

# Letters

## Implementation of Wavelet-Based Robust Differential Control for Electric Vehicle Application

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**Abstract**—This research letter presents the modeling and simulation of electronic differential, employing a novel wavelet controller for two brushless dc motors. The proposed controller uses discrete wavelet transform to decompose the error between actual and reference speed. Error signal that is actually given by the electronic differential based on throttle and steering angle is decomposed into frequency components. Numerical simulation results are provided for both wavelet and proportional-integral-derivate controllers. In comparison, the proposed wavelet control technique provides greater stability and ensures smooth control of the two back driving wheels.

**Index Terms**—Brushless dc (BLDC) motor, electrical vehicles, fuzzy logic, indirect field-oriented control (IFOC), proportional-integral-derivate (PID) controllers, wavelet transforms.

### I. INTRODUCTION

WITH increasing demand on automobiles, the need for vehicle safety on the road too becomes a major concern. Differential system plays an important role to prevent slipping of vehicles on curved roads. Mechanical differentials are heavy and bulky, not suitable for electric vehicles. Electronic differential constitutes a technological advance in electric vehicle design, enabling better stability and control of the vehicle on curved roads. Neighborhood electric vehicles (NEV) is at present the best solution for personal transportation to keep air quality and traffic problems in check. NEV implementation with two independent wheel drives using induction motors, where the current and speed controllers of which were proportional-integral-derivate (PID) compensators [1]. But the PID controller is not robust, need to be tuned for its gain parameters at each operating conditions. Recently, PID controllers are replaced by

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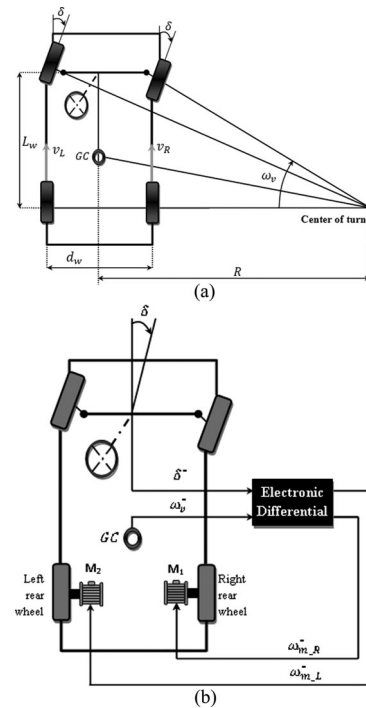


Fig. 1. (a) Proposed electronic differential structure. (b) Model of the vehicle driven during a curve.

discrete wavelet transform (DWT), thanks to the technology for its robustness [2]–[8].

Wavelet transforms found applications in ac drives, where pulse width modulations (PWMs) are carried for single-phase inverter (dc–ac) and three-phase rectifier (ac–dc), shown better performance with experimental implementation than standard PWM techniques [2]–[4].

### II. SYSTEM MODELING OF ELECTRONIC DIFFERENTIAL

Fig. 1(a) depicts the proposed electronic differential structure, where the left and right wheels are controlled using two separate motors. Brushless dc (BLDC) motors are preferred due to high efficiency, high torque density, silent operation, and low maintenance favors the electric vehicle application. Two inputs, the steering angle and throttle position, collectively decide the speeds of the right and the left wheel in order to prevent the vehicle from slipping. For a right turn, the differential has to maintain a higher speed at the left wheel than the right wheel to prevent the tyres from losing traction while turning. Fig. 1(b)

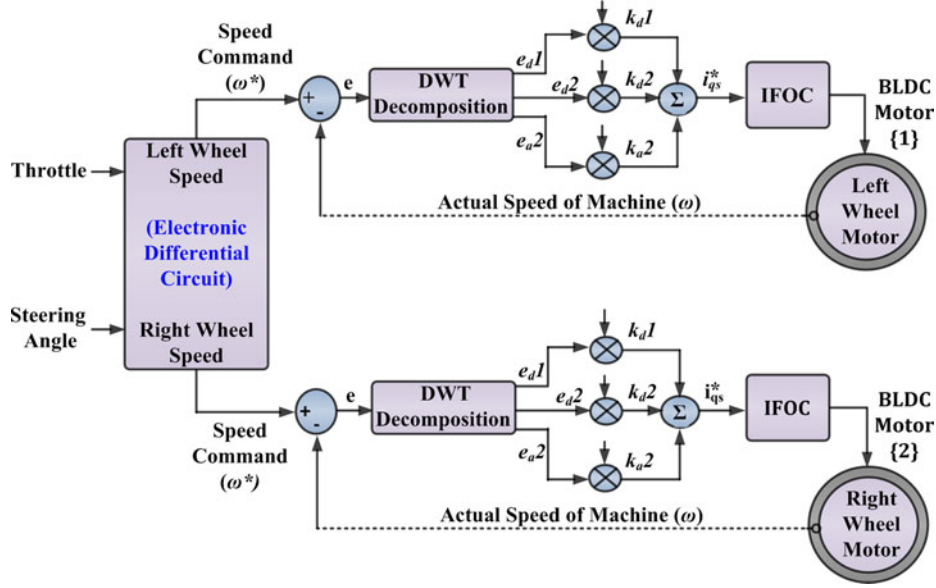


Fig. 2. Schematic circuit of proposed novel wavelet based indirect field oriented controller (IFOC) for electronic differential with two brush-less dc (BLDC) motors.

depicts the vehicle during a turn.  $L_w$  is the wheel base,  $\delta$  is the turning angle,  $d_w$  is the track width,  $R$  is the radius of the turn, and  $\omega_R$  and  $\omega_L$  represent the angular speeds of the left and the right wheel, respectively. The linear speed of each wheel can be represented as a function of the vehicle speed and the radius of the turn as

$$v_L = \omega_v \left( R + \frac{d_w}{2} \right) \text{ and } v_R = \omega_v \left( R - \frac{d_w}{2} \right). \quad (1)$$

The relation between the radius of the turn and steering angle and wheel base is

$$R = \frac{L_w}{\tan \delta}. \quad (2)$$

Substituting (2) into (1), we get angular speed of each wheel as

$$\omega_{r_L} = \frac{L_w + \frac{1}{2}d_w \tan \delta}{L_w} \omega_v \text{ and } \omega_{r_R} = \frac{L_w - \frac{1}{2}d_w \tan \delta}{L_w} \omega_v. \quad (3)$$

The difference between the angular speeds of the wheel drives can be expressed as

$$\Delta\omega = \omega_{r_L} - \omega_{r_R} = \frac{d_w \tan \delta}{L_w} \omega_v. \quad (4)$$

The sign of the steering angle indicates the direction of the turn;  $\delta > 0$  = turn Right,  $\delta < 0$  = turn left, and  $\delta = 0$  = Straight ahead. When the steering input is given by the driver, the electronic differential immediately acts by reducing the speed of the inner wheel and increasing the speed of the outer wheel. The driving speeds of the wheels are

$$\omega_{r_L}^* = \omega_v + \frac{\Delta\omega}{2} \text{ and } \omega_{r_R}^* = \omega_v - \frac{\Delta\omega}{2}. \quad (5)$$

### III. WAVELET BASED CONTROLLER

Fig. 2 shows the overall schematic of the wavelet-based speed controller of two BLDC motor drives. The throttle position and the steering angle were given as input for the electronic differential that generates the desired speed for the left motor and the right motor. The error detector compares the desired speed and actual speed and generates the error speed that will be used by the wavelet controllers to generate the control signal for the drive system. The control component generated by the wavelet controllers are used to drive the two indirect field-oriented control (IFOC) BLDC motor (two).

Resolution of DWT begins when a discrete signal  $x[n]$  of length  $N$  is passed through a high-pass filter resulting in an impulse response  $h[n]$  and through a low-pass filter resulting in an impulse  $g[n]$ . One level of DWT is constituted by the outputs of high- and low-pass filter can be mathematically expressed as [5], [8], [9]

$$d^1[n] = \sum_{k=0}^{N-1} x[k] h[n-k]$$

$$a^1[n] = \sum_{k=0}^{N-1} x[k] g[n-k] \quad (6)$$

where,  $d^1[n]$  and  $a^1[n]$  are the outputs of the high- and low-pass filters. After this again the output from the low-pass filter is down sampled by two and again passed through a low- and a high-pass filter resembling the ones in the first level and expressed as (second level of decomposition) [5], [8]

$$d^2[n] = \sum_{k=0}^{N/2-1} a^1[k] h[n-k]; a^2[n] = \sum_{k=0}^{N/2-1} a^1[k] g[n-k]. \quad (7)$$

TABLE I  
INVESTIGATION DESIGN CRITERION FOR TEST-I

	Time Vector (s)	Amplitude(km/h) and Angle (deg)
Speed Input	[0 0.2 0.3]	[60 60 60]
Steering Angle Input	[0 0.2 0.3]	[0° 30° 30°]

Several types of wavelet filters available, the minimum description length (MDL) criterion select the best and mathematically expressed as

$$\text{MDL}(k, n) = \min \left\{ \frac{3}{2} k \log N + \frac{N}{2} \log \left\| \widetilde{\alpha}_n - \alpha_n^{(k)} \right\|^2 \right\},$$

$$0 < k < N; 1 \leq n \leq M \quad (8)$$

where  $\widetilde{\alpha}_n = W_n f$  denotes a vector of the wavelet transformed coefficients of the signal  $f$  using wavelet filters ( $n$ ).  $\alpha_n^{(k)} = \varnothing^K \widetilde{\alpha}_n = \varnothing^K (W_n f)$  denotes a vector that contains  $k$  nonzero elements. The threshold parameter  $\varnothing^K$  keeps  $k$  number of the largest elements of the vector  $\widetilde{\alpha}_n$  constant and sets all other elements to zero.  $N$  and  $M$  denote the length of the signal and the number of wavelet filters, respectively. The entropy  $H(x)$  of a signal  $x[n]$  of length  $N$  is defined as

$$H(x) = - \sum_{n=0}^{N-1} |x(n)|^2 \log |x(n)|^2. \quad (9)$$

For determining the optimal levels of decomposition, the entropy is evaluated at each level. For a new level  $j$ , if

$$H(x)_j \geq H(x)_{j-1} \quad (10)$$

two levels of decomposition are sufficient for effective representation of the error signal. The components (low-/high-frequency components) were scaled by their respective gains, and then, added together to generate the control signal  $u$

$$u = k_{d1} e_{d1} + k_{d2} e_{d2} + \dots + k_{dN} e_{dN} + k_{a^N} e_{a^N} \quad (11)$$

where gains  $k_{d1}, k_{d2}, \dots, k_{dN}$  are used to tune the high- and medium-frequency components of the error signal ( $e_{d1}, e_{d2}, \dots, e_{dN}$ ). Gain  $k_{a^N}$  is used to tune the low-frequency components of the error signal ( $e_{a^N}$ ) and  $N$  is the number of decomposition levels.

#### IV. NUMERICAL SIMULATION RESULTS

To illustrate the wavelet controller performances, the parameters of the two identical BLDC are taken as 2 hp, 460 V, 60 Hz, 1750 r/min rating, PWM sampling time of 0.5  $\mu$ s.

First investigation test typically designed and framed for straight road followed by a curved road on the right (clockwise) at a constant speed of 60 km/h. During the turn, the speeds of the wheels change according to the command of the electronic differential. For this purposes, the amplitudes and respective time of the speed and steering angle inputs are as given by Table I.

It is observed from the test results of Fig. 3 (PID controller) and Fig. 4 (Wavelet controller), that wavelet-controller-based electronic differential offers smooth performance compared to the conventional PID Controller. Moreover, the wavelet-based

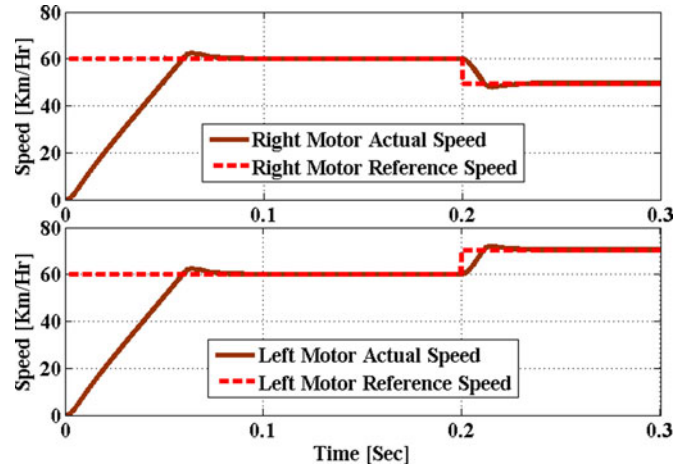


Fig. 3. Numerical simulation output response behavior of BLDC motors with the PID controller (Investigation Test-1).

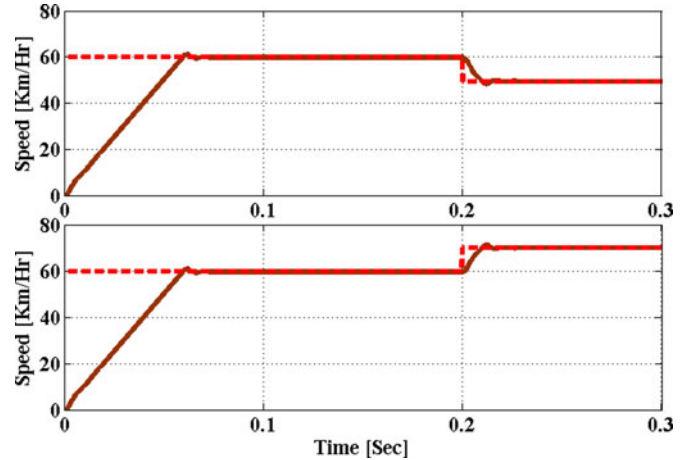


Fig. 4. Numerical simulation output response behavior of BLDC motors with the wavelet controller (Investigation Test-1).

TABLE II  
INVESTIGATION DESIGN CRITERION FOR TEST-II

	Time Vector (S)	Amplitude(km/h) and Angle (Deg)
Speed Input	[0.3 0.4 0.6 0.7]	[60 30 60 60]
Steering Angle Input	[0.3 0.4 0.6 0.7]	[0° 30° 0° 0°]

electronic differential offers lesser overshoot (60.09 km/h) and settles quickly (0.05 s) when compared to the PID controller electronic differential (63 km/h, 0.09 s). Therefore, the left and the right motors produced smooth control with better turning performance of the electric vehicle.

Second investigation test typically designed for straight road with a constant speed of 60 km/h, followed by a right turn (30°) at 30 km/h; followed by a straight road at a constant speed of 60 km/h as given by Table II.

Fig. 5 (PID controller) and Fig. 6 (Wavelet controller) show the response behavior of two BLDC motor. It is observed that the peak overshoot with the PID controller is 63 km/h, whereas with the wavelet controller, it is 60.09 km/h. Where the desired speed though is 60 km/hr and obtained settling time with the

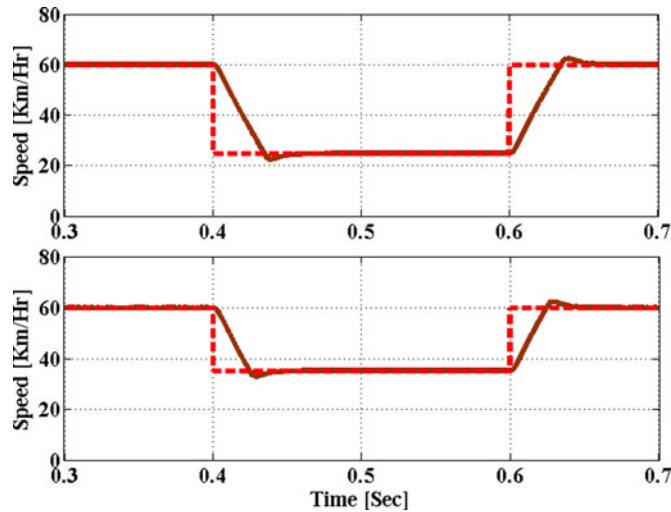


Fig. 5. Numerical simulation output response behavior of BLDC motors with the PID controller (Investigation Test-2).

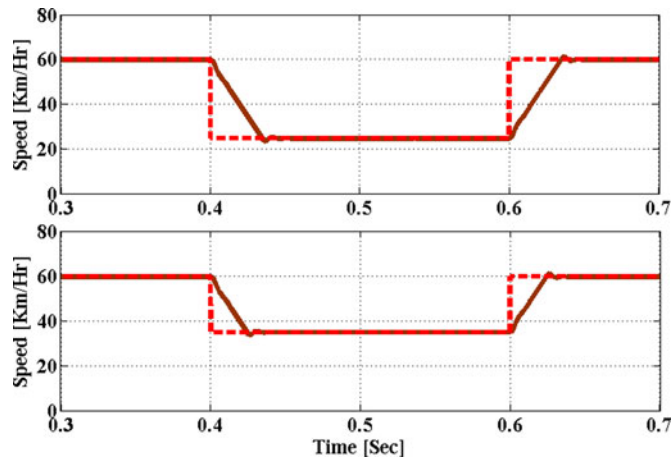


Fig. 6. Numerical simulation output response behavior of BLDC motors with the wavelet controller (Investigation Test-2).

PID controller is 0.09 s, whereas with the wavelet controller, it is 0.05 s.

Finally, the performances by wavelet controller are robust due to its discrete transform provides approximation and detail coefficients. Approximation coefficients ( $k_{dN}$ ) are the low-frequency components responsible for controller functioning, i.e., lesser this gain value, the lesser the peak overshoot. But the detailed coefficients ( $k_{d1}, k_{d2} \dots k_{dN}$ ) are the high-frequency components responsible for controlling the noise signals and

does not affect the output speed performances under ideal noise free condition [9].

## V. CONCLUSION

This letter presented an electronic differential control for an electrical vehicle utilizing a novel wavelet-based speed controller. The proposed electric vehicle with two BLDC systems was implemented in numerical simulation software and the performances are compared with the PID controller. Further, it has been confirmed that the wavelet controller provides smooth control due to decreased peak overshoot and reduced settling time. Hence, the proposed wavelet controller performances are superior and suits electrical vehicle application in particular to curved roads transportation.

Further, real time implementation of the proposed two motor ac drive system with wavelet controller using digital signal processor (DSP) is under construction. Further investigations are under studies, in particular with single wavelet IFOC controller algorithm for multi BLDC motors (more than two motors) driven with single and/or multiple inverter drive system.

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