Implementation of Wavelet Based Robust Differential Control for Electric Vehicle Application

J.L. Febin Daya, P.Sanjeevikumar, *Senior Member, IEEE,* Frede Blaabjerg, *Fellow, IEEE,* Patrick W.Wheeler, *Senior Member, IEEE,* Joseph Olorunfemi Ojo, *fellow, IEEE*

Abstract: This research article 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 which 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 PID controllers. In comparison the proposed wavelet control technique provides greater stability and ensures smooth control of the two back driving wheels.

Keywords: Brushless dc motor, Wavelet transforms, Fuzzy logic, PID controllers, Indirect field oriented control, Electrical Vehicles.

Introduction: 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. Neighbourhood 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 PID controller is not robust, need to be tuned for its gain parameters at each operating conditions. Recently, PID controllers are replaced by discrete wavelet transform, thanks to the technology for its robustness [2-8]. Wavelet transforms found applications in ac drives, where pulse-width modulations 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]. Further, wavelet transform techniques are extended to ac motor applications [5] in particular to electrical vehicles (EV). Fuzzy-neural control wavelet algorithms are implemented for steering control of electrical vehicles (ac motor drives) [6], also applied successfully for energy management system in plug-in hybrid electric vehicles (HEV) [7]. Exploiting the advantages of wavelet technology, this work involved the modelling and simulation of an electronic differential with a novel wavelet controller for two brushless DC motors, which is yet not proposed by the research articles.

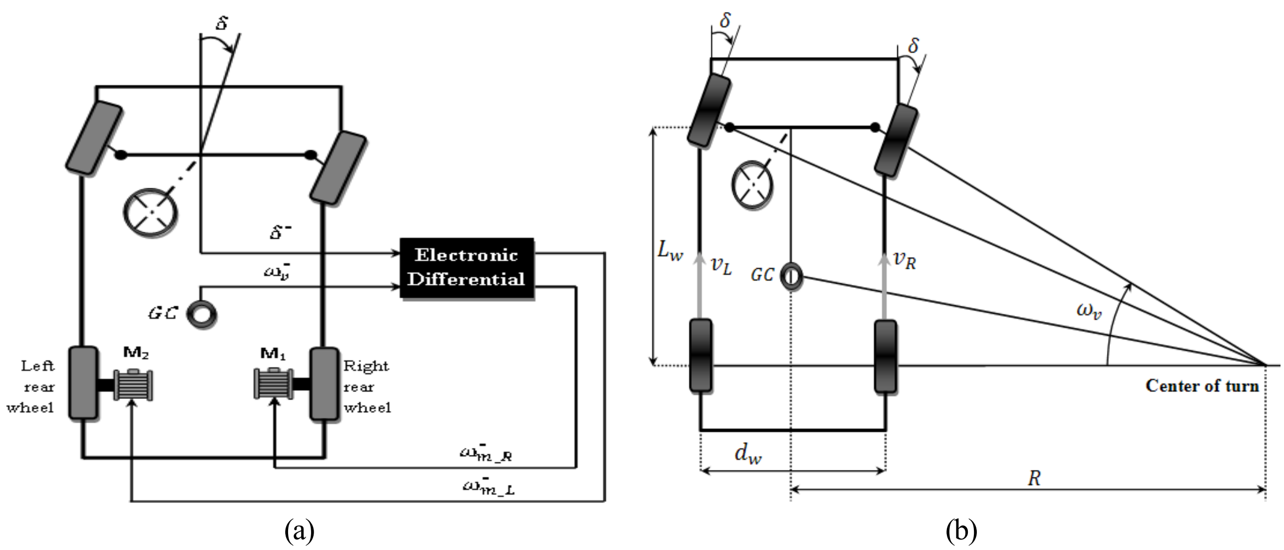

Fig. 1. (a) Proposed electronic differential structure, (b) Model of the vehicle driven during a curve.

System Modelling of Electronic Differential: Fig. 1(a) depicts the proposed electronic differential structure, where the left and rights wheels are controlled using two separate motors. BLDC motors are preferred due to high efficiency, high torque density, silent operation and low maintenance favours 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) depicts the vehicle during a turn. L_w is the wheel base, δ is the turning angle, d_w is the track width, R is the radius of the turn and ω_R and ω_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:

$$v_L = \omega_v \left(R + \frac{d_w}{2}\right) \;\&\; v_R = \omega_v \left(R - \frac{d_w}{2}\right) \tag{1}$$

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

$$R = \frac{L_w}{\tan\delta} \tag{2}$$

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

$$\omega_{r_L} = \frac{L_w + \frac{1}{2} d_w \tan\delta}{L_w}\,\omega_v \;\&\; \omega_{r_R} = \frac{L_w - \frac{1}{2} d_w \tan\delta}{L_w} \tag{3}$$

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

$$\Delta\omega = \omega_{r_L} - \omega_{r_R} = \frac{d_w \tan\delta}{L_w}\,\omega_v \tag{4}$$

The sign of the steering angle indicates the direction of the turn $\delta > 0$ = Turn Right, $\delta < 0$ = Turn left, $\delta = 0$ = 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:

$$\omega_{r_L}^{*} = \omega_v + \frac{\Delta\omega}{2} \;\&\; \omega_{r_R}^{*} = \omega_v - \frac{\Delta\omega}{2} \tag{5}$$

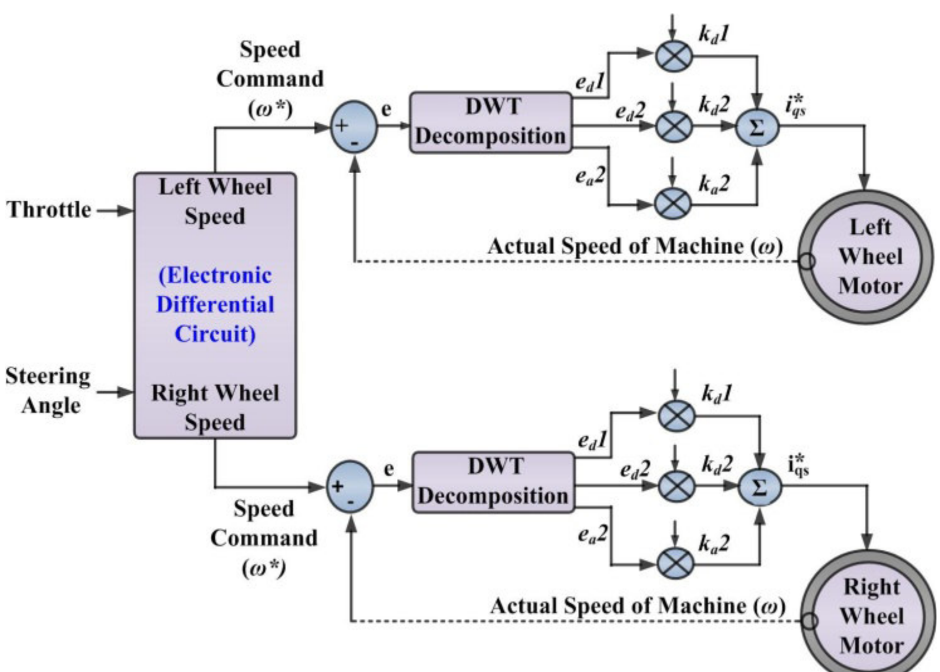

Fig. 2. Schematic circuit of proposed novel wavelet based indirect field oriented controller (IFOC) for electronic differential of two brush-less dc (BLDC) motors.

Discrete Wavelet Controller: Fig. 2 shows the overall schematic of the wavelet based speed controller of two brushless DC motor drives. The throttle position and the steering angle were given (7)input for the electronic differential which 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 which 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]:

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

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

$$MDL(k,n) = min\left\{\frac{3}{2}klogN + \frac{N}{2}\log\left|\left|\widetilde{\alpha_n} - \alpha_n^{(k)}\right|\right|^2\right\}, \quad (8)$$

$$0 < k < N; \; 1 \leq n \leq M$$

where, $\widetilde{\alpha_n} = W_n f$ denotes a vector of the wavelet transformed coefficients of the signal *f* using wavelet filters *(n)*. $\alpha_n^{(k)} = \emptyset^K \widetilde{\alpha_n} = \emptyset^K (W_n f)$ denotes a vector that contains *k* non-zero elements. The threshold parameter $\emptyset^K$ 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:

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

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

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

Two levels of decomposition 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:

$$u = k_{d^1}e_{d^1} + k_{d^2}e_{d^2} + \cdots + k_{d^N}e_{d^N} + k_{a^N}e_{a^N} \tag{11}$$

where, gains $k_{d^1}, k_{d^2}, \ldots, k_{d^N}$ are used to tune the high and medium frequency components of the error signal ($e_{d^1}, e_{d^2}, \ldots, e_{d^N}$). 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.

Numerical Simulation Results: To illustrate the wavelet controller performances, the parameters of the two identical BLDC are taken with 2hp, 460V, 60Hz, 1750rpm rating, PWM sampling time of 0.5μsec. First investigation test typically designed and framed for straight road followed by a curved road on the right (clockwise) at a constant speed of 60km/hr. 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.

TABLE I. INVESTIGATION DESIGN CRITERION FOR TEST-1.

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

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

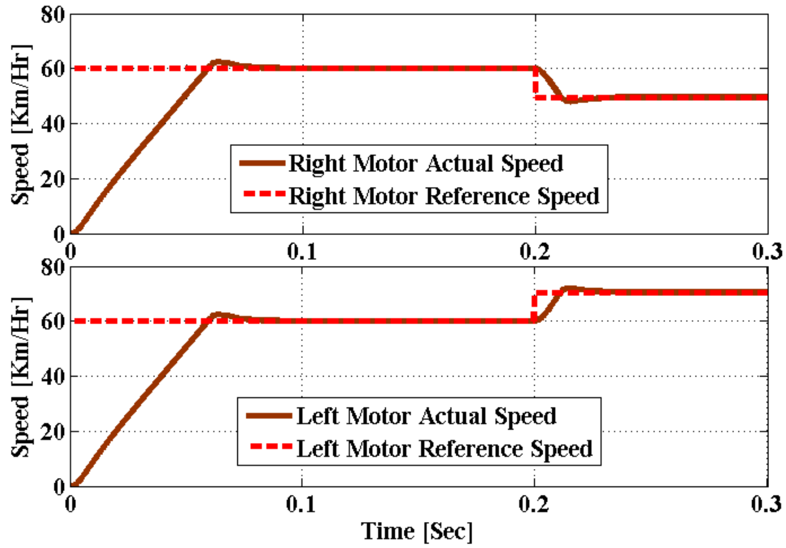

Fig. 3. Numerical simulation output response behaviour of BLDC motors by the PID controller (Investigation Test-1). **Top:** Motor 1, **Bottom:** Motor 2.

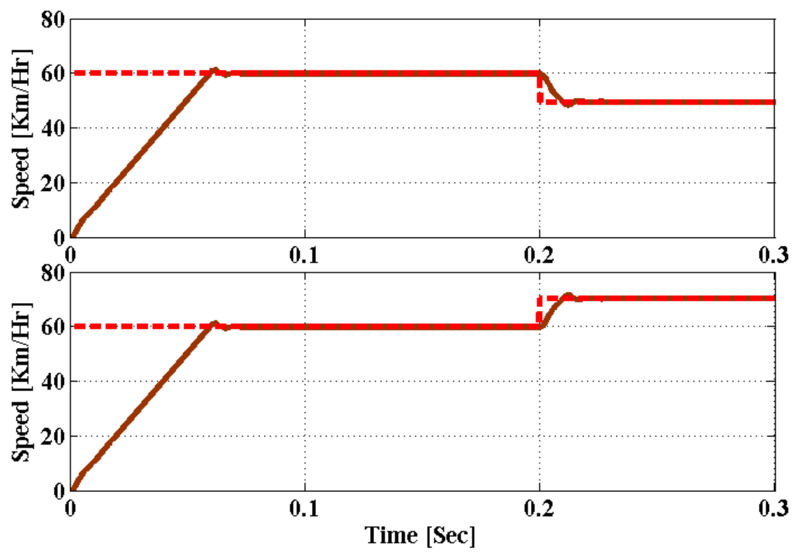

Fig. 4. Numerical simulation output response behaviour of BLDC motors by the wavelet controller (Investigation Test-1). **Top:** Motor 1, **Bottom:** Motor 2.

Second investigation test typically designed for straight road with a constant speed of 60km/hr., followed by a right turn (30^0) at 30km/hr.; followed by a straight road at a constant speed of 60km/hr as given by Table II.

TABLE II. INVESTIGATION DESIGN CRITERION FOR TEST-2.

	Time Vector (Sec)	**Amplitude(km/hr) 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°]

Fig. 5 (PID controller) and Fig. 6 (Wavelet controller) shows the response behaviour of two BLDC motor. It observed the peak overshoot with the PID controller is 63km/hr whereas with the wavelet controller, it is 60.09km/hr. Where the desired speed though is 60 km/hr. and obtained settling time with the PID controller is 0.09sec whereas with the wavelet controller, it is 0.05sec.

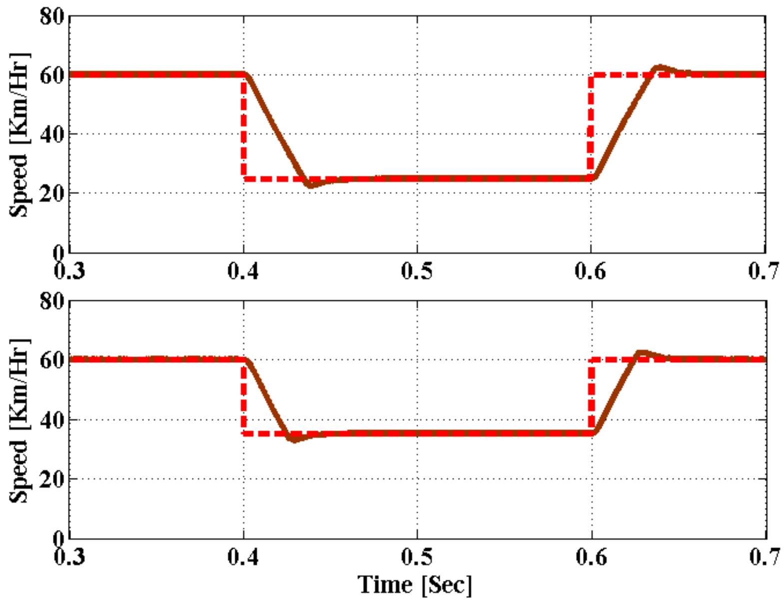

Fig. 5. Numerical simulation output response behaviour of BLDC motors by the PID controller (Investigation Test-2). **Top:** Motor 1, **Bottom:** Motor 2.

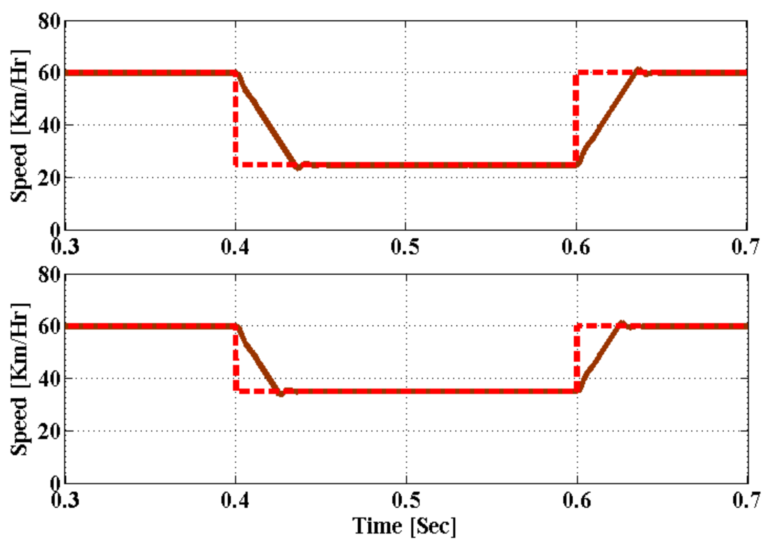

Fig. 6. Numerical simulation output response behaviour of BLDC motors by the wavelet controller (Investigation Test-2). **Top:** Motor 1, **Bottom:** Motor 2.

Finally, the performances by wavelet controller are robust due to its discreet transform provides approximation and detail coefficients. Approximation coefficients (k_{a^N}) are the low frequency components responsible for controller functioning i.e lesser this gain value, the lesser the peak overshoot. But the detailed coefficients ($_{d^1}$, k_{d^2} ... k_{d^N}) are the high frequency components responsible for controlling the noise signals and doesn't affect the output speed performances under ideal noise free condition [9].

Conclusion: This article presented an electronic differential control for 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 PID controller. Further, it has been confirmed that 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 proposed complete two motor ac drives system with wavelet controller using digital signal processor (dsp) is actually under construction. This research article keeps further investigations 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 for future publications.

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