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Design and Control of PMSM for In-Wheel Motor Electric Vehicle Application Based on 3D Transient FEA

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Abstract: Permanent Magnet Synchronous Machine (PMSMs) are considered as the promising electromagnetic structure, especially for In-Wheel motor electric and hybrid propulsion applications. The design for a direct-drive wheel motor PMSM require a 3D Finite Element Analysis (FEA) based investigation of the output torque especially when the end winding is considered and in the case of skewed machine, this paper take in to account the study of the PMSM for the proposed application, The cinematic and dynamic model of the EV study for determining the design requirements permit to choose the design that gives the highest torque production capability between two major rotor topologies of the PMSM, the PMSM selected model must be studied with 3D transient FEA, taking in to account the case of linear motion and the case of driving in bend, the PWM control study of the inverter is presented, considering a typical cruising trip of an automobile. Many design parameters are with greet influence on the cogging torque amplitude and on the EV comfort. The obtained in-wheel PMSM model simulator is used for the transient study in the case of the skewing technique application and the effect on the output torque of the PMSM.

Keywords: (PMSMs); In-Wheel motor, vehicle-dynamics model; 3D transient FEA; control; skewing technique.

Introduction

The use of in-wheel motors, as a source of propulsion for pure electric or hybrid electric vehicles (HEV) has recently received a lot of attention. Since the motor is housed in the limited space within the wheel rim, it must have a high torque density and efficiency. Compared to the induction and electrically excited synchronous machines PMSMs presents the advantages of higher power to weight ratio and efficiency [1] [2] [3] [4] and no additional power supply for the field excitation. Different concepts in R&D are considered to find the promising mechanical structures and features of the PMSMs especially for HEV application [5] [6]. Two major rotor topology of the PMSM are distinguished, the surface mounted magnet and the buried magnet rotor. Although the PMSM with flux concentrating topology, exhibits at first glance higher performances, a comparative study and a FEA of the two topologies is required to choose the PMSM with higher performances. The PMSMs are suffering from the high value of the cogging torque which is superimposed with the output torque and have a great influence on the vehicle comfort especially in transient regime. A transient 3D FEA is required for the adopted PMSM, the study of the vehicle wheels rotational speed make necessity of different control laws and circuits to be implemented, this work develops this idea.

PMSMS Requirements for In-wheel (HEV)

The In-wheel motor HEV with four-wheel drive permit a distribution of resistant forces on the wheel, this gives the system more security and stability with the distribution of the electromagnetic torque, this structure permit the use of a less powerful cooling system because of the greater contact surface with the air than when using a single motor especially in the braking and deceleration phases. This gives the four In-Wheel motor solution the advantages of:

- 30% higher efficiency than with central motor
- 90% of the kinetic energy with the regenerative breaking.

Major requirements for PMSMs use for in-wheel motor hybrid propulsion applications are the following:

- High and continuous torque density;
- High specific power and efficiency;
- The robustness of the structure, and good overload capability.

This in addition to the general requirements related to the application for electric and hybrid propulsion, which are :

- Silent and with less vibration (Low cogging torque and torque harmonics);
- High thermal endurance, (without intensive cooling).
- The lower cost

Mechanical Study

A cinematic study based on the model of Ackermann-Jeantaud as illustrated in figure1 permit, for a given linear speed V_G and a steering angle δ_i, to calculate the angular speed respectively of inner wheel and outer one.

$$\dot{\varphi}_1 = \frac{V_G}{r}\left(1 - \frac{T}{2\left(\frac{L}{\mathrm{tg}\,\delta_i} + \frac{T}{2}\right)}\right) \quad (1)$$

$$\dot{\varphi}_2 = \frac{V_G}{r}\left(1 + \frac{T}{2\left(\frac{L}{\mathrm{tg}\,\delta_i} + \frac{T}{2}\right)}\right) \quad (2)$$

Where L is the length between front and rear wheels and T represent the distance between inner and outer wheels

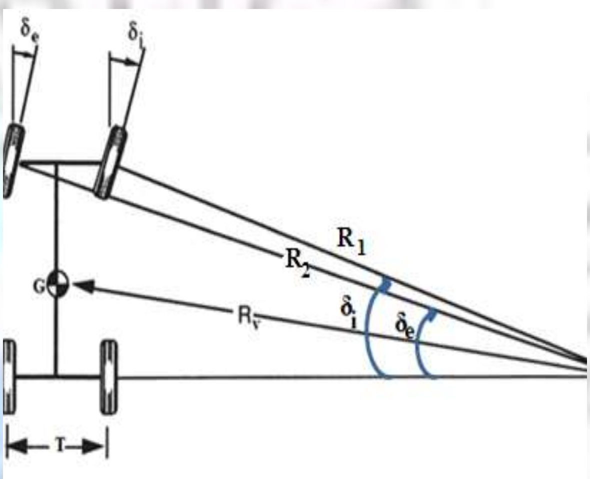


Fig 1: Ackermann- Jeantaud model presentation

Figure 2 is an EV cruising scenario that includes the EV's typical-trip elements such as increased speed V_G , constant speed, and braking action. This Extra Urban Drive Cycle represent the vehicle gravity center speed and represent the linear velocity of the four wheels for linear drive obtained only for null steering angle where the four motor are with the same speed.

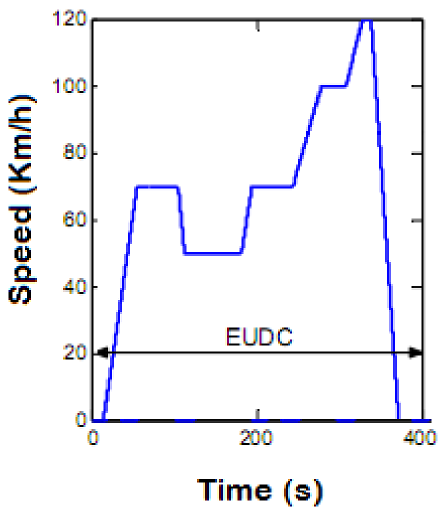


Fig 2: Driving cycles for electric-vehicle design

When driving in bend for exemple with a steering angle of π/6, the wheels angular velocity are calculated by applying the equations (1) and (2) for the inner and outer wheels respectively for the vehicle dimensions described in table 1 the obtained speeds are illustrated in figure 3.

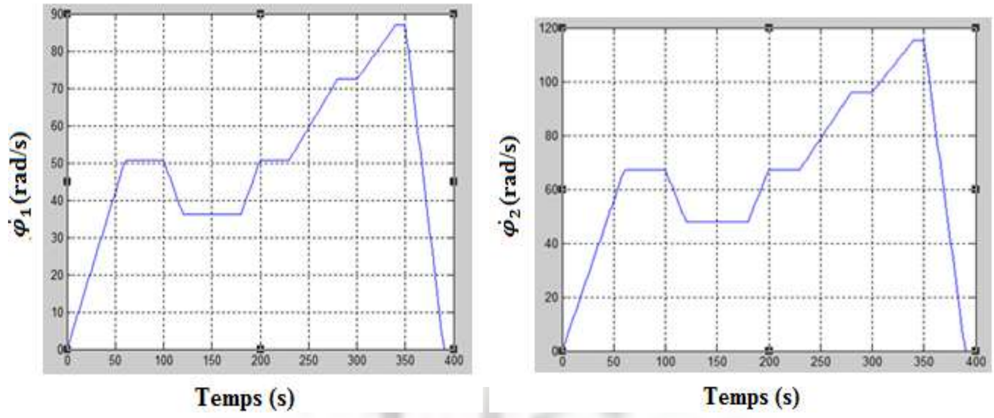


Fig 3: Inner and outer wheels speed for $\delta_i=\pi/6$

A simple model of vehicle dynamics that evaluates vehicle performance is herewith presented.

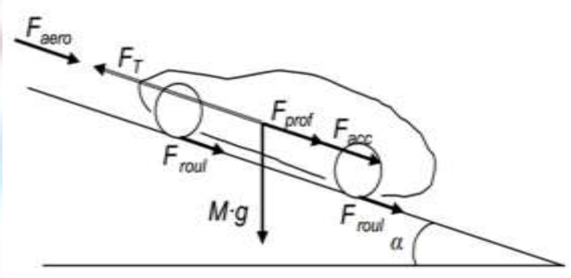


Fig 4: The external forces applied on the vehicle

As illustrated in figure 4, a simplified vehicle driving resistance force or Total road load (FT) consists of rolling resistance force (Froul), climbing resistance force (Fprof), and aerodynamic drag force (Faéro)and acceleration force(Facc) [7]:

$$F_T = F_{roul}+F_{prof} + F_{aéro} + F_{acc} \qquad (3)$$

The rolling resistance force :

$$F_{roul}= M .g .C_r \qquad (4)$$

The climbing resistance force:

$$F_{prof} = M.g.\sin\alpha \qquad (5)$$

where α is angle of vehicle movement relative to horizon

The aerodynamic drag force is given by :

$$F_{aéro}= \frac{1}{2} . \rho .C_x. S_f . V^2 \qquad (6)$$

For the vehicle acceleration the acceleration force is:

$$F_{acc} = M .a \qquad (7)$$

Acting as propulsion, the dynamic study is applied to one wheel to overcome driving resistance. In angular movement, the required torque for vehicle propulsion is:

$$C_m= J \ddot{\varphi} + \frac{1}{4} rF_{roul} \qquad (8)$$

The torque needed by the vehicle wheels is calculated from the proposed driving cycle and the vehicle specifications [7] listed in table 1, the torque needed by the wheels is of about C_{lin}= 9.13Nm for linear trajectory. When driving in bend, for the inner wheels a torque C_{m1}= 8.81Nm is needed and calculated as illustrated in figure 5, a higher value of the needed torque is obtained for the outer wheels and attempt C_{m2}=9.55 Nm, this present the minimum torque value required by the PMSM.

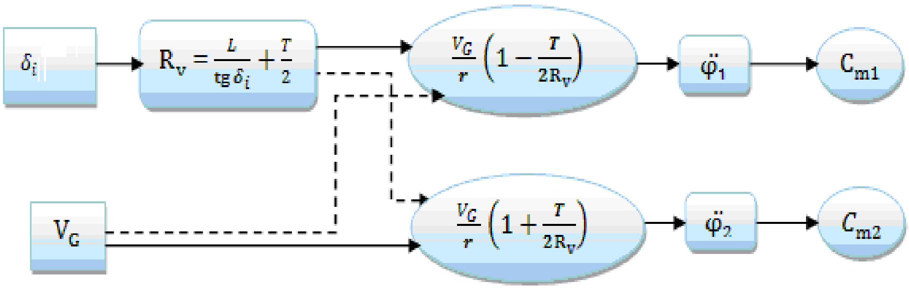


Fig 5: Calculation model of the wheels speed and torque

Table 1: Vehicle Specifications

Symbole	Description	Value
M	Weight of Vehicle	600 Kg
C_r	Tire Resistance Coefficient	0.015
ρ	Air density	1.22 Kg/m^3
C_x	Air Resistance Coefficient	0.35
S_f	Frontal projected Area	2.5 m^2
J	Inertia of rolling elements	1.9 Kg m^2
r	Wheel Radius	0.33 m
L	Distance between front and rear wheels	2.55 m
T	Distance between inner and outer wheels	1.44 m

FEA of different PMSM TOPOLOGIES

Two major topologies of PMSMs are designed and analyzed with finite element analysis FEA, the first one is the radial flux permanent magnet machine (RFPM) topology with surface magnets and a pole-embrace of 70% (Rotor1), the second with buried magnet rotor and flux concentrating topology (Rotor2) as shown in figure6. The same dimensions and features are used for the design as presented in table 2 and the same magnet features and the same magnet volume is used. The magnet material is the Samarium Cobalt, this gives the higher maximum saturation flux density and higher thermal endurance where a high temperature accelerate the permanent magnets demagnetization, also SmCo magnets present high resistance to mechanical strength and to operate at high rotational speeds which is required in hybrid propulsion application.

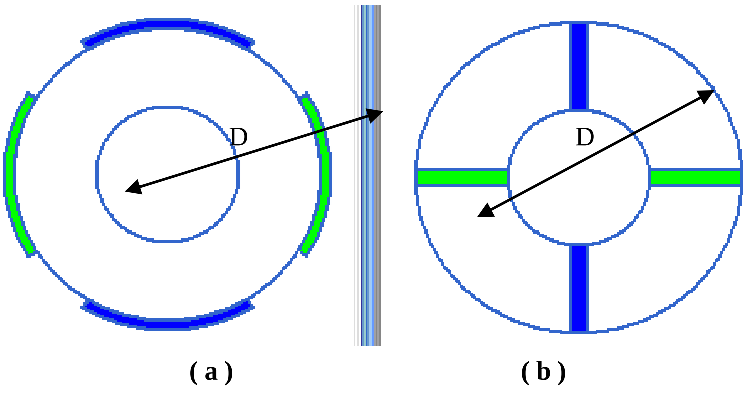
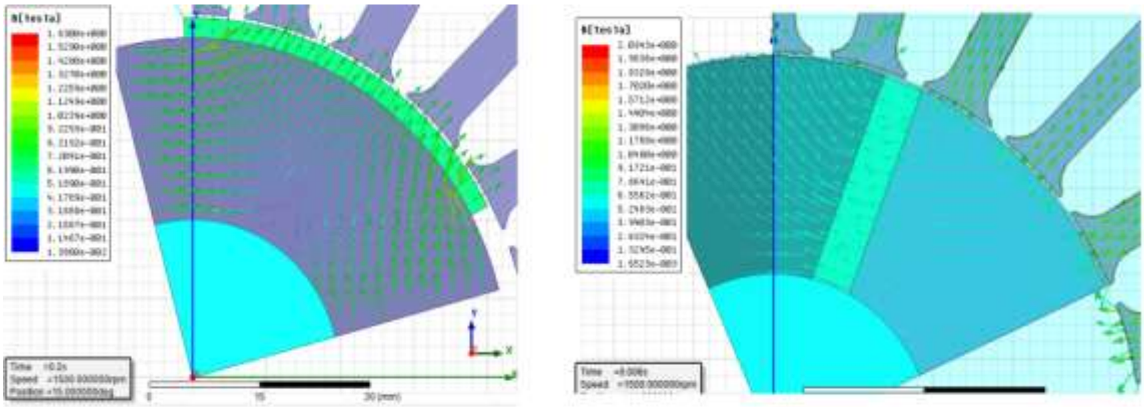


Fig 6: RFPM rotor with (a)surface and (b) buried magnets

Table 2 : PMSM feature

Description	Value
Stator outer diameter	180mm
Rotor outer diameter (D)	91mm
Airgap depth	0.5mm
PMSM length	101mm
Slot number	24
Pole pair number	2
Rated voltage	127 V
Frequency	50 Hz



(a) (b)

Fig 7: Flux distribution through the rotor magnetic circuit(a)surface and (b) buried magnets

The rotor magnetic circuit flux distribution obtained with a 2D FEA is presented in figure 7, the flux distribution for the two designed topologies, highlight the choice of topology effect on the RFPM performance. The FEA results of the two topologies for comparative study are presented in figures 8-a and figure 8-b respectively for the output power and torque. It is clear that the choice of the rotor topology have great influence on the maximum output power, the obtained results are 5596w for Rotor1 and 4531.8w for Rotor2 as illustrated in figure 8-a. These results demonstrate that the surface magnets topology is more powerful in high speeds and we can see the influence of the choice of the magnet on the PMSM ability to turn at high speeds of rotation. As illustrated in figure 8-b. A maximum output torque of 10.32Nm higher than 9.55 required for the vehicle propulsion is obtained for Rotor2 and only 3.8Nm for Rotor1, in what follow the rotor topology the buried mounted magnet giving the higher value of the output torque will be studied in a 3D model taking in to account the end winding and the skewing effect.

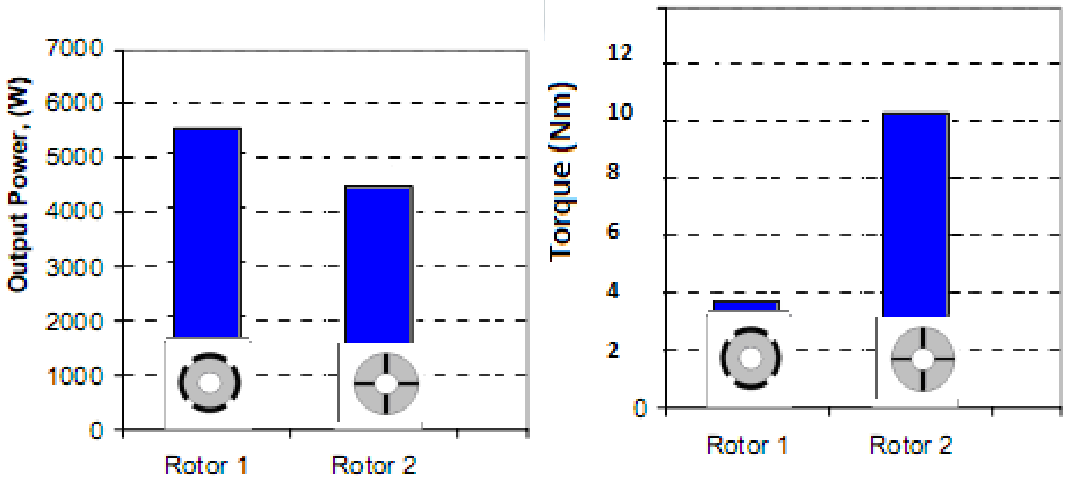


Fig 8: (a) RFPM max output power **(b) RFPM output torque**

PMSMs Control for 3D Transient FEA

The In-Wheel motor permits several advantages, but the wheels control are different and each wheel is separately controlled because the wheel speeds are different when driving in bends where the mechanical study demonstrate that the inner and the outer wheels for the front and rear wheels are with different speeds, the same speed of the four wheels is obtained only for the linear drive for null steering angle δi , this speed difference for a non-null δi given by the driver make necessary to use four controllers installed as shown in the figure 9 of the VEH structure. Referring to equations (1) and (2) one have three control laws for each wheels-motor to obtain the vehicle stability at road, as illustrated in figure 10 of the implementation model of each PMSM for a vehicle velocity V_G and a steering angle δi given by the driver, the calculation of the angular speed, permit for a given pole pair number to calculate the synchronous speed to apply to the inverter for feding the PMSM, we have three control law of the inverters and the introduced pulsations of the PMSM are the following:

- For the case of linear driving:

$$\Omega_s = p. \frac{V_G}{r} \quad (9)$$

- For the front wheel and rear wheel controllers,case of inner wheels:

$$\Omega_{1s} = p. \frac{V_G}{r}\left(1 - \frac{T}{2\left(\frac{L}{\text{tg}\,\delta_i} + \frac{T}{2}\right)}\right) \quad (10)$$

- For the front wheel and rear wheel controllers, case of outer wheels:

$$\Omega_{2s} = p. \frac{V_G}{r}\left(1 + \frac{T}{2\left(\frac{L}{\text{tg}\,\delta_i} + \frac{T}{2}\right)}\right) \quad (11)$$

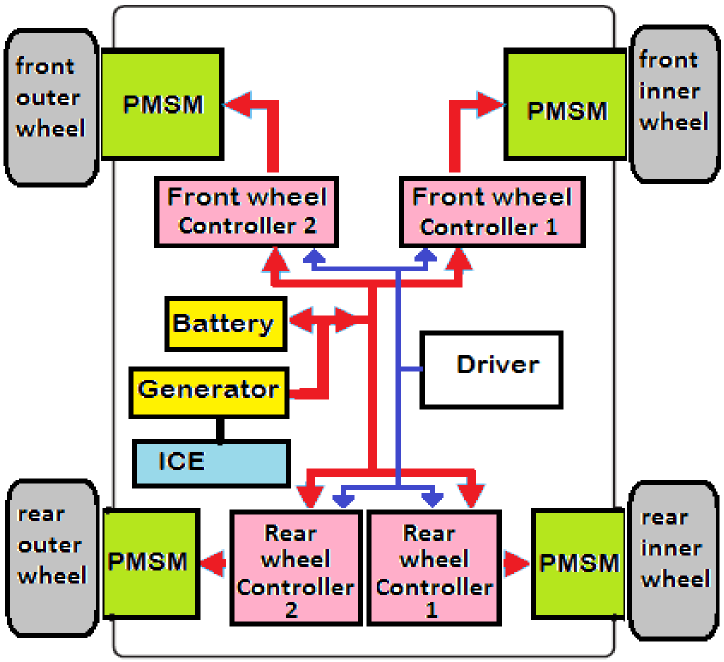


Fig 9: VEH with in-wheels PMSMs structure with four controller

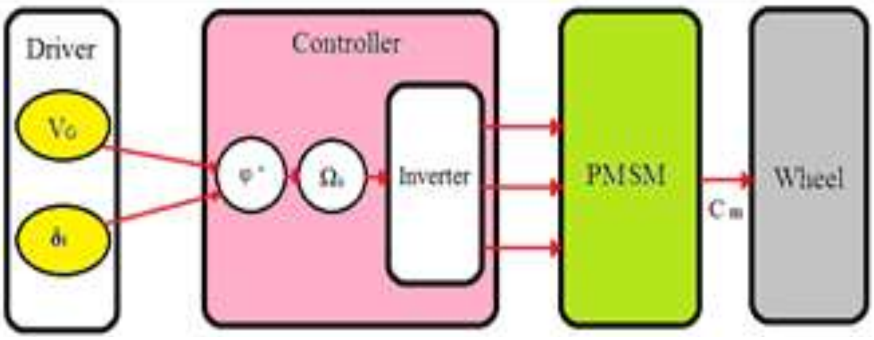


Fig 10: ImplementationModel

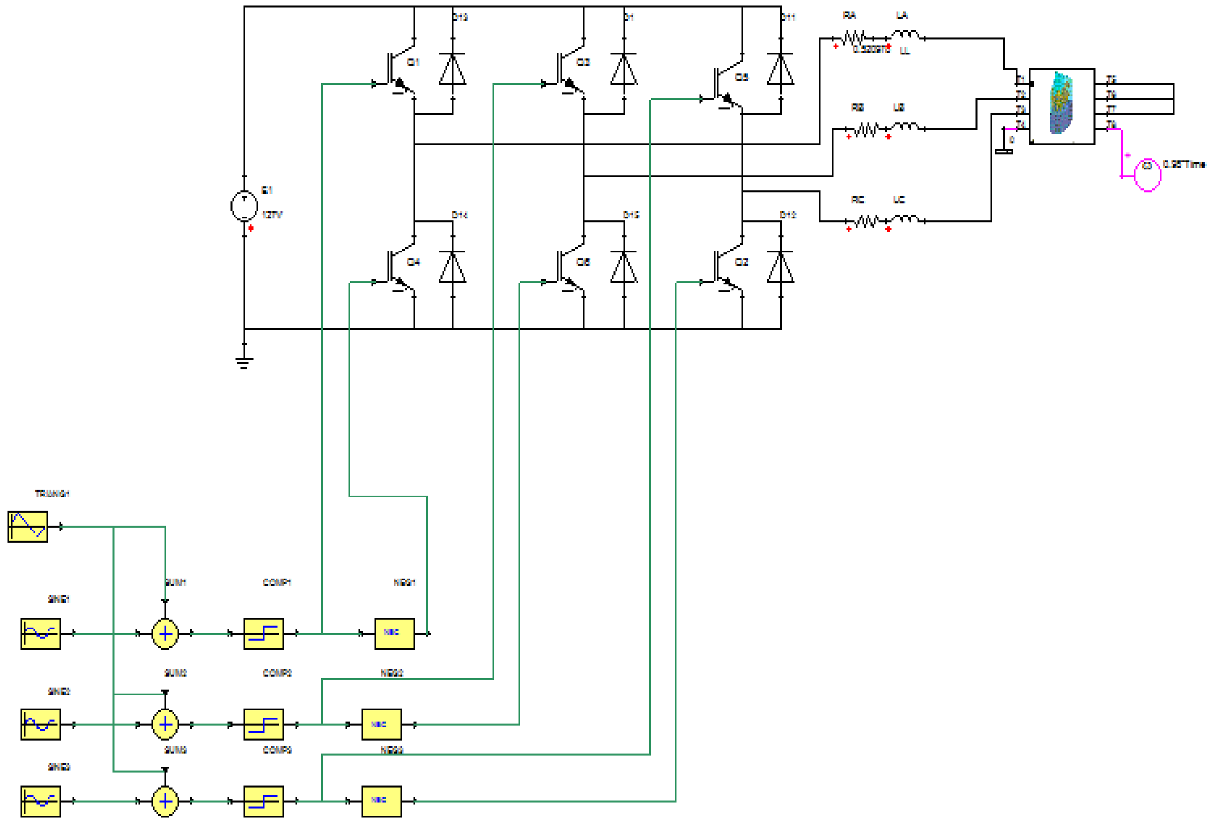


Fig 11: PWM Control circuit and 3D FEA of the PMSM

The control laws and the PWM inverter model is implemented, the control circuits is shown in figure 11. A transient 3D model is made up for the RFPM buried magnet topology study with 3D transient FEA with respect to the driving cycle presented in figure2 for the calculation of the variation of the synchronous pulsations, the 3D study domain of the PMSM taking in to account the end winding effect is presented in figure 12,

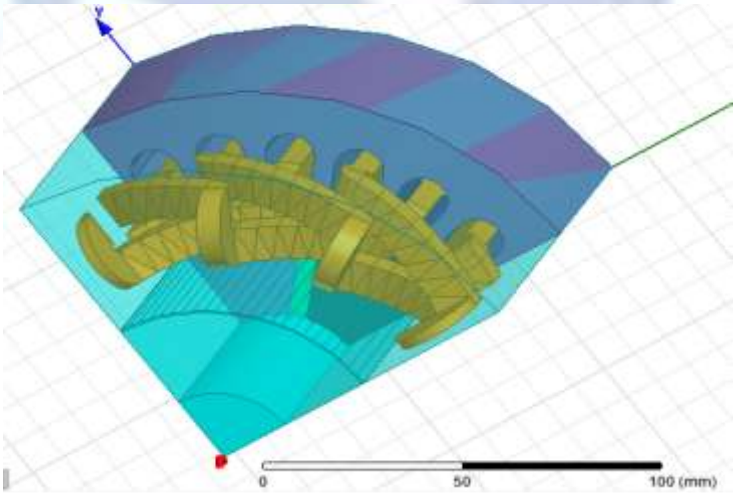


Fig 12: 3D Study domain of the PMSM

The FEA results are of great importance, figures 13 shows the PMSM torque obtained for the linear drive for the four-wheeled motors Figures 14and figure15 show the motor torques of the inner wheels and the outer wheels respectively when driving in bends.

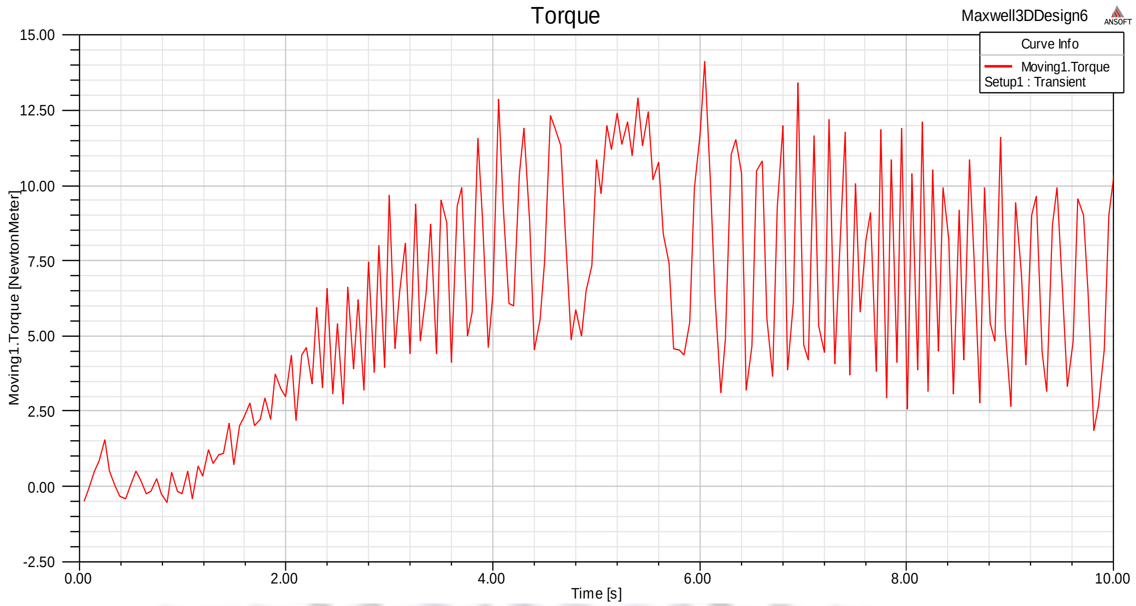


Fig 13: Torque of the wheels motor for linear drive

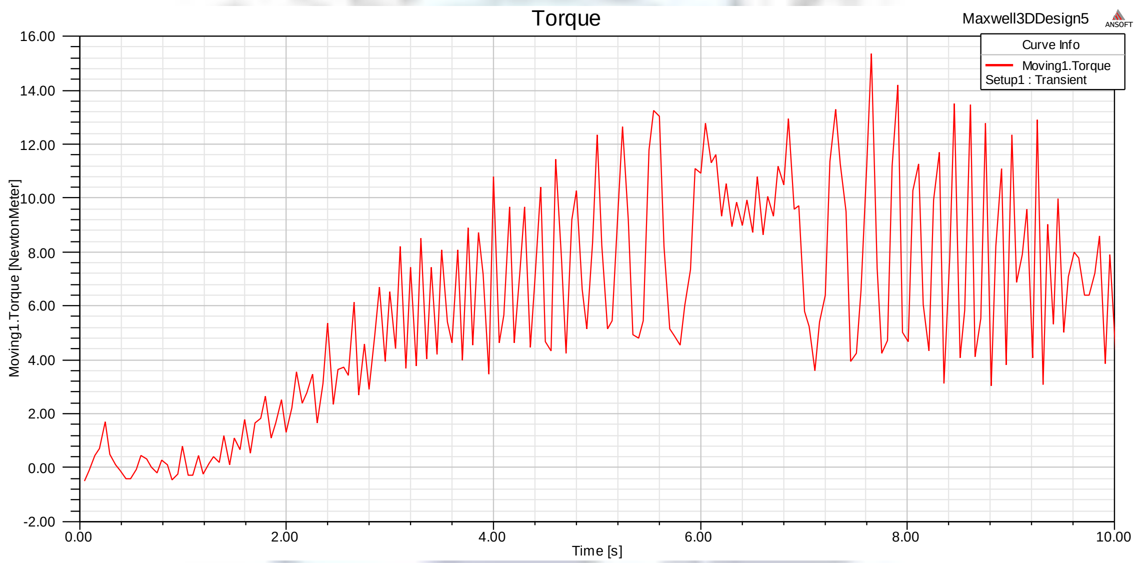


Fig 14: Torque of the motor of the vehicle inner wheels

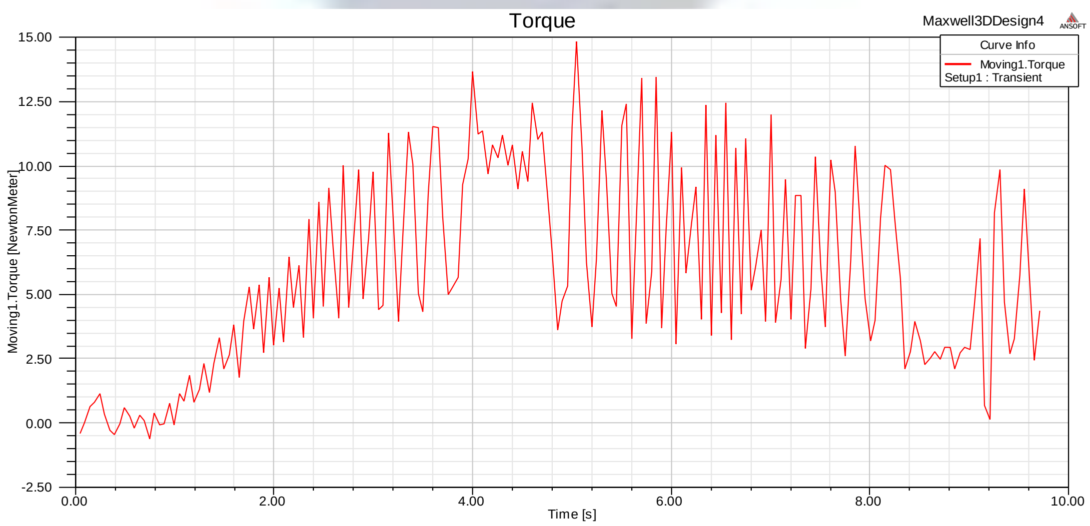


Fig 15: Torque of the motor of the vehicle outer wheels

For the three driving cases we note that we have significant oscillations amplitudes, we explain the oscillations of the resulting torque by the cogging torque which is superimposed with the electromagnetic torque and have the double pulse [8] .

Skewing Technique Application

As an application of the proposed simulator is the study of the transient behavior when using a technique of reduction of the cogging torque, this torque is developed from the magnetic attraction between the permanent magnet mounted on the rotor and the stator teeth, it tends to maintain the alignment between the stator teeth and the rotor poles, while superimposed to the main torque the cogging torque introduce a torque ripple more or less significant depending on the RFPM sizing, such ripple produce noise and vibration which causes problems to the machine mechanical structure. Many techniques have been developed in the literature dealing with the minimization of the cogging torque magnitude of PMSM[9].

Two major classes of cogging torque reduction technique have been reported:

- A generation of convenient supply current which produce a torque ripple opposite to the cogging torque, however, these current waveform penalize the inverter rating.
- An optimized machine sizing, the most design parameter which have direct influence on the cogging torque are:
  -Slot number to pole number combination,
  -Stator slots opening width,
  -Radial air gap length and magnet thickness,
  -Pole arc to pole pitch ratio,
  -Skewing of slots in the stator or magnets in the rotor.

The skewing technique is applied in the case of the buried magnet PMSM for the cogging torque reduction, this technique consist of inclining the rotor elements by one slot pitch, the study for in wheel application in linear trajectory is done, the 3D transient FEA result is presented in figure 16, if we compare to the non-skewed PMSM obtained torque shown in figure 13 a reduction of the torque ripple of about 3Nm is obtained.

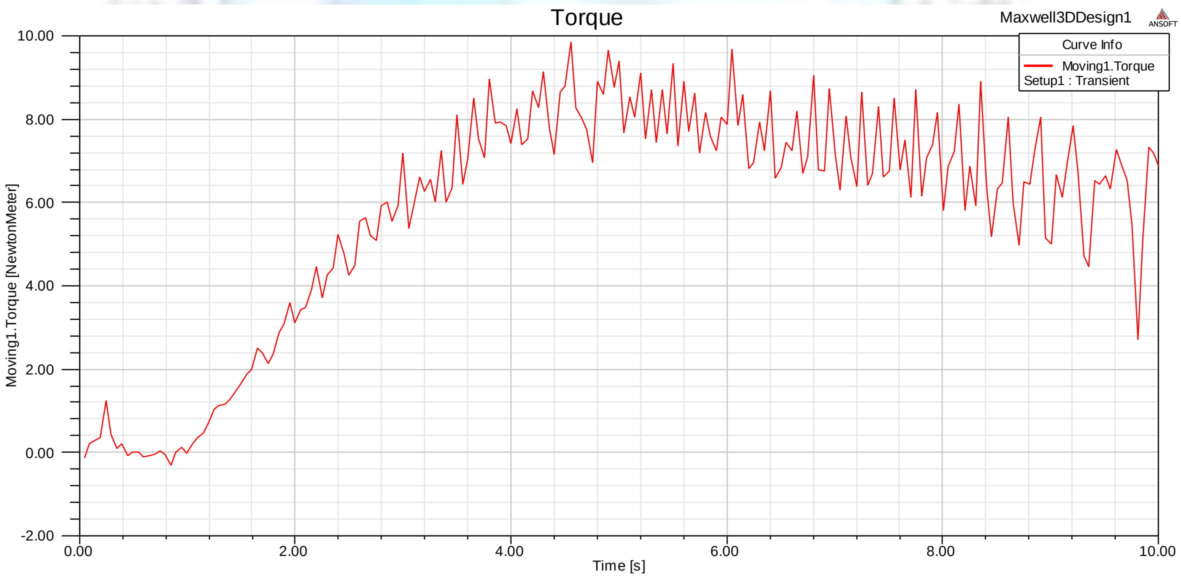


Fig. 16: Torque of a Skewed PMSM in linear motion

Conclusion

In-wheel motor hybrid propulsion vehicle is presented and studied in this work taking in to account the Ackermann-Jeantaud condition for the drive in bend, different topologies of PMSM are studied to compare the PMSM performances. Although the surface mounted magnets topology is more powerful in high rotation speeds, the buried magnet rotor PMSM topology is chosen to the in-wheel motor application because of its higher output torque. A 3D Finite Element Analysis (FEA) based investigation of the output torque is required especially when the end winding is considered and in the case of skewed machine, Doing so the 3D transient study of the PMSM is implemented based on FEA of the output torques, three PWM control laws are introduced considering a typical cruising trip of an automobile for linear motion and the case of driving in bend, the vehicle suffer from the high value of the cogging torque, Many design parameters are with greet influence on the cogging torque amplitude and on the EV comfort. The obtained in-wheel PMSM model simulator is used for the transient study in the case of the skewing technique application, the cogging torque is reduced with a skewed PMSM and a smooth output torque of the PMSM is obtained.

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