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Trapezoidal Control Based on Analytical and Finite Element Identification of Axial Flux Brushless DC Motor Dedicated to Electric Traction

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Abstract: In this paper we are studying a problem related to the traction of an electrical vehicle (EV). The power unit is a Permanent Magnet Synchronous Motor (PMSM) piloted by the trapezoidal control, strategy. The models of the electrical vehicle, of the motor based on finite element identification and the drive, are implemented under Matlab/Simulink 7.1. The control is ensured by four closed loops, one for speed and three other for currents regulation. The results of the simulation show the effectiveness of the trapezoidal control for the electric traction systems.

Keywords: Electric Vehicle, Motor, Trapezoidal Control, Design, Finite Element, Optimization

1. Introduction

In the electrical propulsion, the PMSM becomes the mostly used [1]. The concept of the permanent field of the synchronous motor is developed more and more, thanks to the significant advantages given.

The clear advantages of the concept of the permanent magnet motor are of the origin of the absence of active winding in the rotor. Compared to the synchronous motor with coil rotor, any equipment of excitation is not necessary and the losses in the rotor are minimized. Compared to the conception of the induction motor, the construction without rotor winding gives the possibility of simplifying the construction and the arrangement of a means of effective cooling. This leads to economizing the space and reducing the weight during the construction.

Thus, the clear advantages of the motor lead to the effectiveness of the drive as well as to a higher autonomy.

Permanent magnet synchronous motor (PMSM) drives are today gradually replacing classic dc drives in industry applications [2], [3].

The work presented in this paper is especially to study the PMSM, its drive and its insertion in the traction chain of an electric vehicle

Finally, we are presenting the results of the simulation obtained after our study.

2. Electric Motor

The motor structure is with permanent magnet and axial flux. It has five pairs of poles and twelve slots. A concentrated coil are used to reduce the production cost [4], [5], [6]. The power developed by the motor can be increased by adding additional modules. This structure is compact, it is subsequently with high power density. Moreover, it is easy to achieve since it present a straight and open slots.

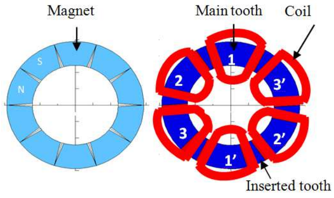


Figure 1. 5 pairs of poles, 6 main teeth, axial flux and trapezoidal configuration.

Figure 1 illustrates à trapezoidal configuration with axial flux and only one stage [4], [5], [6].

3. Analytic Model of the Motor

The motor is designed by the analytical method based on the following simplifying assumptions:

-Magnets and copper relative permeability are assumed near that of air.

-Absolute permeability of iron is assumed very large, which allows us to consider that the magnetic field in the iron is negligible.

-The flux leakage between magnets is assumed to be negligible.

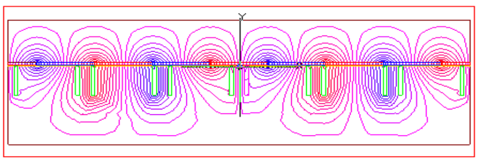
The analytical method used to calculate the dimensions of the motor using the following theorems:

- Ampere theorem.
- Theorem of flow conservation
- Theorem of magnetic fields superposition.

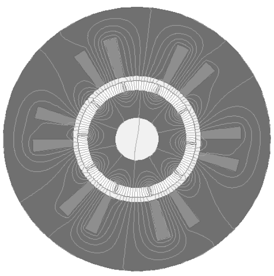
4. Finite Element Modeling of Traction Motor

The analytical model is still insufficient to provide the accuracy needed to start out the motor monitoring. A preliminary phase of analytical design is used to reduce the design time of the motor, since the direct use of finite element to design of an electric motor requests a very important time to achieve the desired physical characteristics. Accordingly, a validation step and adjusting of analytical calculation by the finite element method is performed. Indeed, the motor is analyzed by the finite element method on a cylindrical cutting plane at the middle contour as with a radial flux equivalent model according the dimensions extracted from the analytical model. The mesh at the gap is refined to have a good accuracy of the simulation results [5], [6].

The distribution of the flux lines when the motor operates at no-load is illustrated in figure 2.



Cylindrical cut plan model



Radial flux model

Figure 2. *Filed lines at no-load.*

4.1. Simulation Results

The flux at load is illustrated by the figure 3:

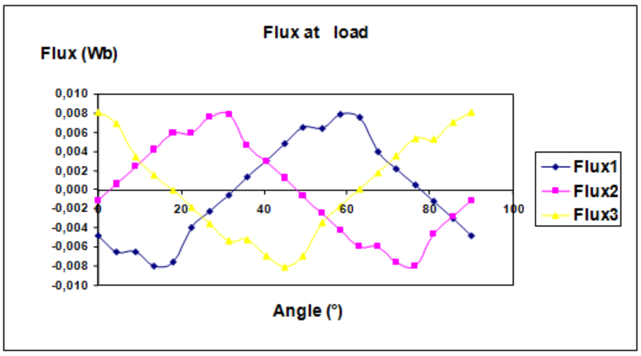


Figure 3. *Flux at load.*

The back electromotive forces (Emf) at load is illustrated by the figure 4 [6]:

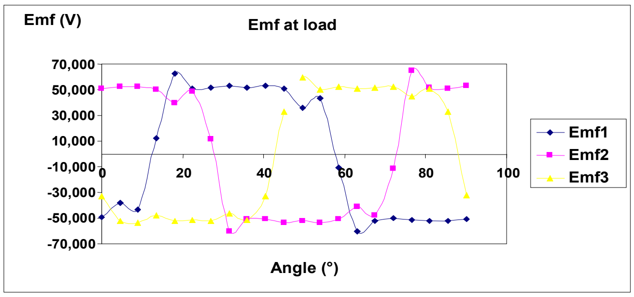


Figure 4. *Emf at load.*

We note that the results obtained by the finite element method are comparable to those obtained by the analytical method

4.2. Model of the Inductance

For a linear system, the inductance value of a phase constituted by two coils may be obtained from [6]:

- The energy calculation:

$$L = \frac{2}{I^2} \times A \times \iint_{area} B_m \times H \times ds \qquad (1)$$

- The flux calculation: The flux calculation:

$$L = \frac{N_s}{I} \times \frac{1}{s_{slot}} \times A \times \int A_s \cdot ds \qquad (2)$$

Where B_m is the flux density, H is the magnetic field, s is the slot area and As is scalar potential.

The finite elements analysis valid the analytic model of inductance.

5. Power Chain Global Model

5.1. Reference Current Generator

The current reference generator is used to generate three currents with trapezoidal waveform in phase with the back electromotive forces to minimize consumption. These three reference currents are shifted by 120 electric degrees. The speed controller is used to provide the amplitude of these currents in order to minimize the speed error. These three references currents are compared to the measured currents, the errors attack three proportional integral controllers to generate the three reference voltages supplying the motor. The Simulink model of the reference current generator is illustrated by figure 5:

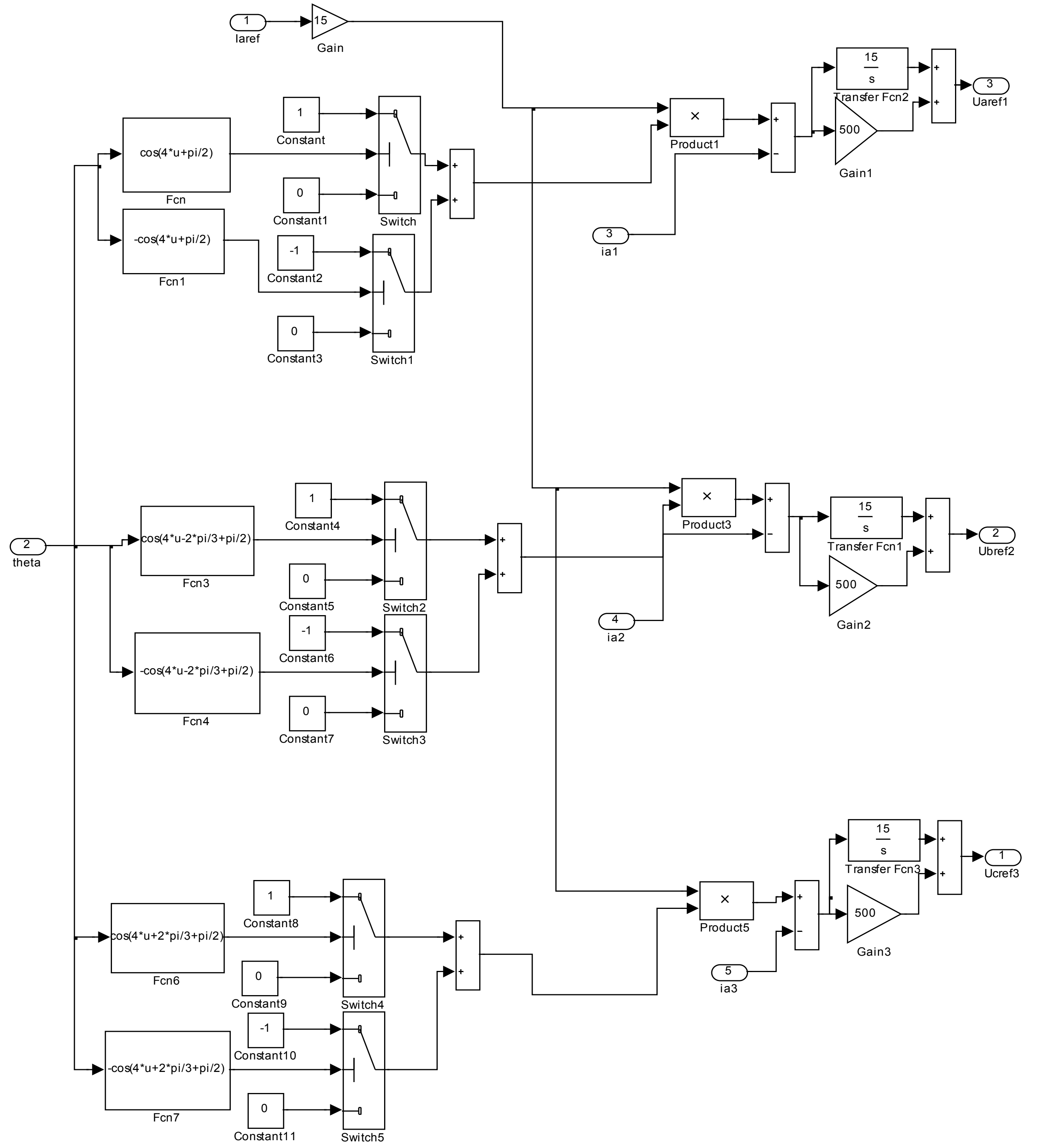


Figure 5. *Simulink model of the reference currents generator.*

5.2. Converter Model

To reproduce the real shape of the motor supply voltage, the reference voltages are compared with a triangular signal of much higher frequency. The output of the three comparators attacks three hysteresis providing the three phase voltages supplying the motor. The Simulink model of the converter is illustrated by figure 6:

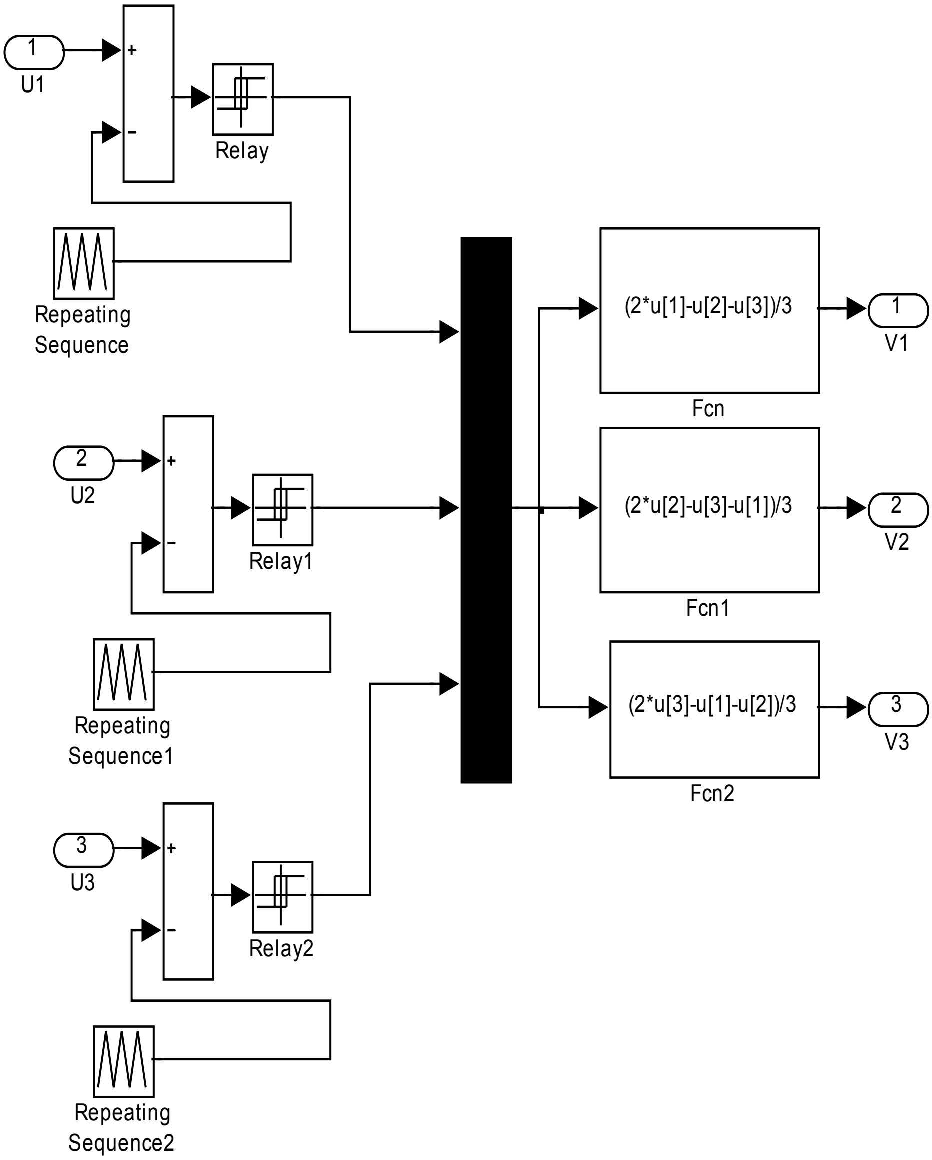


Figure 6. *Simulink model of the converter.*

5.3. Engine Model

The equations of phase voltages are expressed as follows:

$$u_1 = R_{t.} \times i_1 + L_t \times \frac{di_1}{dt} + e_1 \quad (3)$$

$$u_2 = R_{t.} \times i_2 + L_t \times \frac{di}{dt} + e_2 \quad (4)$$

$$u_3 = R_{t.} \times i_3 + L_t \times \frac{di_3}{dt} + e_3 \quad (5)$$

$$L_t = L - M \quad (6)$$

Where e1, e2 and e3 are respectively the electromotive forces of the phases 1, 2 and 3, L is the phase inductance and M is the mutual inductance.

The electromagnetic torque is given by the following equation:

$$T_{em} = \frac{1}{\Omega}\left(e_1 \times i_1 + e_2 \times i_2 + e_3 \times i_3\right) \quad (7)$$

Engine model is implanted under Matlab / Simulink as shown in the figure 7:

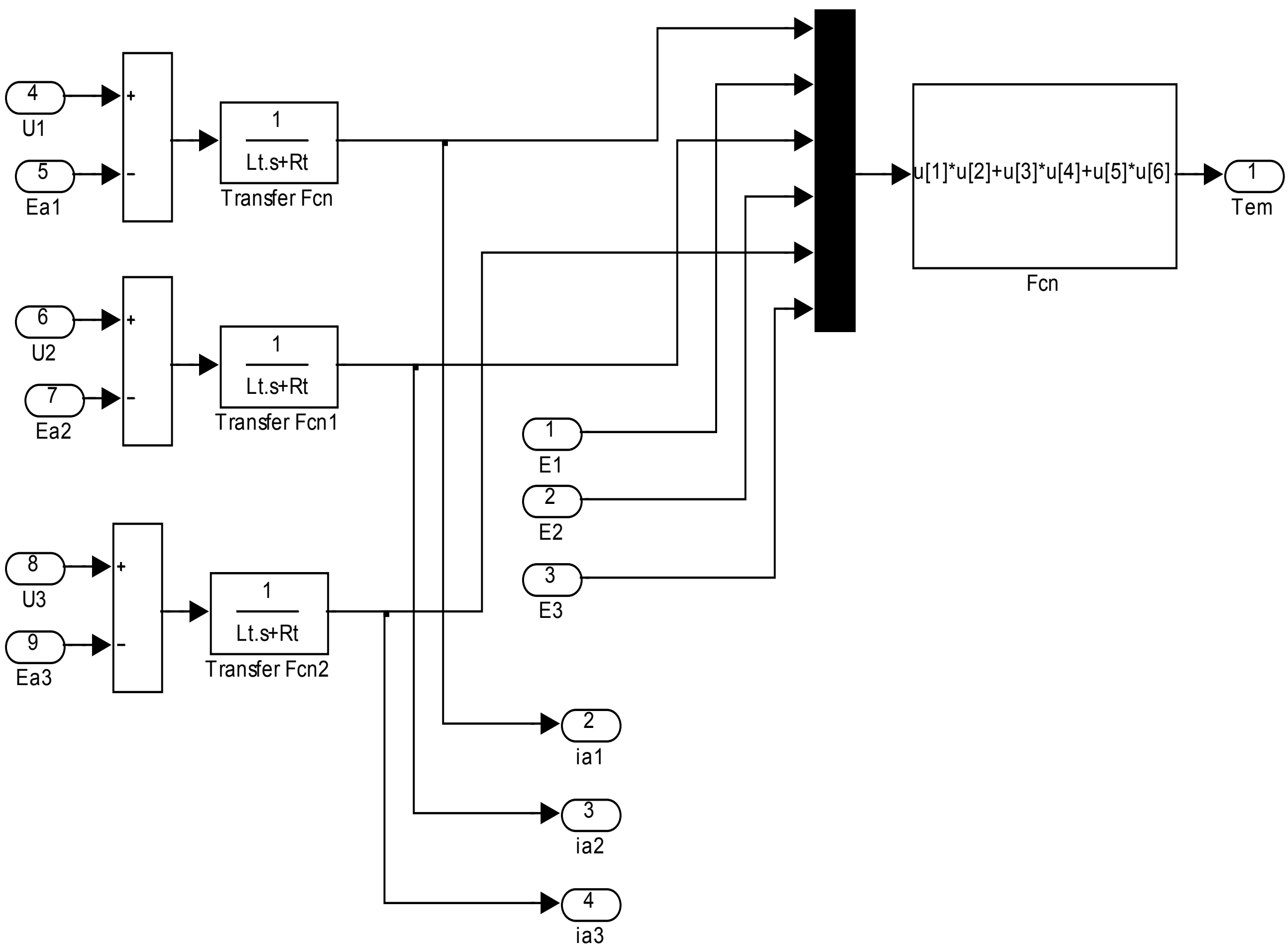


Figure 7. *Simulink model of the motor model.*

5.4. Dynamic Equation

The dynamic equation of the vehicle is expressed by the following relation

$$\left(\frac{J\times r_d}{R_r}+M_v\times R_r\right)\times\frac{dv}{dt}=r_d\times C_m-(F_r+F_a+F_c)\times R_r \quad (8)$$

Where F_r is the rolling resistance force, F_a is the aerodynamic force and F_c is the gravity force.

$$F_r = f_r\times M_v\times g \quad (9)$$

$$F_a=\frac{1}{2}\times M_{va}\times C_x\times S_f\times v^2 \quad (10)$$

$$F_c = M_v\times g\times\sin(\lambda) \quad (11)$$

5.5. Back Electromotive Forces Model

The three back electromotive forces are estimated from the following three equations:

$$a=\cos\left(p\times\Omega\times t+\frac{\pi}{2}\right) \quad (12)$$

$$b=\cos\left(p\times\Omega\times t-\frac{2\times\pi}{3}+\frac{\pi}{2}\right) \quad (13)$$

$$c=\cos\left(p\times\Omega\times t-\frac{4\times\pi}{3}+\frac{\pi}{2}\right) \quad (14)$$

The models of the back electromotive forces (e_1, e_2, e_3) are estimated from the following algorithm:

Begin
if
a>1/2;
a1=1/2.K_e.Ω:
else
a1=0;
if
a<-1/2;
a2=-1/2.K_e.Ω;
else
a2=0;
e1=a1+a2;
if
b>1/2;
b1=1/2.K_e.Ω:
else
b1=0;

if
b<-1/2;
b2=-1/2K_e.Ω;
else
b2=0;
e_2=b1+b2;
if
c>1/2;
c1=1/2.K_e.Ω:
else
c1=0;

if
c<-1/2;
c2=-1/2.K_e.Ω;
else
c2=0;
e_3=c1+c2;
end

With K_e is the back electromotive constant and Ω is the motor angular speed.

The Simulink model of the back electromotive forces is illustrated by the figure 8.

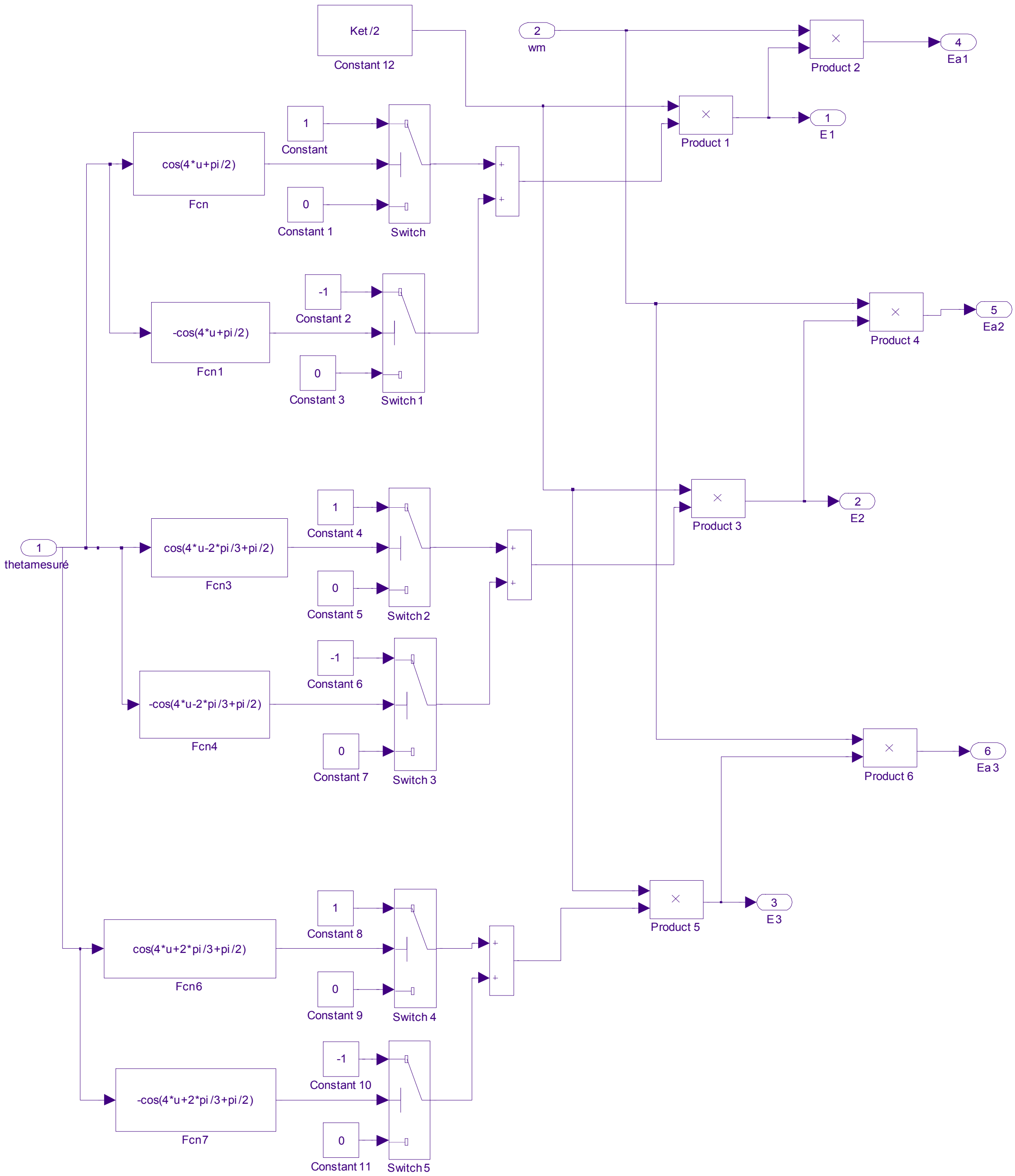


Figure 8. *Simulink model of the back electromotive forces.*

5.6. Global Model of the Power Chain

The different Simulink models are coupled, leading to the global model of the traction chain, implanted under the environment of Matlab / Simulink as shown in the figure 9:

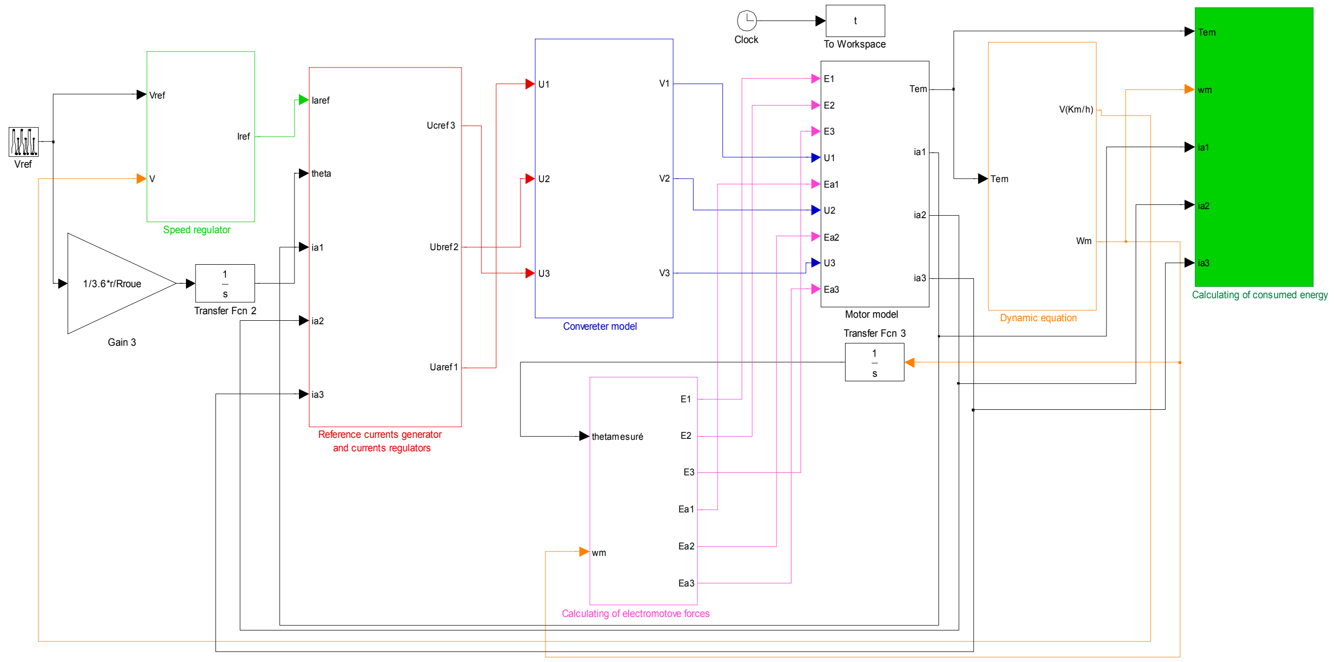


Figure 9. Global model of the power chain.

5.7. Simulation Results

Figure 10 show that the speed of response is close to the reference speed, which shows the performance of the trapezoidal control technique. This result confirms the design approach of the power chain.

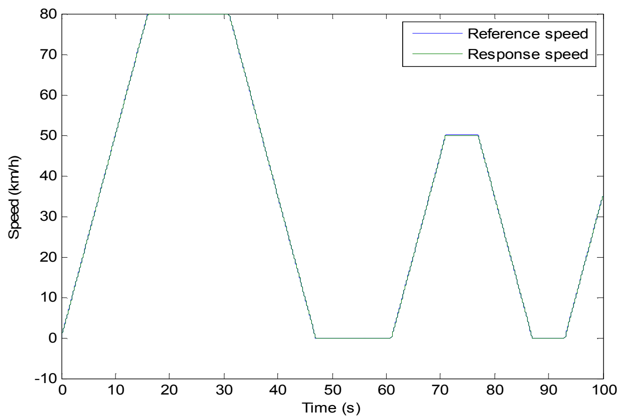


Figure 10. Speed response.

The phase current is illustrated by the figure 11:

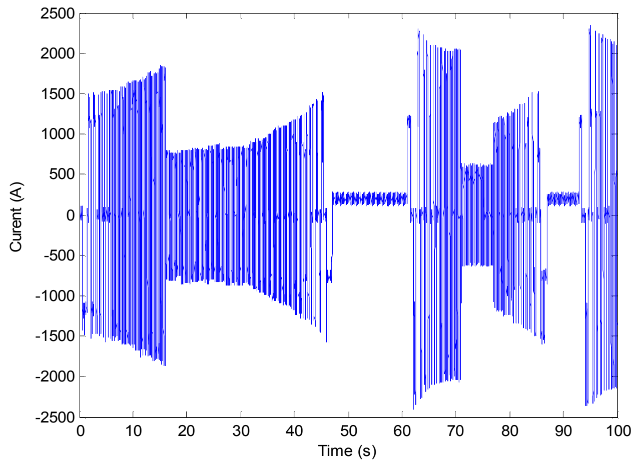


Figure 11. The phase current.

This figure shows that the starting current is reduced, which leads to a reduction of energy consumption.

The paces of the phase current and the phase voltage are illustrated in Figure 12.

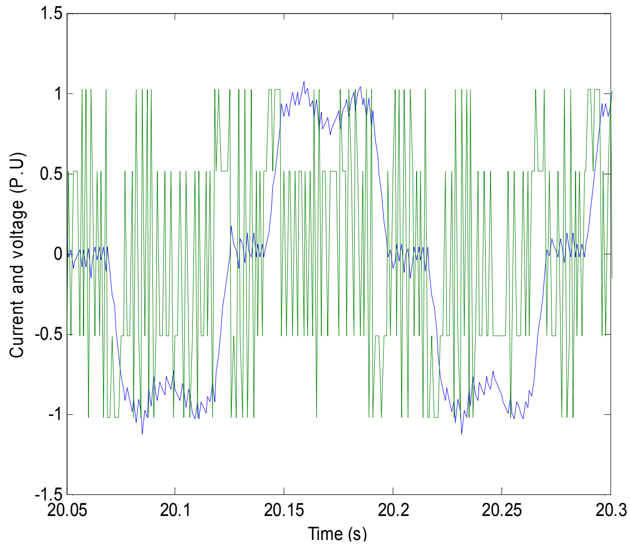


Figure 12. *Phase current and voltage.*

The current is maintained in phase with the back electromotive forces allowing to a reduction in vehicle consumption.

6. Conclusion

In this paper, a finite element model of permanent magnet axial flux motor is developed. A trapezoidal control strategy adapted to this structure of motor and permitting to maintain back electromotive forces in phase of electric currents to reduce electric vehicle consumption is developed. The simulation of the dynamism of the vehicle shows the effectiveness of this mode of control and the PMSM in the field of the electric traction.

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