Fuzzy control and performances amelioration of an electric vehicle drive train based on doubly fed induction machine

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Abstract— The aim of this paper is to show advantages of integration of doubly fed induction machine (DFIM) controlled by fuzzy logic algorithm in an electric vehicle drive train. So the DFIM is powered by two bidirectional converter, and a fuzzy logic controller is designed to control the speed of pulling unit. These give the possibility to operate the machine over wide range of speed variation, for both applications: engine and recovery, while addressing the non-linearity problems of the system. Consequently, the power of the machine can reach twice its rated power, thus the power density is doubled. The latter is an important factor, because in embedded systems, the reduction of weight is very required, especially in the electrics vehicles case. Simulation work is carried out on the software MATLAB/Simulink and the results showed goodness in performances of the fuzzy control algorithm and the feeding structure applied to the DFIM.

Index Terms— DFIM; fuzzy logic; wide speed variation; Power density; PWM converters; battery; control of vehicles drive train.

1. Introduction

The environmental impact of energy production, conversion and final use is more and more influencing our life, and the consensus about the necessity to limit carbon dioxide emissions is widely increasing [1][2]. The transportation sector is the most rapidly growing consumer of the world's energy, consuming 49% of the oil resources [3][4]. Electric vehicles (EVs) can potentially play an important role in transforming the transportation sector towards sustainability, public health and safety, because of it low level of environmental pollution, noise and availability of multiple renewable resources, such as solar energy[5]-[8].

Different kind of electric machines can be used in a drive train of an electric vehicle, the choice of the later depend on his dynamic performances, reliability and cost [9]-[11]. Literature shows the great interest shown in the double-fed induction machine (DFIM) for various applications: as a generator for wind energy and for certain industrial applications, such as rolling and traction or maritime propulsion [12]. Indeed, most work on this machine have been the subject of the study of the structure where the stator is directly connected to the network and the rotor powered by a power electronics converter. The advantage of this solution is that the converter is sized at 30% of the rated power of the system and therefore the variation of speed limit near the speed of synchronization [13][14]. However, the objective of this work is to operate the DFIM in a wide range of speed variation, for application in a drive train of an electric vehicle, using a non-linear algorithm based on fuzzy logic controllers for the speed control of the latter. For this, the machine is connected through two power converters with pulse wide modulation control (PWM), these converters are both powered by a battery, which is a key element for development of electrical vehicles, namely the energy density is low and the charge time very long [14]. In the drive train we use only one machine (DFIM) for the motorization of the vehicle, and for recovering energy during braking. The advantage of the power structure chosen is not only to operate the machine in a wide range of speed variation, but also to give to the machine the capacity to operate up to twice its rated power. So the power density is improved. Figure (1) illustrates the schematic diagram of the drive train:

The ability of the DFIM to start with high torque makes possible the elimination of clutch and gearbox. The torque is the size dimensioning; therefore the machine must be heavier and bulky, so more expensive. The use of fixed ratio gearbox overcome these problems and allows to have a simple machine that can provide the required torque [12].

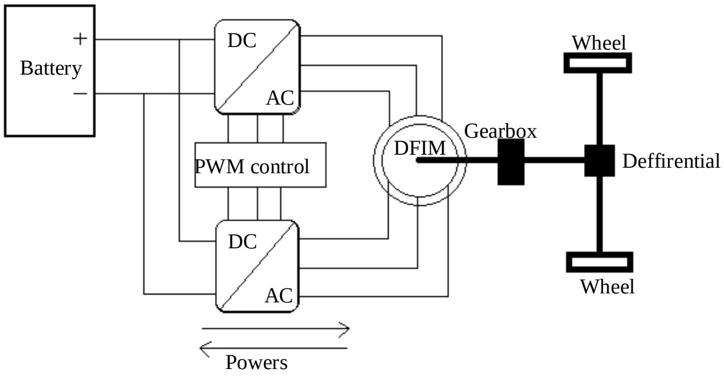

Fig. 1. Representative diagram of the electric vehicle drive train

The power electronic converters used for power transfer between the battery and the DFIM are sized at 100% of rated power of the machine, those are bidirectional converters with PWM control, they absorb power from the battery when the machine operates as a motor and they provide to it when the machine operates as a generator (braking).

Semiconductors used depends on power level passing converters; for low powers are used IGBT. For high power converters based on IGCT or GTO semiconductors can be used. Variable-speed drives with a rated power up to 40MW (IGCT) or 100MW (GTO) have been installed. A disadvantage of these semiconductor types is their lower switching frequency, compared with IGBT's [15].

The control of the drive train of an electric vehicle is very difficult, and this is due to the fact that its dynamics is nonlinear due to the state trajectory that is variable in general, and also the high nonlinearity of the electric machines used, which has the coupling terms between the stator and rotor and the variation of these parameters with temperature [16]. So in this work, a non linear controller based on fuzzy logic is developed for the speed control of the vehicle.

An objective of fuzzy logic has been to make computers think like people. Fuzzy logic can deal with the vagueness intrinsic to human thinking and natural language and recognizes that its nature is different from randomness. Using fuzzy logic algorithms could enable machines to understand and respond to vague human concepts such as hot, cold, large, small, etc. It also could provide a relatively simple approach to reach definite conclusions from imprecise information [17][18]. The basic configuration of a fuzzy-logic controller is composed of four parts: the fuzzifier, the knowledge base, the inference engine and the defuzzifier [19][20].

2. DFIM model

Two-phase equivalent model of the DFIM represented in the reference (dq) linked to the rotating field is given as follows [21][22]:

$$\begin{cases} v_{sd} = R_s i_{sd} + S\varphi_{sd} - \omega_s \varphi_{sq} \\ v_{sq} = R_s i_{sq} + S\varphi_{sq} + \omega_s \varphi_{sd} \\ v_{rd} = R_r i_{rd} + S\varphi_{rd} - (\omega_s - \omega)\varphi_{rq} \\ v_{rq} = R_r i_{rq} + S\varphi_{rq} + (\omega_s - \omega)\varphi_{rd} \end{cases} \quad (1)$$

With S: Laplace Operator

In order to achieve good decoupling between the axes d and q, we define intermediate voltages as follows:

$$\begin{cases} v_{sd} - \frac{M}{L_r} v_{rd} = v_{tsd} \\ v_{rd} - \frac{M}{L_s} v_{sd} = v_{trd} \end{cases} \quad (2)$$

$$\begin{cases} v_{sq} - \frac{M}{L_r} v_{rq} = v_{tsq} \\ v_{rq} - \frac{M}{L_s} v_{sq} = v_{trq} \end{cases} \quad (3)$$

Coupling terms appear to compensate; P_{1d}, P_{1q}, P_{2d}, P_{2q}, these expressions allow to obtain relations between the intermediate voltages and the stator and rotor currents in d or q axes.

So:

$$\begin{cases} v_{tsd} = R_s(1 + ST_s\sigma) i_{sd} + P_{1d} \\ v_{tsq} = R_s(1 + ST_s\sigma) i_{sq} + P_{1q} \\ v_{trd} = R_r(1 + ST_r\sigma) i_{rd} + P_{2d} \\ v_{trq} = R_r(1 + ST_r\sigma) i_{rq} + P_{2q} \end{cases} \quad (4)$$

With:

$T_s = L_s/R_s$: stator electrical time constant;

$T_r = L_r / R_r$: rotor electrical time constant;

$\sigma = (1-M^2/(L_s.L_r))$: dispersion coefficient.

The coupling terms can be expressed as follows:

$$\begin{cases} P_{1d} = -\frac{M}{L_r} R_r i_{rd} - \omega_s \varphi_{sq} + \omega \frac{M}{L_r} \varphi_{rq} \\ P_{1q} = -\frac{M}{L_r} R_r i_{rq} + \omega_s \varphi_{sd} - \omega \frac{M}{L_r} \varphi_{rd} \\ P_{2d} = -\frac{M}{L_s} R_s i_{sd} + \omega_s \frac{M}{L_s} \varphi_{sq} - \omega \varphi_{rq} \\ P_{2d} = -\frac{M}{L_s} R_s i_{sq} - \omega_s \frac{M}{L_s} \varphi_{sd} + \omega \varphi_{rd} \end{cases} \quad (5)$$

From system of equations (4), the transfer's functions following are obtained:

$$\begin{cases} T_{sd} = \frac{I_{sd}}{V_{tsd} - P_{1d}} = \frac{1/R_s}{1 - ST_s\sigma} \\ T_{sq} = \frac{I_{sq}}{V_{tsq} - P_{1q}} = \frac{1/R_s}{1 - ST_s\sigma} \\ T_{rd} = \frac{I_{rd}}{V_{trd} - P_{2d}} = \frac{1/R_r}{1 - ST_r\sigma} \\ T_{rq} = \frac{I_{rq}}{V_{trq} - P_{2q}} = \frac{1/R_r}{1 - ST_r\sigma} \end{cases} \quad (6)$$

3. Converters model

The matrix giving the model of powers electronics converters used is expressed as follows:

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \frac{1}{3} U_0 \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \quad (7)$$

4. Battery model

The model of battery used for application in electric vehicle should have the specifications as follows [23]:

- It should simulate the variation of the battery's terminal voltage on certain load demand or current demand;
- It should be simple and require limited times for mathematical calculation and iteration;
- The model should be involved with as few as possible or none of the parameters that are related to the battery's chemical process.

There have been many proposals battery model; one of this is the Thevenin equivalent circuit, shown in figure (2). It is a linear electrical battery model [24].

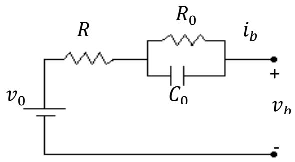

Fig. 2. Thevenin equivalent circuit of battery

$$v_b = v_0 - v_{c0} - Ri_b \tag{8}$$

5. Vehicle Dynamics

Equation governing vehicle dynamics is given as following [25]:

$$T_r = \left(F_r + F_w + F_g\right) r + \delta M_v \frac{dV_v}{dt} \tag{9}$$

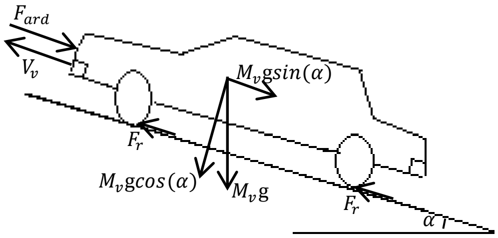

Fig. 3. Various forces applied to the vehicle

$$F_r = P.C_r \tag{10}$$

$$C_r = 0{,}01\left(1 + \frac{V_v}{100}\right) \tag{11}$$

Which C_r is called the rolling resistance coefficient and P is the normal load on the Wheel.

$$F_w = 0.5\rho A_f C_d (V_v + V_w)^2 \tag{12}$$

Where ρ is the air density, A_f is the frontal area of the vehicle, C_d is aerodynamic coefficient, V_v is the vehicle speed and V_w is the wind speed.

$$F_g = M_v \,\mathrm{g}\sin(\alpha) \tag{13}$$

Where g is the earth gravity and M_v is the total weight of the vehicle.

6. Vector control of the DFIM

A vector controlled doubly fed induction machine is an attractive solution for high restricted speed rang electric drive and generation application, it consists in guiding an electromagnetic flux of the DFIM along the axis d or q.[15] In our case we choose the direction of reference (d,q) according to the direct stator flux vector ϕ_{sd} , so the DFIM model in static state will be simplified as follows:

$$\begin{cases} v_{sd} = R_{sd} i_{sd} \\ v_{sq} = R_s i_{sq} + \omega_s \phi_{sd} \\ v_{rd} = R_r i_{rd} - \omega_r \phi_{rq} \\ v_{rq} = R_r i_{rq} + \omega_r \phi_{rd} \end{cases} \tag{14}$$

Such as:

$$\omega_r = \omega_s - \omega \tag{15}$$

The magnetization of machine is assured by the rotor direct current, so the stator current in the d axis is taken to zero ($i_{sd} = 0$). The current and voltage in this line are then in phase:

$$v_{sq} = v_s \text{ and } i_{sq} = i_s \tag{16}$$

In this case we obtain a unity power factor at the stator, so the stator reactive power is zero Q_s = 0.These simplifications lead to the electromagnetic torque expression:

$$T_{em} = p\phi_s i_{sq} \tag{17}$$

From the expressions of equations which have been established, we can draw a connection summary table setting the objectives of the control strategy with the references of action variables involved:

Objectifs	References
$\phi_{sd} = \phi_s = \phi_{sn}$	$i_{rd}^* = \frac{\phi_{sn}}{M}$
$\phi_{sq} = 0$	$i_{rq}^* = -\frac{L_s}{M} i_{sq}^*$
$Q_s = 0, (cos\varphi = 1)$	$i_{sd}^* = 0$
$T_{em} = T_{em}^*$	$i_{sq}^* = \frac{T_{em}^*}{K_{Tem}}$

Table. 1. Control strategy applied to the DFIG model

7. Fuzzy speed control of the drive train

Fuzzy logic systems address the imprecision of the input and output variables directly by defining them with fuzzy numbers (and fuzzy set) that can be expressed in linguistic terms (e.g., small, medium and large).

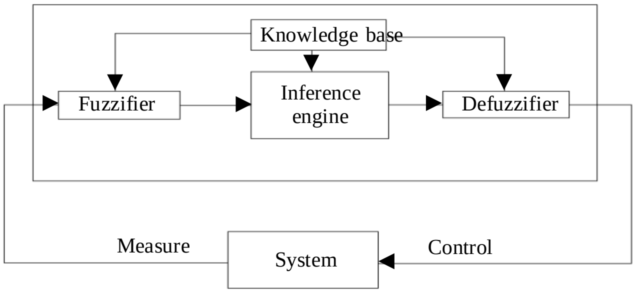

Fig. 4. General diagram of fuzzy controller

The basic configuration of the FLC includes a fuzzy rule base, which consist of a collection of fuzzy IF-THEN rules [26].

A block diagram of a fuzzy control system is shown in Figure. 4. The fuzzy controller is composed of the following four elements [26]-[28]:

1. A rule-base (a set of If-Then rules), which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control.
2. An inference mechanism (also called an "inference engine" or "fuzzy inference" module), which emulates the expert's decision making in interpreting and ap- plying knowledge about how best to control the system.
3. A fuzzification interface, which converts controller inputs into information that the inference mechanism can easily use to activate and apply rules.
4. A defuzzification interface, which converts the conclusions of the inference mechanism into actual inputs for the process

The diagram showing the fuzzy logic control of the drive train speed of the vehicle is given in fig. 5. Whith K_1, K_2, K_3 are the adjustment factors associated with the error, its variation and the command.

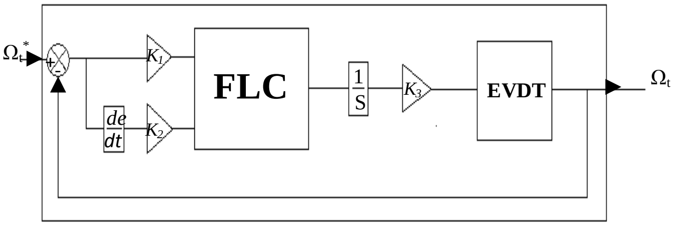

Fig. 5. Fuzzy control of drive train speed

The input of the fuzzy controller is the error and error variation of the rotational speed of the machine, the quantities concerned are noted E and dE successively, that are numerical values. The fuzzification interface transforms these numerical values into linguistic values.

Five fuzzy sets represented by membership functions are used for describe input and output values: large negative (LN); negative (N); zero (Z); positive (P); large positive (LP).

In this study a two-dimensional array is used. Entries in the table (2) represent the fuzzy sets of input variables. The intersection of a column and a line shows the fuzzy set of the output variable defined by the rule.

E dE	NL	N	Z	P	PL
NL	NL	LN	N	N	Z
N	NL	N	N	Z	P
Z	N	N	Z	P	P
P	N	Z	P	P	LP
PL	Z	P	P	LP	LP

Table. 2. Rules table

8. Powers distribution

The distribution of stator and rotor active powers is a requirement in the control strategy to be applied. Indeed, this allows increasing the range of speed variation and the power density of the machine. Such as if the stator and rotor resistance windings terms are neglected, the following relationship is imposed:

$$\frac{|P_s|}{|P_r|} = \frac{|\omega_s|}{|\omega_r|} \qquad (18)$$

Therefore, the stator and rotor active powers distribution, involve the stator and rotor pulses distribution and vice versa.

Working with a slip s = -1 we obtain the following relationship:

$$\frac{\omega_s - \omega}{\omega_s} = \frac{\omega_r}{\omega_s} = -1 \qquad (19)$$

So:

$$\omega_s = -\omega_r \qquad (20)$$

The diagram representing the complete system with the control strategy applied is given by figure (6).

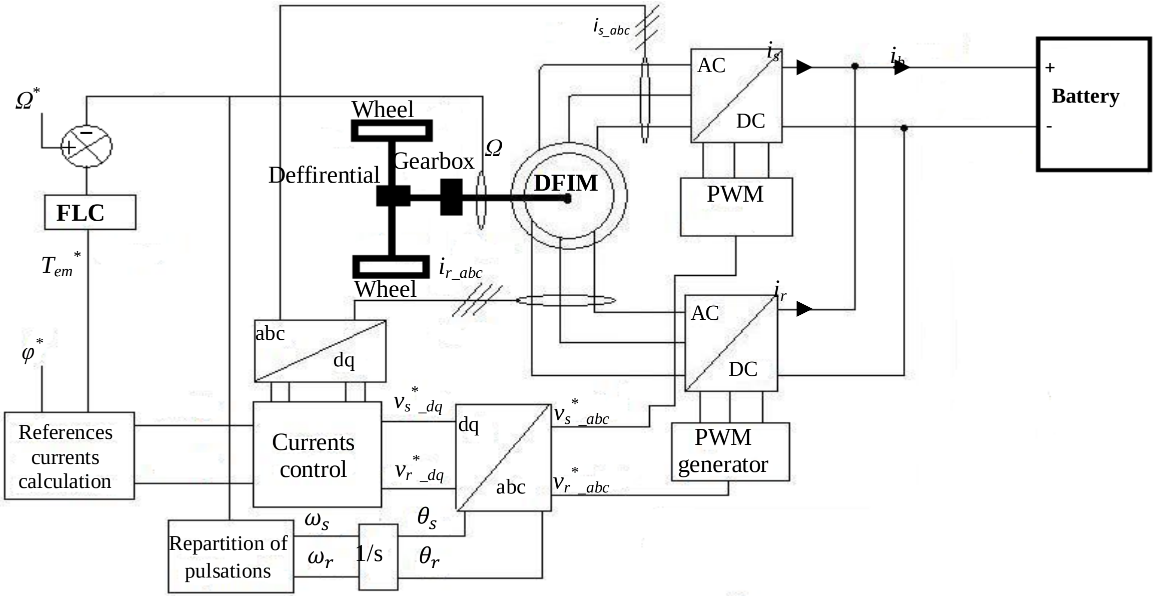

Fig. 6. Control diagram of the electric vehicle drive train

9. Simulation results and discussion

A fuzzy speed control with pulses repartition ($slip = -1$) is applied to the DFIM for a path of a road with variable slopes. The overall system simulation is performed on the MATLAB / Simulink, the following figures show the simulation results:

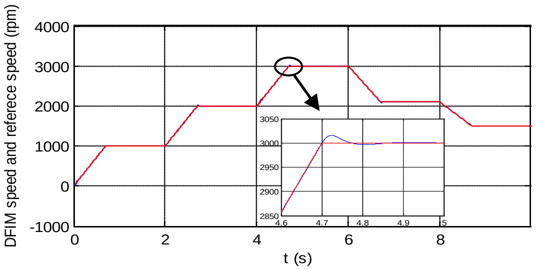

Fig. 7. DFIM speed and reference speed (rpm)

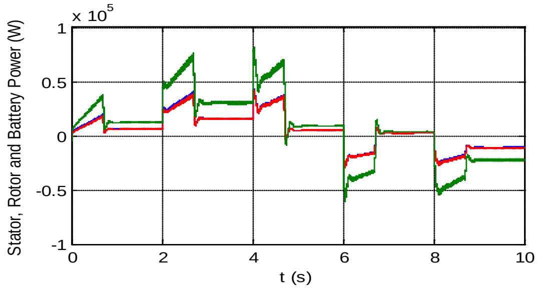

Fig. 8. Stator, rotor and battery powers (W)

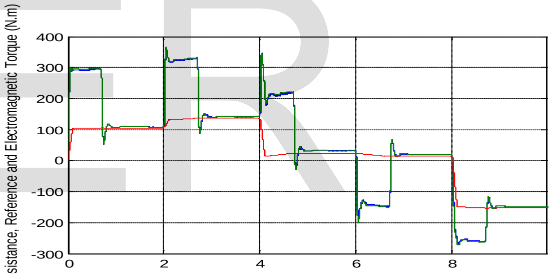

Fig. 9. Resistance, reference and electromagnetic torque (N.m)

According to the simulation results, it was noted that the DFIM operates over a wide range of speed variation (twice the nominal speed), while following the reference imposed; consequence of the good performances of the fuzzy logic algorithm applied for the speed control of the pulling unity. The distribution of pulsations applied for the control of DFIM has allowed to have the distribution of stator and rotor actives powers (fig. 8.), however, there is a slight difference and this is due to the stator resistance that is greater than the rotor resistance, and we note that the total power exchanged between the battery and DFIM equal to the sum of the stator and rotor actives powers.

During the acceleration phase, figure (9) shows that the electromagnetic torque developed by the machine is far greater than the resistive torque imposed by the vehicle, and this is for overcome the total inertia for bring the vehicle to a highest speed, therefore the power supplied by the DFIM is greater than the power in the steady state, and for a rotational speed equal to twice the nominal speed, the power absorbed from the battery equal to twice of rated power of the machine. During deceleration (braking) or downhill, the electromagnetic torque becomes negative. Therefore the DFIM provides power for recharging the battery.

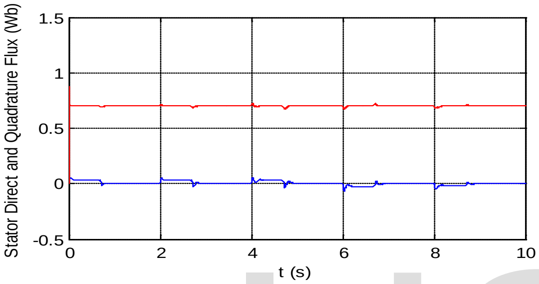

Fig. 10. Stator direct and quadrature flux (Wb)

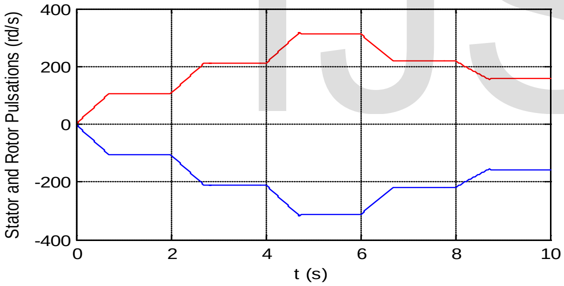

Fig. 11. Stator and rotor pulsations (rd/s)

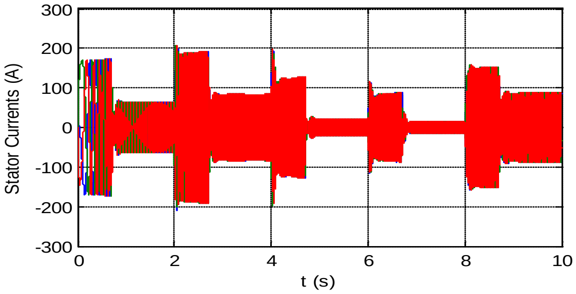

Fig. 12. Stator currents (A)

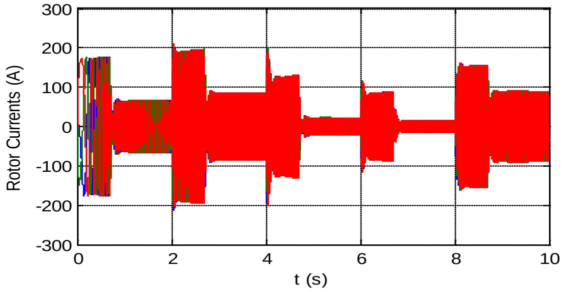

Fig. 13. Rotor currents (A)

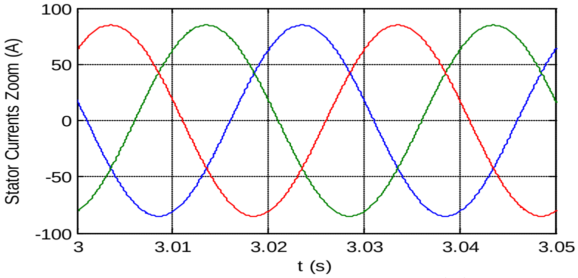

Fig. 14. Stator currents zoom (A)

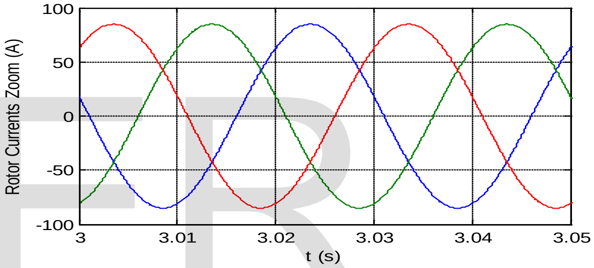

Fig. 15. Rotor currents zoom (A)

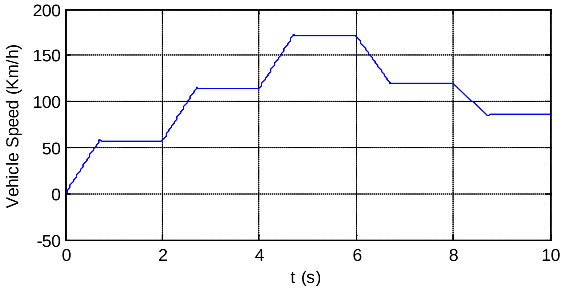

Fig. 16. Vehicle speed (km/h)

Figure (11) shows the pulsations shapes of the stator and rotor, the two pulsations values have equal amplitude and opposite sign justifying the pulsationsdistribution law applied to the DFIM. The stator and rotor currents are shown respectively in figures (12, 13), and their respective zoom are given in figures (14, 15). Both figures have an identical shape, and same pulse for a given rotational speed

10. Conclusion

The aim of this work is to integrate DFIM in a drive train of an electric vehicle, and to show the performances of fuzzy logic control used for the speed control of this vehicle. Indeed, the simulation results obtained show that the DFIM can operate over wide range of speed variation, with following imposed speed reference. The first advantage of this system is to replace the gearbox with a speed reducer, and remove the clutch, which are very complicated and expensive systems. The second advantage is that the power of the machine rises up twice of its rated power providing an increase of its power density, which is an important factor in embedded systems. The third advantage is the use of fuzzy logic algorithm for the control of the pulling unit. So the driver controls the vehicle perfectly, whatever the exterior disturbances and parametric variation of the machine.

Seen these benefits, the DFIM with the control strategy applied is a very good alternative for use in a drive train of an electric vehicles.

Nomenclature

A_f: Frontal area of the vehicle
C_0: Battery capacity
C_d: Aerodynamics coefficient
F_{ard}: Aerodynamic force
F_g: Gravitational strength
F_r: rolling force
g: Earth gravity
i_b: Battery current
$i_{sd}, i_{sq}, i_{rd}, i_{rq}$: Direct and quadrature of stator and rotor currents
L_s,L_r: Stator and rotor inductances
M: Mutual inductance
M_v: Vehicle total weight
R: Battery resistance
r_d: Wheels radius
R_s,R_r: Stator and rotor resistances
T_{em}: Electromagnetic torque
T_{em}^*: Reference torque
v_0: Open circuit voltage
v_b : Battery voltage
v_{c0} : The double layer capacity voltage
$v_{sd}, v_{sq}, v_{rd}, v_{rq}$: Direct and quadrature of stator and rotor voltages
V_v : Vehicle speed
V_w: Wind speed
$\varphi_{sd}, \varphi_{sq}, \varphi_{rd}, \varphi_{rq}$: Direct and quadrature of stator and rotor flux
ω_s, ω_r: Stator and rotor pulsations
Ω: DFIM speed
Ω^*: Reference speed
ρ: Air density

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