This paper proposes a traction drive system for electric vehicles (EVs) with two separate induction motor drive-based wheels. In this context, two three-phase induction motors are associated to five legs power inverter which one leg is shared by two phases of the motors. The independent control of the two induction motors allows replacing the mechanical differential speeds by an equivalent electrical module called electric differential (ED). In the proposed EV powertrain based on 5-leg inverter, the challenge is to achieve a decoupled control of the induction motors to ensure the EV stability while cornering or under slippery road condition. For this, the proposed independent control uses Indirect Field Oriented Control to ensure speed and rotor flux control of each induction motor, a Pulse Width Modulation to provide the command sequences to the 5-leg inverter and electric differential to generate the appropriate reference when the two induction motors should be controlled at different speeds. For this, a numerical implementation of the independent controls on an embedded board (TMS 320F2812) to ensure a separate control of induction motor fed by the 5-leg inverter. Moreover, the proposed control takes into account the EV context such as the EV dynamic and uses European and American normalized driving cycles. EV-specific experimental tests on a digital signal processor TMS320LF2812 are carried out to show the effectiveness of the proposed independent control for ED in terms of robustness and stability.

Keywords: 5-leg inverter; electric vehicle; independent control; indirect field oriented control; induction motor; PWM.

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1. Introduction

The electric powertrain system is the heart of EV. It consists of the motor drive, transmission device, and wheels. In fact, the motor drive, comprising of the electric motor, power converter, and electronic controller, is the core of the EV powertrain system. Indeed, many advanced technologies are employed to extend the driving range and reduce the cost [1].

Focusing on the variation in electric powertrain, there are many possible EV configurations due to the variations in electric propulsion and energy sources: single-motor and multi-motor configurations. In this paper, the focus has been put on a two-wheel drive configuration. This configuration includes at least two independent electric powertrain which two electric motors are connected to the wheels by a fixed reduction gears. Indeed, the induction motor has been adopted as the EV propulsion base. The separate control of
the induction motors allows replacing the mechanical differential speeds by an equivalent electrical module called electric differential (ED) (Fig.1) [2-3].

In general, EV powertrain of two-wheel drive configuration require two three-phase inverters feeding two induction motors [4-5]. Each three-phase inverter contains six legs and each leg has two electronic power switches (IGBTs - Insulated Gate Bipolar Transistors).

In this context, this paper proposes an EV powertrain based on only five legs inverter feeding the two induction motors. This EV powertrain allows reducing power switches, mechanical components and therefore the cost [6-7].

Moreover, in the event of a failure in the power inverter, conventional EV powertrain with six legs cannot ensure the vehicle traction operation. In this case, during post-fault operation, the faulty leg is isolated by a specific switch (i.e. fast-acting fuse) and the drive operates with 5-leg inverter [8]. So, using five legs inverter in EV powertrain can: 1) reduce the number of power electronic and mechanical devices required in two drive wheels EV configuration [9-10]; 2) reduce the overall complexity and therefore the EV powertrain cost [11]; and 3) operate the system in faulty conditions [12].

In the proposed EV powertrain based on 5-leg inverter, the challenge is to achieve an independent control of the induction motors allowing the implementation of an electric differential to ensure the EV stability while cornering or under slippery road condition. For this, the proposed independent control is based on the Indirect Field Oriented Control (IFOC) to ensure speed and rotor flux control of each induction motor. Indeed, a specified Pulse Width Modulation based on the zero-sequence component is associated to the main control that can provide the command sequences to the 5-leg inverter.

Finally, the following points are used to achieve this goal: 1) A numerical implementation of the independent controls on an embedded board (TMS 320F2812) to ensure a separate control of induction motor fed by the 5-leg inverter. 2) The proposed control takes into account the EV context such as the EV dynamic and uses European and American normalized driving cycles. 3) The control system includes an electric differential to ensure the EV stability while cornering or under slippery road condition.

Specific experimental tests on a DSP TMS 320F2812 are carried out to demonstrate the feasibility and the effectiveness of the proposed independent control for electric differential in terms of robustness and stability.
2. Notation

The notation used throughout the paper is stated below.

**EV** Electric vehicle;
**ED** Electric differential;
**IM** Induction motor;
**IFOC** Indirect field oriented control;
**PWM** Pulse width modulation;
**FG** Fixed gear;

*Indexes:*

- $l, r$: Left and right motor subscripts.
- $s, (r)$: Stator (rotor) index;
- $d, q$: Synchronous reference frame index;
- $a, b, c$: Three phases reference frame index;
- $V (I)$: Voltage (Current);
- $R$: Resistance;
- $L (L_m)$: Inductance (Magnetizing inductance);
- $\sigma$: Leakage coefficient, $\sigma = 1 - L_m^2 / L_s L_r$;
- $T_r$: Rotor time constant ($T_r = L_r / R_r$);
- $T_s$: Stator time constant ($T_s = L_s / R_s$);
- $p$: Pole-pair number;
- $v$: Vehicle speed;
- $F_w$: Road load;
- $F_{ro}$: Rolling resistance force;
- $F_{sf}$: Stokes or viscous friction force;
- $F_{ad}$: Aerodynamic drag force;
- $F_{cr}$: Climbing and downgrade resistance force;
- $P_v$: Vehicle driving power;
- $J$: Total inertia (rotor and load);
- $\omega_m$: Electric motor speed;
- $T_B$: Load torque accounting for friction and windage;
- $T_L$: Load torque;
- $\text{ref}$: Reference index;
- $T_m$: Electric motor torque.

3. Electric Vehicle and Dual-Motor Configuration

There are several possible EV configurations regarding the electric propulsion and the energy sources. In the adopted dual-motor configuration, two three-phase PWM inverters are associated to two induction motors for the EV propulsion [13-14]. In particular, the proposed electric power train consists in the association of a 5-leg inverter to drive the two induction motors as show by Fig. 2a. This topology allows the reduction of the number of the power components and therefore the weight and the cost of the EV powertrain. In other hand, this structure can also be used in event of an IGBT failure [15].
4. Vector Control for Electric Differential-Based Electric Vehicle Traction Drive

The proposed independent control for ED-based EV dual-motor traction drive is shown in Fig. 3. In this configuration, the EV wheels are coupled to the induction motors via fixed gears. The left and right induction motors are fed by five leg power inverters and controlled by an indirect field oriented control associated to an appropriate PWM strategy. In a turning way, the quantity provided by the steering wheel is added to the vehicle reference speed for the external wheel and extracted from the vehicle reference speed for the internal wheel. This will generate the left and right induction motor reference speeds.

![Fig. 3. Proposed EV propulsion and control system schematic diagram.](image-url)
4.1. Vector Representation of a 5-Leg PWM Inverter

Figure 2b shows the 5-leg inverter feeding two induction motors using the common leg C. The voltage vector applied to the two induction motors in Concordia frame ($\alpha, \beta$) of the 5-leg inverter is defined by:

$$\bar{V}_s = V_{sa} + jV_{sb}$$

$$= \sqrt{2}E \left[ V_a + V_d e^{\frac{2\pi}{5}} + V_c e^{\frac{2\pi}{5}} + V_d e^{\frac{4\pi}{5}} + V_c e^{\frac{4\pi}{5}} \right]$$

where $V_a$, $V_b$, $V_c$, $V_d$, and $V_e$ are the inverter voltages.

As each switch has only two possible states (open or closed), the 5-leg inverter has 32 different voltage vectors [16-17].

4.2. Indirect Field Oriented Control

IFOC aim is to decouple flux and torque control [18-19]. To achieve this goal, the flux must be oriented on the $d$-axis in the $d-q$ frame and the flux $q$-axis component set to zero [20].

$$\begin{align*}
\phi_{rd} &= \phi_r \\
\phi_{rq} &= 0
\end{align*}$$

(2)

The induction motor model in the $d-q$ reference frame is then described by

$$\begin{align*}
V_{sd} &= R_s I_{sd} + \sigma L_s \frac{dI_{sd}}{dt} + \frac{M}{L_r} \frac{d\phi_r}{dt} - \omega_s \sigma L_s I_{sq} \\
V_{sq} &= R_s I_{sq} + \sigma L_s \frac{dI_{sq}}{dt} + \omega_s \frac{M}{L_r} \phi_r + \omega_s \sigma L_s I_{sd} \\
T_r \frac{d\phi_r}{dt} + \phi_r &= M I_{sd} \\
\omega_{sl} &= \omega_s - \omega_r = \frac{M I_{sq}}{T_r \phi_r}
\end{align*}$$

(3)

And the steady-state motor torque can be written as

$$T_e = p \frac{M}{L_r} \phi_r I_{sq}$$

(4)

4.3. Pulse Width Modulation Strategy for 5-leg inverter
The 5-leg inverter is used to feed two induction motors (Fig. 2b) sharing leg C. Legs A and B of the inverter are connected directly to phases $a_1$ and $b_1$ of the first motor. Legs D and E are connected to the inverter phases $a_2$ and $b_2$ of the second motor.

The three-phase inverter is a voltage source, which can generally generate three-phase AC voltage by applying PWM techniques. PWM techniques applied to a three-phase inverter cannot be applied to 5-leg inverter to ensure independent control [21 -22].

Therefore, it is possible to provide various commands to each motor and control the 5-leg inverter under different conditions: different references, load and motor parameters.

The principle of this technique is applied to each leg of the inverter a control voltage calculated based on the common leg C of the inverter. It consists to set the control voltage of the common leg to zero. For that purpose, the reference voltages of the two motors can be written as

\[
\begin{align*}
V^*_A &= V^{*}_{a1} - V^{*}_{c1} \\
V^*_B &= V^{*}_{b1} - V^{*}_{c1} \\
V^*_C &= V^{*}_{c1} = V^{*}_{c2} = 0 \\
V^*_D &= V^{*}_{a2} - V^{*}_{c2} \\
V^*_E &= V^{*}_{b2} - V^{*}_{c2}
\end{align*}
\]

Where * denotes reference values; $V_A$, $V_B$, $V_C$, $V_D$ and $V_E$ are 5-leg inverter voltages; $V_{a1}$, $V_{b1}$, $V_{c1}$ and $V_{a2}$, $V_{b2}$, $V_{c2}$ are control voltages provided by the first and the second indirect torque controls, respectively. It should be noted that the control voltage applied to the common leg of the 5-legs inverter is set to zero.

The principle of this technique is summarized in Fig.4.

![Fig. 4. PWM strategy Scheme](image)

Where $(K_{11}, K_{12})$, $(K_{21}, K_{22})$, $(K_{31}, K_{32})$, $(K_{41}, K_{42})$ and $(K_{51}, K_{52})$ are respectively the control power switches of the legs A, B, C, D and E of the inverter.
In this technique, the reference voltages calculated by the indirect field oriented control are replaced by control voltages calculated based on the common leg C of the 5-leg inverter.

4.4. Electric Differential

In two-wheel EV configuration, both induction motors are directly coupled to wheels to simplify the mechanical structure and therefore reduce the cost and the vehicle powertrain weight. For that purpose, the structure of this vehicle requires an electric differential to maintain the vehicle stability especially in turning ways.

To handle EV stability while cornering or under slippery road condition, the two induction motors should be controlled at different speeds. In this context, the electric differential allows to provide the speed reference of each induction motor [5]. The principle of the electric differential is shown by Fig. 3.

For the straight-line regime, the motor rotation speeds have the same value. For the turning regime, the rotation speeds for each motor are different [4].

5. Experimental Results

5.1. Experimental Setup

The test bench used to validate the proposed control strategies is illustrated by Fig. 5. Its main components, in addition to the induction motors, whose ratings are given in the Appendix, are: 1) a DSP TMS320F2812 development board interfaced to a standard PC, 2) speed sensors attached to the motors shafts, 3) Hall effect sensors for voltage and current measurements, 4) a 5-leg PWM inverter. The load torque is provided by a braking powder to emulate the EV dynamics.

![Experimental Setup Diagram](image)

Fig. 5. The experimental setup.

The DSP system is interfaced to a standard PC. At each sampling instant, the DSP receives stator current and voltage measurements and then runs the PWM algorithm, the IFOC scheme and the electric differential.
The control algorithm is implemented on the DSP through Matlab and the code Composer software. To load the program, Real Time Workshop module (RTW) of MATLAB Simulink compiles automatically the source code to build applications and implement them in real time.

The experimentally obtained results are then summarized in the following section.

5.2. Experimental Results

Figure 6 illustrates the first induction motor responses. To check out the independent control, a different reference speed is given to the first induction motor. For this, the following driving cycle is emulated: acceleration, constant speed, and deceleration.

As shown by Fig. 6a the speed of the first induction motor perfectly follows its reference. Moreover, the motor absorbs a sinusoidal current such as fed by conventional three-phase inverter, which means fewer torque ripples (Fig. 6b).

![Induction motor speed.](image1)

![Induction motor currents.](image2)
c) Line to line voltages.

d) Currents delivered by the 5-leg inverter to the first motor.

Fig. 6. First induction motor responses.

The motor voltages of the 5-leg inverter of the first induction motor presented by Fig. 6c are similar to those provided by a conventional three-phase inverter.

At different induction motors speeds, the common leg, shared by two the induction motors phases, generates non-sinusoidal current, represented by the orange line, as shown by Fig. 6d (upper curve). The green and the blue line in the lower curve of Fig. 6d represents the current of the induction motor phases.

As show by Fig.6, the first induction motor can maintain the reference speed with a sinusoidal current despite the common leg delivers a non-sinusoidal current.

Figure 7 represents the second induction motor responses. In this case, the speed reference has been changed to confirm the tracking performance. As in the first case, the second induction motor perfectly follows its reference (Fig. 7a). The motor also absorbs a sinusoidal current such as fed by conventional three-phase inverter (Fig. 7b). The motor voltage of the 5-leg inverter of the first induction motor is given by Fig. 7c.
a) Induction motor speed.

b) Induction motor currents.

c) Line to line voltages.
The common leg, shared by two induction motors phases, generates non-sinusoidal current as shown by Fig. 7d (lower curve) at different inductions motors speeds. In Fig. 7d, the common leg current is given by the orange line. The purple and the blue line represent the two current phases.

As show by Fig.7, the second induction motor can also maintain the reference speed with a sinusoidal current despite the common leg delivers a non-sinusoidal current.

To test decoupling control performance, two different speeds trajectories for the two induction motors are imposed (Fig. 8).
b) Second scenario.

Fig. 8. Induction motors speeds.

In Fig.8, blue and orange lines represent respectively the first and the second induction motors speeds. As shown by this figure, the proposed technique ensures the separate control of the two induction motors and therefore confirms their independent control.

At different induction motors speeds, the common leg provides a non-sinusoidal current (lower curve) as given by Fig. 9a. The upper curve of Fig.9a shows one phase current absorbed by the induction motor.

At the same induction motor speeds, the common leg provides a sinusoidal current (lower curve) as shows by Fig. 9b. In this case, the common leg current has an amplitude equals two times the induction motors currents with the same frequency. Figure 9b (upper curve) represents one phase current absorbed by the induction motor.
6. EV Application

In order to evaluate the proposed independent control strategy performance, simulations have been carried-out on an electric vehicle using a 37-kW induction motor-based powertrain. The EV and the used cage induction motor rated data and parameters are given in the Appendix.

The proposed control strategy takes into account the EV aerodynamics, and is not applied to the sole induction motor.

6.1. Electric Vehicle Modeling and Dynamics

The vehicle model is based on mechanics and aerodynamics principles [23]. The road load is then given as follows.

\[ F_w = F_{ro} + F_{sf} + F_{ad} + F_{cr} \]  

(6)

The power required to drive the EV at a speed \( v \) has to compensate the road load \( F_w \) and is given as follows.

\[ P_v = vF_w \]  

(7)

The mechanical equation (in the motor referential) used to describe each wheel drive is expressed by

\[ J \frac{d\omega_m}{dt} + T_H + T_L = T_m \]  

(8)

6.2. Vehicle Reference Speed Profile

To evaluate the EV dynamic performances with a 5-leg inverter, a series of tests for different load conditions were carried-out to emulate different types of traction behavior. For that purpose, a New European Driving Cycle (NEDC) and a Federal Urban Driving Schedules (FUDS) are used as speed reference.
Moreover, to validate the proposed independent control with the electric differential, three driving scenarios are simulated: straight line, right turning, and left turning.

Figs. 10 and Figs. 11 illustrate the EV induction motor speeds with NEDC and FUDS driving cycles. In the two turning ways (left and right) the electric vehicle is maintained constant.

In left and right turning scenarios, the ED gives different reference speeds to maintain the stability of the EV. In straight-line regime, the ED generates the same reference speeds of the two induction motors.

**Fig. 10.** EV induction motors speeds with the NEDC driving cycle.

**Fig. 11.** EV induction motors speeds with the FUDS driving cycle.

7. Conclusion

This paper dealt with an independent control for ED-based EV. In this case, The EV traction drive system uses two separate induction motors fed by 5-leg inverter-based wheels. The proposed system for ED will reduce the power components, thus improving the overall reliability and efficiency in event of power inverter failure in classical system with two three-phase inverters. The independent control for ED has been developed to handle the EV stability while cornering or under slippery road conditions. For that purpose, it uses an IFOC and an appropriate PWM strategy. The carried-out specific experimental tests on a DSP TMS 320F2812 have clearly demonstrated the feasibility and the effectiveness of the proposed independent control for ED in terms of robustness and stability.
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