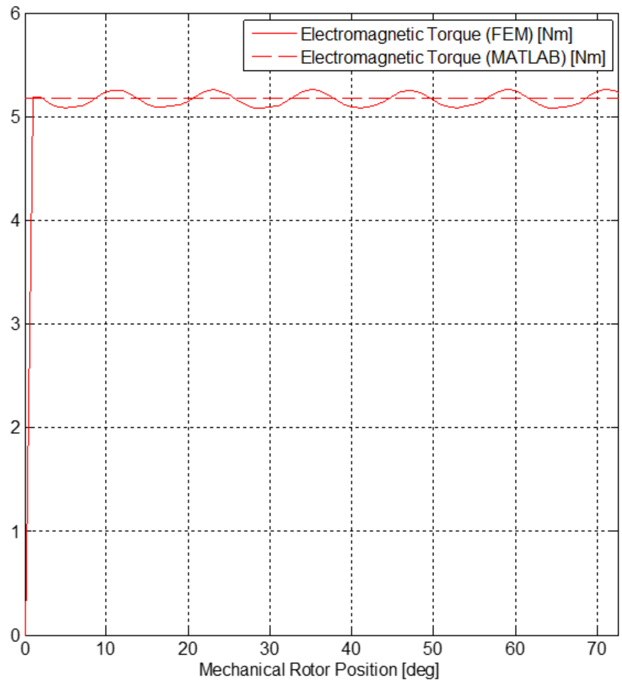


*Fig. 8. Maximum Torque at 1000 rpm and 55 A sinusoidal phase currents (one full electrical rotation) for BLDC 9 Slots 10 Poles*

A similar simulation test case (as previously described) is shown in figure 9, but for the second BLDC motor model with 12 stator slots and 10 rotor poles.

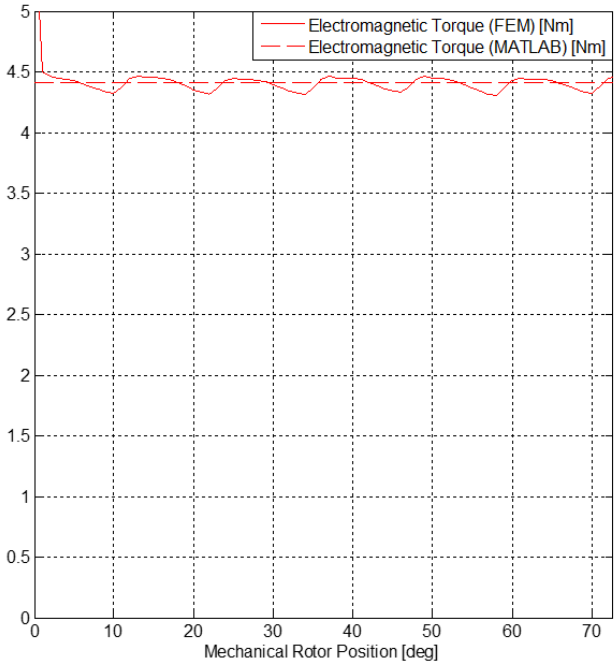


*Fig. 9. Maximum Torque at 1000 rpm and 55 A sinusoidal phase currents (one full electrical rotation) for BLDC 12Slots 10Poles*

From the presented comparative simulation results it can be seen that the two BLDC motor models implemented both in FEM and MATLAB / Simulink environments behave in a similar manner, thus obtaining areciprocal validation of the models.

## VI. SIMULATION RESULTS (MATLAB / SIMULINK)

This section provides the simulation tests results for the entire system (motor control, B6 power bridge inverterand equivalent BLDC motor model) implemented inMATLAB / Simulink environment.

In order to determine the *behaviour of the entire system* (that includs both the motor control algorithm and the BLDC motor model), another simulation test scenario was considered. For this case, the speed control mode was applied with a rotor referencespeed ramp signal that vary from 0 to 2500 rpm. The simulation results are presented only for the first variant model of BLDC with 9 stator slots and 10 rotor poles. The load torque applied to the rotor shaft is a constant 1 Nm.

Figure 10 shows the instantaneous stator phases (a,b,c) voltages and currents corresponding to the BLDC motor.

The resulting rotating voltage vector trace in *(α,β,γ)* coordinate system can be seen in figure 11. For the normal operating regime, where the asymmetrical γ component is zero, the resulting spatial vector is placed in the plane described by *(α,β)* axis coordinates as expected. The almost perfect circle described by the vector trace suggests that the control method is adequate and accurate.

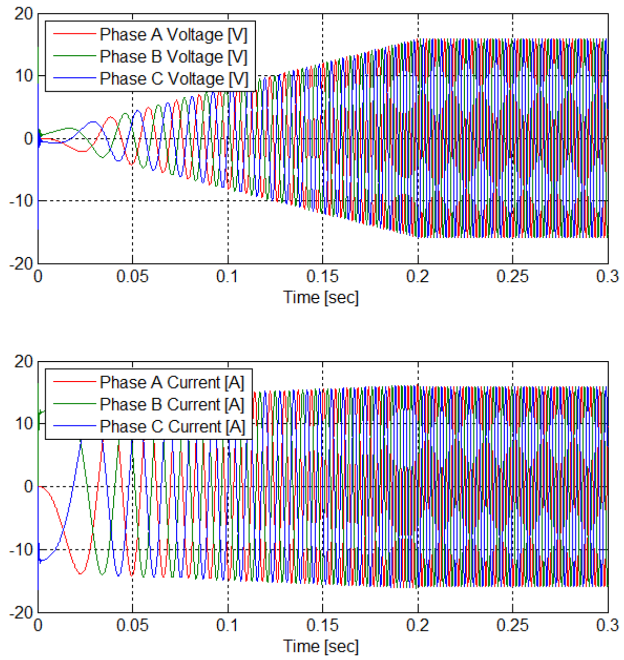


*Fig. 10. Stator phases (a,b,c) voltages and currents of BLDC 9 Slots 10 Poles in case of speed control mode from 0 to 2500 rpm*

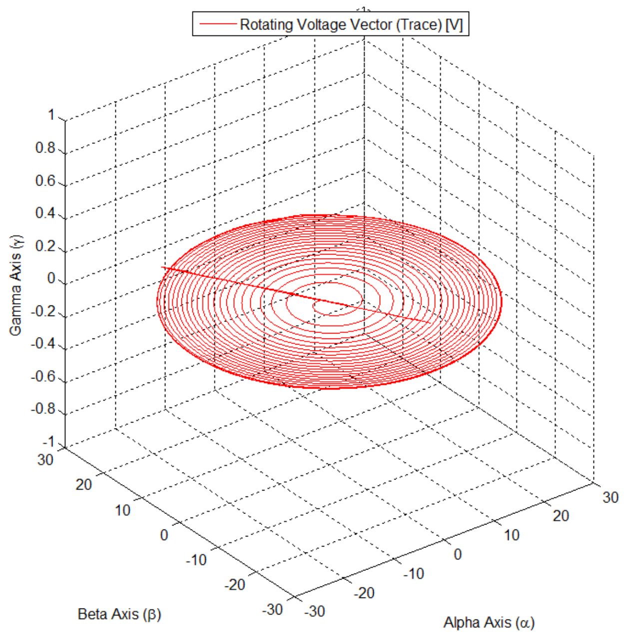


*Fig. 11. Rotatingvoltage vector trace in (α,β,γ) coordinatesfor BLDC with 9 Slots 10 Polesin speed control mode*

Figure 12 presents the electromagnetic torque andmechanical rotor speed developed by the BLDC motor. It can be seen that the reference speed is accurately followed by the actual mechanical rotor speed.

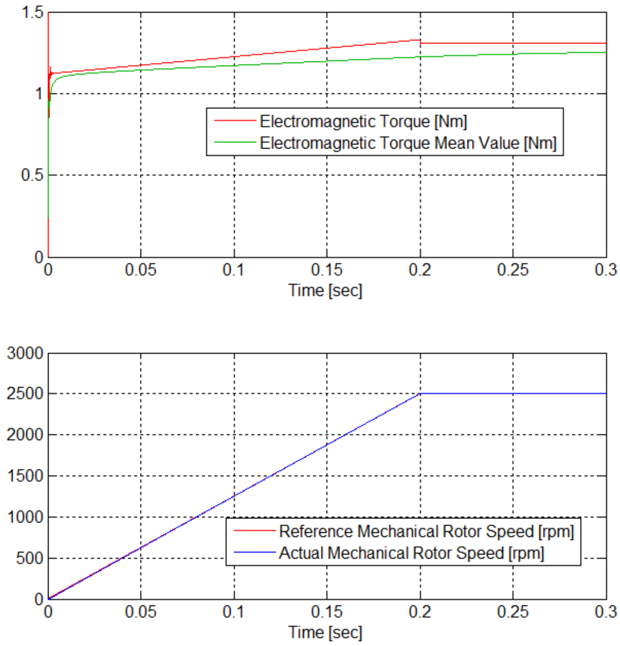


*Fig. 12. Electromagnetic torque and mechanical rotor speed developed by BLDC with 9 Slots 10 Poles in speed control mode*

## VII. CONCLUSIONS

This paper presents a comparative study regarding different constructive types concepts of BLDC electrical machines and different control methods related to them.

Two distinct modelling and simulation methods were used in parallel for validating the theoretical aspects of the study: the first method based on FEM (Finite Element Method) analysis and the second analytical method using MATLAB / Simulink environment. The simulation results confirms the related theoretical aspects and provides a case study for further investigations.

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