Research on Sensorless control strategies for Vehicle stability using Fuzzy based EDC

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Abstract : This paper presents an efficient and robust control scheme of Fuzzy Logic Electronic Differential Controller (FLEDC) for sensorless drive based electric vehicle. The proposed system consists of two Brushless DC motors (BLDC) that ensure the drive of the two back driving wheels of an electric vehicle. Electronic differential controller (EDC) ensures the maximum torque and it can control both the driving wheel independently to turn at different speeds in any curve according to the steering angle. The sensorless control strategies include back EMF zero crossing detection and third harmonic voltage integration. Fuzzy logic based EDC is used on these sensorless control strategies which optimizes the slip rate within the specified limit and thus enhances the vehicle stability The performances in terms of slip rate, current, Torque, back EMF are obtained by the proposed method and are compared with those obtained using conventional control method. By this comparative investigation, a suitable control strategy has been identified. The effectiveness and substantiation of these analysis are ascertained in the MATLAB/Simulink environment and also experimentally validated.

Keywords: Back EMF Zero crossing detection, Third harmonics voltage integration, BLDC, Electric vehicle, Electronic differential, Fuzzy logic, Sensor less control, steering angle

I. INTRODUCTION

Environmental and economical issues are the major driving forces in the development of electric vehicles (EVs).The selection of the right electric motor is the primary importance to the EVs. Several types of electric motors have been used in the past for EV applications. However from efficiency point of view, BLDC motor drives are the best choice for EV is explained in [1]. In particular, the BLDC motor of the hub type is used in this work to avoid mechanical transmission losses. BLDC motors with their electromagnetic force (EMF) requires six discrete rotor position information for the inverter operation. These are generated by Hall-effect sensors placed within the motor. However it is a well known fact that these sensors have a number of drawbacks. So, sensorless control is the only viable option to operate the motor for applications in harsh environments. Thus many of the drawbacks can be eliminated or reduced with position sensorless operation based on the back EMF of the motor. Many research works on sensorless control technique for BLDC have been conducted and reported in [6]. A deep overview of back EMF sensing methods of BLDC motor which includes terminal voltage sensing, third harmonic voltage integrations and Terminal current sensing techniques are briefly analyzed in [7].

Further, Electronic Differential Controller (EDC) is used in this research work to avoid mechanical differential system. EDC based electric vehicles have many advantages over classical EV with a central motor is expressed in [3] and [4]. Indeed , mounting the motors directly to the wheels simplifies the mechanical layout as well as improves the overall reliability and efficiency. However one of the main issues in the design of these EVs is to ensure the vehicle stability while cornering and under slippery road conditions is explained in [5] and [8]. In order to maintain the stability of the electric vehicle, adhesion coefficient with slip rate should be considered. To ensure the vehicle travel on the road safely, enough friction force is needed between the tire and road. It is represented by adhesion coefficient in [9]. The adhesion coefficient is directly related to the wheel slip rate. In Electric vehicle, friction between wheel and road decreases on several occasions which leads to increased slip rate and causes unpredictable crisis on the vehicle and this necessiates the use of an appropriate slip control schemes. These sensorless control strategies include back EMF zero crossing detection and third harmonic voltage integration. Fuzzy logic based EDC is used on these sensorless control strategies which optimizes the slip rate within the specified limit and thus enhances the vehicle stability.

The remaining part of the paper is organized as follows. In section II, basic electronic differential controller is presented. Section III describes the proposed Fuzzy based Electronic Differential Controller (FEDC).In section IV, simulation with comparative investigation is presented and discussed. Finally, conclusion regarding this research work is made.

II. ELECTRONIC DIFFERENTIAL SYSTEM

The electronic differential is to replace the mechanical differential, which provides the required torque for each driving wheel and allows different wheel speeds. When cornering, the inner and outer wheels rotate at different speeds, because the inner wheels describe a small turning radius. The electronic differential uses the steering wheel command signal to control the power to each wheel.

Figure (1) shows the vehicle structure describing a curve, where L represents the wheel base, δ the steering angle, d the distance between the wheels of the same axle and $\omega 3$ & $\omega 4$ the angular speed of the wheel drives, respectively.

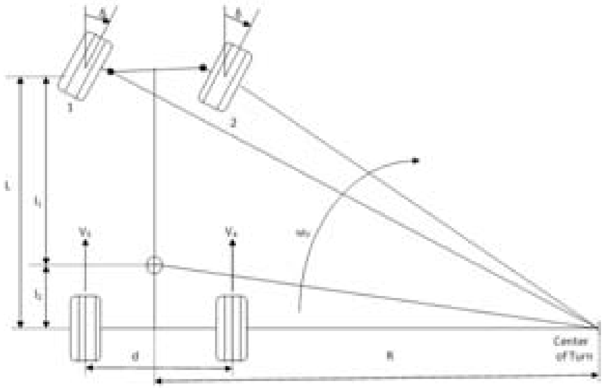

Figure.1. vehicle structure

The linear speed of each wheel drive is expressed as a function of the vehicle speed and the radius of curve, in Equations (1) & (2) which are given below,

$$V_3 = \omega_r\left(R + {}^{d}/_{2}\right) \quad (1)$$

$$V_4 = \omega_r\left(R - {}^{d}/_{2}\right) \quad (2)$$

The radius of curve depends on the wheel base and steering angle

$$R = \frac{L}{\tan\delta} \quad (3)$$

Substituting Equation (3) in Equations (1) & (2), we obtain the angular speed of each wheel drive as ,

$$\omega_3 = \frac{L + {}^{d}/_{2}\ \tan\delta}{L}\ \omega_r \quad (4)$$

$$\omega_4 = \frac{L - {}^{d}/_{2}\ \tan\delta}{L}\ \omega_r \quad (5)$$

The difference between the angular speeds of the wheel drive is expressed by the equation (6) as

$$\Delta\omega = \omega_3 - \omega_4 = \frac{d\tan\delta}{L}\omega_r \quad (6)$$

The signal of the steering angle indicates the curve direction as

$\delta > 0$ ⟹ turn right

$\delta = 0$ ⟹ straight ahead

$\delta < 0$ ⟹ turn left

The simulation results of the described system were obtained from the block diagram represented in fig (2)

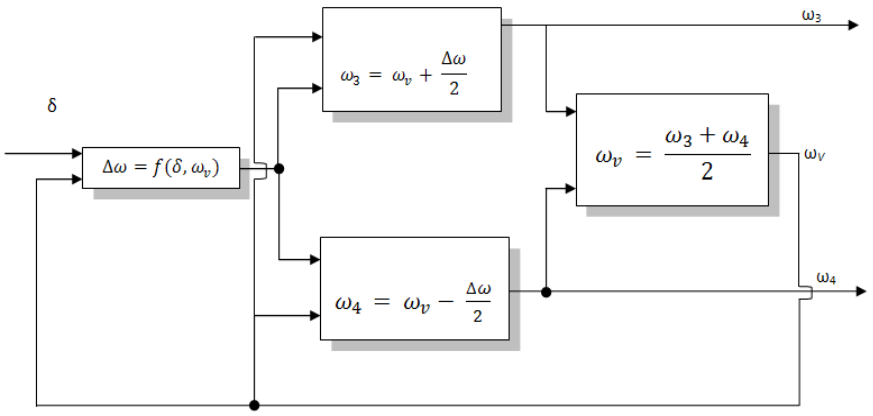

Figure.2. Block diagram of the ED System.

III. FUZZY BASED EDC

In order to maintain the stability of the electric vehicle, two things should be considered ie, Torque distribution and adhesion coefficient with slip rate. Two rear wheels require a symmetrical distribution of the torque. This is an essential condition for safety and stability of the electric vehicle. However, this symmetric distribution is not satisfactory when the adhesion coefficients of the tires vary. Tire to road adhesion has a great influence on transmitting forces between wheels and road surface and in the consequences on the safety of vehicle motion. It plays significant role in vehicle stability and the development of active safety systems on electric vehicles. The adhesion coefficient is directly related to the wheel slip[2] which is defined as

$$\mathrm{Si} = \frac{\omega - r}{\omega} \tag{7}$$

The best value for the adhesion coefficient for different roads is obtained when Si equals to 0.05-0.25. Therefore, a control algorithm is necessary to adjust the slip rate of each wheel. This control is possible only if the slip rate is closely estimated. In the case of straight-line motion, a limitation of a slip rate is not important. During a turn, the two driven wheels have different speeds. That kind of situation, the estimation of the slip value must take into account these differences in order to improve the stability of the electric vehicles. For these reason, the fuzzy-logic control method is employed to determine the slip rate of the wheels.

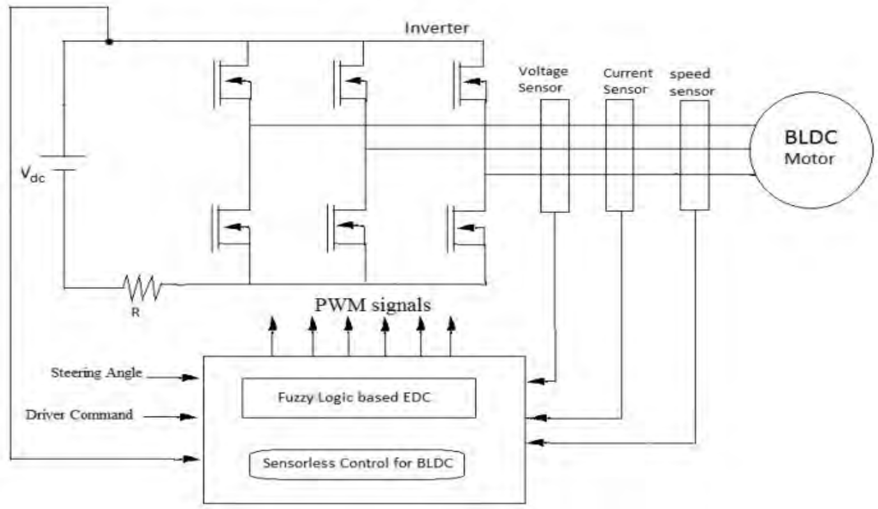

Figure 3. Fuzzy Logic based Electronic Differential Controller.

The figure(3) shows that fuzzy based electronic differential controller (FEDC) . We have used potentiometer on the steering wheel and sense the steering voltage which is equivalent to the steering angle. When the steering angle is equal to zero, the EV drives on a straight line and the FEDC does not work. On the other hand, if the angle of the steering wheel is not equal to zero , it indicates that the vehicle makes a turn. Then the FEDC begins to work. Fuzzy EDC block receives the speed signal based on the accelerator pedal command and steering angle, after calculating the speed differences of the two wheels and send the signals back to the motor controllers to adjust the speed of the wheel. At the same time, fuzzy logic control system estimates the slip rate and the change in slip rate then calculate the difference of compensate value and send it back to each wheel. With this approach FEDC controls and adjust the speed of each wheel.

(A) Fuzzy membership function

Let us take S=0.2 is the desired vehicle slip rate. The slip rate error and change in slip rate error are the input variables. The change of the motor speed is the output variables. The range of slip rate error is [0,1] and range of change in slip rate error is [-0.2,-0.8]. The universe of discourse and the linguistic terms of the input variable is defined to distinguish the situations when the vehicle is accelerating (PS, PM, PB) decelerating (NS,NM, NB) and purely rolling (ZO). The other input variable has a universe of discourse and a set of seven linguistic variables (NS, NM, NB, ZO, NS, NM, NB) containing the information on the degree of the change of the slip rate. The rule table component of the Fuzzy logic controller is created based on the relationship of the slip rate and motor speed. The rule table is shown in Table 1. The fuzzification membership functions are shown in figure(4).

Table. 1. Rule table of Fuzzy logic Controller.

Slip rate	Change in Slip rate						
	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	PS	PB
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PS	PS	ZO	NS	NM
ZO	PS	PM	PS	ZO	NS	NS	NM
PS	PM	PM	PS	NS	NM	NM	NB
PM	PM	PS	ZO	NM	NM	NM	NB
PB	PM	PS	ZO	NB	NB	NB	NB

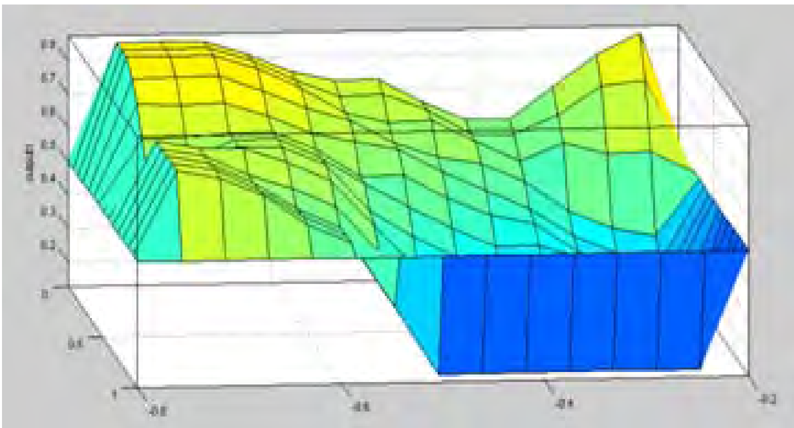

Figure.4. Fuzzyfication membership function of input and output variables.

IV. SIMULATION RESULTS : COMPARITIVE INVESTIGATIONS

In this research work, two sensorless control strategies include back EMF zero crossing detection and third harmonic voltage integration are adopted to analyse the vehicle performances. The performances are obtained by the proposed method are compared with those obtained using conventional control method.

Fig (5) shows the simulation results of the performance of conventional method ie, Fuzzy based EDC with hall sensor. Fig 5(a) shows a speed waveform for the right and left side motor. Under steady speed of 300rpm, the steering angle $\delta = 0$. Now at time t = 0.8s, the vehicle is turned left and now $\delta<0$, the right side motor increases the speed 330 rpm and left side motor decreases the speed 260 rpm. At t= 1.2s, the vehicle is steered to the right and now $\delta>0$. The speed of the right wheel decreases from 330 rpm to 300 rpm and that of the left wheel increases from 260 rpm to 300 rpm. Then at t=1.5s, the vehicle again turned to right, now the speed of the right wheel decreases from 300 rpm to 225 rpm and that of the left wheel increases to 375 rpm.

The motor current , torque and back EMF under the above operating conditions are shown in fig 5(b) ,5(c) and 5(d) respectively. Fig 5(b) illustrates the current waveform of right and left side motor while fig 5(c) represents the torque waveform of right and left side motor and fig.5(d) illustrates the back EMF wave form of right and left motor.

It is observed, from the current and torque curve that when the motor turns left, the current drawn by the BLDC motor attached with the left wheel decreases and thus electromechanical torque applied to the left wheel also decreases. The opposite effect occurs the motor attached to the right wheel where the torque and current are increased. Similarly when the vehicle is turn right, the current drawn by the motor attached to the right wheel decreases and thus electromechanical torque applied to the right wheel also decreases. The opposite effect occurs the motor attached to the left wheel where the torque and current are increased. Fig 5(e). shows that the slip rate varies from 0.095 to 0.1 under the above conditions. It infers that the slip rate of the driven wheel is controlled within the permitted range [0.05-0.25].

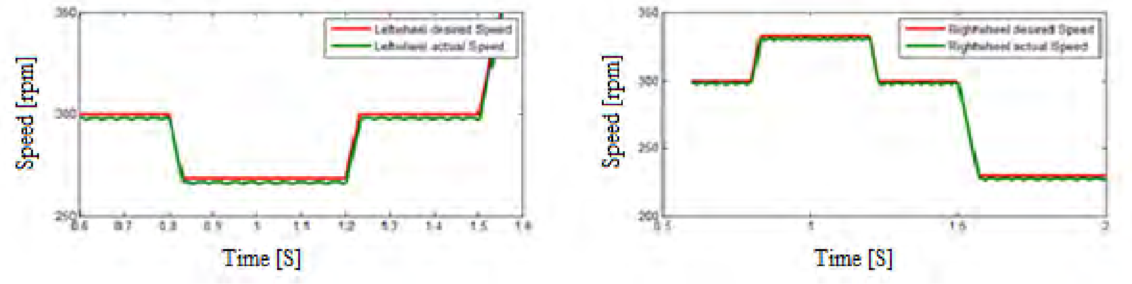

Figure 5(a) speed waveform of right and left side motor

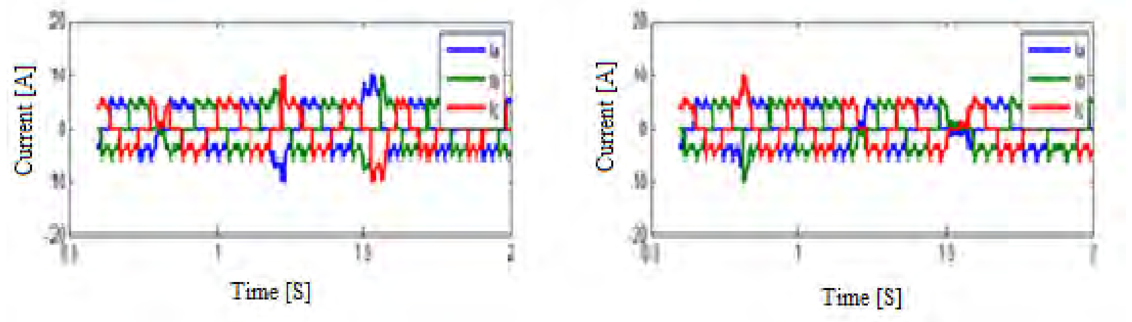

Figure. 5(b) Current waveform for right and left side motor

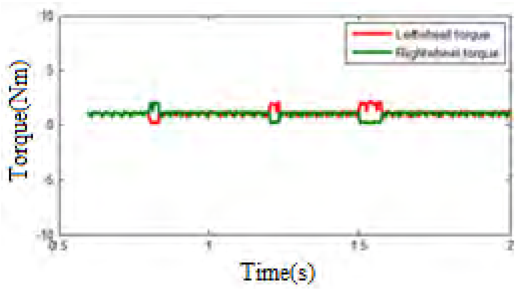

Figure.5(c) Torque waveform for right and left side motors

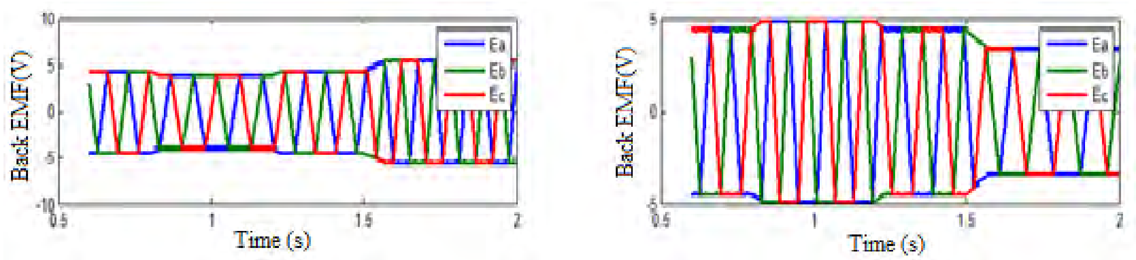

Figure. 5 (d) back EMF waveform of right and left side motor.

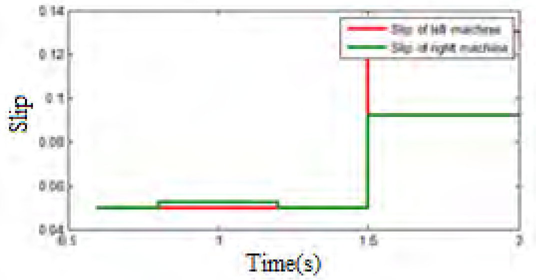

Figure 5(e) Slip rate of the left and right rear wheels

Fig (6) shows the performance of the Fuzzy based EDC with back EMF zero crossing detection . The speed, current ,torque waveform of right and left side motor under the above operating conditions are shown in fig 6(a) ,6(b) and 6(c) respectively. Fig. 6(d) and fig.6(e) illustrate the back EMF and slip rate of right and left side motor.

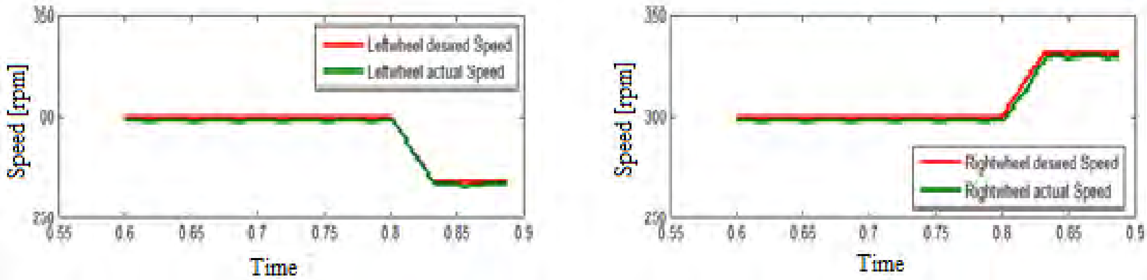

Figure.6(a) Speed waveform of right and left side motor.

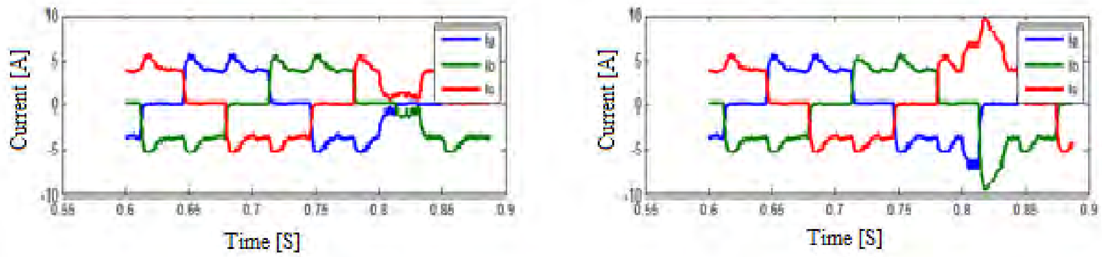

Figure.6(b) current waveform of right and left motor.

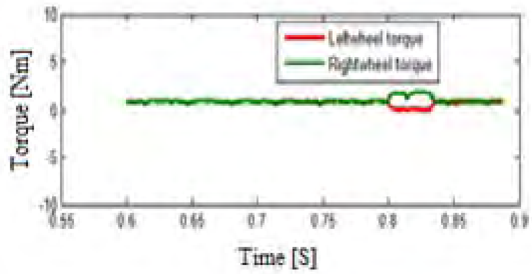

Figure.6(c) Torque waveform of right and left motor.

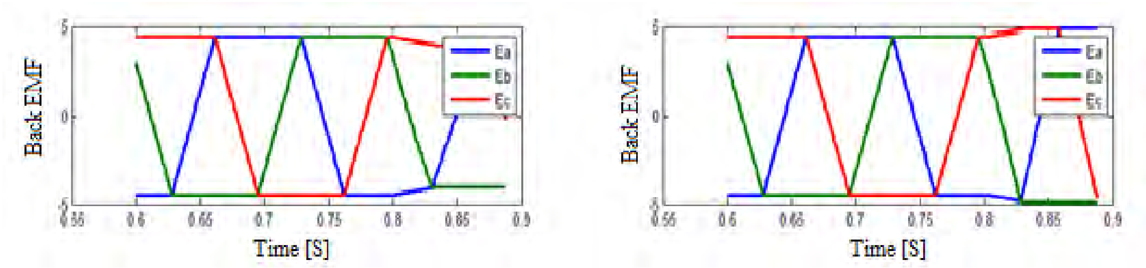

Figure. 6(d) Back EMF waveform of right and left motor.

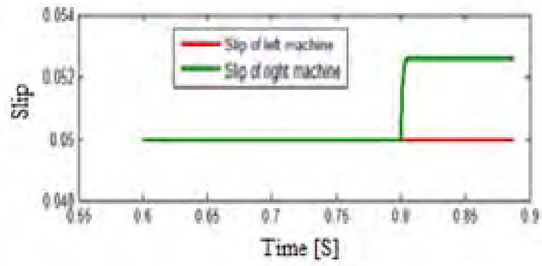

Figure 6(e) Slip rate of right and left motor.

Fig (7) shows that the performance of the Fuzzy based EDC with third harmonics voltage integration. The speed, current, torque waveform of right and left side motor under the above operating conditions are shown in fig 7(a) ,7(b) and 7(c) respectively. Fig 7(d) and fig.7 (e) illustrate the back EMF and slip rate of right and left side motor.

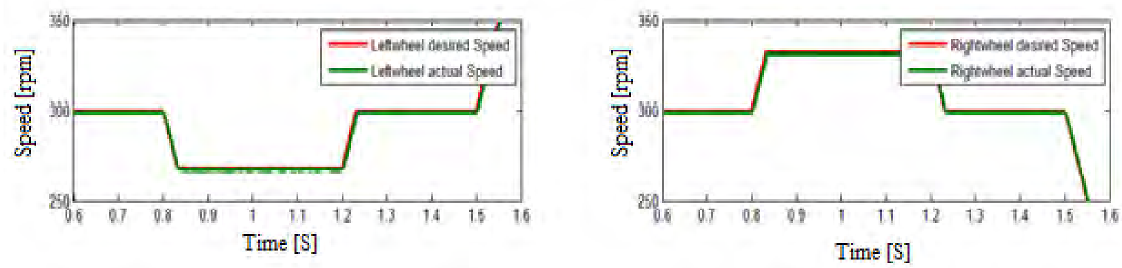

Figure.7. (a) speed waveform of right and left side motor.

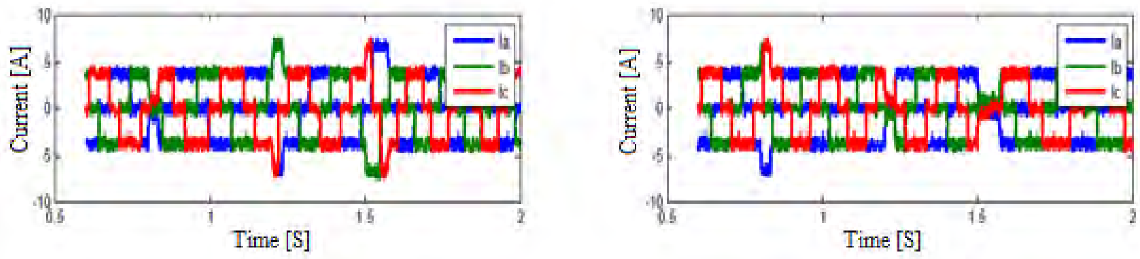

Figure 7 (b) Current wave form of right and left side motor

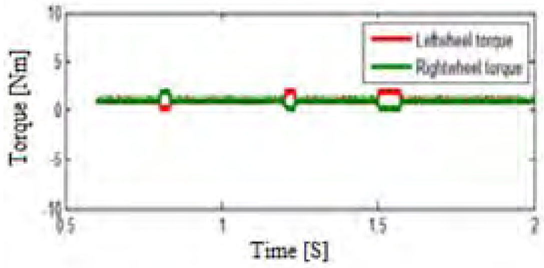

Figure. 7 (c) Torque waveform of right and left side motor.

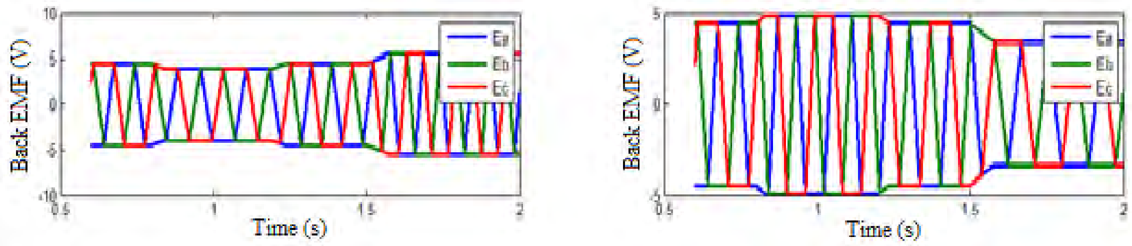

Figure.7 (d) back EMF of right and left side motor.

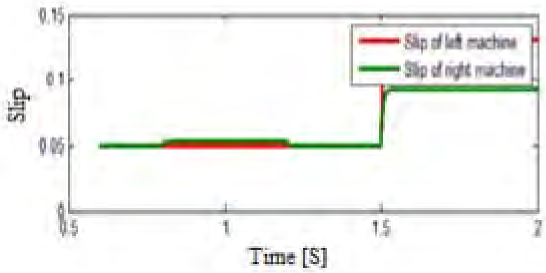

Figure. 7 (e) Slip rate of right and left side motor.

Observations : From the above analysis, it is observed that Speed variations and back EMF generation are same in these three methods but slight changes occur in the Torque distribution, Current distribution and Slip rate. First consider the back EMF detection method, at initial conditions ie, $\delta = 0$, $t = 0$ the vehicle starts to move with 300 rpm. The starting current varies up to 25A then comes back to 5A and maintain the same value for some period of time. Starting torque also varies up to 5.5Nm then comes back to 1Nm and maintain the same state for the same period. Now at time t=0.8s, the vehicle is turned left and now steering angle changes , current varies up to 10A then back to 5A and maintaining the same value likewise, torque varies up to 2 Nm then back to 1Nm and maintaining the same state up to next changes occurs in steering angle.

Second consider Third harmonics voltage integration method, At initial conditions, the starting current varies up to 8A then comes back to 5A and maintain the same value for some period of time. Starting torque also varies up to 2.2Nm then back to 1Nm and maintain the same state for the same period. Now at time t=0.8s, the vehicle is turned left and now steering angle changes , current varies up to 10A then back to 5A and maintain the same value likewise, torque varies up to 2 Nm then back to 1Nm and maintain the same state up to next changes occurs in steering angle.

Third consider the hall sensor based control method, at initial conditions, the starting current varies up to 24A then comes back to 5A and maintain the same value for some period of time. Starting torque also varies up to 5.5Nm then back to 1Nm and maintain the same state for the same period. Now at time t=0.8s, the vehicle is turned left and now steering angle changes , current varies up to 10A then back to 5A and maintain the same value likewise, torque varies up to 2 Nm then back to 1Nm and maintain the same state up to next changes occurs in steering angle.

As far as the slip rate concern, same slip rate variation occurs in the sensor and sensorless control method during turning state of the vehicle ie, at t=0.8s slip rate of the right motor varies between the range of 0.05 to 0.052 and the slip rate of the left motor is 0.05 as constant and at t=1.5s, Slip rate of the right motor varies between the range of 0.05 to 0.092 and the range of the left motor is 0.05 to 0.13.

From these results, Fuzzy based EDC works well in all the methods. Out of these methods, current is evenly distributed for a long period of time, not accumulated in a particular point while using third harmonics voltage integration method. Due to this, power losses and EMI can be significantly reduced. torque distribution and current distribution, we can say that, Fuzzy based EDC with third harmonic voltage integration method is more suitable for Electric vehicles.

V. CONCLUSION

This research paper has dealt with robust electronic differential controller for an electric vehicle. The EV drive system uses two separate BLDC motor drive based wheels. The fuzzy logic control method employed to optimize the slip rate within the specified limit.. The performances are obtained by the proposed method are compared with those obtained using conventional control method. By this investigations, more suitable control strategy identified for stability improvement of two in-wheel motor drive electric vehicle. The performance of the proposed Electronic Differential System has been investigated and excellent results have been obtained under various environmental conditions which also ensure the vehicle stability while cornering and moving in slippery road condition.

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