DISCRETE-TIME SLIP CONTROL ALGORITHMS FOR A HYBRID ELECTRIC VEHICLE

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE
REQUIRMENTS FOR THE DEGREE OF

Master of Technology

In

CONTROL AND AUTOMATION

By

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DEPARTMENT OF ELECTRICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

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Under the Guidance of

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CERTIFICATE

This is to certify that the thesis titled "**Discrete-Time Slip Control Algorithms for a Hybrid Electric Vehicle**", submitted to the National Institute of Technology, Rourkela by **Chaudhari Khushal Kawaduji**, Roll No. **211EE3148** for the award of **Master of Technology** in **Control & Automation**, is a bona fide record of research work carried out by him under my supervision and guidance.

The candidate has fulfilled all the prescribed requirements.

The Thesis which is based on candidate's own work, has not submitted elsewhere for a degree/diploma.

In my opinion, the thesis is of standard required for the award of a Master of Technology degree in Control & Automation.

To the best of my knowledge, he bears a good moral character and decent behavior.

Place: Rourkela
Date:

Prof. Bidyadhar Subudhi

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CHAUDHARI KHUSHAL K.

CONTENTS

ABSTRACT

This thesis develops a discrete-time sliding mode control scheme for a slip control of a hybrid electric vehicle. In order to handle different road conditions, fuzzy logic technique is employed to develop control of slip ratio. A discrete-time Sliding mode observer is also designed to estimate the vehicle velocity online. Furthermore, in order to cope up with changing slip dynamic for varying road conditions an Adaptive sliding mode control has been designed by employing Lyapunov theory. The performances of developed adaptive sliding mode control, Sliding mode control and Fuzzy logic control for slip ratio are compared through extensive Matlab simulation and it is observed that the discrete time Fuzzy adaptive sliding mode control perform effectively.

Keywords- discrete time sliding mode control, observer, adaptive sliding mode control, slip ratio, fuzzy sliding mode control, fuzzy PID

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ACRONYMS

HEV	Hybrid Electric Vehicle
FLC	Fuzzy Logic Control
SMC	Sliding Mode Control
SMO	Sliding Mode Observer
ASMC	Adaptive Sliding Mode Control
FSMC	Fuzzy Sliding Mode Control
FASMC	Fuzzy Adaptive Sliding Mode Control
SRC	Slip Ratio Control

CHAPTER 1

Introduction

1.1 HEV introduction

The internal combustion (IC) engine has been the most prominent propulsion system used for transportation throughout the last century. The depletion and the increase in the cost of fossil fuel resources and the rise in emissions have resulted in a need for more robust and sustainable transportation methods. It causes a significant interest in hybrid electric vehicle (HEV) globally due to the environmental concerns and solution for an increase in the price of oils. As modern society continues to increase in the use of vehicles, so does the need for an increasing number of vehicles for transportation. Trends predict that the fossil fuels located under the earth's surface are at risk of being entirely consumed in the near future. Hybrid electric vehicles (HEVs) offer superior fuel economy and are a logical step in the direction towards zero emissions vehicles.

A HEV uses both an electric motor with a battery and a combustion engine with a fuel tank for propulsion; hence it called as a hybrid between electric and conventional vehicle. Not fully electric vehicles, HEVs are a bridging technology for a developed and transitional countries and markets. Their increasing share in the global fleet is a move toward greater eventual fleet electrification through the use of plug-in hybrid (PHEVs) and pure electric vehicles (EVs) as HEVs require no infrastructure changes. This is why HEVs are of particular interest now, even as countries struggle with fuel quality, the sustainable use and production of biofuels and the adoption of a clean diesel technology. HEV technology is more expensive than conventional vehicles, is self-assured for entry into new markets. This will provide a number of opportunities and advantages provided that the right policies and complementary standards including fuel good quality standards are in place, industry groups, consumers, and vehicle maintenance providers are sufficiently informed and have right expectations of HEV technology.

The focus of nowadays research towards hybrid electric vehicles has been on increasing energy efficiency and reducing emissions. From the viewpoint of electric and control engineering, Electric and Hybrid electric vehicles (HEVs) have more advantages over conventional internal combustion engine vehicles (ICVs)[1]. Moreover, HEVs use multiple sources of power for propulsion because motor and TCS (traction control system) should be integrated into "Hybrid Traction Control System (HTCS)", since a motor can both accelerate or decelerate the wheel and also it is easier to achieve advanced driving performance by using control features such as antilock braking systems (ABSs) and traction control systems [2],[17]. Its performance should be advanced, if we can utilize the fast torque response of motor. There exists little uncertainty in driving or braking torque produced by motor, compared to that of combustion engine and hydraulic brake. The use of electric motors in HEV propulsion makes it possible to eliminate the expensive ABS associated with conventional hydraulic brakes. In addition to the primary function of propulsion, the electric motor can also be used effectively as the braking device because of its fast torque response characteristics and capability of regeneration[18]. The fast torque response provides the opportunity to improve the vehicle antilock performance through the control of motor torque, without conventional ABS. Torque generation is very quick and accurate, for accelerating and decelerating.

The problem during braking on slippery roads is that the wheels of the vehicle may lock that is wheel speed approaches to zero and vehicle may lose control on road. So it creates the chances of accident. The objective of ABSs is to maximize wheel traction by preventing the wheels from locking during braking while maintaining adequate vehicle stability and steer ability. Control of a braking system and traction of a vehicle are difficult due to the nonlinear characteristics and unknown time-varying parameters associated with vehicle and wheel dynamics.

1.2 Literature survey on slip ratio control of HEV

The last ten decades have witnessed the development of several control approach for slip control of a HEV. The slip ratio control is a challenging control problem, because HEV is having uncertainty problem with nonlinearity problem in dynamic of HEV. The literature [2], [5] and [11] describe the mathematical model of HEV. Past work related to slip control problem of HEV gives a number of control techniques. Literature [5] describes sliding mode control for controlling slip of a HEV. This literature also describes the design of observer for vehicle speed. Iterative learning control algorithms have been developed in literature [2] for slip control of a HEV. This paper also gives the design of observer for vehicle speed. In the literature [11], detailed designs of controller are given which solve at most all problems of uncertainty and nonlinearity in HEV dynamic. Sliding mode control is designed for slippery roads, adaptive SMC and non-model based neural network control are designed for road change or slip change of a HEV. Also it gives simple observer design for vehicle speed as it is not present online. Also number of control approach such as fuzzy logic control [3], neural network [4] have been reported for slip ratio control of a HEV and conventional vehicles. Advanced control algorithms, such as fuzzy logic control [6], neural network [7], hybrid control [8], adaptive control [9], and other intelligent control [19], [20] have been developed to achieve antilock braking performance for conventional vehicles.

Reviews of all these paper gives motivation as controller algorithms developed is in continuous time and designed controller is unable to solve the problem of chattering i.e. high frequency oscillation present torque, slip ratio, voltage which will damage braking system (DC motor). Also recent advances in digital computing develop as dSPACE and DSP motivate control design in discrete time domain. Although SMC and observer have been designed for slip ratio control of HEV but for real time implementation discrete time controller are needed. Hence unlike [2], [5], [11], present work is focused on develop of discrete time SMC, adaptive SMC, FLC and PID using fuzzy logic for slip control of HEV.

1.3 Thesis objective

- To develop a control algorithms that enable achieving desired slip ratio such that wheel lock is prevented.
- The controller must be adaptively handle uncertainty in the nonlinear and time varying vehicle and wheel dynamics.

1.4 Contribution of thesis

- Provide discrete time modeling for Slip ratio of HEV.
- Design of discrete time FSMC.
- Design of observer for vehicle speed estimation.
- Design of ASMC for adaptation of nonlinear tire road dynamic.

1.5 Continuous time model of HEV

The dynamics of vehicle is given by [11] so that angular motion and linear motion of wheel is as follows (fig.1)

$$I_w \dot{\omega}_w = \tau_m - r_w \left(\mu(\lambda) mg + f_w \right) \tag{1.1}$$

$$m\dot{v} = n_w \mu(\lambda) mg - c_v v^2 \tag{1.2}$$

where

I_w - Moment of inertia of wheel

r_w - Radius of wheel

m - Mass of vehicle

g - Acceleration due to gravity

n_w - Number of wheel

f_w - Viscous wheel friction force

μ - Adhesive coefficient

τ_m - Braking torque

ω_w - Wheel angular velocity

ω_v - Vehicle angular velocity

v - Linear velocity of vehicle

c_v - Aero-dynamic drag coefficient

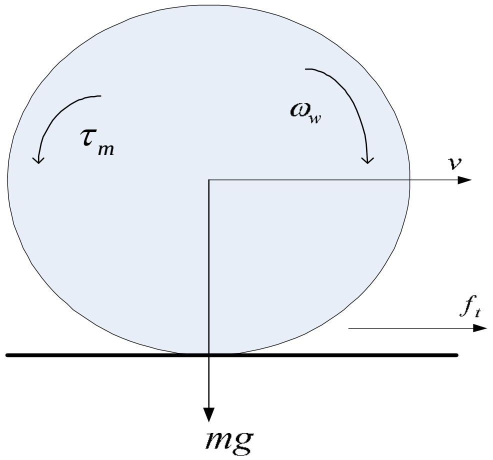

Fig 1.1**:** Single wheel model

Slip ratio is defined as [10]

$$\lambda = \frac{\omega_w - \omega_v}{\max(\omega_v, \omega_w)} \tag{1.3}$$

The linear velocity and angular velocity is related as

$$v = r_w \omega_v \tag{1.4}$$

Using equations (1.1), (1.2) and (1.4), dynamics of a hybrid electric vehicle can be represented as

$$\dot{\omega}_v = \frac{n_w g}{r_w} \mu(\lambda) - \frac{c_v r_w}{m} \omega_v^{\,2} \tag{1.5}$$

$$\dot{\omega}_w = \frac{\tau_m}{I_w} - \frac{r_w}{I_w} \mu(\lambda) mg - \frac{r_w}{I_w} f_w \tag{1.6}$$

Choosing state variable as

$x_1 = \omega_v$ and $x_2 = \omega_w$

Equation (1.5) and (1.6) can be rewritten as

$$\dot{x}_1 = f_1(x_1) + d_1 \mu(\lambda) \tag{1.7}$$

$$\dot{x}_2 = f_2(x_2) + d_2 \mu(\lambda) + d_3 \tau_m \tag{1.8}$$

where

$$f_1(x_1) = -\frac{c_v r_w}{m} x_1^{\,2} \tag{1.9}$$

$$f_2(x_2) = -\frac{r_w f_w(x_2)}{I_w} \tag{1.10}$$

$$d_1 = \frac{n_w g}{r_w} \tag{1.11}$$

$$d_2 = -\frac{r_w m g}{I_w} \tag{1.12}$$

$$d_3 = \frac{1}{I_w} \tag{1.13}$$

1.6 Discrete time model of HEV

Discretized form of equation (1.7) and (1.8) can be written as discrete-time model of HEV

$$\frac{x_1(k+1) - x_1(k)}{T} = f_1(x_1(k)) + d_1 \mu(\lambda(k)) \tag{1.14}$$

$$\frac{x_2(k+1) - x_2(k)}{T} = f_2(x_2(k)) + d_2 \mu(\lambda(k)) + d_3 \tau_m(k) \tag{1.15}$$

where T is sampling time.

1.7 Actuator Dynamic

The actuation system of HEV given in [11] consists of a dc motor. It is controlled by impressing a variable armature voltage, keeping the field current constant. During the traction, the torque is considered to be positive, and during braking, the torque is negative. Applying Kirchhoff’s voltage law to the armature circuit of the motor shown in fig 1.2, we get

$$L\dot{i}_a + R i_a + e_b = e \tag{1.16}$$

$$e_b = K_b \omega_w \tag{1.17}$$

where

e - Applied voltage to the armature circuit

R, L - Resistors and Inductors of the armature circuit

i_a - Armature current

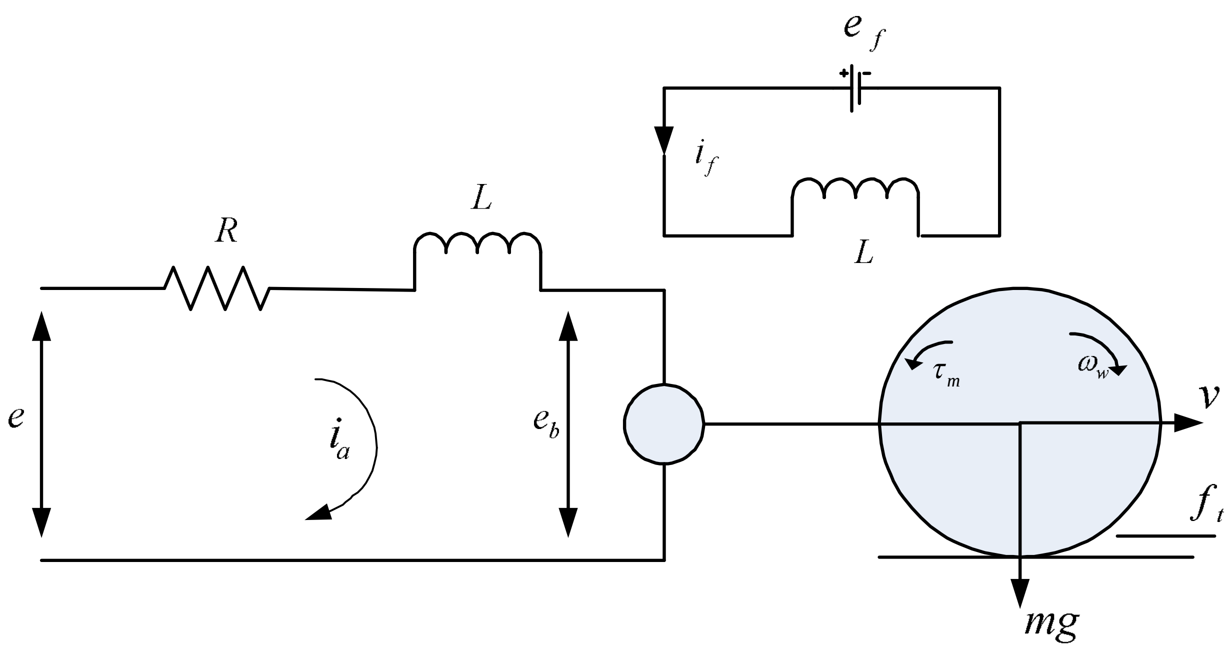

Fig 1.2: Actuator Diagram

i_f - Field current

e_b - Back electromotive force (EMF)

K_b - Back EMF constant

e_f - Field voltage

L_f - Field inductance

The torque developed by the motor is given by

$$\tau_m = K_m i_a \tag{1.18}$$

where K_m is the motor torque constant. Substituting (1.17) and (1.18) in (1.16), we have

$$e = \frac{L}{K_m}\dot{\tau}_m + \frac{R}{K_m}\tau_m + K_b\omega_w \tag{1.19}$$

In discrete domain the above equation can be written as

$$e(k) = \frac{L}{K_m} \frac{\tau_m(k+1) - \tau_m(k)}{T} + \frac{R}{K_m} \tau_m(k) + K_b \omega_w(k) \tag{1.20}$$

1.8 Problem Formulation for slip ratio control

From equation (1.3), we obtain

$$\lambda(k) = \frac{x_2(k) - x_1(k)}{\max\left(x_1(k), x_2(k)\right)} \tag{1.21}$$

Deceleration:

For deceleration, $x_1 > x_2$ and hence

$$\lambda(k) = \frac{x_2(k) - x_1(k)}{x_1(k)} \tag{1.22}$$

Equation (1.22) can be rewritten as

$$\lambda(k+1) = \frac{x_2(k+1) - x_1(k+1)}{x_1(k+1)} \tag{1.23}$$

From equation (1.22) and (1.23), solving for $\frac{\lambda(k+1) - \lambda(k)}{T}$ one gets

$$\frac{\lambda(k+1) - \lambda(k)}{T} = f(\lambda, x) + bu \tag{1.24}$$

where

$$f(\lambda, x) = f_2(x_2) - (1+\lambda) f_1(x_1) + \left[d_2 - (1+\lambda) d_1\right] \mu(\lambda) \tag{1.25}$$

$$u = \frac{\tau_m}{x_1} \tag{1.26}$$

$$b = d_3 \tag{1.27}$$

$$x = [x_1, x_2]^T \tag{1.28}$$

Acceleration:

For acceleration, $x_2 > x_1$ therefore,

$$\lambda(k) = \frac{x_2(k) - x_1(k)}{x_2(k)} \tag{1.29}$$

Equation (1.29) can be rewritten as

$$\lambda(k+1) = \frac{x_2(k+1) - x_1(k+1)}{x_2(k+1)} \tag{1.30}$$

On solving for $\frac{\lambda(k+1) - \lambda(k)}{T}$ using equation (1.29) and (1.30), we get

$$\frac{\lambda(k+1) - \lambda(k)}{T} = f(\lambda, x) + bu \tag{1.31}$$

where

$$f(\lambda, x) = (1-\lambda) f_2(x_2) - f_1(x_1) + \left[d_2(1-\lambda) - d_1 \right] \mu(\lambda) \tag{1.32}$$

$$u = \frac{\tau_m}{x_2} \tag{1.33}$$

$$b = (1-\lambda) d_3 \tag{1.34}$$

Our main concern is for achieving effective braking, thus it is required to find control input u by using equation (1.24) as b is an unknown constant gain which is related with I_w. Let $\hat{b}$ be the estimated value of b. $\mu - \lambda$ characteristics of surface vehicle is given in ref. [12] by

$$\mu(\lambda) = \frac{2\mu_p \lambda_p \lambda}{\lambda_p^{\,2} + \lambda^2} \tag{1.35}$$

where μ_p is optimal adhesive coefficient and λ_p is optimal slip.

Now our objective is to find the control input u such that desired slip is being tracked by the HEV in presence of nonlinearity in $f(\lambda, x)$ due to adhesive coefficient and slip relation.

1.9 Organization of Thesis

This thesis is divided into five chapters.

Chapter 1 discusses briefly about introduction of HEV and literature survey on Slip ratio of HEV. Also it gives continuous and discrete time modeling for slip ratio of HEV.

Chapter 2 discusses briefly about the actuator dynamic i.e. DC motor modeling, problem formulation for slip ratio control, design of discrete time sliding mode control and estimation of uncertainty due to changing parameter of HEV model by using Fuzzy logic.

Chapter 3 discusses briefly about design of observer for vehicle speed and also design of Adaptive sliding mode control for road change condition.

Chapter 4 discusses briefly about design of discrete time fuzzy logic control and fuzzy logic PID control for faster response.

Chapter 5 provide brief conclusion of slip ratio control problem and suggestion for the future work.

1.10 Chapter summary

This chapter describes briefly about introduction about HEV i.e. why HEV is a subject of recent research. Also brief literature review on slip control problem of a HEV is described. It also gives thesis objective, contribution of thesis, continuous time, discrete time modeling and problem formulation for slip ratio control for HEV.

CHAPTER 2

Development of SMC and FSMC for SRC of HEV

2.1 Design of discrete time SMC

In this section, the design of a discrete-time sliding mode controller for slip ratio control of a HEV is presented.

Choose a sliding surface as

$$s(k)=\lambda_e(k) \tag{2.1}$$

where

$$\lambda_e(k)=\lambda(k)-\lambda_d(k) \tag{2.2}$$

A reaching law for this problem in order the state should lie on sliding surface within band and should not leave sliding can be designed referring to [13]

$$s(k+1)=(1-qT)s(k)-\varepsilon T\,\mathrm{sgn}(s(k)) \tag{2.3}$$

where ε is the reaching rate and q is the approximation rate and $\varepsilon>0$, $q>0, (1-qT)>0$.

To maintain state on the sliding surface

$$s(k+1)=0 \tag{2.4}$$

and $s(k)\neq 0$. Substituting equations (1.24), (2.1) and (2.2) in equation (2.3), we get the control input as

$$u_1(k)=-\hat{b}^{-1}\hat{f}(\lambda,x)-\hat{b}^{-1}qs(k)+\hat{b}^{-1}\varepsilon\mathrm{sgn}(s(k)) \tag{2.5}$$

Referring to [14] new control input is designed as

$$u(k)=\begin{cases} u_1(k) & if\ |u_1(k)|\le u_0(k), \\ u_0(k)\dfrac{u_1(k)}{|u_1(k)|} & if\ |u_1(k)|> u_0(k), \end{cases} \tag{2.6}$$

u_0 can be calculated from the condition that $|s(k+1)|<|s(k)|$. Thus

$$u_0(k) \geq \left| -\hat{b}^{-1}\hat{f}(\lambda, x) + \hat{b}^{-1}\frac{(1-qT)}{T}s(k) + \hat{b}^{-1}\varepsilon\,\mathrm{sgn}(s(k)) \right| \tag{2.7}$$

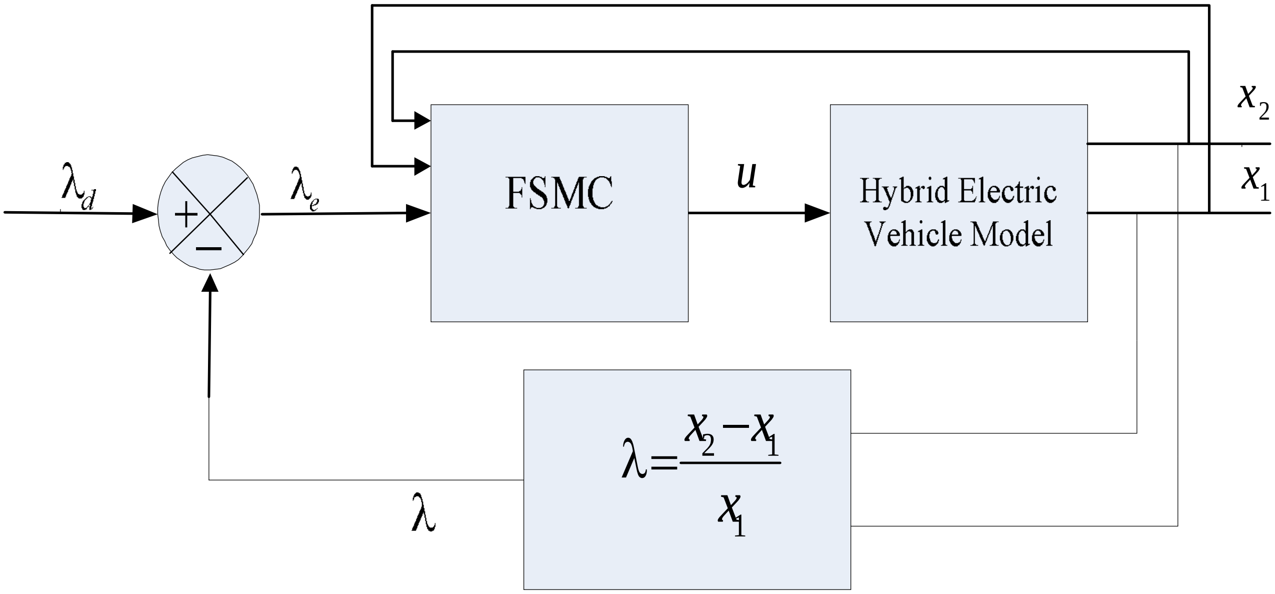

Fig 2.1: Fuzzy Sliding mode control structure

2.2 Estimation of uncertainty in HEV model using fuzzy logic

Define uncertainty estimation error as follows

$$\tilde{f}(k) = f(k) - \hat{f}(k) \tag{2.8}$$

Dynamic equation for $\hat{f}(k)$ can be constructed given in ref [15] as

$$\hat{f}(k+1) = \hat{f}(k) + \alpha\left|\hat{f}(k) - \hat{f}(k-1)\right| + \tilde{f}(k) + \alpha\left|\tilde{f}(k) - \tilde{f}(k-1)\right| \tag{2.9}$$

where $|\alpha| \leq 1$.

We consider two inputs and one output fuzzy sets for computing α and membership function is considered as triangular.

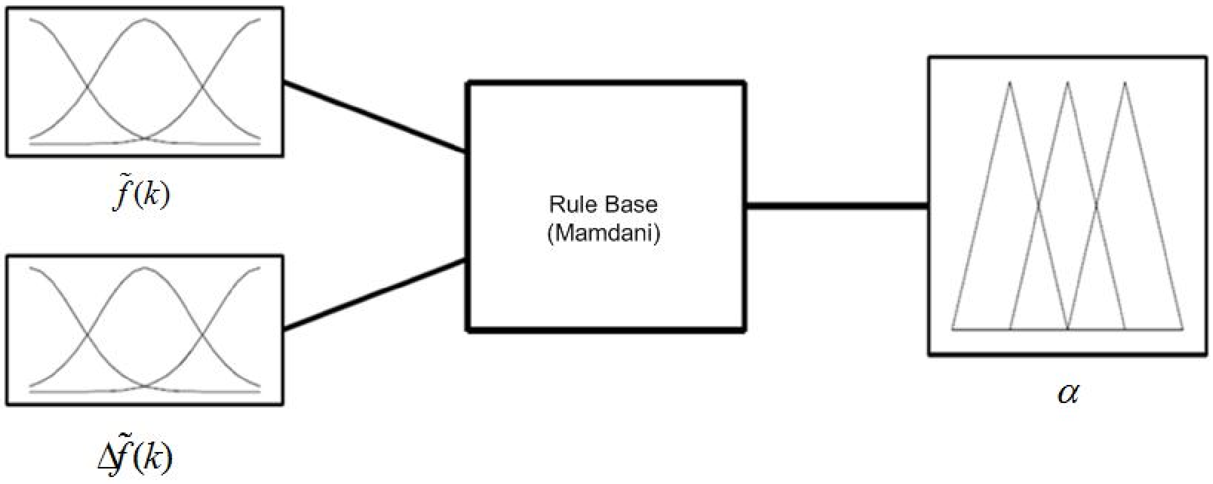

Fig 2.2: Fuzzy inference block

Linguistic labels for input and output variables are chosen as PB- Positive Big, PM- Positive Medium, PS- Positive Small, Z- Zero, NB- Negative Big, NM- Negative Medium, and NS- Negative Small (Fig. 2.2).

Table 1: Rule base for computing α

$\tilde{f}(k)$ $\Delta\tilde{f}(k)$	NB	NM	NS	Z	PS	PM	PB
PB	Z	NS	NS	NM	NM	NB	NB
PM	PS	Z	NS	NS	NM	NM	NB
PS	PS	PS	Z	NS	NS	NM	NM
Z	PM	PS	PS	Z	NS	NS	NS
NS	PM	PM	PS	PS	Z	NS	NS
NM	PB	PM	PM	PS	PS	Z	NS
NB	PB	PB	PM	PM	PS	PS	Z

Rule i: If $\tilde{f}(k)$ is NB and $\Delta\tilde{f}(k)$ is PB then α is Z.

Where i = 1, 2, 3, ….n and n is number of rules and list of rules is given in table 3.

2.3 Simulation results

Table 2: Vehicle and Actuator parameter

Parameter	Value	Parameter	Value
I_w	$0.65\ km\ m^2$	λ_p	-0.17
r_w	$0.31\,m$	c_v	$0.595\,N_{/}m^2{}_{/}s^2$
m	$1400\ kg$	T	$0.001\ s$
g	$9.8\ m/s^2$	K_m	$0.2073\,m\ kg/h$
n_w	4	K_b	$2.2\ V/rad/s$
f_w	$3500\,N$	R	$0.125\,\Omega$
μ_p	-0.8	L	$0.0028\,H$

Values of parameter used in simulation are shown in table 2. For simulation, the initial value of vehicle velocity is 90 km/h, wheel velocity is 88 km/h , $\hat{x}_1$ is 89.2 km/h.

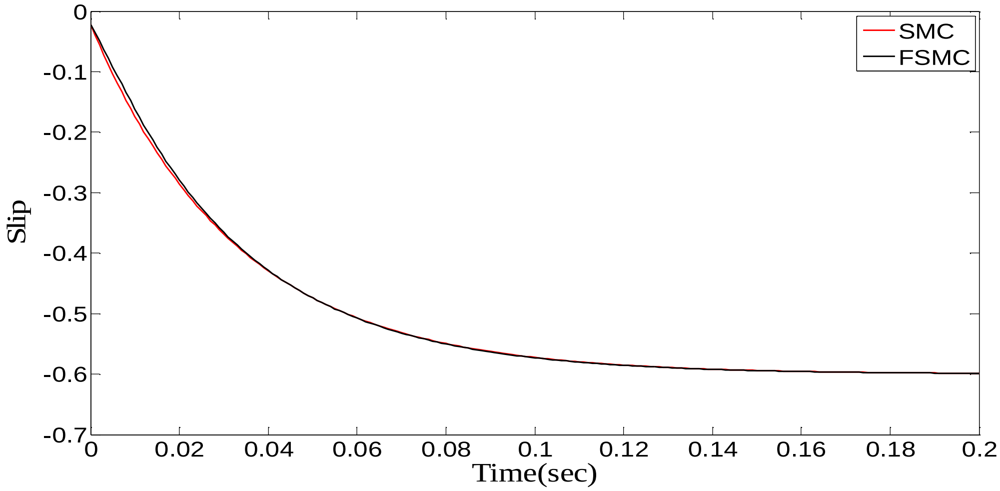

Fig 2.3: Slip (SMC & FSMC)

Section 2.3 shows result of discrete-time sliding mode control and fuzzy sliding mode control for desired value of slip ratio λ_d is -0.6, q is 300, ε is 0.05. Fig 2.3 shows that desired value of slip ratio is tracked and settling time is also very less i.e. 0.12 sec. Fig 2.4 shows that sliding variable converges to zero that means states remains on the desired sliding surface. Fig 2.5 and 2.6 show about the vehicle speed and wheel speed and which are decreasing which is required in deceleration to maintain slip ratio at desired value. Fig 2.7 shows braking torque

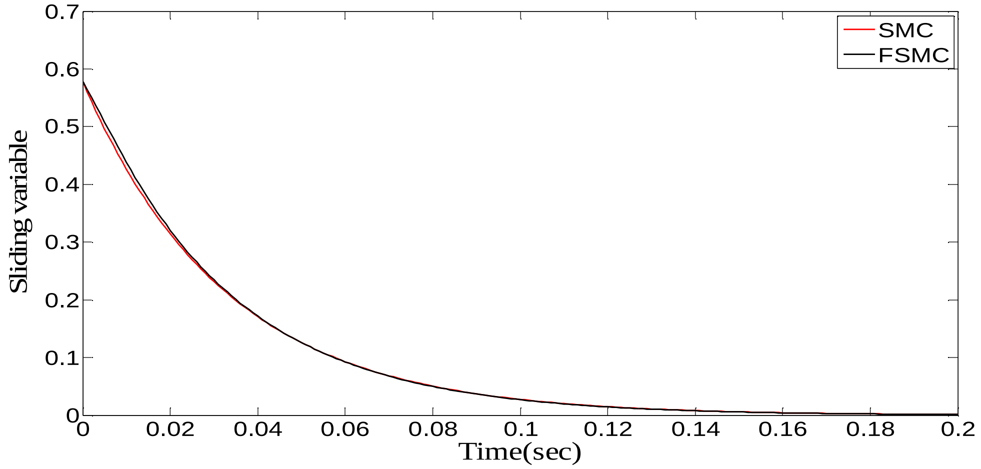

Fig 2.4: Sliding Variable (SMC & FSMC)

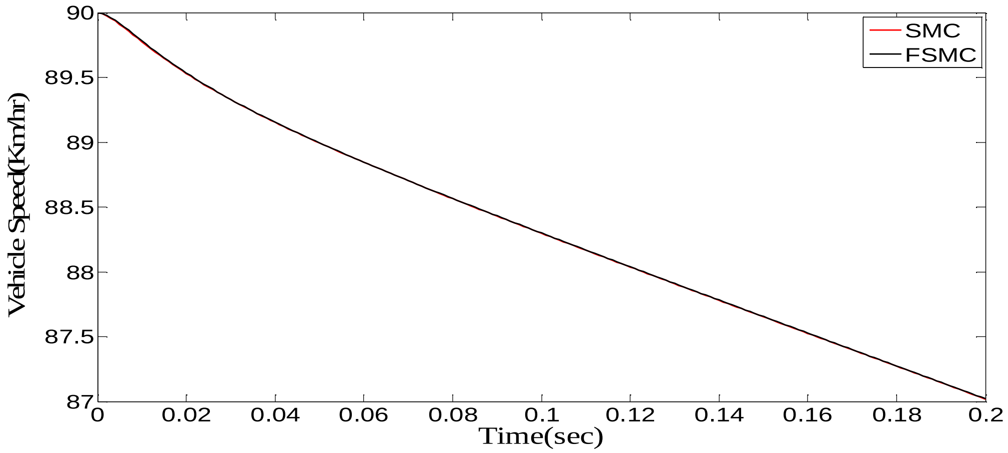

Fig 2.5: Vehicle speed (SMC & FSMC)

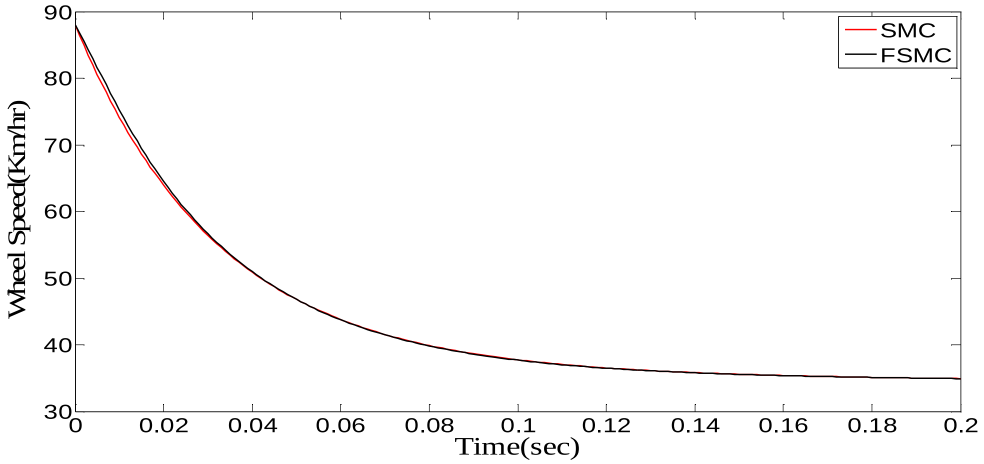

Fig 2.6: Wheel Speed (SMC & FSMC)

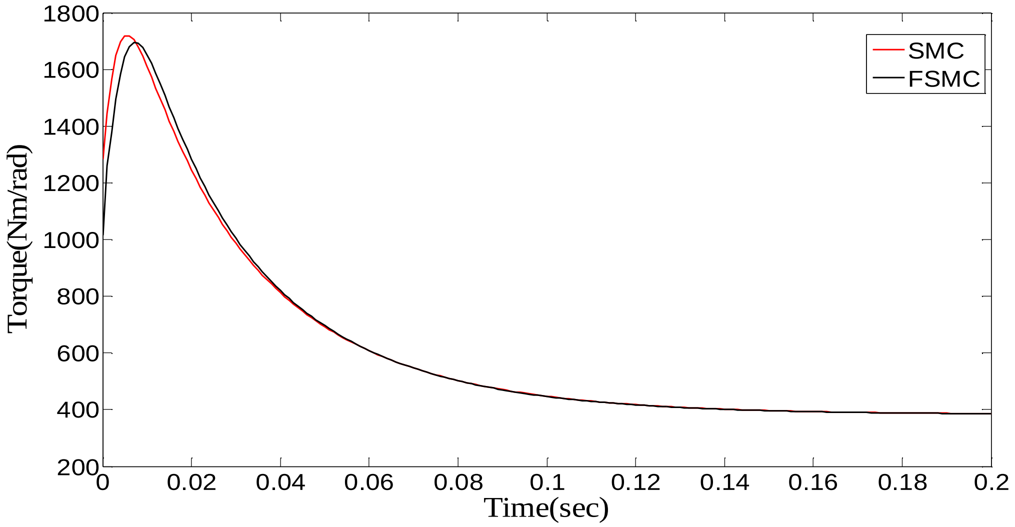

Fig 2.7: Torque (SMC & FSMC)

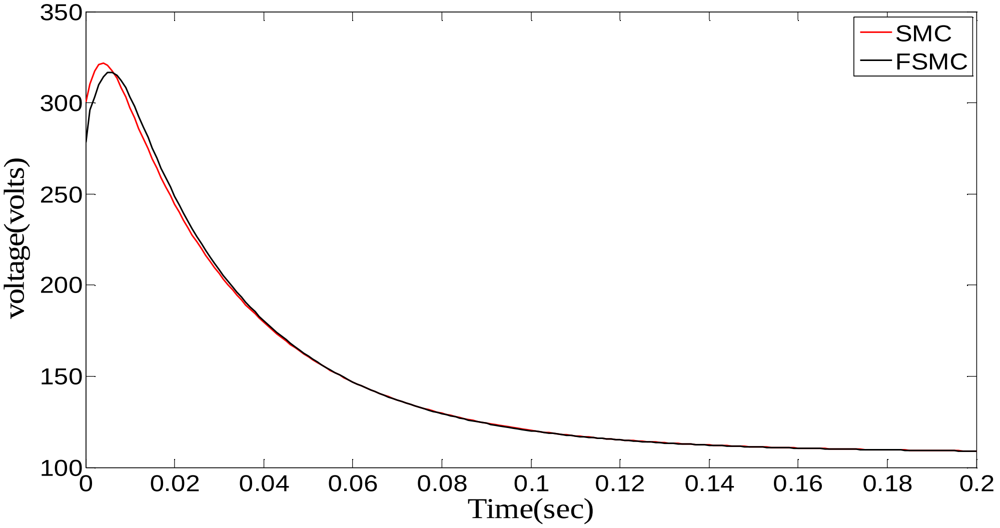

Fig 2.8: Voltage (SMC & FSMC)

is without chattering and fig 2.8 shows what voltage require to provide torque from actuator. Uncertainty estimation shows in fig 2.9 which goes to zero because of FSMC. Hence, it is proved that FSMC will take of the problem of uncertainty and response of SMC and FSMC is also exactly similar. In all, there is no chattering. So discrete-time fuzzy sliding mode controller working well for slip tracking problem for HEV. Tabular comparison is provided in table 3.

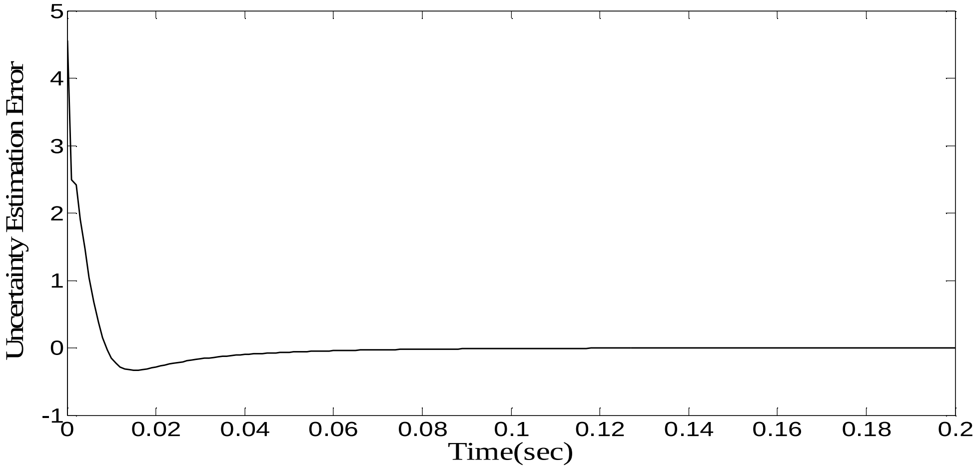

Fig 2.9: Uncertainty Estimation Error (FSMC)

Table 3: Tabular Comparison for SMC and FSMC

Controller	Chattering	Setting time
SMC	Zero	0.12 sec
FSMC	Zero	0.12 sec

2.6 Chapter summary

In this chapter, Conventional SMC and FSMC are designed and respective simulation results is also explained briefly and comparison of both controllers is provided.

CHAPTER 3

Design of SMO and Adaptive SMC

3.1 Discrete time SMO

In HEV, basically wheel speed is measured with help of speedometer. But there is no provision for measuring vehicle speed means it is difficult to measure vehicle speed online and to calculate slip ratio, it is necessary to measure vehicle speed. So observer is needed to estimate vehicle speed online. Next section describes the design of observer.

3.1.1 Design of Discrete time SMO

Here, design of a discrete time sliding mode observer for estimating vehicle velocity is presented and its structure is provided in Fig 3.1. So observer dynamic is chosen in following form

$$\hat{x}_1(k+1) = \hat{x}_1(k) - \frac{Tc_v r_w \hat{x}_1^{\,2}}{m} - TK_v \operatorname{sgn}(\tilde{y}) + d_1 \mu T \tag{3.1}$$

where $\hat{x}_1$ is estimated vehicle velocity, $\tilde{y} = x_2 - \hat{x}_1$ is measurement error and K_v is observer gain. Now estimation error $\tilde{x}_1$ is defined as

$$\tilde{x}_1(k) = x_1(k) - \hat{x}_1(k) \tag{3.2}$$

Equation (3.2) can be rewritten as

$$\tilde{x}_1(k+1) = x_1(k+1) - \hat{x}_1(k+1) \tag{3.3}$$

Substituting $x_1\left(k+1\right)$ and $\hat{x}_1(k+1)$ from equation (1.14) and (3.1) in (3.3) and solving for $\tilde{x}_1(k+1)$ we get

$$\tilde{x}_1(k+1) = \tilde{x}_1(k) - \frac{Tc_v r_w \tilde{x}_1^{\,2}}{m} + TK_v \operatorname{sgn}(\tilde{y}) \tag{3.4}$$

where

$$\tilde{x}_1^{\,2} = x_1^{\,2} - \hat{x}_1^{\,2} \tag{3.5}$$

The sliding mode observer dynamic given in equation (3.1) is asymptotically stable if observer gain should be chosen as

$$K_v \leq \left| \frac{c_v r_w \tilde{x}_1^{\,2}}{m} \right| \tag{3.6}$$

To prove it, we choose the Lyapunov candidate function as

$$V = \frac{1}{2} \tilde{x}_1^{\,2} \tag{3.7}$$

and

$$\Delta V = V(k+1) - V(k) = \tilde{x}_1(k)\left[\tilde{x}_1(k+1) - \tilde{x}_1(k)\right] \leq 0 \tag{3.8}$$

Substituting equation (3.1) and (3.3) in (3.8), we get

$$T\tilde{x}_1(k)\left[-\frac{c_v r_w \tilde{x}_1^{\,2}}{m} + K_v \operatorname{sgn}(\tilde{y}) \right] \leq 0 \tag{3.9}$$

The vehicle velocity and wheel velocity are assumed to be a positive, so finally we get the condition as

$$K_v \leq \left| \frac{c_v r_w \tilde{x}_1^{\,2}}{m} \right| \tag{3.10}$$

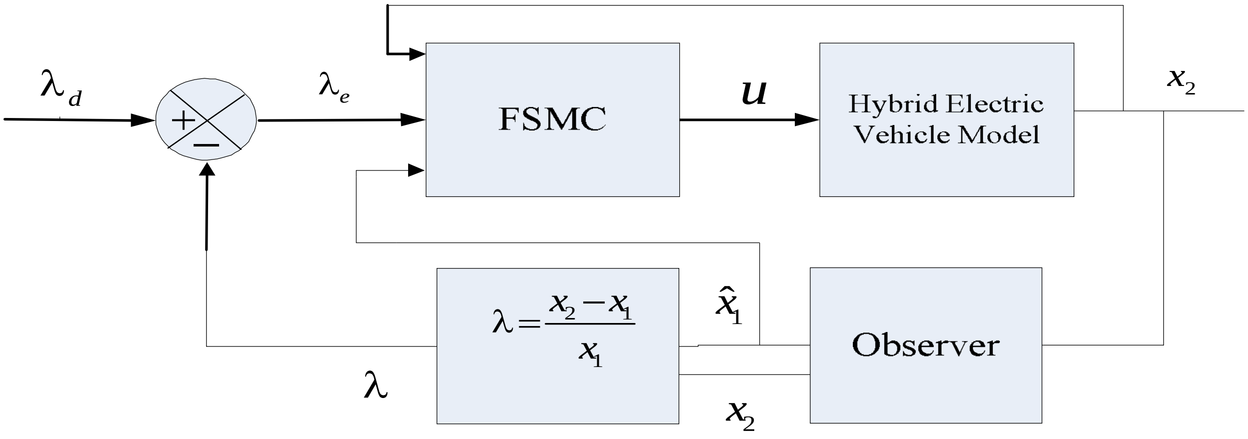

Fig 3.1: SMO structure

3.1.2 Simulation results

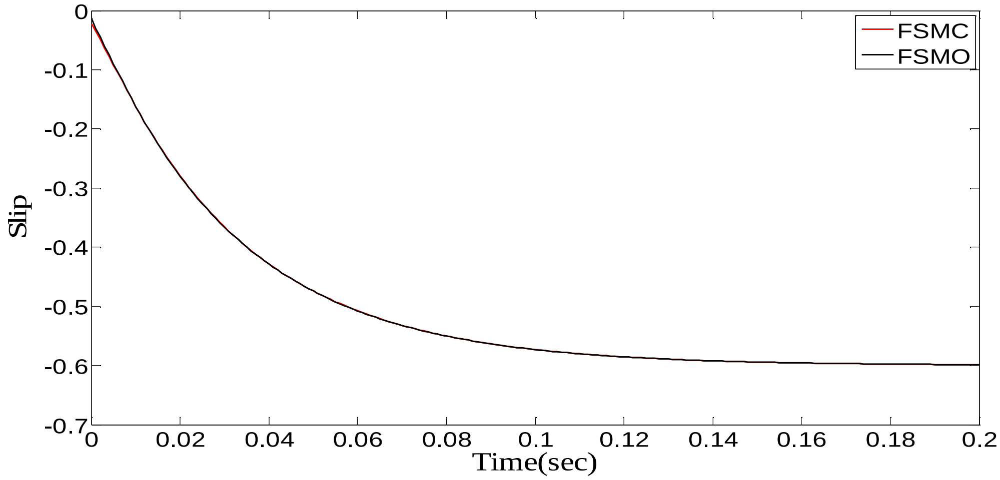

Fig 3.2: Slip (SMC & SMO)

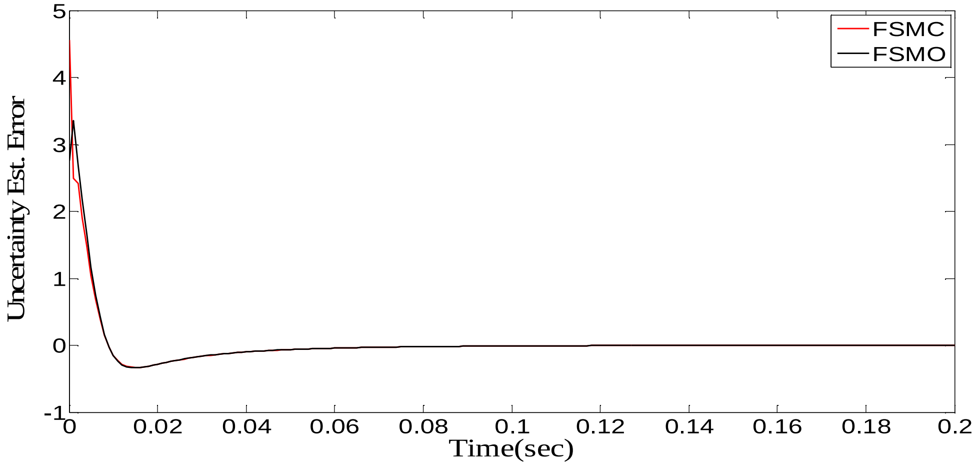

Fig 3.3: Uncertainty Estimation Error (SMC & SMO)

Section 3.1.2 shows result of discrete-time fuzzy sliding mode control and fuzzy sliding mode control with observe for desired value of slip ratio λ_d is -0.6, q is 300, ε is 0.05. Sliding mode observer is to estimate the value of vehicle speed as it not available online. Fig. 3.2 shows that desired slip ratio is tracked and settling time is also very i.e. 0.12 sec. Fig. 3.3 shows estimation error for FSMC and FMSO with observer. Fig 3.4 shows estimated vehicle speed (FSMO) closely mate to vehicle speed and velocity estimation error shown in fig 3.5 nearly equals to zero. Fig 3.6 shows break torque and fig 3.7 shows voltage excitation needed for the actuator.

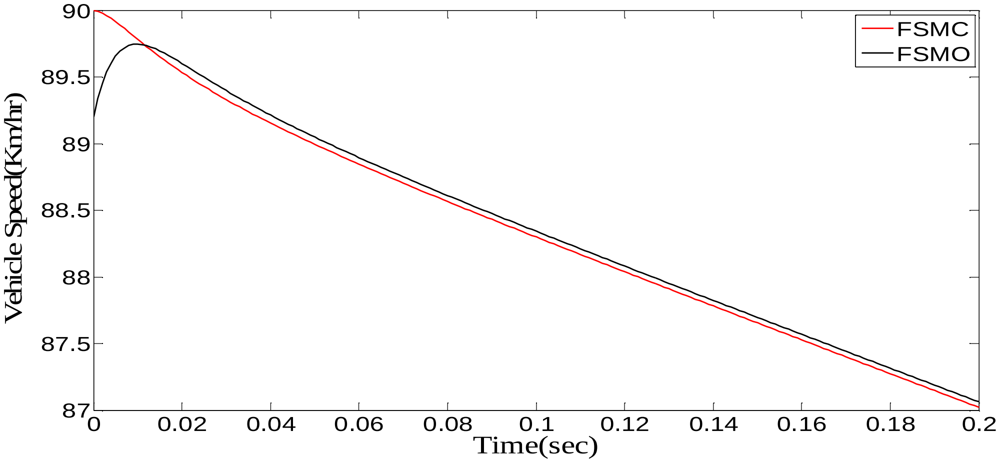

Fig 3.4: Vehicle Speed (SMC & SMO)

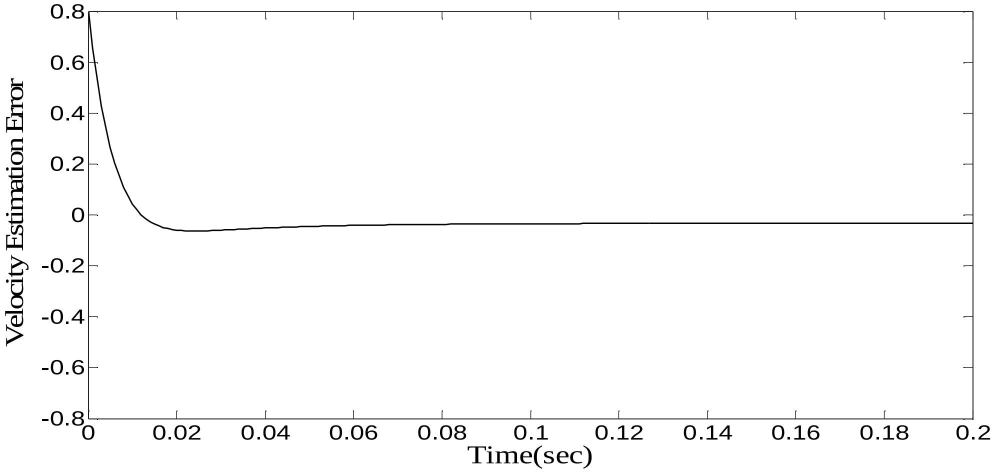

Fig 3.5: Velocity Estimation Error (SMO)

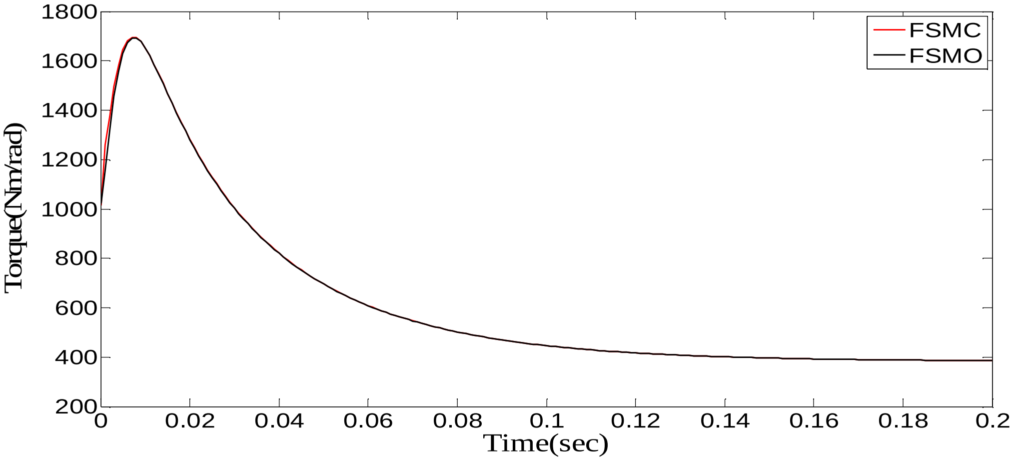

Fig 3.6: Torque (SMC & SMO)

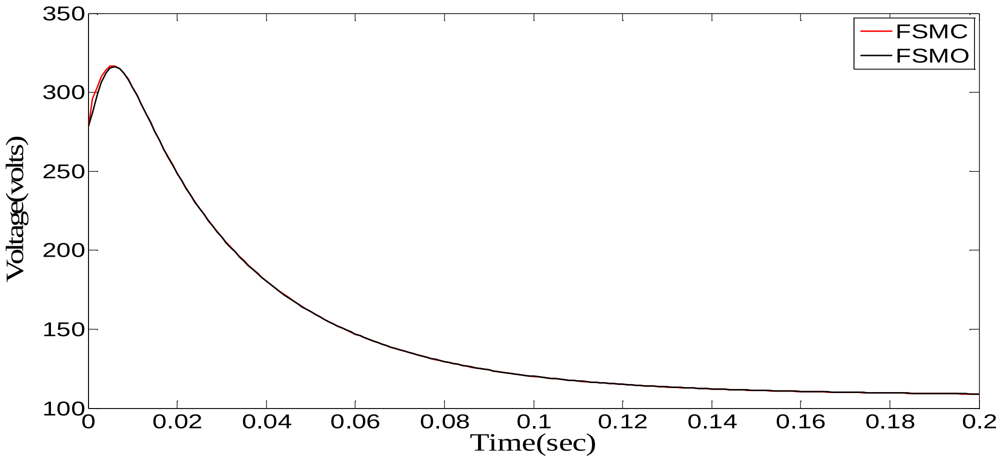

Fig 3.7: Voltage (SMC & SMO)

3.2 Discrete time ASMC

HEV system is full of nonlinearity and uncertainty. Due to this, tire road dynamic will change and also, desired value of slip ratio may change. Only SMC is unable to solve this problem. So, adaptation is necessary. Next section describes the design of adaptive SMC based on Lypunov stability theory.

3.2.1 Design of Discrete time ASMC

Equation (2.9) can also be written as

$$\frac{\lambda(k+1)-\lambda(k)}{T} = f_a(\lambda, x) + \theta h(\lambda, x) + bu \tag{3.11}$$

where

$$f_a(\lambda, x) = \frac{f_2(x_2) - (1+\lambda) f_1(x_1)}{x_1} \tag{3.12}$$

$$h(\lambda, x) = \frac{1}{x_1} \frac{2[d_2 - (1+\lambda)d_1]\lambda_p \lambda}{\lambda_p{}^2 + \lambda^2} \tag{3.13}$$

$$\theta = \mu_p \tag{3.14}$$

Design of sliding surface is same as the given in the section IV.

Choosing Lyapunov candidate function as

$$V = \frac{1}{2}s^2 + \frac{1}{2}(\theta - \hat{\theta})^2 \tag{3.15}$$

So,

$$\Delta V = V(k+1) - V(k) = s(k)\left[s(k+1) - s(k)\right] - \tilde{\theta}[\hat{\theta}(k+1) - \hat{\theta}(k)] \le 0 \tag{3.16}$$

where

$$\tilde{\theta} = \theta - \hat{\theta} \tag{3.17}$$

Substituting equation (3.11) in (3.16) leads to

$$\Delta V = s(k)T\left[f_a + \theta h + b\hat{b}^{-1}\left(-\widehat{f}_a - \hat{\theta}\hat{h} + \lambda_d + (1-qT)s(k)\right) + b\varepsilon T \operatorname{sgn}(s(k)) \right] - \tilde{\theta}[\hat{\theta}(k+1) - \hat{\theta}(k)] \tag{3.18}$$

Now, rearranging different terms of (3.18), we get

$$\Delta V = s(k)T\left[f_a + \theta h - b\hat{b}^{-1}\widehat{f}_a - b\hat{b}^{-1}\hat{\theta}\hat{h} + b\hat{b}^{-1}\lambda_d + b\hat{b}^{-1}(1-qT)s(k) + b\varepsilon T \operatorname{sgn}(s(k)) \right] - \tilde{\theta}[\hat{\theta}(k+1) - \hat{\theta}(k)] \tag{3.19}$$

Equation (3.19) can be rewritten as

$$\Delta V = s(k)T(f_a - \widehat{f}_a + (1 - b\hat{b}^{-1})\widehat{f}_a + (1 - b\hat{b}^{-1})\hat{\theta}\hat{h} + b\hat{b}^{-1}\lambda_d + \theta h - \hat{\theta}\hat{h} + b\hat{b}^{-1}(1-qT)s(k)$$

$$+ b\varepsilon T \operatorname{sgn}(s(k))) - \tilde{\theta}[\hat{\theta}(k+1) - \hat{\theta}(k)] \tag{3.20}$$

We consider following assumptions for bounds in function f_a and h.

$$\left| f_a - \hat{f}_a \right| \le F_a \quad \text{and} \quad \left| h - \hat{h} \right| \le H$$

Using above assumption in equation (3.20) leads to

$$\Delta V = s(k)T(f_a - \hat{f}_a + (1 - b\hat{b}^{-1})\hat{f}_a + (1 - b\hat{b}^{-1})\hat{\theta}\hat{h} + b\hat{b}^{-1}\lambda_d + \theta\hat{h} + \theta H - \hat{\theta}\hat{h} + b\hat{b}^{-1}(1-qT)s(k)$$

$$+ b\varepsilon T \operatorname{sgn}(s(k))) - \tilde{\theta}[\hat{\theta}(k+1) - \hat{\theta}(k)] \le 0 \tag{3.21}$$

Now, rearranging different terms, we get

$$\Delta V = s(k)T(f_a - \hat{f}_a + (1 - b\hat{b}^{-1})\hat{f}_a + (1 - b\hat{b}^{-1})\hat{\theta}\hat{h} + b\hat{b}^{-1}\lambda_d + \theta H + b\hat{b}^{-1}(1 - qT)s(k)$$

$$+ b\varepsilon T\,\mathrm{sgn}(s(k))) - \tilde{\theta}[\hat{\theta}(k+1) - \hat{\theta}(k)] + s(k)T\tilde{\theta}\hat{h} \le 0 \qquad (3.22)$$

For asymptotically stable system

$\Delta V \le 0$ and hence

$$s(k)T\Big[\, f_a - \hat{f}_a + (1 - b\hat{b}^{-1})\hat{f}_a + (1 - b\hat{b}^{-1})\hat{\theta}\hat{h} + b\hat{b}^{-1}\lambda_d + \theta H + b\hat{b}^{-1}(1 - qT)s(k) + b\varepsilon T\,\mathrm{sgn}(s(k))\Big] = 0 \quad (3.23)$$

and

$$-\tilde{\theta}[\hat{\theta}(k+1) - \hat{\theta}(k)] + s(k)T\tilde{\theta}\hat{h} = 0 \qquad (3.24)$$

From equation (3.23), we get

$$\varepsilon \ge \Big[\, f_a - \hat{f}_a + (1 - b\hat{b}^{-1})\hat{f}_a + (1 - b\hat{b}^{-1})\hat{\theta}\hat{h} + b\hat{b}^{-1}\lambda_d + \theta H + b\hat{b}^{-1}(1 - qT)s(k)\Big]\big(bT\,\mathrm{sgn}(s(k))\big)^{-1} \quad (3.25)$$

Also from equation (3.25), one obtains

$$\hat{\theta}(k+1) = \hat{\theta}(k) + s(k)T\hat{h} \qquad (3.26$$

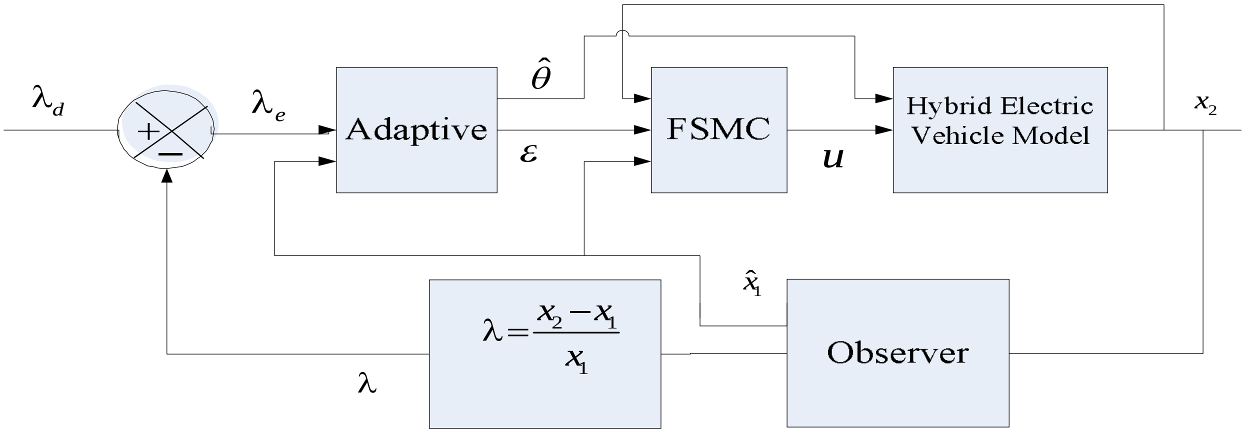

Fig 3.8: FASMC Structure

The value of ε can be calculated from equation (3.25) and estimated value of optimal adhesive coefficient can be calculated from equation (3.26). Structure for FASMC is provided in Fig 3.8.

3.2.2 Simulation results

Section 3.3.2 shows result of discrete-time adaptive sliding mode control. Here desired slip λ_d is changing from -0.8 to -0.4 and fig 3.9 shows that slip is adapting according to the desired value of slip and also from fig 3.11, sliding variable converges to zero that means states remains on the desired sliding surface. Fig 3.12 shows vehicle speed and wheel speed both are decreasing in order to track desired slip ratio.

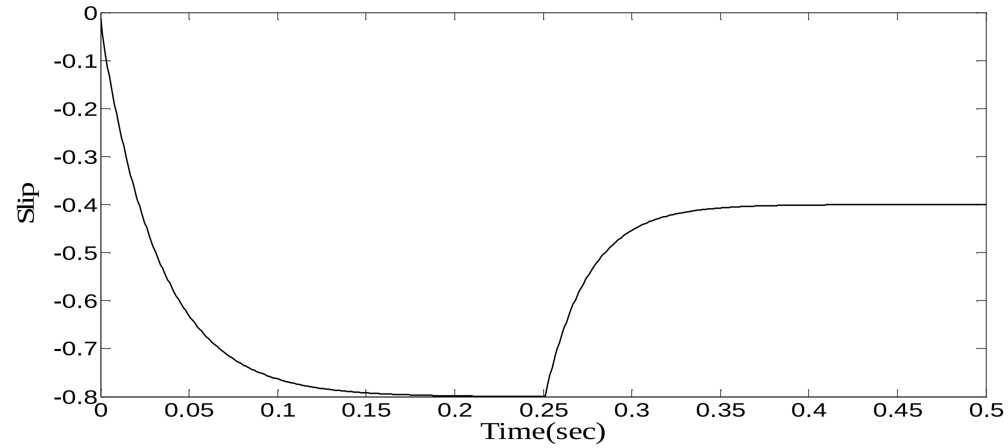

Fig 3.9: Slip (ASMC)

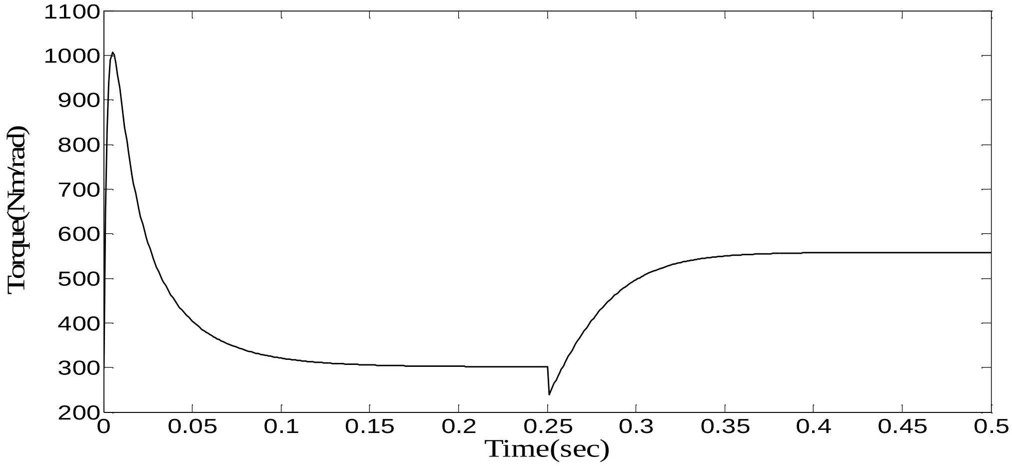

Fig 3.10: Torque (ASMC)

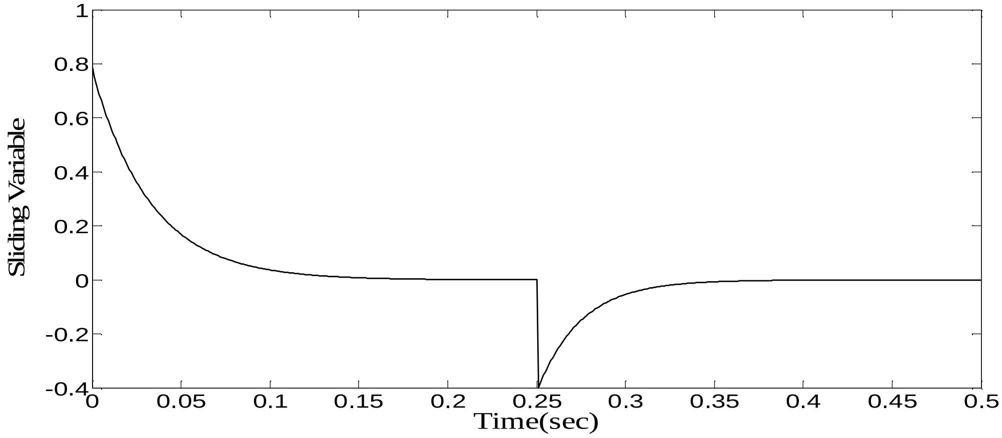

Fig 3.11: Sliding Variable (ASMC)

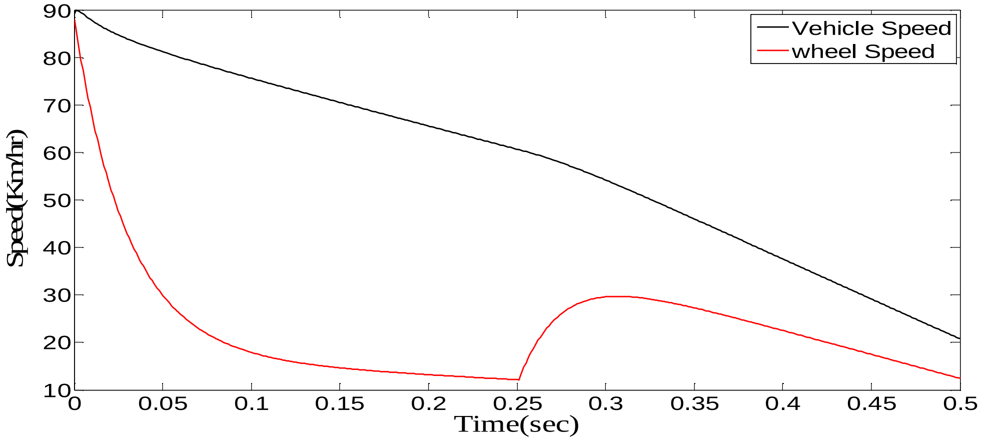

Fig 3.12: Speed (ASMC)

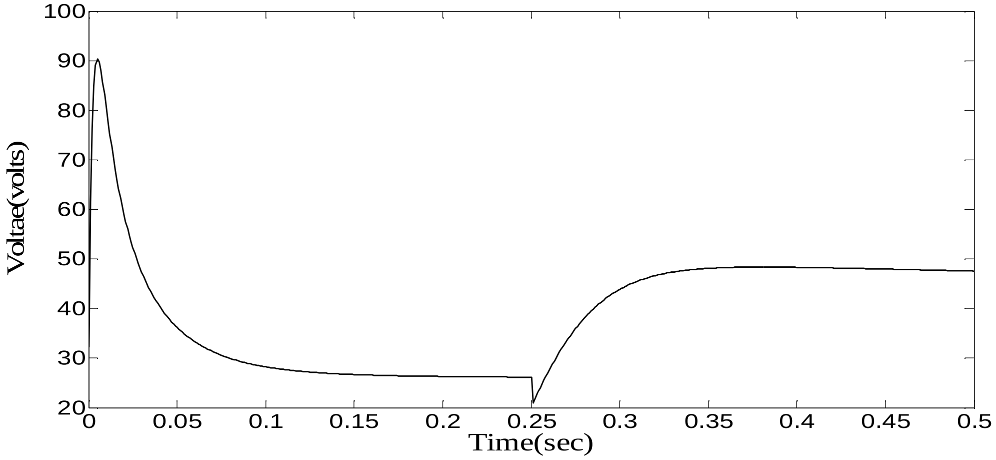

Fig 3.13: Voltage (ASMC)

Figure 3.10 shows braking torque and fig 3.13 shows what voltage required to provide torque from actuator. Also braking torque is also adapted according to desired value of slip and it is without chattering. In all, tracking is without chattering.

3.3 Chapter summary

This chapter described the design of observer for vehicle speed and its simulation results are compared with conventional SMC. Also, to solve the problem of uncertainty in tire road dynamic, adaptive SMC is designed and its working performance is proved through Matlab simulation.

CHAPTER 4

Design of FLC and PID using Fuzzy Logic

4.1 FLC

Reasons behind the popularity of Fuzzy Logic Controllers is that its logical resemblance to human operator. It operates on the detailed foundations of a knowledge base which in turn rely upon if then rules, similar to a human knowledge. Unlike other control algorithms, this is simple as there is no complex mathematical knowledge required. The FLC requires only qualitative knowledge of the system which makes the controller design easy.

4.1.1 Design of Discrete time FLC

The design of a FLC for SRC consider the appropriate choice of membership Functions. Membership functions should be chosen such that they will cover the whole universe of discourse and it should be taken care that the membership functions chosen should overlap each other. This is done to avoid any kind of discontinuity that is present when designing controller with respect to the minor changes in the inputs. To achieve finer control action, the membership functions near zero should be made narrow and always wider membership functions away from the zero regions provide faster response to the system and hence, the membership functions should be adjusted accordingly. After this, the appropriate membership functions are chosen, a rule base should be decided. It consists of a number of Fuzzy If-Then rules that completely define the behavior of the system.

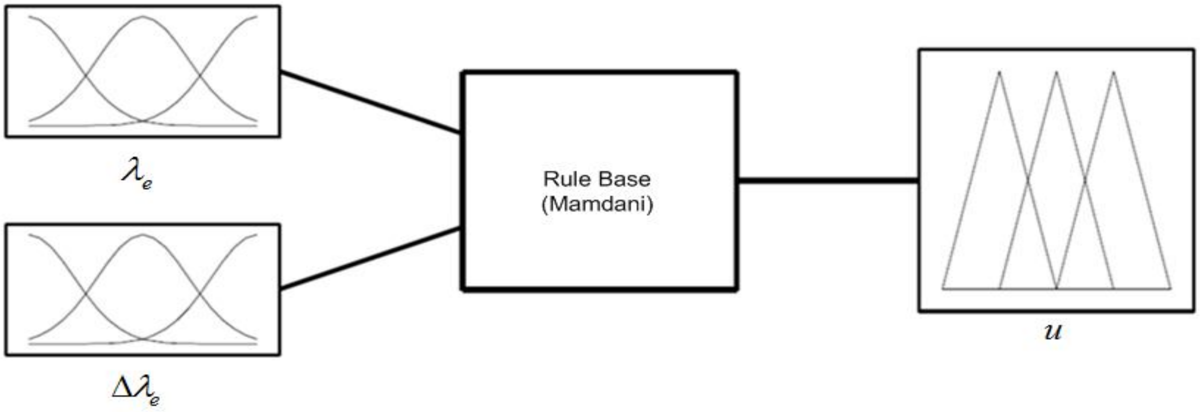

Fig 4.1: Fuzzy Inference Block

For the slip tracking problem of HEV, we develop a two input one output Fuzzy Logic controller to achieve the desired value of slip for the HEV. Two inputs are λ_e and $\Delta\lambda_e$ and output is u that is control action. For each of input and output variable we choose 7 numbers of triangular mfs as shown in fig 4.1.

The following rules are formulated for implementation of FLC for slip ratio of HEV (table 4).

As problem is of tracking of slip ratio, so design of rule is simply based on general step response for tracking of desired value as it is given in [16]. Linguistic levels for input and output as: PB- Positive Big, PM- Positive Medium, PS- Positive Small, Z- Zero, NB- Negative Big, NM- Negative Medium, and NS- Negative Small.

Rule i: If λ_e is NB and $\Delta\lambda_e$ is NB, then u is NB

where i=1, 2, 3… n and n is number of rules and it is equal to 49.

Table 4.1: Rule base for computing control action

λ_e $\Delta\lambda_e$	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NM	NM	NS	NS	Z
NM	NB	NM	NM	NS	NS	Z	PS
NS	NM	NM	NS	NS	Z	PS	PS
Z	NM	NS	NS	Z	PS	PS	PM
PS	NS	NS	Z	PS	PS	PM	PM
PM	NS	Z	PS	PS	PM	PM	PB
PB	Z	PS	PS	PM	PM	PB	PB

4.1.2 Design of Discrete time PID using FL

Next we design a PID controller by tuning gains using fuzzy logic. This controller is consists of two inputs and three outputs. Two inputs are λ_e and $\Delta\lambda_e$ and three outputs are K_p, K_i, K_d.Now, choose 7 triangular membership functions for $\lambda_e, \Delta\lambda_e, K_p, K_i, K_d$.

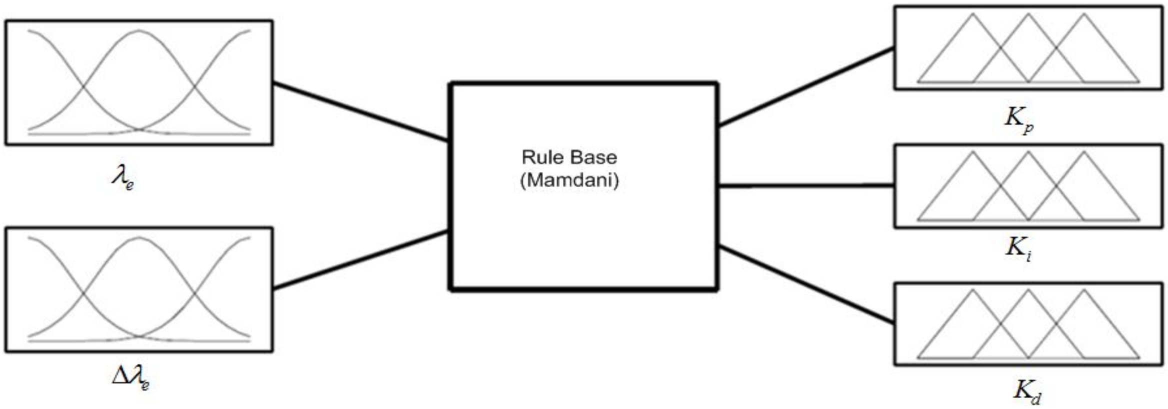

Fig 4.2: Fuzzy PID Inference Block

Table 4.2: Rule base for computing K_p, K_i, K_d

$\Delta\lambda_e$ \ λ_e	NB	NM	NS	Z	PS	PM	PB
NB	BS	BS	S	S	MS	MS	M
NM	BS	S	S	MS	MS	M	M
NS	S	S	MS	MS	M	M	MB
Z	S	MS	MS	M	MB	MB	B
PS	MS	M	M	MB	MB	B	B
PM	M	M	MB	MB	B	B	BB
PB	M	MB	MB	B	B	BB	BB

Rule i: If λ_e is NB and $\Delta\lambda_e$ is NB, then K_p is BS and K_i is BS and K_d is BS

Where i=1, 2, 3,…..,n and n is number of rules and it is equal to 49.

Linguistic level assigned for inputs as: PB-Positive Big, PM-Positive Medium, PS-Positive Small, Z-Zero, NS-Negative Small, NM-Negative Medium, NB-Negative Big and Linguistic level assigned for outputs as: BS-Big Small, S-Small, MS-Medium Small, M-Medium, MB-Medium Big, B-Big ,BB-Big Big. Fuzzy rules for these are always to be chosen according to requirement of plant or system to be controlled.

4.3 Simulation results

FLC and PID using Fl is been verified for slippery road and road change problem. Hence, section 4.3.1 shows simulation results for SMC, FLC and PID and section 4.3.1 shows simulation results for ASMC, FLC and PID using FL.

4.3.1 Performance of SMC, FLC and PID using FL

Section 4.3.1 shows result of discrete-time sliding mode control, fuzzy logic control and fuzzy PID control for desired value of slip ratio λ_d is -0.6, q is 300, ε is 0.05. Three control algorithms namely SMC, FLC and F-PID are applied to the HEV for tracking the desired slip ratio and responses obtained are compared.

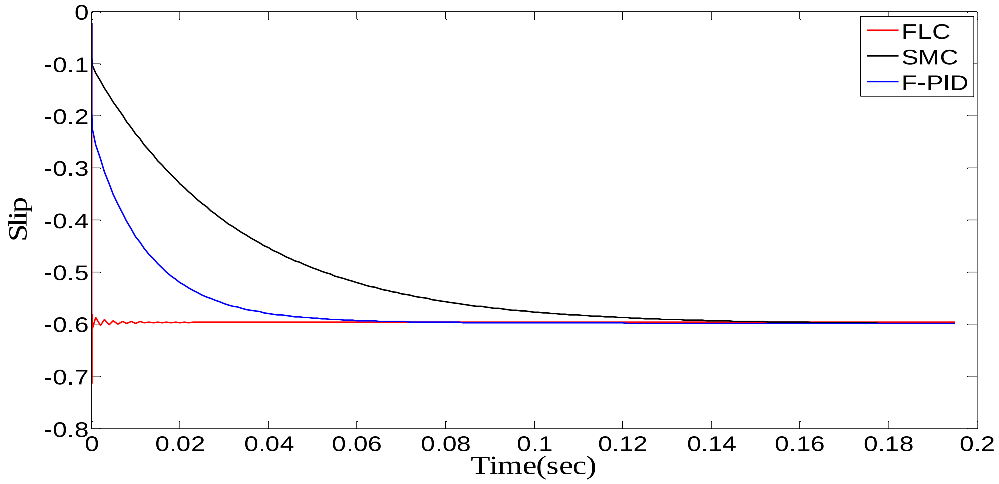

Fig 4.3: Slip (SMC, FLC & PID using FL)

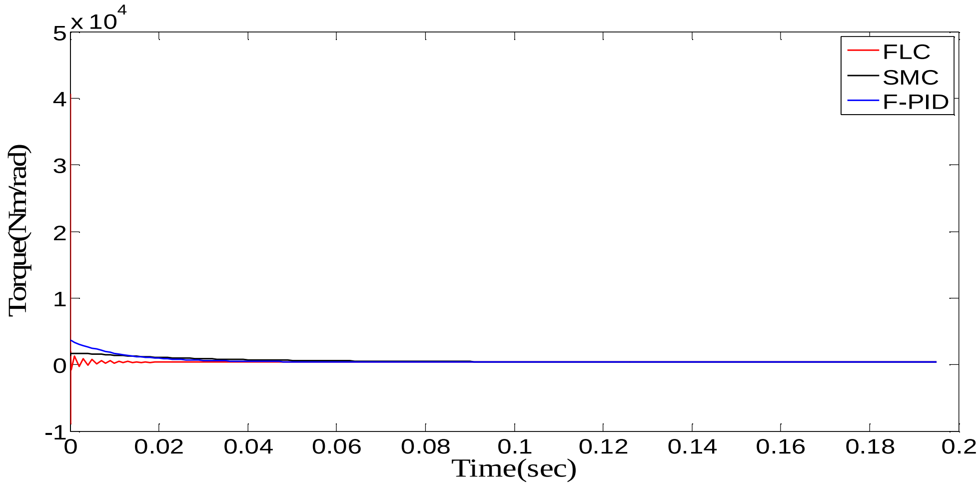

Fig 4.4: Torque (SMC, FLC & PID using FL)

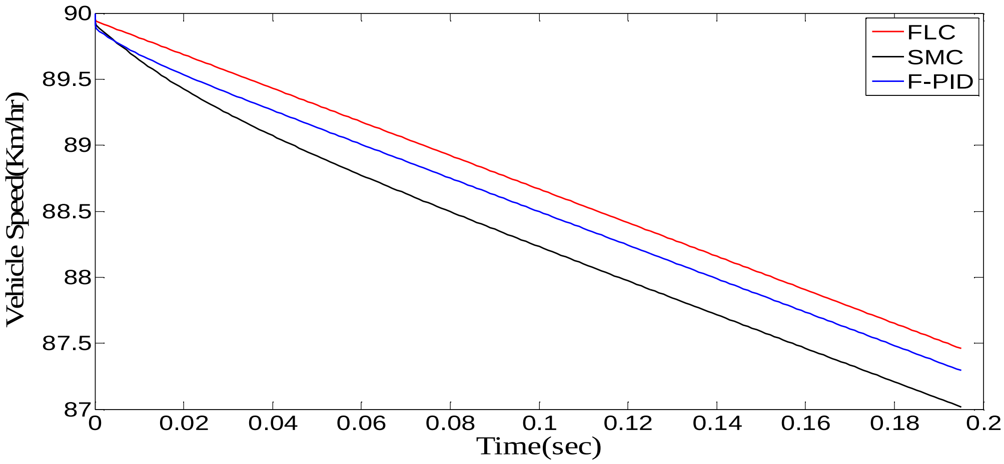

Fig 4.5: Vehicle Speed (SMC, FLC & PID using FL)

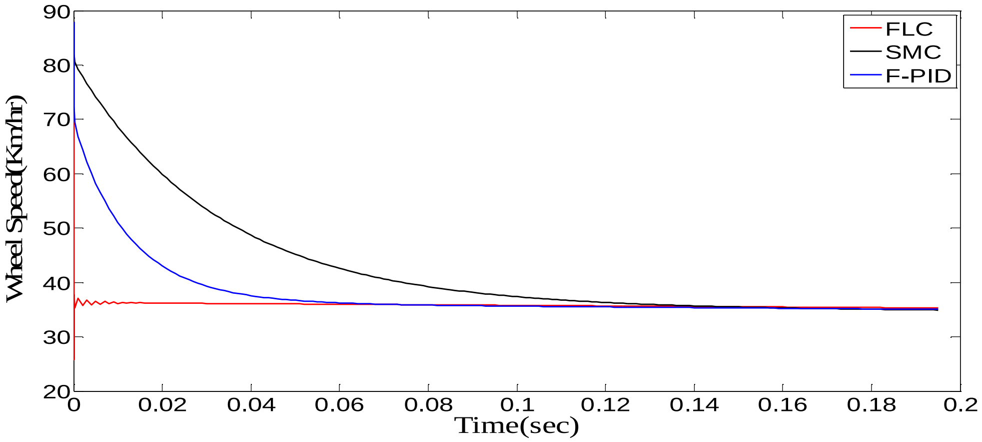

Fig 4.6: Wheel Speed (SMC, FLC & PID using FL)

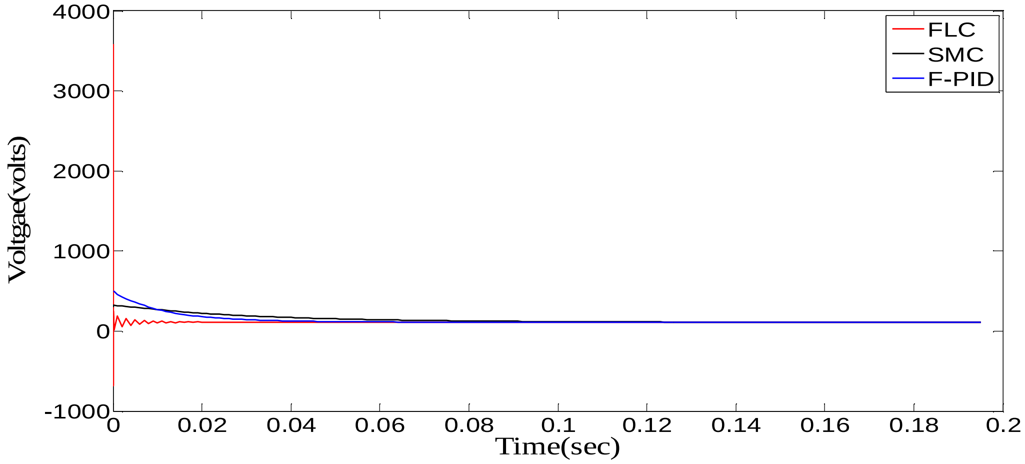

Fig 4.7: Voltage (SMC, FLC & PID using FL)

Fig 4.3 shows that desired value of slip ratio is tracked by all three controllers but response of FLC is more effective than PID and SMC and the response of PID using FL is effective than SMC. Fig 4.4 shows braking torque required. Initial value of torque is much higher in case of FLC than PID and SMC and also PID produce initial value torque which is higher as compared to SMC but after 0.02 sec value is same in all controllers. Fig 4.5 and 4.6 show vehicle speed and wheel speed profile both are decreasing which is required in deceleration to maintain slip ratio at desired value. Wheel speed becomes constant earlier than to both PID and SMC. Fig 4.7 shows voltage excitation required for producing torque. In all, if we compare then PID using FL is giving effective response as compared to FLC and SMC. Comparison of controllers is provided in table 6.

Table 4.3: Tabular Comparison for SMC, FLC and PID

Controller	Chattering	Rise time	Setting time
SMC	Zero	0.0699 sec	0.12 sec
FLC	Zero	0.0066 sec	0.0042 sec
F-PID	Zero	0.0243 sec	0.048 sec

4.3.2 Performance of ASMC, FLC AND PID

Section 4.3.2 shows performance of discrete-time adaptive sliding mode control, fuzzy logic control and PID control for desired value of slip ratio λ_d changing from -0.8 to -0.4, q is 300. Here, three control algorithms namely ASMC, FLC and PID are using for tracking of slip ratio which is suddenly changing from -0.8 to -0.4 and comparing response obtained by those control. Fig 4.8 shows that desired value of slip ratio is tracked by all three controls but response of FLC is better than PID and SMC and the response of PID is better than SMC. Fig 4.9 shows braking torque required. By comparing, initial value torque is much higher in FLC than PID and SMC and also PID produce initial value torque which is higher as compared to SMC.

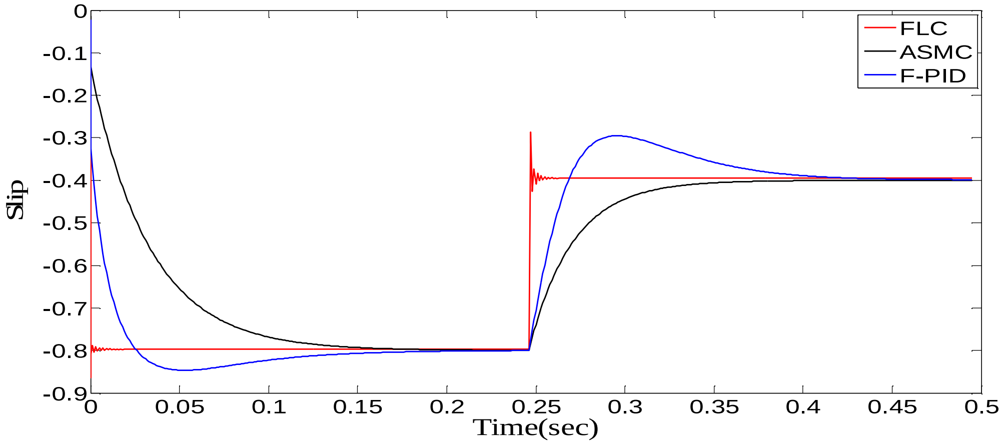

Fig 4.8: Slip (ASMC, FLC & PID using FL)

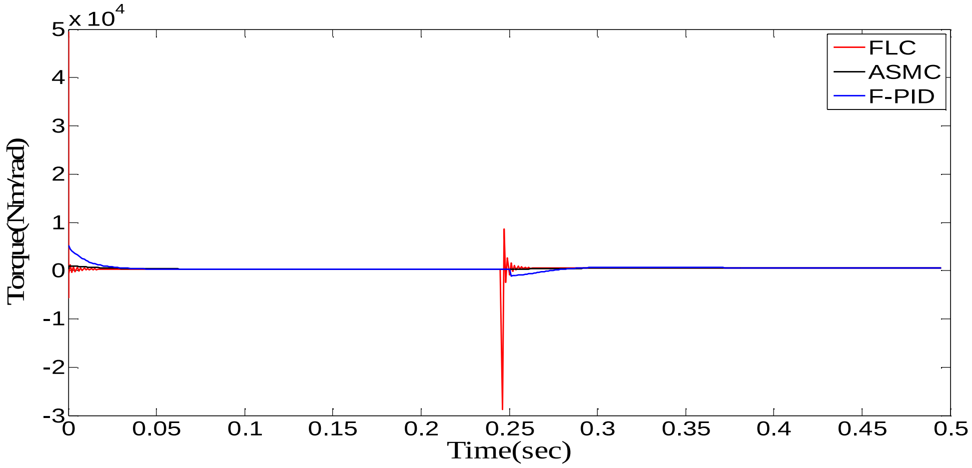

Fig 4.9: Torque (ASMC, FLC & PID using FL)

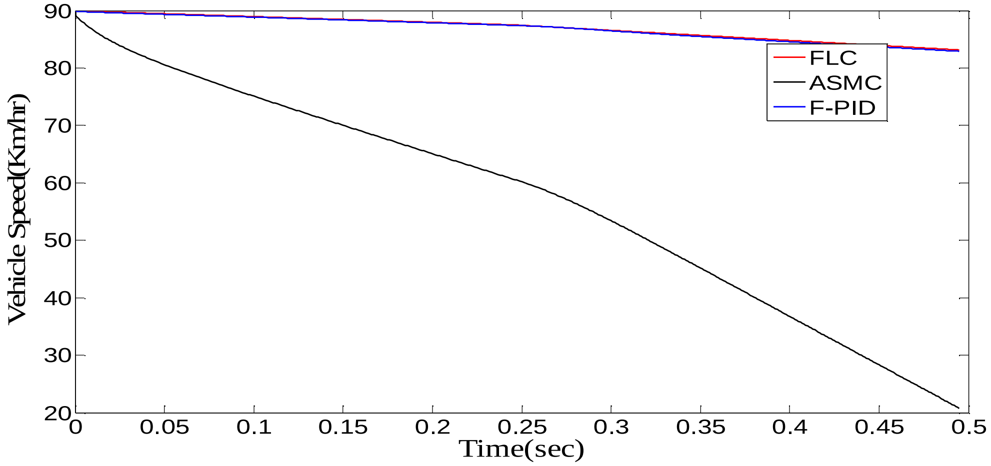

Fig 4.10: Vehicle Speed (ASMC, FLC & PID using FL)

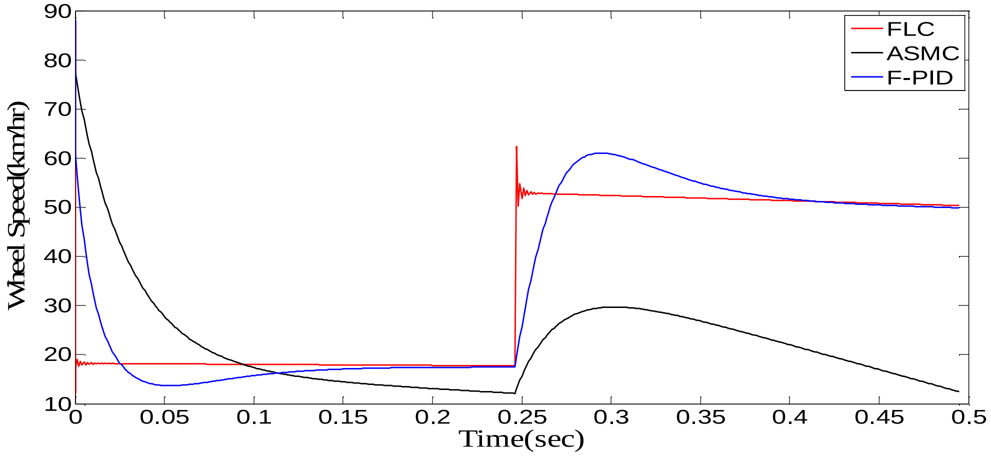

Fig 4.11: Wheel Speed (ASMC, FLC & PID using FL)

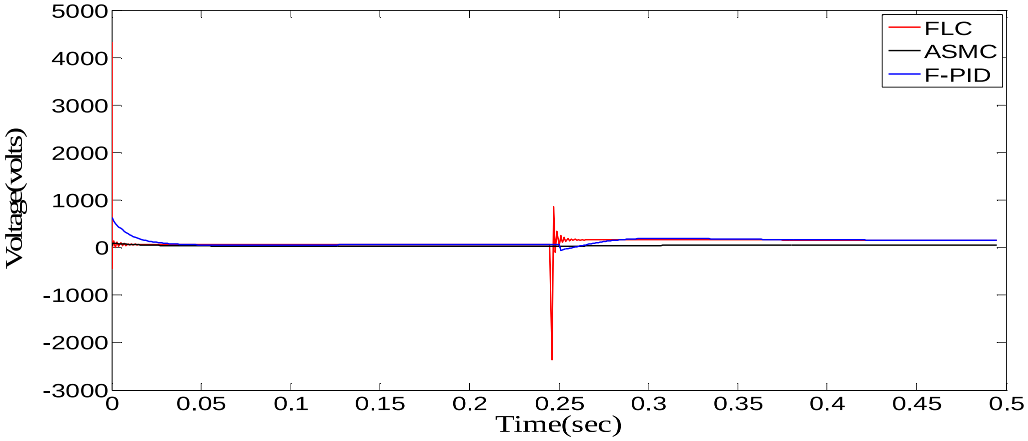

Fig 4.12: Voltage (ASMC, FLC & PID using FL)

Fig 4.10 and 4.11 shows about vehicle speed and wheel speed and which are decreasing which is required in deceleration to maintain slip ratio at desired value an also wheel speed attain constant value earlier than PID and SMC. Fig 4.12 shows voltage required for producing torque and response is just similar to torque as initial voltage is much higher than PID and SMC and in PID than SMC.

4.4 Chapter summary

This chapter described the design of FLC and PID by tuning K_p, K_i, K_d using fuzzy logic. The comparison of SMC, FLC and PID is provided through simulation results and tabular comparison is provided. ASMC, FLC and PID is also compared and explained briefly.

CHAPTER 5

Conclusions and Suggestion for future work

5.1 Conclusions

This thesis presented control algorithms for achieving slip ratio control of a HEV such as discrete time SMC, FLC and F-PID. Also, FLC and F-PID impressively speed up response of slip ratio control of a HEV. Simulation results provide the effectiveness of mentioned controllers. Problem of uncertainty in the slip dynamic are addressed by designing a fuzzy SMC. Furthermore, a discrete time SMO is developed that successfully estimates vehicle velocity online. Designed discrete time FASMC overcome the slip changes or road changes and tire road dynamic problem. In order to this, chattering is removed by all suggested control algorithms and hence damage of actuation system is avoided.

5.2 Suggestion for Future work

Real time implementation of control algorithms may be a future scope for this work. Also, one can try for design of an optimal control for slip ratio control of a HEV.

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