Journal of Engineering Science and Technology
Vol. 10, No.11 (2015) 1497 - 1507

SLIP RATE ESTIMATION FOR VEHICLE STABILITY ENHANCEMENT USING FUZZY BASED ELECTRONIC DIFFERENTIAL CONTROLLER

A. RAVI[1,*], S. PALANI[2]

[1]Department of Electrical and Electronics Engineering, Sudharsan Engineering College, Sathiyamangalam, Kulathur taluk, Pudukottai, Tamilnadu, India
[2]Sudharsan Engineering College, Sathiyamangalam, Pudukottai, Tamilnadu, India.
*Corresponding author: gdrai24@gmail.com

Abstract

Fuzzy Logic based Electronic Differential Controller (FLEDC) for sensorless drive based electric vehicle is presented. 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) 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 are used to analyse the proposed system. Fuzzy logic based EDC is used on these sensorless control strategies which optimizes the slip rate within the specified limit. To enhances the vehicle stability, the performances in terms of optimum value of slip rate and also current, torque, back EMF are obtained by the proposed method. By this investigation, a suitable control strategy has been identified and also experimentally validated.

Keywords: Back EMF zero crossing detection, Third harmonics voltage integration, BLDC, Electric vehicle, Electronic differential, Fuzzy logic, Sensorless control.

1. Introduction

Even though, a lot of electric motors have been used for the EV applications, but efficiency point of view, BLDC motor drives are the finest choice for EV [1]. In particular, the two BLDC motor is used and fixed on the hub of the rear. Due to the sensor based motor control method have a number of drawbacks, it can be

Nomenclatures

r	Wheel base
v	Vehicle velocity
S	Slip rate
i	Rear wheel number
V_{dc}	DC Voltage

Greek Symbols

ω	Vehicle speed

Abbreviations

BLDC	Brushless Direct Current
EDC	Electronic Differential Controller
EMF	Electro Motive Force
EV	Electric Vehicle
FLEDC	Fuzzy based Electronic Differential Controller
NB	Negative Big
NM	Negative Medium
NS	Negative Small
PB	Positive Big
PM	Positive Medium
PS	Positive small

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 the literatures [2, 3].

Further, Electronic Differential Controller (EDC) is used in this research work. EDC based electric vehicles have many advantages over classical EV with a central motor [4, 5]. One of the main concern in the design of these EVs is to ensure the vehicle stability while cornering and under greasy road conditions [6]. 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 [7] which depends on the wheel slip rate. Due to maintain the slip rate within the optimized range, it will be ensured the vehicle stability in all road condition. The performance of the EDC is simulated and also experimentally validated which has been presented in my research article [8, 9].

2. Fuzzy based Electronic Differential Controller

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 ω3 & ω4 the angular speed of the wheel drives, respectively.

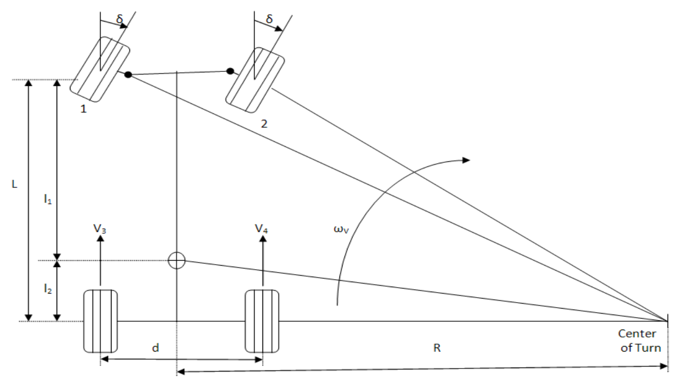


Fig. 1. Vehicle structure.

The signal of the steering angle indicates the curve direction as

$\delta > 0$	⇨	turn right
$\delta = 0$	⇨	straight ahead
$\delta < 0$	⇨	turn left

During the cornering and slippery conditions at either high speed or low speed, rollover will occur. In this circumstances, in order to maintain the stability of the electric vehicle, two things should be considered ie, symmetrical torque distribution of rear wheels and adhesion coefficient with slip rate. This is an essential condition for safety and stability of the electric vehicle. The adhesion coefficient depends on the wheel slip [10] which is defined as

$$Si = \frac{\omega r - v}{\omega r} \tag{1}$$

where r represents the wheel radius, v represents the vehicle velocity and i denotes the rear wheels.

To obtain the finest value of the adhesion coefficient for different roads, slip rate Si equals to 0.05-0.25. The fuzzy-logic control method is employed to determine the slip rate of the wheels. With this approach, the electronic differential distributes the torque according to the requirements of each wheel in order to maintain electric vehicle stability. To obtain a good estimation of the slip rate during cornering, the speed values of each wheel must be measured correctly. The performance of this system depends on the quality of the estimation of the slip rate of each wheel. The fuzzy control system estimates the slip rate and the rate of change of slip rate. Then the system calculate the difference of compensate and output in to each wheel. With this approach, the electronic differential system controls each of the motor torque to adjust the speed of each wheel. Suppose S_0 = 0.2 is the desired vehicle slip ratio. The slip error e is defined as e = Si – S_0 (i = 3rd and 4th rear wheels). The change rate of the error is defined as ė = de/dt. e and ė are the input variables. The change of the motor torque is the output variable.

The Changing rate of e is [0, 1]. The changing rate of ė is [-0.2, -0.8]. The terms of the input variable e is defined to distinguish the situations when the vehicle is accelerating (positive small (PS), Positive middle (PM), positive big (PB) , decelerating (negative small(NS), negative middle(NM), Negative big (NB) and purely rolling zero (ZO). A set of seven linguistic variables (PB, PM, PB, ZO, NS, NM, NB) which contain the information on the degree of the change of the slip rate. Based on this fuzzy set, the input and output membership functions components of the fuzzy controller have been formed.

Figure 2 shows the fuzzy based electronic differential controller (FEDC). Potentiometer has been used on the steering wheel and sense the steering voltage which is equivalent to the steering angle. If the steering angle is zero, then the fuzzy based EDC does not respond. If the steering angle is as definite angle, then the FEDC will respond. It means that the vehicle requires control over turning points only. This proposed system is designed in such a manner to get the desired speed from the steering angle and speed of the vehicle. With this approach FEDC controls the speed of each wheel and at the same time, optimized slip rate will be obtained. The fuzzy rule table is shown in Table.1. The membership functions are shown in Fig. 3.

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

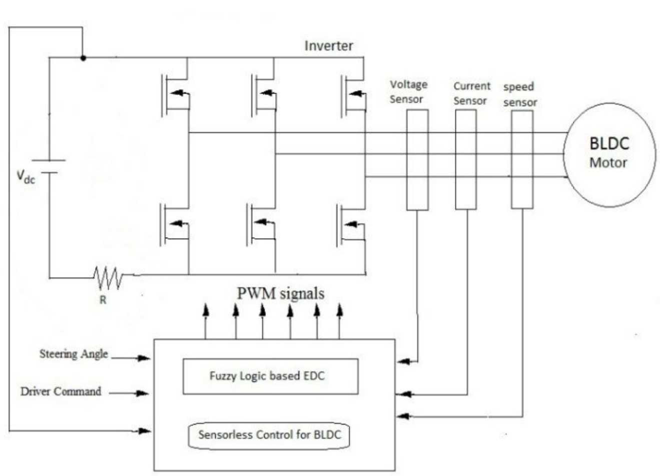


Fig. 2. Fuzzy logic based electronic differential controller.

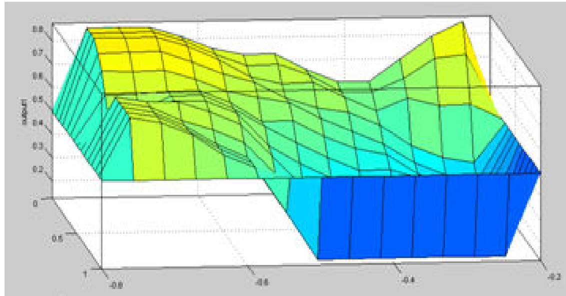


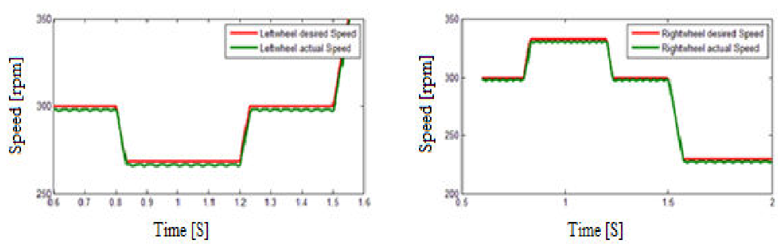
Fig. 3. Membership function of input and output variables.

3. Simulation Results: Comparative Investigations

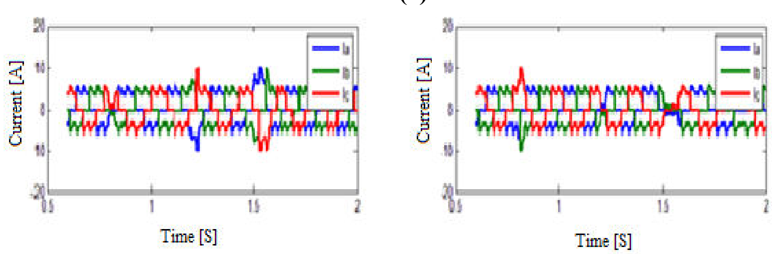
In this research work, two sensorless control strategies include back EMF zero crossing detection and third harmonic voltage integration are adopted to analyse the vehicle performances. The performances are obtained by the proposed method are compared with those obtained using conventional control method. The main parameters have been taken from the reference [10] for this analysis.

Figure 4 shows the simulation results of the performance of conventional method ie, Fuzzy based EDC with hall sensor. Figure 4(a) shows a speed waveform for the left and right side motor. The motor current, Torque, Slip rate and Back EMF under the above operating conditions are shown in Fig. 4(b), 4(c), 4(d) and 4(e) respectively.

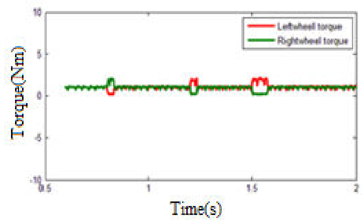
From these investigation, it is observed that the current and torque varies linearly with the direction of the rotation of the wheel. Figure 4(d) shows the slip rate varies from 0.095 to 0.1 under the above conditions. It infers that the slip rate of the driven wheel is controlled within the permitted range as 0.05-0.25.



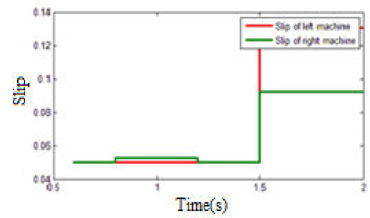
(a)



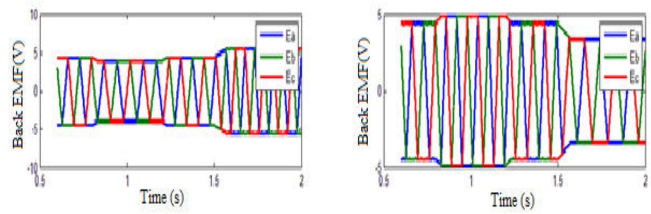
(b)



(c)



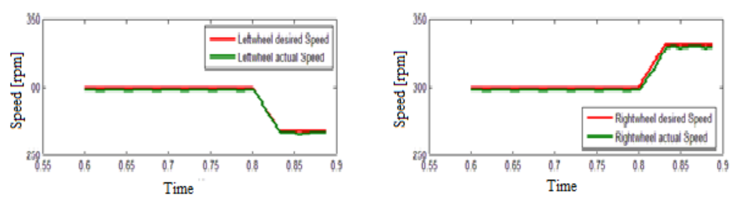
(d)



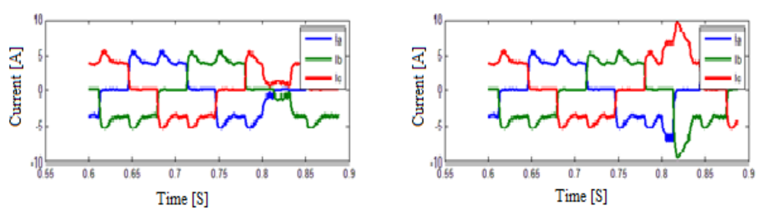
(e)

Fig. 4. The performance of Fuzzy based EDC with Hall sensor.
(a) Speed waveform for left and right side motor ,(b) Current wave form for left and right side motor, (c) Torque wave form for left and right side motor, (d) Slip rate waveform for left and right side motor (e) Back EMF waveform for left and right side motor.

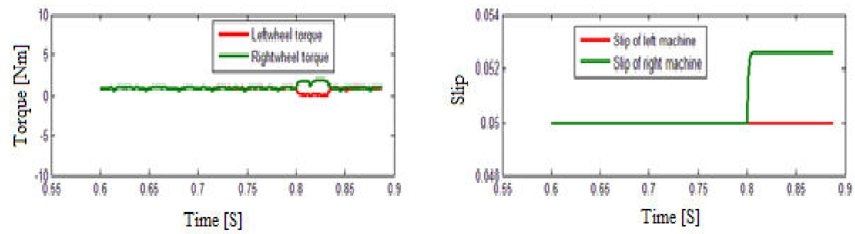
Figure 5 shows the performance of the Fuzzy based EDC with back EMF zero crossing detection. The speed, current , torque, slip and back EMF waveform of left and right side motor under the above operating conditions are shown in Figs. 5(a), (b), (c), (d) and (e) respectively.



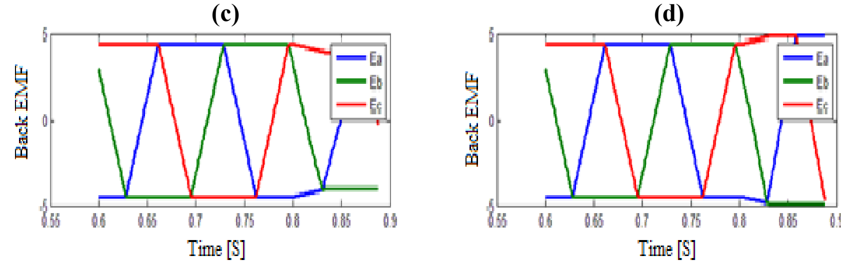
(a)



(b)



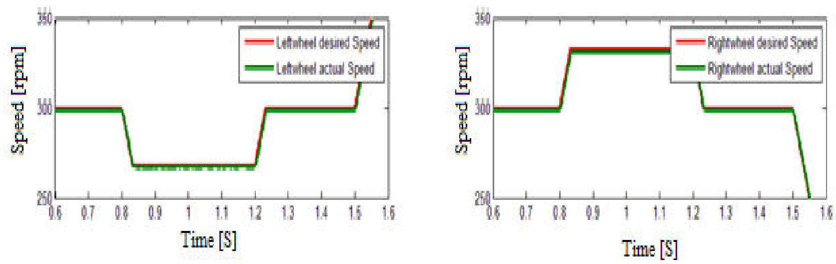
(c) **(d)**



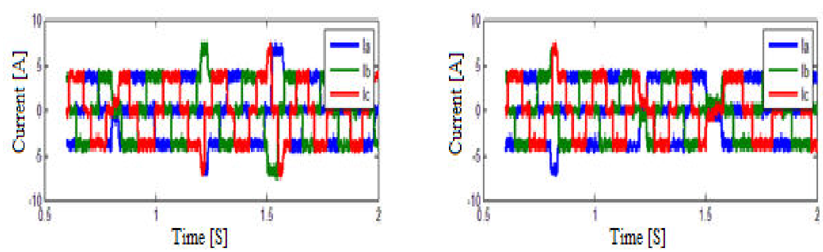
(e)

Fig. 5. The performance of the Fuzzy based EDC with back EMF zero crossing detection. (a) Speed waveform for left and right side motor (b) Current wave form for left and right side motor (c) Torque wave form for left and right side motor (d) Slip rate waveform for left and right side motor. (e) Back EMF waveform for left and right side motor.

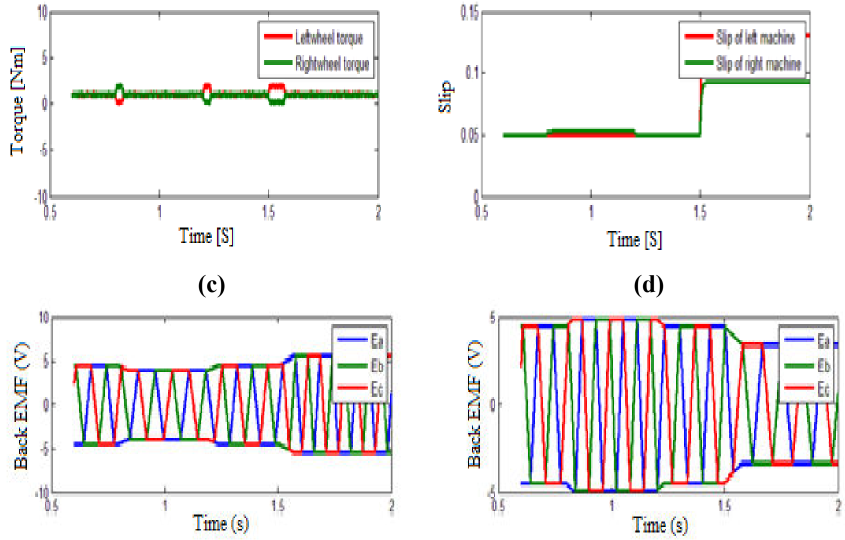
Figure 6 shows that the performance of the Fuzzy based EDC with third harmonics voltage integration. The speed, current, torque, slip and back EMF waveform of left and right side motor under the above operating conditions are shown in Figs. 6(a), (b), (c), (d) and (e) respectively.



(a)



(b)



(c) (d)

(e)

Fig. 6. The performance of the Fuzzy based EDC with third harmonics voltage integration. (a) Speed waveform of left and right side motor (b) Current wave form for left and right side motor (c) Torque wave form for left and right side motor (d) Slip rate waveform for left and right side motor (e) Back EMF wave form of left and right side motor.

Observations:

From the above three 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 among the sensorless control methods.

First consider the sensorless based 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 maintains the same value for some period of time. Starting torque also varies up to 5.5 Nm then comes back to 1Nm and maintains 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 the 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 1 Nm 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. 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.

The results of the sensorless control strategies are summarised in Table 2.

Table. 2. Performances of the sensorless control strategies.

S. No.	Sensorless Control Strategies	Conditions	Torque (Nm)	Current (A)	Slip rate
1.	Back EMF zero crossing detection method	t = 0 s	5.5	25	-
		t = 0.8s	2	10	0.05 - 0.052
2.	Third harmonic voltage integration method	t = 0 s	2.2	8	-
		t = 0.8s	2	10	0.05 - 0.052

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. From the torque distribution and current distribution, it is proved that, fuzzy based EDC with third harmonic voltage integration method is more suitable to improve the stability in Electric vehicles.

4. Experimental Investigations

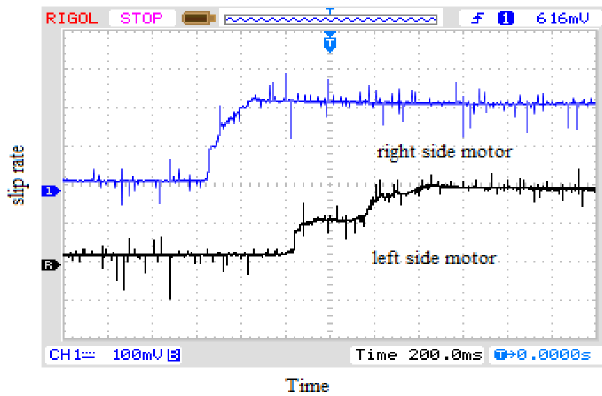
4.1. Experimental set up

Figure 7 shows the EV structure for experimental investigation. Specific experimental tests are carried out to demonstrate the feasibility and the effectiveness of the proposed Fuzzy based EDC with third harmonic voltage integration method in terms of vehicle stability. Evaluation of the vehicle parameter is done by using ARM processor.

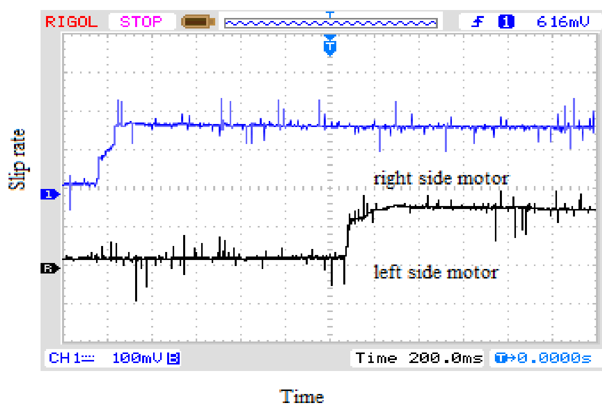
Fig. 7. EV Structure for investigation.

4.2. Experimental results

Figure 8 shows the variation of slip rate with different vehicle speed. Figure 8(a) shows slip rate with vehicle speed is 300 rpm. When the vehicle speed is 300 rpm and steering angle is changed according to the curve linear path. In this condition, slip rate of the right wheel varies from 0 to 0.22 and left wheel varies from 0 to 0.12 then goes to 0.2. Figure 8(b) illustrates the variation of slip rate with vehicle speed is 600 rpm. In this condition, slip rate of the right wheel varies from 0 to 0.17 and left wheel varies from 0 to 0.15. It infers that Fuzzy logic based EDC with third harmonic voltage integration works well which optimizes the slip rate within the specified limit and thus enhances the vehicle stability.



(a)



(b)

Fig. 8. Slip rate with different vehicle speed
(a) Vehicle speed is 300 rpm. (b) Vehicle speed is 600 rpm.

5.Conclusion

This research paper has dealt with Fuzzy based electronic differential system for an electric vehicle. The fuzzy logic control method employed to optimize the slip rate within the specified limit. 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. Slip rate is an important factor for the performance of two in wheel motor drive system. If slip rate exceeds 0.25, it is estimated that the system will lose its stability. Of the many methods available in literature, back EMF detection method, third harmonics voltage integration method and conventional method (sensor method) has been taken for this work. It has been observed that by using third harmonic voltage integration method, we get the best results followed by back EMF detection Method and conventional method. It is concluded that Fuzzy based EDC with third harmonic voltage integration is highly suitable for the two in wheel motor drive electric vehicle which gives high range of stability with improved efficiency.

References

1. Xue, X.D.; Cheng, K.W.E.; and Cheung N.C. (2008) Selection of electric motor drives for electric vehicles. *Australasian Universities Power Engineering Conference*, University of New south Wales, Sydney, Australia.
2. Shao, J.; Nolan, D.; Teissier, M.; and Swanson, D. (2003). A novel Microcontroller based sensorless brushless DC BLDC) motor drive for automotive fuel pumps. *IEEE Transaction on Industrial Applications*, 39, 1734-1740.
3. Gamazo-Real, J.C.; Vazquez-Sanchez, E.; and Gómez-Gil, J. (2010). Position and speed control of brushless DC motors using sensorless techniques and application trends. *Sensors*; 10, 6901-6947.
4. Perez-pinal, F.J.; Cervantes, I., and Emadi, A. (2009). Stability of an electronic differential for traction applications. *IEEE Transactions on Vehicle Technology*, 58, 3224-3233.
5. Haddoun, A; Hachemi Benbouzid, M.; Diallo, D.; Abdessemed, R.; Ghouili, J.; and Srairi, K. (2008). Modelling, analysis and neural network control of an electric vehicle electrical differential. *IEEE Transactions on Industrial Electronics*; 55, 2286- 2294.
6. Hartani, K.; Miloud, Y.; and Miloudi A. (2010). Electric vehicle stability with rear electronic differential traction. *International Symposium on Environment Friendly Energies in Electrical Applications*, 39, 1-5.
7. Pokorski, J.; Reski, A.; and Sar, H. (2012). Investigation of adhesion characteristics of different tyre types in different weather conditions. *Journal of KONES Powertrain and Transportation*, 19, 363-369.
8. Ravi, A.; and Palani, S. (2013) . Simulation of electronic differential system for sensorless control based electric vehicle. *International Review of Modeling and Simulation*, 6, 189-194.
9. Ravi, A., and Palani, S.(2013). Robust electronic differential controller for an electric vehicle. *American Journal of Applied Science*, 10, 1356-1362.
10. Zhoa, Y.E.; and Zhang, J.W. (2009). Modeling and simulation of an electronic differential system for an electric vehicle with two motor wheel drive. *International Journal of Vehicle systems Modeling and Testing*, 4, 117-131.