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Wheel Load Torque Emulation for Electric Propulsion Structure using Dual Induction Motors

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ABSTRACT

Electric vehicle is an adaptation of conventional vehicle, with an integration of electrical motors. It seems to be one of the most promising technologies that can lead to significant improvements in vehicle performance and polluting emissions. However, for any vehicle in urban traffic requires regime changes, frequent acceleration, deceleration, and stopping phases, which lead to serious breakdowns. During the above phases, electric motors are continuously being exposed to thermal and mechanical effects.This paper highlights the possibility of representing the wheel load torque emulation of an electric propulsion structure using dual induction motors vector-controlled. The emulation of load torque acting on one of both electric motors placed at the rear wheels of electric vehicle (EV) structure is accomplished by a DC-generator coupled with an induction motor during vehicle drive cycle operation andunpredictable load profiles. Simulation results confirm widely the feasibility and the effectiveness of the proposed emulator scheme of induction motor-based vector-control in the electric vehicle application.

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NOMENCLATURE

R_a, L_a	Armature resistance, armature inductance	ϕ_{rd}, ϕ_{rq}	Quadrate , direct rotor flux components
U_a, i_a	Armature voltage, armature current	L_r, T_r	Rotor induction, rotor time constant
K_ϕ	Constant based on flux and machine construction	ω_s, M	Synchronous angular speed, mutual inductance
i_{sd}, i_{sd}	Direct, quadrate stator current compnents	Ω	Speed of motor
Ω_o, Ω_{diff}	EV speed, speed-difference	Ω_{Left}, Ω_{Right}	Speeds of left motor 1, right motor 2
e_a	Generated voltage	R_s, L_s	Stator resistance and winding inductance
J_{IM}, J_{DCG}	IM inertia, DC-generator inertia	v_{sd}, v_{sq}	Stator voltage
f_{IM}, f_{DCG}	IM friction, DC-generator friction	σ	The redefined leakage inductance
T_L, T_e	Load torque, electromagnetic torque	J_{tot}, *	Total inertia, input command variable
e_d, e_q	Nonlinear coupling terms	θ_s	The rotor flux position angle
p	Number of pole pairs	f_{tot}	Total viscous friction of the coupled system

1. INTRODUCTION

Environment protection and energy conservation have urged the development of electric vehicle (EV). It seems to be one of the most promising technologies for the next century and will probably be one of the most interesting solutions to the rational and effective use of energy reducing environmental damage caused by conventional vehicles [1, 2].

Electric vehicles present a lot of similarities with conventional vehicles which are already optimized for minimum energy consumption in rolling. EV is an adaptation of conventional vehicle; with an integration of electrical motors.

Different research works of EV configurations and drive association possibilities can be found in literature, e.g., one to four electrical motors, direct current or alternative current motors, with or without a clutch and a

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gearbox, etc. [3, 4]. Electric propulsion control system or power train is the main part of an EV. It consists of three main blocs: electric motors, power electronic converters and command or controller. The controller bloc is an essential part of an EV. Therefore, electric propulsion system cannot be designed without this bloc. In fact, it's undoubtedly essential to control or to get optimal operations during the different propulsion phases: starting, acceleration, deceleration, cruising and stopping phases. During the above operations, electric motors are continuously being exposed to load disturbances, road gradient, surface roughness and various traffic conditions effects. The occurred effects might influence electric motor control and from which the control of the vehicle might be lost. Therefore, in order to maintain desired performances even in the presence of any external disturbances, particularly, motor mechanical load changes. Motor control system with high robustness is an important challenge in research due to its different applications. Therefore, motor mechanical loads identification and analysis under parametric variations of the load are often problematic. Thus, several research studies in the literature have focused on EV emulation system, proposing different approaches [5-23]. In fact, motor mechanical load emulation allows to analyze a motor performance under real operation condition.

However, in most cases studied, the main elements for motor load emulation are an electric dynamometer and its control system. On this topic, main used strategies directly related to the control system include field-oriented control (F.O.C.), direct torque control (D.T.C.) and position control [6-11]. Other research works has been proposed in literature [12-21] using different test benches platforms with different emulation approaches.

The interest of the emulator is to be able to introduce different loads and disturbances which can be applied to the vehicle wheel and which in fact are reported on any profile. This explains why these applications are generated via a torque controller by a DC-generator. Therefore, the load emulation must follow any regime regarding load variation according to a desired load profile. In this context, after this brief outline (research background) of the most important studies related to the emulation system; this paper highlights the possibility of representing the wheel load torque emulation of an electric propulsion structure purposed for an EV using dual-induction motors vector-controlled, which separately drive the rear wheels of the vehicle. The aim of this paper is to check the wheel load torque emulator based propulsion structure performance in the face of the unpredictable load profiles acting on one of both electric motors encountered during vehicle drive cycle operation with specific maneuvers.

For this purpose, a control scheme was developed for a DC-generator coupled with an induction motor and takes into account the effect of rotational inertia. The simulation results showed a good performance of the control system and also validated the feasibility of the proposed emulator scheme for three scenarios, of unpredictable load profiles as shown further from three loads profiles in section 4.

The paper is organized as follows. Section 2 presents the field-oriented control (FOC) of induction motor. In section 3, we will first present the proposed electric propulsion structure using dual induction motors, then the emulator block diagram. Simulation results are presented in section 4. Conclusion is done in section 5.

2. FIELD-ORIENTEDCONTROL

The complex mathematical model and non-linear characteristic make the control of an induction motor difficult and call for the use of a high performance control algorithms such as vector control, commonly called Field-Oriented Control (F.O.C.). This is a strategy that provides a decoupled control similar to a DC motor, between flux and torque of an induction motor [24-26]. With decoupling between magnetizing flux and torque, the torque producing component of the stator flux can be controlled independently.

Based on the orientation rotor flux process described by the imposed zero constraint of quadrate rotor flux component, such as [24, 25]:

$$\phi_{rq} = 0 \text{ and } \phi_{rd} = \phi_r \tag{1}$$

where ϕ_{rq}, ϕ_{rd} : quadrate, direct rotor flux components.

When the rotor flux orientation assumption is verified, the basic field-oriented control expressions of an induction motor (IM) are simplified as:
The stator voltage equations are given by [24, 25]:

$$v_{sd} = (R_s i_{sd} + \sigma L_s \frac{di_{sd}}{dt}) + e_q \tag{2}$$

$$v_{sq} = (R_s i_{sq} + \sigma L_s \frac{di_{sq}}{dt}) + e_d \tag{3}$$

The nonlinear coupling terms are [24]:

$$e_d = \omega_s (\sigma L_s i_{sd} + \frac{M}{L_r} \phi_r) \tag{4}$$

$$e_q = \frac{M}{L_r} \frac{d\phi_r}{dt} - \sigma L_s \omega_s \tag{5}$$

where R_s, L_s denote stator resistance, stator winding inductance. σ is the redefined leakage inductance. i_{sd}, i_{sq}, denote direct, quadrate stator current components. ω_s, M, L_r, ϕ_r are: synchronous angular speed, mutual inductance, rotor inductance and rotor flux, respectively.
The rotor flux formulation is [24]:

$$\phi_r = \frac{M}{1+T_r S} i_{sd} \tag{6}$$

T_r, S: rotor time constant, differential or laplaceoperator, respectively.
The rotor flux position angle can be derived by [24]:

$$\theta_s = \int (\omega_s + p\Omega)dt \tag{7}$$

The electromagnetic torque is [24]:

$$T_e = p\frac{M}{L_r}\phi_{rd} i_{sq} \tag{8}$$

p denotes the number of pole pairs. From Equation (8) it's very clear, that the electromagnetic torque can be controlled only from quadrate stator current component i_{sq} when the rotor flux is maintained constant. This is appropriate for EV applications, for which the loads can be largely varied. From this point of view, the induction motor does not operate normally in filed weakening region; thus, the flux must be maintained constant to its rated value.

3. ELECTRIC PROPULSION STRUCTURE

For conventional vehicle, when a turn is reached, the speed difference of the rear wheels is regulated via a mechanical differential in order to avoid vehicle slipping. This mechanical device is an arrangement of gears connecting two shafts on the same line and enabling one shaft to revolve faster than the other when required. So when the inner wheel speed is reduced, the outer one is increased. Besides the mechanical means, the differential action of an EV when cornering can be electrically provided by two electric motors operating at different speeds [3].
As can be seen from Figure 1, for the proposed electric structure, this difference is regulated by an electric differential based on two induction motors operating at difference speeds drives separately the rear wheels of the vehicle via fixed gearing [27].

The differential function has to verify the following expressions [28]:

$$\begin{cases} \Omega_{Left} = \Omega_o + \Omega_{diff} \\ \Omega_{Right} = \Omega_o - \Omega_{diff} \end{cases} \tag{9}$$

where Ω_{Left}, Ω_{Right}: speeds of left motor 1, right motor 2.

Therefore, from the above system of equations (9), the vehicle speed Ω_o and the difference speed Ω_{diff} may be done simply by [28]:

$$\begin{cases} \Omega_o = \frac{1}{2}(\Omega_{Left} + \Omega_{Right}) \\ \Omega_{diff} = \frac{1}{2}(\Omega_{Left} - \Omega_{Right}) \end{cases} \tag{10}$$

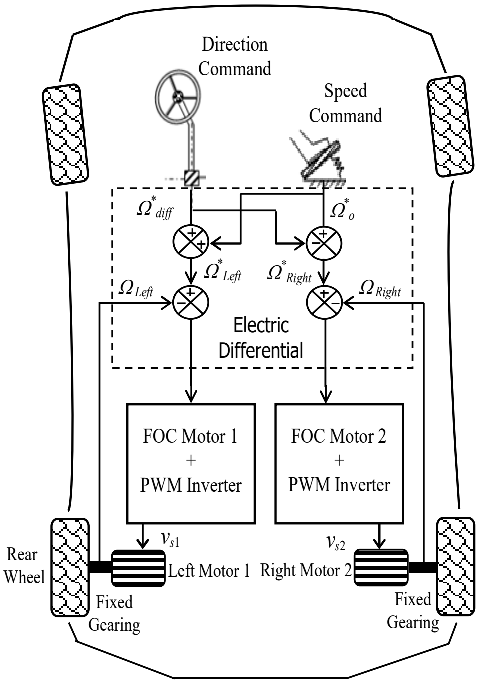

Figure 1. Electric propulsion structure

As mentioned before, for the purpose of emulating a wheel load torque acting on one of both electric motors for an EV structure, a control scheme consisting of an induction motor vector controlled connected to a DC-generator has been presented.

Let us first present the mathematical model of a DC-generator given by the following equations.

The armature voltage can be written as [21]:

$$U_a = -(R_a i_a + L_a \frac{di_a}{dt}) + e_a \tag{11}$$

where R_a, L_a, i_a, denote armature resistance, armature inductance and armature current, respectively.

The generated voltage e_a is relative to rotational speed by [21]:

$$e_a = K_\phi \Omega \tag{12}$$

where $K\phi$, Ω, denote a constant based on flux and machine construction, rotational speed.

The load torque is related to armature current bytorque constant [21].

$$T_L = -K_\phi i_a \tag{13}$$

Knowing that the induction motor is coupled with a DC generator, the mechanical equation can be written as [21]:

$$T_e = J_{tot}\frac{d\Omega}{dt} + f_{tot}\Omega + T_L \tag{14}$$

where T_e is the electromagnetic torque, Ω is the rotating speed, T_L is the load torque and J_{tot}, f_{tot} are total inertia, total viscous friction of the coupled system (Induction motor and DC-Generator) respectively, expressed by

$$J_{tot} = J_{IM} + J_{DCG} \tag{15}$$

$$f_{tot} = f_{IM} + f_{DCG} \tag{16}$$

Based on the system's block diagram shown in Figure 2, emulating wheel load torque is realized with a DC-generator torque control using a PI controller.

4. SIMULATION RESULTS AND DISCUSSION

The aim of this section is to check the wheel load emulator-based EV performance in the face of the load disturbances encountered during specific maneuvers.

Simulation results are carried out under a desired torque load for three different profiles (scenarios) using MATLAB/Simulink software package where rated data are given next in Tables 1 and 2.

The main idea is to test both a control scheme for torque load emulation acting on one of both electric motors encountered during vehicle drive cycle operation, taking into account the effect of rotational inertia, as well as to verify the validity of the electric differential principle resulting from the pruposed propulsion struture may be used in EV substituting the conventional mechanical differential system.

In order to verify the control scheme performances, particularly when the vehicle accomplishes the turning maneuvers, let us take a given speed profile for the EV defined as illustrated in Figures 3, 5, 7and the evolution of line stator current under the load perturbations based on three references profiles (references 1, 2 and 3) presented in Figures 4, 6 and 8, respectively.

From a starting point, the vehicle starts with a constant acceleration until attains the speed of 118 rad/s, then it will be maintained constant. After, the vehicle will turn left, the electric differentialaction allows the outer (right) wheel to rotate faster than the inner (left) wheel: $\Omega_{Right},>\Omega_{Left}$. Then the vehicle should continue directly its trajectory by a constant cruising speed, it results inequality of the two motors speed: $\Omega_{Right}=\Omega_{Left}$.

As may be seen in Figures 3-8, for all scenarios the simulation results show that the load emulation method is effective, and has good adaptability to unpredictable load profiles associated with specifics vehicle maneuvers.

Figures 3, 5 and 7 show that the speed response follows its refernce precisely. The same figures also illustrate the time evolution of the first phase stator current. The current behave according to the dynamic behaviour of the motors,where its magnitude changes following the developed load torque.

Figures 4, 6 depict the load torque responses according to the load references 1 and 2, respectively. Desipate the load variation, the responses that were obtained arevery close for the desired and the emulated torque load with relatively very small emulation error.

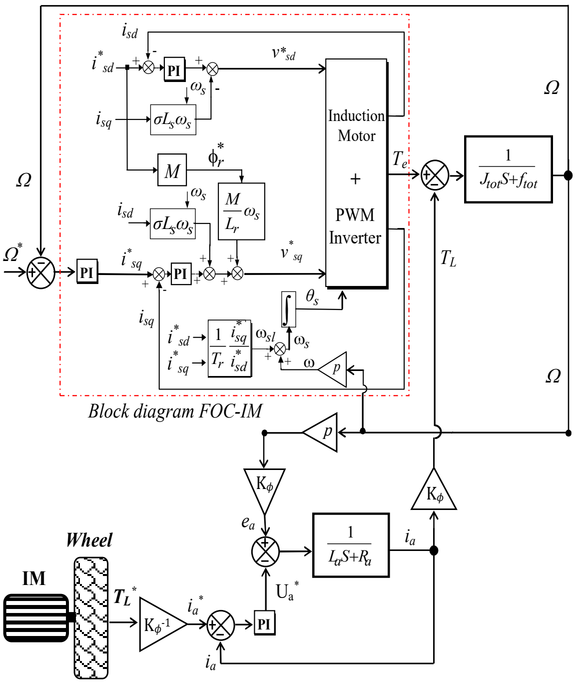

Figure 2. Emulator block diagram

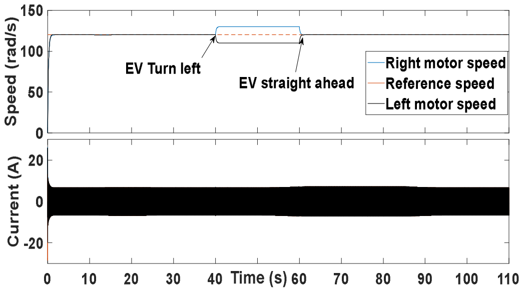

Figure 3. Speed and current evolution versus times

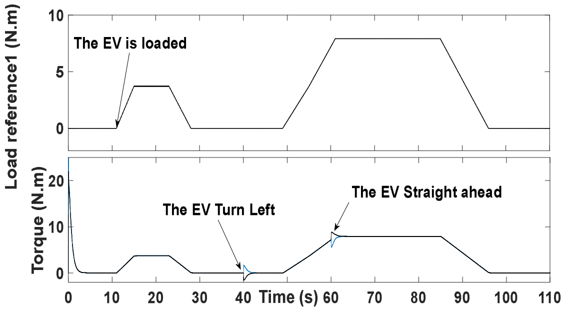

Figure 4. Torque response versus times for load reference 1

Further, to test severely the control scheme performances, another test is carried out, in Figures 7, 8 and its zoom in Figure 9 for the load perturbation profile (reference 3), taking into account the measurement noise effect.

In this case, reference load and the emulated load response show close correspondance, but associated with torque oscillations.

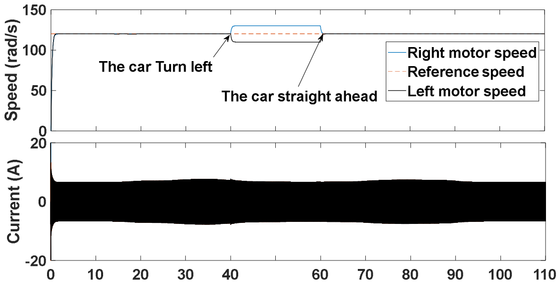

Figure 5. Speed and current evolution versus times

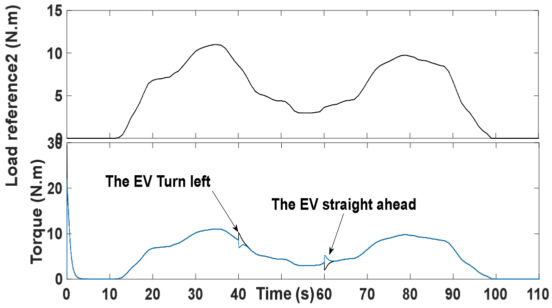

Figure 6. Torque response versus times for load reference 2

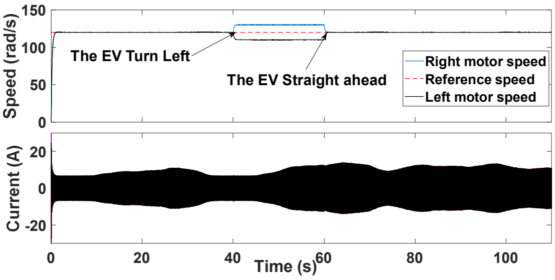

Figure 7. Speed and current evolution versus times

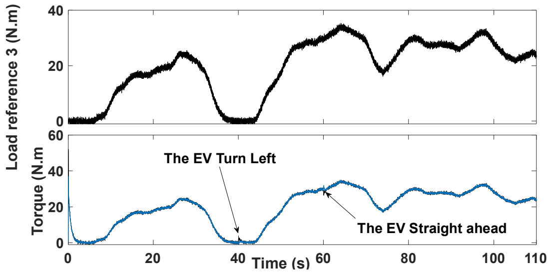

Figure 8. Torque response versus times for load reference 3

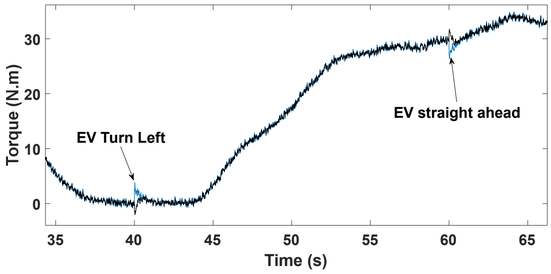

Figure 9. Zoom of torque response for load reference 3

TABLE 1. Induction motor paprametrs

Parameters	Values	Unity
Power	1.1	kW
Speed	1400	rev. min^{-1}
Stator phase resistance R_s	7.5	Ω
Rotor phase resistance R_r	3.8	Ω
Stator inductance L_s	0.3594	H
Rotor inductance L_r	0.3032	H
Mutual inductance M	0.303	H
Rotor inertia J_{IM}	0.0052	Kg.m^2
Friction coefficient f_{IM}	0.0005	Nm.s.rd^{-1}
Number of pole pairs p	2	

TABLE 2. DC-Generator paprametrs

Parameters	Values	Unity
Power	1.5	kW
Speed	1400	rev. min^{-1}
Armature resistance R_a	1	Ω
Armature inductance L_a	0.005	H
Constant $K_\emptyset$	1	V.s
Inertia J_{DCG}	0.0015	Kg.m^2
Friction coefficient f_{DCG}	0.0001	Nm.s.rd^{-1}

5. CONCLUSIONS

In this paper, we focused on emulating a wheel load torque of an electric propulsion structure using dual induction motors vector-controlled. For that purpose, a control scheme using a DC-generator coupled with an induction motor has been adopted to carry-out control tests during specifics vehicle maneuvers for different unpredictable torque load profiles (scenarios).

Simulation results confirm widely the feasibility and the effectiveness of the emulation scheme applied for electric vehicle. In fact, the speed responses have a good dynamic reference speed tracking, while the emulated torque load closely matches of the desired load torque with relatively very small emulation error for different scenarios, but only torque oscillations for the load profile with measurement noise effect exist.

The investigation of the impact of the emulation of more complex load behaviors, the variation in rotational inertia and a hot values of phase resistances on the emulation performance, this last case might be occurred. For example, when one wheel vehicle is stopped by a strong obstacle while the induction motor is called to develop an important torque under zero speed, as well as the implementation and experimental validation of the emulation scheme applied for EV propulsion structure via a test bench, which constitute others interesting topics, will be the subject of future works.

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Persian Abstract

چکیده

خودروی الکتریکی اقتباسی از وسیله نقلیه معمولی با ادغام موتورهای الکتریکی است. به نظر می رسد این یکی از امیدوارکننده ترین فناوری هایی است که می تواند به بهبود قابل توجهی در عملکرد خودرو و انتشار آلاینده ها منجر شود. با این حال، برای هر وسیله نقلیه ای در ترافیک شهری نیاز به تغییرات رژیم، شتاب گیری مکرر، کاهش سرعت و مراحل توقف است که منجر به خرابی های جدی می شود. در طول مراحل فوق، موتورهای الکتریکی به طور مداوم در معرض اثرات حرارتی و مکانیکی قرار می‌گیرند. این مقاله امکان نمایش گشتاور بار چرخ را در ساختار پیشرانه الکتریکی با استفاده از موتورهای القایی دوگانه با کنترل بردار نشان می‌دهد. تقلید گشتاور بار که بر روی یکی از هر دو موتور الکتریکی قرار گرفته در چرخ‌های عقب ساختار خودروی الکتریکی (EV)عمل می‌کند، توسط یک ژنراتور DC همراه با یک موتور القایی در طول عملیات چرخه رانندگی خودرو و پروفایل‌های بار غیرقابل پیش‌بینی انجام می‌شود. نتایج شبیه‌سازی به‌طور گسترده امکان‌سنجی و اثربخشی طرح شبیه‌ساز پیشنهادی کنترل بردار مبتنی بر موتور القایی در کاربرد خودروی الکتریکی را تأیید می‌کند.