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New independent control of a Bi Machine system powered by a multi-leg inverter applied to four in-wheel motor drive electric vehicle

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ABSTRACT

The four-wheel-drive electric vehicle's traction chain is powered by four permanent-magnet synchronous motors (PMSM), powered by a single three-phase, five-leg inverter (FLI). In order to achieve the behavior of a mechanical differential and to require the parallel wheel-motors to turn at identical or different speeds, using this structure, an independent control is applied on each driving wheel. For this particular structure, there is a shared inverter leg between the two phases of two machines. The other two phases of each machine are attached to their own two inverter legs. This work's main focus is the suggestion of a new DTC technique for the control of an electric vehicle (EV) with two set bi-PMSM motor-wheels fed in parallel by a single three-phase five-leg inverter. The simulation results show that this new control technique can ensure excellent dynamics of the electric vehicle driving system.

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1. INTRODUCTION

One of the most typical configurations in electric vehicles is the incorporation of an electric motor inside a wheel [1], [2]. We always seek to carry out an independent control of each motor-wheel. This is made possible by the use of an all-electric motorization, i.e. using an electric vehicle with all-wheel drive. These in-wheel motors are individually controlled to deal the wheel torque according to steering, acceleration or braking commands from the driver [3]-[5].

In the field of electric traction, multi-machine multi-converter systems (MMS) play a significant role [6]. These systems are usually employed as individual systems, where each electrical machine is powered by a separate inverter and is independently controlled by vector control and DTC. In these systems, depending on the number of machines used, the power electronics components, microprocessors, microcontrollers and sensors are duplicated.

Numerous researches have been done to lower the number of inverters [7]-[10]. Developing new control techniques or revising the inverter's topology are two ways to improve the performance of multi-machine drives [11]-[14]. Recently, with the development of power electronic devices and the powerful microprocessors, greater attention is paid to systems comprising several electrical machines powered by a single inverter [15].

The use of a single three-phase voltage inverter that simultaneously feeds many motors can result in an attractive decrease in the multi-machine multi-converter systems (SMM) volumes [16]. Our approach is based on new power topology that can fed two or more electrical machines simultaneously and provide control rules to increase energy efficiency.

In recent years, for variable speed applications like the electric vehicle, numerous different motor topologies have been proposed. The PMSM is motivated by its high torque and power density and better efficiency among the electric actuators used in embedded systems [17]. Currently, direct torque control (DTC) for permanent magnet synchronous machine drives has received considerable attention in embedded systems, such as electric vehicles [16], [18]-[21].

In this work, in order to improve the stability of the all-wheel-drive electric vehicle during critical situations, we impose a new control technique on each set bi-PMSM motor-wheels fed by a single three-phase five-leg inverter. By imposing independent control on each driving wheel, this new control seeks to simulate the actions of a mechanical differential. The simulation results show that this new control technique can ensure excellent dynamics of the electric vehicle driving system.

2. POWER STRUCTURE OF THE TRACTION SYSTEM STUDIED

We have chosen the configuration presented in Figure 1 as the study system [22]. It is composed of four motors fed by a five-leg three-phase inverter and driving the four-wheel drive of an electric vehicle. The configuration chosen allows the machines to turn at the same or different speed profiles with different load torques (case of turns) [23]. In this study, we were interested in the improved DTC control of two machines fed by a three-phase five-leg inverter (with 10 switches). For the studied power structure, two phases of two motors share one inverter leg. The five-leg inverter's topology is depicted in Figure 2. It simultaneously supplies two three-phase PMSMs with two different phases and a common leg C between two phases (c1, c2). The five-leg inverter has 32 switching states that can be used to control the two motors, Figure 3. Using this topology, the two machines can operate at the same or different speeds [15], [24].

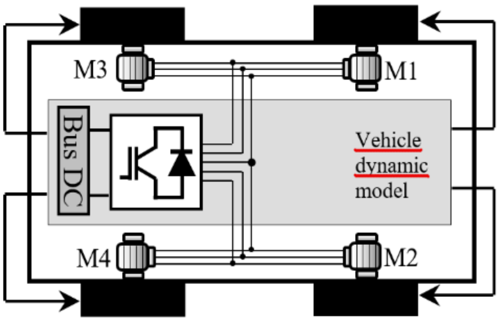

Figure 1. Configuration of the electric vehicle studied

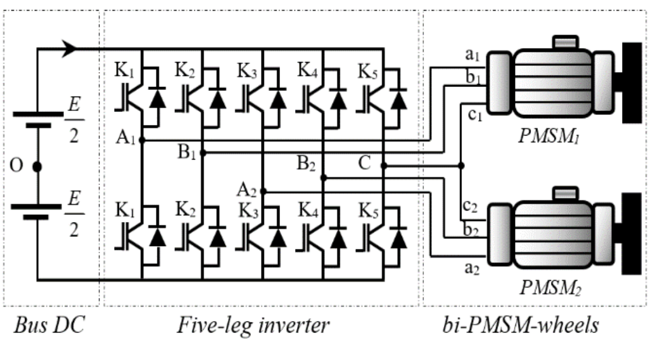

Figure 2. Parallel structure of bi-PMSM-wheels supplied by FLI

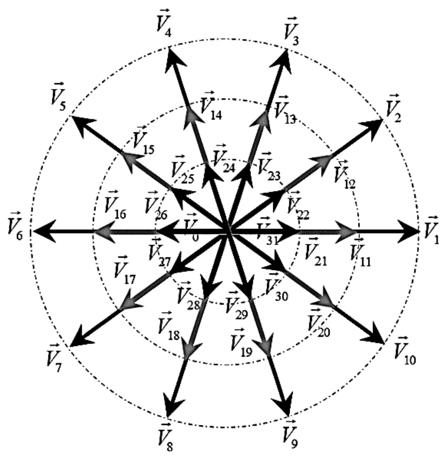

Figure 3. Illustration of the various FLI's vectors

The switching functions in FLI inverter are defined as [25]:

$$S_{ij} = \begin{cases} 1 \text{ if the upper switch is ON} \\ 0 \text{ if the upper switch is OFF} \end{cases} \; i = 1,\ldots,5 \text{ and } j = 1,2 \tag{1}$$

The five-leg inverter's voltage vector is given by (2):

$$\begin{aligned} \vec{V_s} &= V_{s\alpha} + jV_{s\beta} \\ &= \sqrt{\frac{2}{3}} E \left(S_{11} + S_{21} e^{j\frac{2\pi}{5}} + S_{31} e^{j\frac{4\pi}{5}} + S_{41} e^{j\frac{6\pi}{5}} + S_{51} e^{j\frac{8\pi}{5}} \right) \end{aligned} \tag{2}$$

The equations below can be derived from Figure 2 as (3):

$$\begin{cases} V_{A1N1} = V_{A1O} + V_{ON1} \\ V_{B1N1} = V_{B1O} + V_{ON1} \\ V_{CN1} = V_{CO} + V_{ON1} \\ V_{A2N2} = V_{A2O} + V_{ON2} \\ V_{B2N2} = V_{B2O} + V_{ON2} \\ V_{CN2} = V_{CO} + V_{ON2} \end{cases} \tag{3}$$

Assuming that the loads are equal, the following results as (4):

$$\begin{cases} V_{A1N1} + V_{B1N1} + V_{CN1} = 0 \\ V_{A2N2} + V_{B2N2} + V_{CN2} = 0 \end{cases} \tag{4}$$

Therefore:

$$\begin{cases} V_{ON1} = -\frac{1}{3}(V_{A1O} + V_{B1O} + V_{CO}) \\ V_{ON2} = -\frac{1}{3}(V_{A2O} + V_{B2O} + V_{CO}) \end{cases} \tag{5}$$

If (5) is substituted in (3), the following results (5):

$$\begin{cases} V_{A1N1} = \frac{2}{3}V_{A1O} - \frac{1}{3}V_{B1O} - \frac{1}{3}V_{CO} \\ V_{B1N1} = -\frac{1}{3}V_{A1O} + \frac{2}{3}V_{B1O} - \frac{1}{3}V_{CO} \\ V_{CN1} = -\frac{1}{3}V_{A1O} - \frac{1}{3}V_{B1O} + \frac{2}{3}V_{CO} \\ V_{A2N2} = \frac{2}{3}V_{A2O} - \frac{1}{3}V_{B2O} - \frac{1}{3}V_{CO} \\ V_{B2N2} = -\frac{1}{3}V_{A2O} + \frac{2}{3}V_{B2O} - \frac{1}{3}V_{CO} \\ V_{CN2} = -\frac{1}{3}V_{A2O} - \frac{1}{3}V_{B2O} + \frac{2}{3}V_{CO} \end{cases} \tag{6}$$

As a result, the inverter output voltages are as (7):

$$\begin{cases} V_{A1O} = (2S_{11} - 1)\frac{E}{2} \\ V_{B1O} = (2S_{21} - 1)\frac{E}{2} \\ V_{A2O} = (2S_{31} - 1)\frac{E}{2} \\ V_{B2O} = (2S_{41} - 1)\frac{E}{2} \\ V_{CO} = (2S_{51} - 1)\frac{E}{2} \end{cases} \tag{7}$$

By substituting (7) in place of (6), the output voltages of the five-leg inverter can be represented as a function of Boolean control variables as follows:

$$\begin{bmatrix} V_{AN1} \\ V_{BN1} \\ V_{CN} \\ V_{AN2} \\ V_{BN2} \end{bmatrix} = \frac{E}{3} \begin{bmatrix} 2 & -1 & 0 & 0 & -1 \\ -1 & 2 & 0 & 0 & -1 \\ -1 & -1 & 0 & 0 & 2 \\ 0 & 0 & 2 & -1 & -1 \\ 0 & 0 & -1 & 2 & -1 \end{bmatrix} \begin{bmatrix} S_{11} \\ S_{21} \\ S_{31} \\ S_{41} \\ S_{51} \end{bmatrix} \quad (8)$$

According to [26] the maximum voltage value at the terminals of an open switch for a FLI is always equal to the DC voltage Vdc, which must be higher than the highest phase-to-phase voltage.

3. PROPOSED DTC CONTROL FOR DRIVING A BI-PMSM SINGLE INVERTER SYSTEM

Figure 4 illustrates the fundamentals of a new DTC control approach used to control the 2 PMSMs supplied by the FLI. The proposed control must make sure that the two MSAPs are independently controlled with respect to flux, torque, and speed. The torque reference is the output of the speed regulation loop, which is intended to enhance dynamic performance. Hysteresis comparators and a commutation table are used for flux and torque control for selecting the proper voltage vector [22]. From Figure 4 and using the topology of the FLI, it is possible to impose a various speed on the 2 PMSMs, independently regulated. Additionally, an electric differential can be implemented due to the control of the driving wheels' speed.

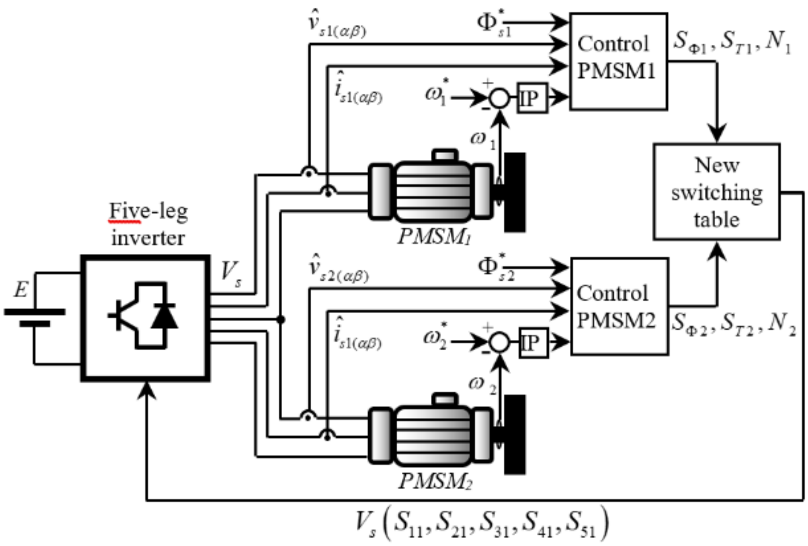

Figure 4. New control scheme of 2 PMSMs powered by FLI

Before to choosing the appropriate FLI-generated voltage vector. the novel idea is to consider the two motor torques and estimate the needs of the entire system. The stator flux errors and torques and the sector numbers of the 2 PMSM, are used in the proposed commutation table. This table can be developed using the DTC principle and the following reasoning. The voltage vectors $V_{s1}(S_{a1}, S_{b1}, S_{c1})$and $V_{s2}(S_{a2}, S_{b2}, S_{c2})$applied to the dual-motors, respectively, are developed in accordance with the following principles:

- If $(S_{T1}, S_{T2}) = (0,1)$, FLI applied the appropriate vector: $V_s(S_{c2}, S_{c2}, S_{a2}, S_{b2}, S_{c2})$.
- If $(S_{T1}, S_{T2}) \neq (0,1)$, FLI applied the appropriate vector:

$$\begin{cases} V_s(S_{a1}, S_{b2}, S_{a2}, S_{b2}, S_c) \text{ if } S_{c1} = S_{c2} = S_c \\ V_s(S_{a1}, S_{b2}, S_{c1}, S_{c1}, S_{c1}) \text{ if } S_{c1} \neq S_{c2} \end{cases}$$

The proposed idea is schematized in detail by Tables 1, 2 and 3. In these tables, the different possible situations for the torque errors of the two motors (S_{T1}, S_{T2}) in the control loop are presented.

Table 1. Switching table definition if $S_{T1} = 1$ and $S_{T2} = 1$

N_2	N_1 / $S_{\Phi1}$ / $S_{\Phi2}$	1		2		3		4		5		6	
		1	0	1	0	1	0	1	0	1	0	1	0
1	1	V_{14}	V_5	V_5	V_{16}	V_{16}	V_7	V_7	V_{18}	V_{18}	V_{26}	V_{26}	V_{14}
	0	V_{22}	V_{25}	V_{25}	V_{16}	V_{16}	V_7	V_7	V_{18}	V_{18}	V_{29}	V_{29}	V_{22}
2	1	V_{22}	V_{25}	V_{25}	V_{16}	V_{16}	V_7	V_7	V_{18}	V_{18}	V_{29}	V_{29}	V_{22}
	0	V_2	V_{13}	V_{13}	V_{28}	V_{28}	V_8	V_8	V_9	V_9	V_{11}	V_{11}	V_2
3	1	V_2	V_{13}	V_{13}	V_{28}	V_{28}	V_8	V_8	V_9	V_9	V_{11}	V_{11}	V_2
	0	V_2	V_{13}	V_{13}	V_{21}	V_{21}	V_{19}	V_{19}	V_{10}	V_{10}	V_{11}	V_{11}	V_2
4	1	V_2	V_{13}	V_{13}	V_{21}	V_{21}	V_{19}	V_{19}	V_{10}	V_{10}	V_{11}	V_{11}	V_2
	0	V_2	V_{13}	V_{13}	V_{24}	V_{24}	V_{27}	V_{27}	V_{30}	V_{30}	V_{11}	V_{11}	V_2
5	1	V_2	V_{13}	V_{13}	V_{24}	V_{24}	V_{27}	V_{27}	V_{30}	V_{30}	V_{11}	V_{11}	V_2
	0	V_3	V_4	V_4	V_{16}	V_{16}	V_7	V_7	V_{18}	V_{18}	V_{23}	V_{23}	V_3
6	1	V_3	V_4	V_4	V_{16}	V_{16}	V_7	V_7	V_{18}	V_{18}	V_{23}	V_{23}	V_3
	0	V_{14}	V_5	V_5	V_{16}	V_{16}	V_7	V_7	V_{18}	V_{18}	V_{26}	V_{26}	V_{14}

Table 2. Switching table definition if $S_{T1} = 1$ and, if $S_{T2} = 1$and $S_{T1} = 0$

N_1 N_2	$S_{\Phi1}$ $S_{\Phi2}$	If $S_{T1} = 1$ *and* $S_{T2} = 0$ For N_2et $S_{\Phi2}$	If $S_{T2} = 1$*and* $S_{T1} = 0$ For N_1et $S_{\Phi1}$
1	1	V_2	V_2
	0	V_{13}	V_{13}
2	1	V_{13}	V_{13}
	0	V_{16}	V_{16}
3	1	V_{16}	V_{16}
	0	V_7	V_7
4	1	V_7	V_7
	0	V_{18}	V_{18}
5	1	V_{18}	V_{18}
	0	V_{11}	V_{11}
6	1	V_{11}	V_{11}
	0	V_2	V_2

Table 3. Provides a list of the PMSM's specifications

Parameters	Value
Permanent magnet flux	0.08 Wb
Pole pairs	4
Stator resistance	0.03 Ω
d-q axis inductance	0.2 mH

4. SIMULATION RESULTS

To demonstrate the previously established DTC control of a system consisting of 2 PMS motors supplied by a FLI, the model shown in Figure 4 has been built on MATLAB/Simulink. The specifications of the PMSM used are listed in Table 3. The vehicle's driver imposes a reference speed of 14.45m/s in several turns, Figure 5(a). As a result, during a turn, the front wheels of the vehicle are oriented according to the direction of the turn and the traction system will be subject to different speed for each motor. Typically, the wheels' rotational speeds are identical while the vehicle is traveling across a straight road, and during turns, the wheels on the inside of the turn rotate at a slower speed than the wheels that are on the outside turn, Figure 5(b). The simulation results demonstrate how the suggested DTC control performs better in terms of quick torque response and precise speed tracking. Figures 5(b) and 5(c). It is essential for EV control that our suggested DTC control offers quick and accurate torque responses with less torque ripple. Figure 5(d) show the changing load torques which applied to the in-wheel PMS motors. The better stator flux response for both motors is shown in Figure 5(e). The stator currents of the two PMS motors exhibit good forms and verify the motors' reactions, Figure 5(f) and 5(g). The two motors' entire traction forces are shown in Figure 5(e). As the vehicle starts to move, the motors produce high traction forces; however, as the vehicle turns, the traction forces diverge. Shown in Figure 5(h) and 5(i) are the longitudinal velocity and lateral velocity of the vehicle. When the driver applies a steering, the vehicle takes turns and we notice a slight decrease in the longitudinal velocity and existence of the lateral velocity. It can be seen that the lateral velocity only occurs during turns and it is cancelled out when the vehicle is driving on a straight road. The robustness of the suggested control strategy is confirmed by the simulation results under various driving conditions. Figure 5(j) show the Lateral speed of vehicle during turns.

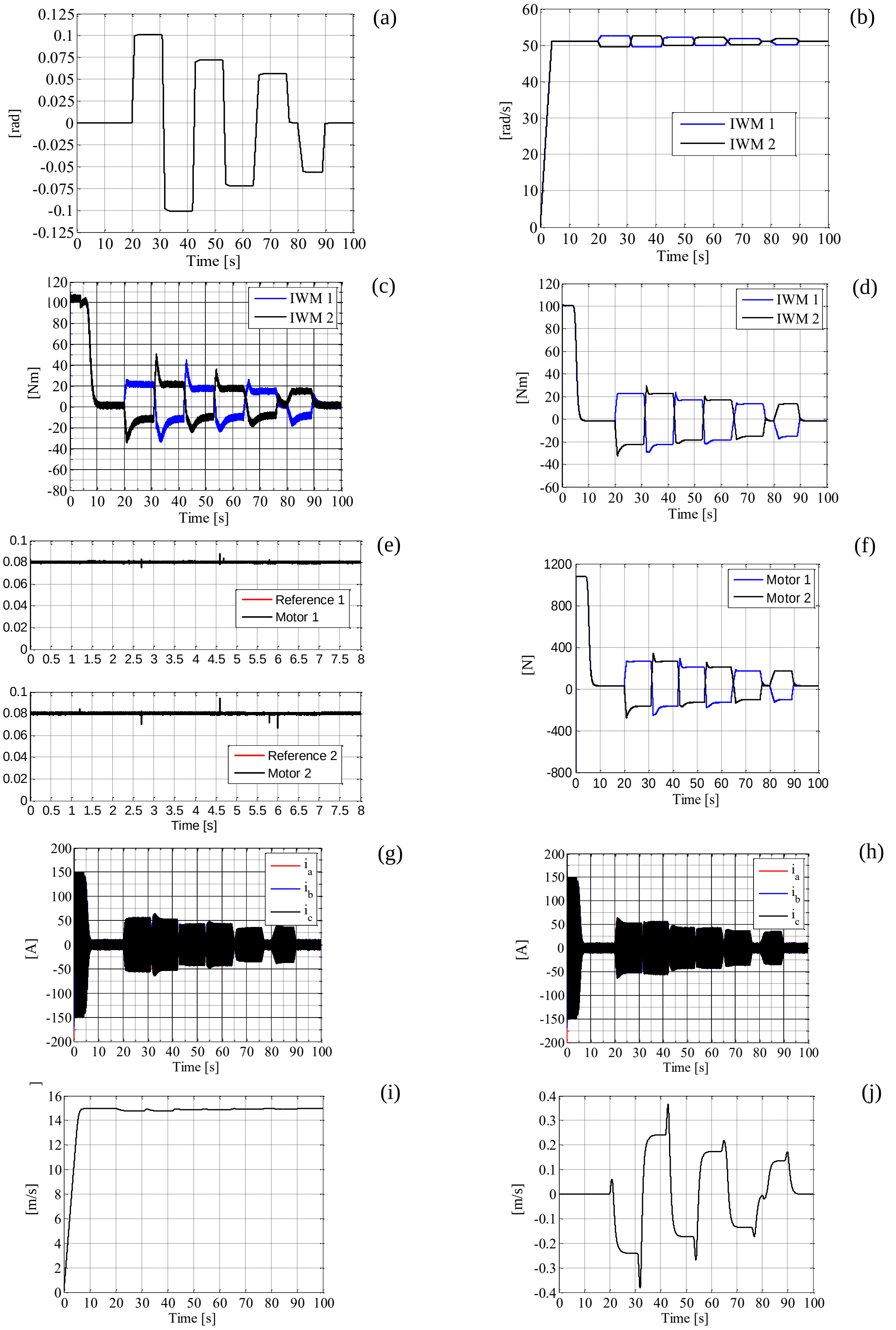

Figure 5. Simulation results of traction system studied; (a) steering angle, (b) in-wheel motor speeds, (c) motor torques, (d) load torques, (e) stator flux, (f) traction forces, (g) three-phase current for motor 1, (h) three-phase current for motor 2, (i) longitudinal speed of vehicle and (d) lateral speed of vehicle

5. CONCLUSION

This research proposes a new control approach for a system of two PMS motors supplied by a single FLI is proposed. Simulation is used to show the effectiveness of the established control and its ability to provide a simple configuration with excellent responses. The results demonstrated that the EV runs under a variety of maneuvers with a rapid torque response and precise speed tracking. The suggested control method increases the electric vehicle lateral stability and offers the EV a dynamic behavior that is comparable to that given by a mechanical differential.

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