Dynamic Control of an Electric Vehicle with Traction Induction Motor

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Abstract. During recent years, to solve as soon as possible the environment pollution problem, considerable improvements have been made in research and in international legislation. As research and manufacturing results are mentioned the new types of hybrid and electric vehicles and as legislation improvements have started to view carbon dioxide as a greenhouse gas that traps the earth's heat and contributes to global warming. The present paper has, as a main target, the description of a modern and environmentally friendly solution regarding the dynamic control of an electric vehicle with traction induction motor. The dynamic control proposed by the author provides better traffic safety and an efficient management of electrical energy for the vehicle (reduced consumption by approximately 12 %).

**Keywords:** Electric vehicle · Induction motor · Dynamic control

1 Introduction

Automobile releases many liquid or/and gaseous wastage which are the cause of environment pollution. These components are: nitrogen oxide (NO_x), hydrocarbon (HC), carbon monoxide (CO), volatile organic compounds (VOCs) and sulphur di-and tri-oxide (SO_x). All of them are depending on the content of fuel-based engine. To avoid the environment pollution, the development politics of an eco-friendly and sustainable transport promote more and more electric vehicles use. Requirements for electrical motors, as main vehicle propulsion sources, are getting more and more demanding. In this aim, passenger and freight vehicles must accomplish a large autonomy, short re-fueling time, acceleration of 10–15 s to reach speeds of 0–100 km/h, drive uphill on 5–10 % ramps at legal top speeds and without environmental hazards. To have a good selection of electrical traction motors, must be respected the main following requirements: high torque at starting, good power/gauge ratio, flexible traction characteristics, energy efficiency, extended speed range ability, good thermal cooling conditions, safety/reliability and acceptable costs. The traction characteristics help to optimal evaluate the vehicle dynamics in acceptable economic conditions.

2 Vehicle Propulsion Dynamics

2.1 Motion Forces

In order to respect the vehicle's operating constraints and to have good dynamics, it requires an extended speed range and a constant power operating flexible region for different hill climbing conditions. Figure 1 presents a schematic representation of the forces acting on the vehicle in motion [1].
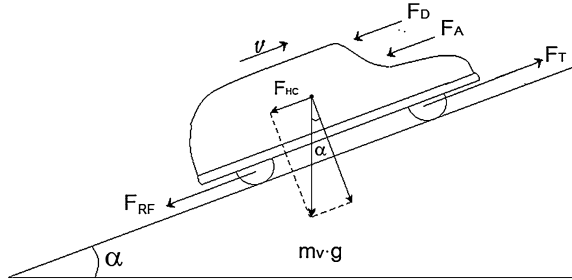
Fig. 1. Forces during vehicle motion

From the figure results the expression of the vehicle movement equation, as follows:

$$m_v \cdot \frac{d}{dt} v(t) = F_T(t) - [F_A(t) + F_{RF}(t) + F_{HC}(t) + F_D(t)], \qquad (1)$$

where m_v is the loaded vehicle mass [kg], v the vehicle longitudinal speed [m/s], F_T the traction force [N], F_A the aerodynamic friction force [N], F_{RF} the rolling friction force [N], F_{HC} the hill climbing force [N] and F_D the disturbance force [N] that includes all other not yet specified effects. The traction force is negative, for instance during the vehicle braking. For the electrical vehicles case, the mathematical expressions for all these main forces are the followings [1]:
• traction force F_T, is calculated as

$$F_T(t) = \frac{T_{em} \cdot i_r}{R} \cdot \eta_{tr} = 2700 \cdot \frac{P_{em}}{v} \cdot \eta_{tr}, \qquad (2)$$

where T_{em} is the electric motor torque [Nm], i_r the gear ratio, η_{tr} the transmission efficiency, R the tire radius [m], P_{em} the electric motor power expressed in [HP]. The vehicle longitudinal speed v, expressed in [km/h] is calculated as:

$$v = 0,377 \cdot \frac{i_r}{R} \cdot n_m, \qquad (3)$$

where n_m is the motor rotation in [rpm].

• aerodynamic friction force F_A, is calculated as

$$F_A = \frac{\rho_a \cdot A_f \cdot C_d}{2} \cdot v^2, \qquad (4)$$

where ρ_a is the air density [kg/m^3], A_f the vehicle frontal area [m^2] and C_d the aerodynamic drag coefficient estimated by experiments or by computer programs.

• rolling friction force F_{RF}, is calculated as

$$F_{RF} = \mu_{rf} \cdot m_v \cdot g \cdot \cos \alpha, \qquad (5)$$

where μ_{rf} is the rolling friction coefficient, g the gravity acceleration [m/s^2] and α the uphill driving angle. The rolling friction coefficient depends on vehicle speed, tires pressure and road surface conditions.

• hill climbing force F_{HC}, due to the gravity, is calculated as

$$F_{HC} = m_v \cdot g \cdot \sin \alpha. \qquad (6)$$

• disturbance force F_D [N], that summarizes all other not yet specified effects [1].

To have a complete estimation of traction characteristics, one must calculate the dependence between the vehicle power P_v and its speed within traffic, as follows:

$$P_v = \left(m_v \cdot g \cdot C_r + \frac{\rho_a \cdot A_f \cdot C_d}{2} \cdot v^2 \right) \cdot v, \qquad (7)$$

where C_r is the wheel rolling coefficient.

2.2   Traction Induction Motor

Presently, brushed dc motor, brushless dc motor, ac induction motor, permanent magnet synchronous motor and switched reluctance motor are the main motors used for Electric Vehicle (EV) driving. The choice of traction electric motor for a specific electric vehicle is dependent on main factors, such as: utility of the EV, easy, smooth and accurate control, efficient output power at shaft, conversion efficiency of 90 %, constructive simplicity, high torque when the vehicle slows down or stops, no extra gears for higher power curves and good power/weight ratio. As consequence, induction motors are among the top candidates in electric vehicle propulsion [3, 4]. They are widely used in modern electric vehicles. Some research even concludes that induction motor provides better overall performance compared to other motors [4]. An induction squirrel-cage motor has some advantages as: low-cost for maintenance, high efficiency, high reliability, easy for cooling and firm structure, making it very competitive in EV driving. In this paper the traction induction motor is considered a time-varying multi-variable non-linear system, hence the modeling task is not easy. The induction motor fed by a PWM voltage inverter is field oriented controlled [2].

Adjusting of vehicle running speed must be completed by limiting the acceleration/deceleration torque at suitable values, for passengers. To easy reproduces the acceleration pedal function, the direct torque control method can be also used [3].

As traction motor it has been used an induction motor with the following technical data: rated power P_n = 90 kW (120 HP), rated line voltage U_n = 400 V, rated current I_n = 153,5 A, pole pairs p = 1, rated rotor speed n = 2975 rpm, rated mechanical torque T_m = 288,8 Nm, stator resistance R_1 = 0.1113 Ω, rotor resistance R_2 = 0.01685 Ω, stator inductance L_1 = 0.0002373 H, rotor inductance L_2 = 0.0003075 H, mutual inductance L_m = 0.014 H and efficiency η = 94.1 %. The induction motor is fed at rated voltage by a PWM inverter with IGBT power transistors, having 10 kHz commutation frequency, efficiency of 95 % and power density of 3.5 W/cm^3.

3 Dynamic Control of the Vehicle

3.1 Traction Control

The traction control system is required to be fast in response and low-ripple. Electric vehicles require that traction induction motor has a wide range of speed regulation. In this aim, two requirements must be fulfilled:

– to guarantee the speed-up time, the induction motor must have large torque output under low speed and high over-load capability;
– to operate at high speed, the driving motor must have certain power output at high-speed operation.

For EV one of the most advantages is the quick and precise torque response of the electric motor. Besides, important information including wheel angular velocity and torque, can be achieved much easier by measuring the electric current passing through the motor. Based on these remarkable advantages, a couple of advanced motion controllers are developed, in order to improve the handling and stability of EV [4]. To develop a Traction Control System (TCS) with high performances, the control algorithm must be independent on the identification of the road adhesion coefficient. Also it must have an excellent robustness to estimate the vehicle velocity error. In this aim, has been developed an anti-slip controller for an EV based on Variable Structure Control (VSC) method. In order to have a VSC with good robustness, the control law adopted is an equivalent control with switching control [5]. In this case, the output torque of the induction motor is expressed as [4]

$$T_m = T_{meq} - \Delta T \text{sgn}(s), \tag{8}$$

where T_{meq} is the induction motor equivalent torque, ΔT the hitting torque of control drive and $sgn(s) = \{-1,0,1\}$ is the system switching function.

The sliding motion includes two processes:

– approaching motion which makes the system at any time in any position approach to the sliding face in limited time;
– sliding motion which occurs when the EV reaches sliding surfaces.

The control process is based on a correct estimation of the wheel slip ratio λ calculated with the following relation:

$$\lambda = \frac{\omega R - v}{\omega R},\tag{9}$$

where ω is the wheel angular velocity [rad/s], R the tire radius [m] and v the vehicle longitudinal speed [m/s]. In relation 9 are using the standards SAE wheel slip definition. In this case, ωR represents the longitudinal speed of the wheel center. The TCS based on VSC strategy is presented in Fig. 2.
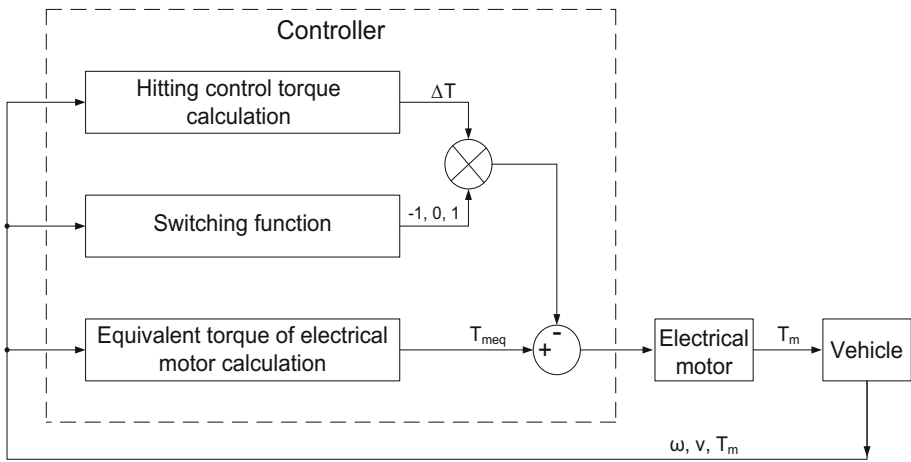
Fig. 2. Torque control system based on VSC strategy

Regarding the high-frequency-chattering on sliding surface, is better to combine the VSC advantages with the Model Following Control (MFC), [4], [6].

The MFC strategy is recommended in order to decrease the fluctuation to the motor torque and slip ratio of the tire. It only requires the induction motor's output driving torque and the tire's angular speed signal to put TCS into practice. This combined strategy between VSC with MFC is practical because the longitudinal velocity estimation and the optimal slip ratio identification can be ignored. Thus, the high-frequency-chattering near the sliding surface can be avoided [4]. The author estimates that with such combined system the induction motor consumption can be reduced by approximately 12 % and the efficiency of energy recovery from braking increases by about 5 %, which lead to the expansion of distance traveled on a single charge by more than 15 %. These estimations take into account the standard European driving cycles.

3.2   Induction Motor Control

There are different control methods for induction motor, recommended by some authors [2–4]. To control in speed and torque the induction motor, the Field Oriented

Control (FOC) method is used [2]. The drive system simulation is provided in Simulink, as shown in Fig. 3. As shown in this figure, the block with induction motor, contains the following subsystems: speed controller, drive control with FOC, three-phase voltage inverter and induction motor. This block drive was created using the block *AC3* from the *SimPowerSistems/Electric drives* library and is intended to simulate the FOC of the induction motor.

To use the original block *AC3* for traction purpose, some modifications are set to use it in a three-phase system with speed-control. The *Asynchronous machine* block implements a squirrel cage induction machine that works as a motor and as a regenerative brake.
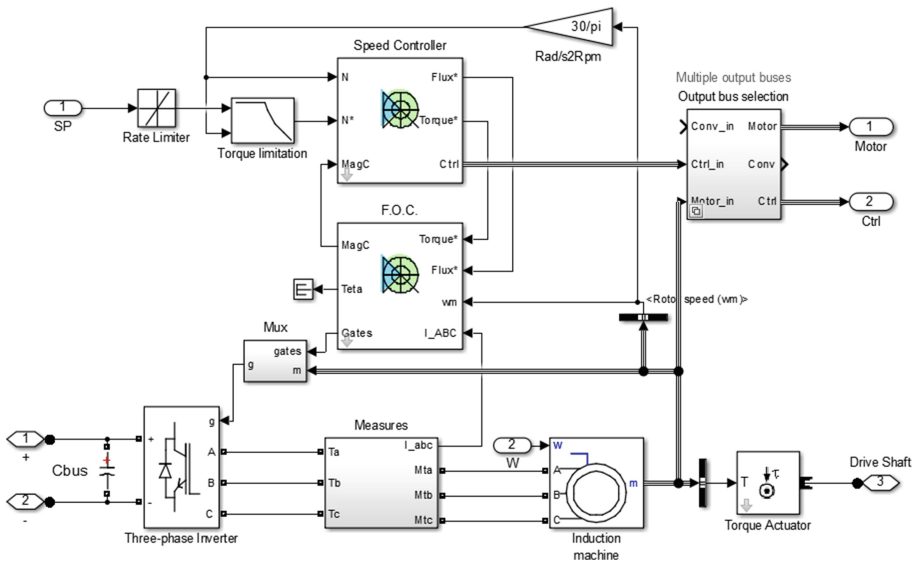

Fig. 3. Simulink diagram of control drive simulation

3.3 Vehicle Dynamics

The vehicle dynamics describes the EV behavior based on its parameters and depending on external factors which influence motion. This block is depicted in the Fig. 4.

The main vehicle technical data are: traction induction motor rated power P_n = 90 kW, maximum longitudinal speed v = 160 km/h, acceleration time of 10 s (0-100 km/h), autonomy away of 470 km, total mass m_v = 1200 kg, no tire wheel radius r_w = 0.3 m.

In the vehicle dynamics block diagram the main subsystems are: the *Longitudinal Vehicle Dynamics* and the *Drive Wheels (Tire, Tire1)*. These blocks are interconnected with each other, the differential mechanism beeing also connected to the transmission shaft which is driven by the traction induction motor.
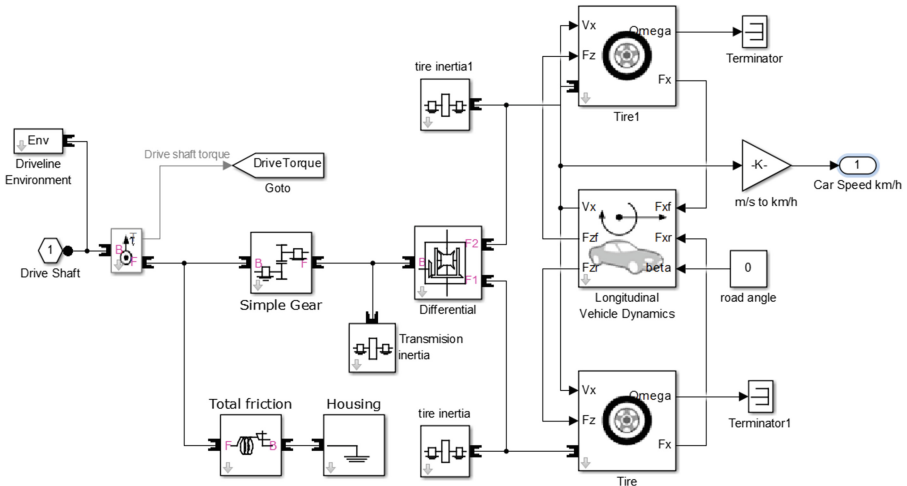
Fig. 4. Vehicle dynamics block diagram

4   Practical Results

After conducting real-life experiments the following waveforms represent the behavior of the modelled system. In Fig. 5 are depicted the waveforms representing the parameters evolution of traction induction motor.
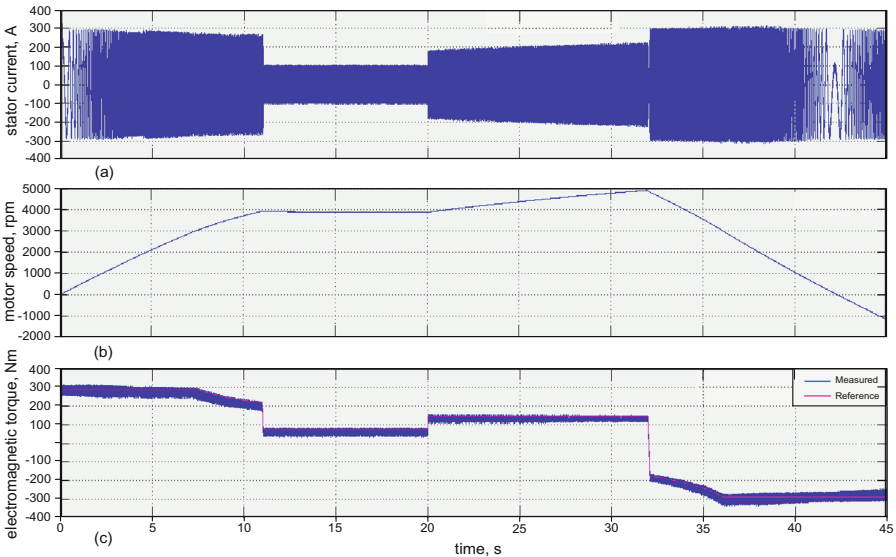

Fig. 5. Parameters evolution of traction induction motor

Refering to this figure, some comments are made:

– during starting (0–12 s), the stator current is around 300 A at constant magnitude and its frequency increases with increasing in speed. The electromagnetic torque is quite constant around 300 Nm;
– at time t = 12 s the rotor speed becomes almost constant at 4000 rpm and maintained in a time of 8 s. During this time the stator current decreases at a third of the current value of the acceleration and electromagnetic torque becomes constant having 60–70 Nm. These are the values of current and torque to keep speed rotor shaft that drives the vehicle at a constant speed, but over rated motor speed.
– at time t = 20 s the speed is controlled to rise, so it is a slower acceleration. There is a low constant torque region sufficient to achieve a slower acceleration.

In Fig. 6 a simulation of the vehicle acceleration is presented, during 45 s until the maximum speed of 160 km/h.
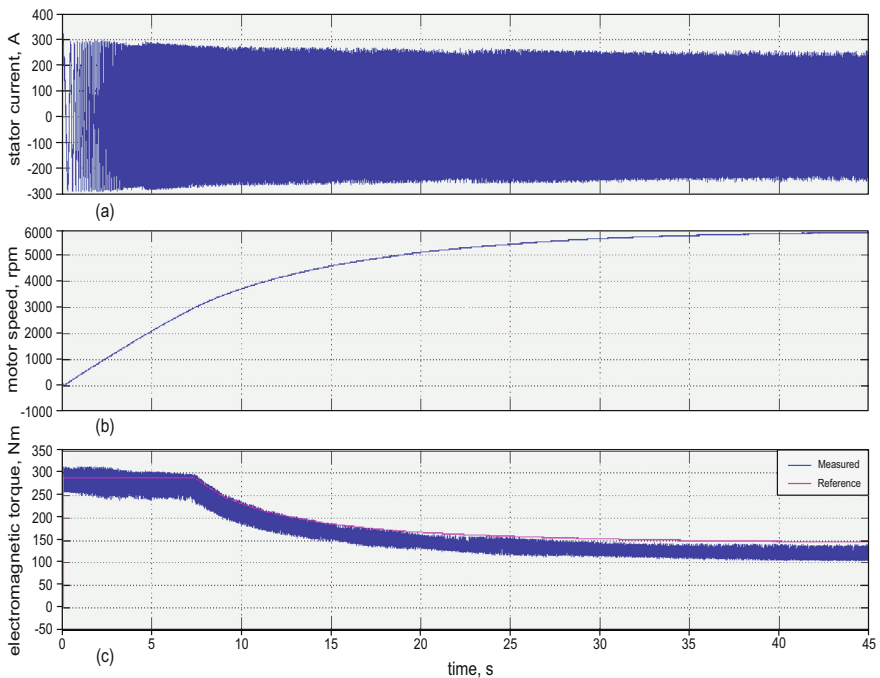
Fig. 6. Simulation of vehicle acceleration

5   Conclusions

This paper presents computer modeling and simulations related to a system drive for vehicle propulsion with an induction motor control system based on VSC strategy. As future research the author follows the implementation of a soft controller which combines the VSC advantages with the MFC.

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