A Suitable Electronic Stability Control System Using Sliding Mode Controller for an In-wheel Electric Vehicle

M. M. Al Emran Hasan, Mehran Ektesabi, and Ajay Kapoor

***Abstract*—Different electronic stability control (ESC) techniques for electric vehicles with four in-wheel electric motors have been investigated to find the most suitable method. An analysis of differential braking, steer-by-wire and differential torque based ESC has been undertaken based on the required resources complexity and performance of the systems in a vehicle. An electric vehicle with four in-wheel motors has been developed as the test bench. This kind of electric vehicle has a greater flexibility than conventional EVs in terms of control for the simplified drive train that allows independent control of wheels' torque. Flexibility and the available resources for differential torque based ESC are used here with a sliding mode control law for expected longitudinal response while the ESC is acting. Comprehensive model of the proposed EV is created with sub-systems of vehicle body, individual wheel and sliding mode controller using Matlab/Simulink basic blocks for simulation to find the required torque. This is followed by a bench test using in-wheel motors to control the wheels, based on the rotation demanding differential torque. This method can be implemented in a four in-wheel motor electric vehicle. The research will be very useful for finding a suitable technique for electronic stability control for an in-wheel electric vehicle in different situations, considering the required resources and complexity of the system.**

***Index Terms*— electric vehicle, four in-wheel electric motor, electronic stability control, compact RIO, sliding mode control**

I. INTRODUCTION

ELECTRONIC Stability Control (ESC) is an active safety control system to assist the driver to maintain directional control of the ground vehicle in critical maneuverings. This system continuously monitors the dynamics of the vehicle. ESC system uses some sensors to measure some dynamic parameters and then estimates more parameters from the measured values. From these measurements and estimations, system detects the loss of control like over steering or under steering. After detecting the instability ESC system restores the direction of the vehicle automatically by using actuators. Normal operations or performance of the vehicle is not affected by this intelligent system. ESC improves controllability and prevents accident due to loss of control. There are different variants of ESC for the same purpose of vehicle control, majority of these are for conventional Internal Combustion Engine Vehicles (ICEV) s.

Many studies have been done from different perspectives to realize the effectiveness of ESC in reducing loss of control and in accident prevention. It is found that, loss of control of vehicle decreases by 24.6% when ESC is present[1]. For passenger car, ESC reduces 30-50% fatal crash and for Sports Utility Vehicle (SUV) s it reduces 50-70% fatal crash [2]. In another study[3] on effectiveness of ESC in Australia and New Zealand shows that ESC reduces risk of single vehicle crashes of all severities by 54.5%. Electric vehicles are potential candidates towards sustainability if improvements continue in EV technology and infrastructure developments [4]. Electric motors are very effective for electric drive. The most remarkable features of electric motors are:

- Electric motors can generate accurate torque very quickly and it is easier and quicker to control compared to ICEV.
- Torque can be measured easily from their electrical characteristics in real time for applying control techniques.

Advanced design and miniature size of these motors to fit them inside the hub of the wheel generated the excellent idea of the in-wheel motor electric vehicle.

In this study, the chosen EV contains four in-wheel motors. These new concept EVs are getting attention from researchers as well as from industry. Having a different and very simple architecture these vehicles need to have different ESC than the other conventional ICEVs and EVs. Though the vehicle has a simple architecture, it is challenging to control of all these four motors even for normal operations. While driving the vehicle at limited road traction if sudden maneuvers are needed, the vehicle would respond differently than normal to the drivers input.

Consider a situation when a vehicle is spinning out and the driver may give some counter steering to control it. This could be successful but it is not possible for the average drivers. If it is not possible to control by counter steering then it will lead to loss of control and the vehicle will leave the road and also an accident can occur. If the situation becomes more extreme

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when side slip angle of the vehicle increases due to a greater speed or slippery road then the counter steering by the driver will not create any corrective yaw moment and it will decrease the steer-ability of the vehicle. Figure 1 shows the decrease of yaw moment due to steering angle when side slip angle increases.

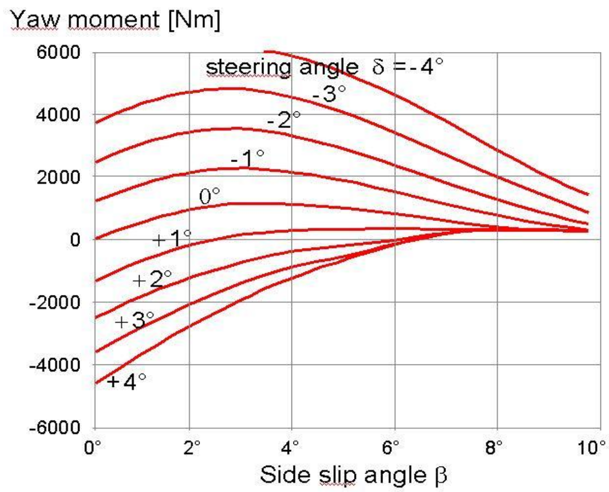

Fig.1. Yaw moments for different steering angle [5].

When side slip angle is higher in the range of 10 to 12 degrees, the steering induces yaw moment becomes close to zero then a different mechanism is needed to regain control of the vehicle [5]. Other situations when the vehicle is over-steered or under-steered and corrective yaw moment by the driver's counter steering fails to control it then the vehicle responds with unexpected behavior. These unexpected behaviors of the vehicle cause loss of control and induced panic seizes the driver which creates more difficulty to gain control of the vehicle. These create the necessity for an intelligent control like ESC.

ESC includes some sensors like wheel speed, yaw rate, lateral acceleration, and steering wheel sensors to identify the dynamics of the vehicle. ESC has different mode for yaw stability control and roll stability control. In this study yaw stability control mode is discussed. In yaw stability control mode ESC calculates:

- Heading of the vehicle using steering angle sensor and vehicle speed sensor.
- Radius of the current path using lateral acceleration sensor and vehicle speed.
- Correct yaw rate of the vehicle travelling on the path by calculated radius and measured vehicle speed using on board yaw rate sensor from which ESC system measures actual yaw rate.

In ESC system usually a microcontroller based system does these required calculations mentioned above and estimates the intended heading and ideal motion then compares with the actual motion. If the difference between the measured yaw rate and calculated yaw rate exceeds the threshold value then the ESC system sends control signals to the actuators to apply corrective force on the vehicle. There are different techniques for correcting the vehicle motion. ESC in the conventional vehicles with single electric motor or ICE has limitations for control with the existing resources, so different additional sensors and actuators are introduced in different techniques for ESC. Providing the expected longitudinal response the driver needs is another key point to focus on for ESC. In this research all these different types of ESC are briefly discussed and analyzed to find a suitable type for the proposed EV. Then an ESC is proposed with sliding mode controller using a comprehensive dynamic vehicle model.

II. Four in-wheel EV

In-wheel motor EVs are of great interest in electric vehicle technology for researchers and industry. Locating the electric motor within the wheel offers many advantages in development. Use of in-wheel motors offer many advantages, some of these advanced features as technical feasibilities are:

1) In-wheel motors allow regulating the torque and braking with high precision which offers a greater controllability.
2) As the electric motor is located within the wheel, there is no need of transmission, differential, drive-shaft or any other complex mechanism as a part of the drive train.
3) Elimination of mechanical drive train, transmission and differential saves space and reduces the weight.
4) In-wheel motors give enough space for layout design and offer flexibility in body design.
5) Regeneration by these in-wheel electric motors, offers energy saving.

On the other hand, controlling these four in-wheel motors remains the challenge as it requires an intelligent way of control. Using the electrical characteristics of the motor, measuring torque and controlling torque is much easier. It is possible to create torque difference between the left and right wheels by actuating them individually without any help of gear or clutch systems. These in-wheel electric motors have integrated breaking systems as well as integrated wheel rotation sensors. Operating voltages levels of the in-wheel motor can be shifted to a higher value for switching from normal operation to turbo operation for more speed and maneuvers. This research work concerns electric vehicles with four in-wheel motors, where each wheel is driven individually by an electric motor. Development of a four In-Wheel EV is in progress in Swinburne University of Technology for implementing and testing of ESC and other control techniques. Figure 2 shows the 4 in-wheel EV in Swinburne University of Technology.

III. Comparison and selection of ESC type

Identification of unexpected behavior of the vehicle and generation of control signals for the actuators are done by the ESC system. These actuators apply corrective forces on the wheels to change the yaw for maintaining yaw stability. In

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some cases controller applies corrective steering wheel for yaw stability.

Fig.2: EV with four in-wheel motors in progress at Swinburne university of Technology

Based on the actuating behavior of different Esc systems for yaw stability there are three types of popular ESC system developed by industry and proposed by researchers, they are:

- Differential braking based ESC
- Differential torque based ESC
- Steer by wire based ESC

Discussion is done here addressing several issues to select a most suitable type ESC for this 4 in-wheel EV from three basic types of ESC.

A. Required sensor

If required sensors are taken into account to select the type of ESC, any of these basic types ESC can be used in this proposed vehicle. In case of steer by wire ESC system, multiple lateral acceleration sensors are required [6]. Differential torque based ESC requires to sense the wheel speed and electrical characteristics of motors. As the proposed vehicle has 4 in-wheel motors where each wheel can give feedback of wheel speed by its built in Hall Effect sensors. Electrical characteristics can be measured from the circuit. So, in case of 4 in-wheel EV, differential torque based ESC system may not require more sensors than other two types of ESC thus it is more preferable.

B. Required Actuators

If require actuators are taken into account then steer by wire based ESC can be chosen because in this system actuation is done only on the steering wheel to control. To make indirect connection between steering wheel and axle, two electric motors are used and they work as actuators in this ESC system which are additional components compared to proposed EV. The proposed EV has 4 in wheel motors as existing drive train and can be used as actuators for differential torque based ESC.

C. Complexity and performance

Implementation of steer by wire ESC system is very complex for estimations and assumptions made to control. Simplification is made in this method by assuming that the velocity is constant or slowly varying during steering and small yaw rate which shows a limitation for this method. Differential Braking type ESC requires measurement and control of brake pressure which requires extra component. Also it has the demerits of slowing down the vehicle while differential braking ESC is active [7]. On the other hand using differential torque type ESC driver can get the expected longitudinal response while it is active. Also determination of parameters is easier from existing EV components.

Based on the discussion it can be concluded that differential torque type ESC would be more suitable for this in-wheel EV. This differential torque based ESC system may not be able to generate adequate yaw rate to respond the driver’s needs when the coefficient of road friction was small or if the vehicle speed was too high. As the yaw moment is generated by generating different torque in different wheels, the possibility of achieving expected yaw rate may not be the nominal but it is possible to make the yaw rate closer to the nominal yaw rate and yaw can be control partially. But the challenge is how this differential torque based ESC will work for in-wheel EV so that it can overcome the limitation of torque generation for adequate yaw moment. As a solution to this problem, yaw rate can be taken closer more by operating these electric motors to a higher voltage than the normal operation.

IV. PROPOSED ESC TYPE “IN-WHEEL ESC”

To select a certain type of ESC from the basic types or to develop new type of ESC, it is important to focus on available resources and feasibilities in the proposed EV as well as to focus on the improvement of the proposed ESC type. Considering all these available resources and technical feasibility of controlling individual motors of In-wheel EV, and requirement for keeping expected longitudinal response by the driver in controlling stability, differential torque based ESC can be chosen with some changes in working principle or algorithm. More focus is given in this proposed ESC type named as “In-Wheel ESC” to find the possible ways for controlling the force of four wheels so that it can generate corrective yaw moment. Using sensors and a dynamic vehicle model, the In-Wheel ESC, finds the required longitudinal force in each wheel for a corrective yaw moment then generates the torque according to the force. In-Wheel ESC will determine the required differential longitudinal force difference “ΔFx” between the wheels to generate corrective yaw moment. Then the controller will try to create that longitudinal force different by generating torque in the individual wheel. This can be done by manipulating the individual throttle for wheel internally in the controller. To create the corrective force difference “ΔFx”, the individually required torque should remain in the limit of possible torque generation by this electric motor. If “ΔFx” is large enough and it requires the torque beyond the capacity of the electric motor, then the torque distribution system may not afford adequate

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yaw moment. In practice besides the normal operating voltage and current there is a higher level voltage and current kept for running the in-wheel motors in turbo mode. In turbo mode, the limit of operating voltage increases to a higher level and motors generate higher torque than they usually generate in the normal operation mode. This voltage level shifting is able to solve the problem for generating required differential torque by these in-wheel motors.

V. MODELING AND SIMULATIONS

Dynamic vehicle model of 4 in-wheels EV with its associated components are required to calculate and to estimate different vehicle parameters. These parameters are used to determine the desired and targeted values of yaw rate and side–slip angle. A sliding mode control law [8] uses these desired values and actual values of yaw rate and side-slip angle to find differential torque that need to be applied for creating corrective yaw moment.

Simulation is done for In-Wheel ESC, by creating model for the entire environment with different model blocks in MATLAB/SIMULINK as shown in fig.3. The model blocks are (1) Vehicle body (2) Front and rear wheel blocks (3) Desired value generator (4) Sliding mode controller block (5) Actuating torque generator.

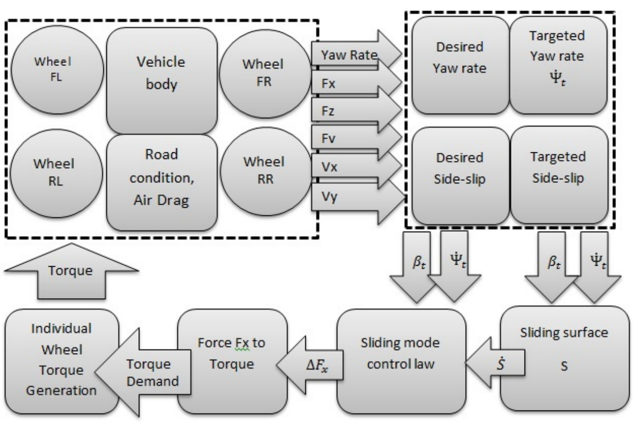

Fig.3: Simulation environment

A. *Vehicle body block:*

Equations of motion are used here to find the velocity of the vehicle and its yaw rate. Let $\dot{x}$ is the longitudinal velocity of vehicle, Let $\dot{y}$ is the lateral velocity of vehicle and I_z is yaw moment of inertia of vehicle then equations of motions of a vehicle body are:

$$m\ddot{x} = (F_{xfl} + F_{xfr})cos(\delta) + F_{xrl} + F_{xrr} - (F_{yfl} + F_{yfr})sin(\delta) + m\dot{\Psi}\dot{y} - \frac{1}{2}C_D\rho_a A\dot{x}^2 \quad (1)$$

$$m\ddot{y} = F_{yrl} + F_{yrr} + (F_{xfl} + F_{xfr})sin(\delta) + (F_{yfl} + F_{yfr})cos(\delta) - m\dot{\Psi}\dot{x} \quad (2)$$

$$I_z\ddot{\Psi} = l_f(F_{xfl} + F_{xfr})sin(\delta) + l_f(F_{yfl} + F_{yfr})cos(\delta) - l_r(F_{yrl} + F_{yrr}) + \frac{l_w}{2}(F_{xfr} - F_{xfl})cos(\delta) + \frac{l_w}{2}(F_{xrr} - F_{xrl}) + \frac{l_w}{2}(F_{yfl} - F_{yfr})sin(\delta) \quad (3)$$

B. *Wheel block*:

Longitudinal forces of wheels F_{xfl}, F_{xfr}, F_{xrl}, F_{xrr} denote as F_x and lateral forces of the vehicle F_{yfl} , F_{yfl} , F_{yfr} , F_{yrl} as F_y then according to the Dugoff tire model [9] for tire force calculation,

Longitudinal tire force $F_x = C_\sigma \frac{\sigma}{1+\sigma} f(\lambda)$ (4)

Lateral tire force is $F_y = C_\alpha \frac{\tan\alpha}{1+\sigma} f(\lambda)$ (5)

Where, longitudinal slip ratios for each wheels for braking is $\sigma = \frac{r_{eff}\omega_w - \dot{x}}{\dot{x}}$ and for acceleration is $\sigma = \frac{r_{eff}\omega_w - \dot{x}}{r_{eff}\omega_w}$.

Slip angles at the front and rear tires are $\alpha_f = \delta - \frac{\dot{y} + l_f\dot{\Psi}}{\dot{x}}$ and $\alpha_r = -\frac{\dot{y} - l_r\dot{\Psi}}{\dot{x}}$

Function $\lambda = \frac{\mu F_z(1+\sigma)}{2\{(C_\sigma\sigma)^2 + (C_\alpha \tan\alpha)^2\}^{\frac{1}{2}}}$ here μ is tire road friction coefficient and F_z is the vertical force on tire, if value of $\lambda < 1$ then function, $(\lambda) = (2-\lambda)\lambda$. If value of $\lambda \geq 1$ then function, $f(\lambda) = 1$

C. *Desired value generator*:

Desired yaw rate and desired side-slip angle is calculated here to use them in the control law for simulation.

Desired yaw rate $\dot{\Psi}_{desired} = \frac{\dot{x}}{R}$ (6)

Here R is the radius of the circular road calculated using steering angle.

Relation between steady state steering angle δ_{ss} for a circular path and radius R of the path is

$$\delta_{ss} = \frac{l_f + l_r}{R} + \left(\frac{m l_r C_{\alpha r} - m l_f C_{\alpha f}}{2C_{\alpha f}C_{\alpha r}(l_f + l_r)}\right)\frac{\dot{x}}{R} \quad (7)$$

From steady state cornering equations radius $R = \frac{MV^2}{F_y}$ (8)

$C_{\alpha f}$ and $C_{\alpha r}$ are the cornering stiffness of front tire and rear tire respectively

From equation 6 desired yaw rates $\dot{\Psi}_{desired}$ can be derived as

$$\dot{\Psi}_{desired} = \frac{\dot{x}}{l_f + l_r + \frac{m\dot{x}^2(l_r C_{\alpha r} - l_f C_{\alpha f})}{2C_{\alpha f}C_{\alpha r}(l_f + l_r)}}\delta \quad (9)$$

Desired side slip angle

$$\beta_{desired} = \frac{l_r - \frac{l_f m\dot{x}^2}{2C_{\alpha r}(l_f + l_r)}}{(l_f + l_r) + \frac{m\dot{x}^2(l_r C_{\alpha r} - l_f C_{\alpha f})}{2C_{\alpha f}C_{\alpha r}(l_f + l_r)}}\delta_{ss} \quad (10)$$

These desired value are not always achievable, sometimes they have dependency on the physical property of road like road tire friction coefficientμ. Thus target value of desired yaw rate $\dot{\Psi}_{target}$ and desired side slip angle β_{target} is considered after calculating the upper bound.

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D. Control Law:

To keep the yaw velocity and slip angle of the vehicle limited to the values that correspond to coefficient of friction of the road, the controller should take both of the yaw velocity and slip angle as controlled variables [10]. The following sliding surface has been chosen which have weighted combination of yaw rate and slip angle[11]. Sliding surface for controller

$$S = \dot{\Psi} - \dot{\Psi}_{target} + \xi(\beta - \beta_{target}) \quad (11)$$

Differentiating equation 11

$$\dot{S} = \ddot{\Psi} - \ddot{\Psi}_{target} + \xi(\dot{\beta} - \dot{\beta}_{target}) \quad (12)$$

E. Required longitudinal force difference calculation:

If driving torque is used for actuating the vehicle to create corrective yaw moment, a fixed ratio ρ_t of front to back torque distribution is assumed, here $\rho_t = 1$ as each wheel are similar in terms of generating of torque. Considering $F_{xrl} = \rho_t F_{xfl}$ and $F_{xrr} = \rho_t F_{xfr}$ in (3) we get:

$$\ddot{\Psi} = \frac{1}{I_z}\left[l_f\left(F_{yfl} + F_{yfr}\right)\cos\delta \ - l_r\left(F_{yrl} + F_{yrr}\right) + (\cos\delta + \rho_t)\left(\frac{l_w}{2}\left(F_{xfr} - F_{xfl}\right)\right)\right] \quad (13)$$

Using (12) and (13) desired yaw torque $M_{\psi t}$ determined by the control law as

$$M_{\psi t} = \frac{I_z}{(\cos\delta + \rho_t)} \times \left[\frac{1}{I_z}\left[-l_f\left(F_{yfl} + F_{yfr}\right)\cos\delta + l_r\left(F_{yrl} + F_{yrr}\right)\right] - \eta S + \ddot{\Psi}_{target} - \xi\left(\dot{\beta} - \dot{\beta}_{target}\right)\right] \quad (14)$$

Detail of this calculation can be found in R. Rajamani[11]. In differential driving torque ESC the In-Wheel ESC controller determines amount of required torque at each wheels to generate a corrective yaw moment to meet the targeted yaw rate determined desired value generator. The extra differential longitudinal tire force $F_{xfr} - F_{xfl} = \Delta F_{xft}$ can be calculated as

$$\Delta F_{xf} = \frac{l_w M_{\psi t}}{2} \quad (15)$$

F. Calculation of torque and wheel rotation:

Calculation of torque can be done using the longitudinal force difference ΔF_{xf} or ΔF_{xr} from wheel rotational dynamics as given below for front left wheel:

$$J_w \dot{\omega}_{fl} = T_{dfl} - r_{eff}(F_{xfl} \pm \Delta F_{xf}) \quad (16)$$

The required differential torque is to be created by four electric motors on the rear and front axle. Generate and observation of this required torque can be done using (19) and the electrical characteristics like applied voltage and current. In the implementation of differential torque, wheel rotation can be observed from the built in Hall Effect sensor, which can be used as a supporting feedback parameter along with the estimated longitudinal force. These wheel rotation speed can be compared and bring them to the expected rotation for the calculated required torque. Figure 4 shows the entire model of the vehicle with its components and controller. Simulation is done here using the standard parameter of europian sedan. The table is given here for the vehicle parameters values used in this simulation.

G. Simulation Result:

For simulation Sine with Dwell [12] maneuver is used here which is very popular and suggested by authorities for ESC testing. First simulation test is done here without the controller intervention and torques for each wheel was kept constant. Later on in the second simulation test with In-wheel ESC differential torque is generated and used for each wheels.
Figure 5 shows different results of simulation when in-wheel ESC is not activated. Figure 5 (a) shows that the torque in each wheel is almost similar. It is observed from figure 5 (b) that the yaw rate is not returning to zero and from figure 5 (c)vehicle longitudinal velocity kept varying for the steering angle input. Without differential torque ESC, vehicle is not following the desired values.

With differential torque controller, vehicle is following the steering angle and yaw rate is returning to zero. The noticeable behavior of the vehicle here is the longitudinal velocity which is almost constant. Figure 6 (a) shows the differential torque in the wheels, 6 (b) shows the yaw rate is crossing zero and figure 6 (c) shows the vehicle velocity which is almost constant.

H. Control Structure:

A dynamic vehicle model or observer is used in the closed loop control system to determine how the vehicle should response during operation. Figure 7 shows the closed loop control structure for this vehicle. Input variables to the observer from EV (plant) are steering angle, wheel speed, lateral acceleration, vehicle lateral and longitudinal velocity. Observer estimates coefficient of friction from measured longitudinal acceleration ax and lateral acceleration ay [10]. It also estimates tire forces Fx and Fy, tire slip, nominal vehicle side slip and nominal yaw rate. Control variances are the difference between measured yaw rate and nominal yaw rate and difference between measured side slip and nominal side slip.

VI. Experiment

In this vehicle 4 in-wheel brushless DC motors are used. Each of these motors has a motor controller with it and these motors can be control by its throttle input. Transforming the throttle pedal signal to a desired wheel velocity is very complex and involves tested data of the motors with the all possible throttle input. Initially, experiment has been done to all the motors and controllers to find the speed and Hall Effect sensor signals for almost all possible throttle input voltages from 0 volt to 3.6 volts. From this experimental data, throttle pedal signal to a desired wheel velocity correlation is realized for all the motors.
Before going to a real time test in the track of this proposed in-wheel ESC like a commercial ESC, an experiment is done to control the in-wheel motors for generating the expected differential torque. This test helps us to remove human error and reduced cost.

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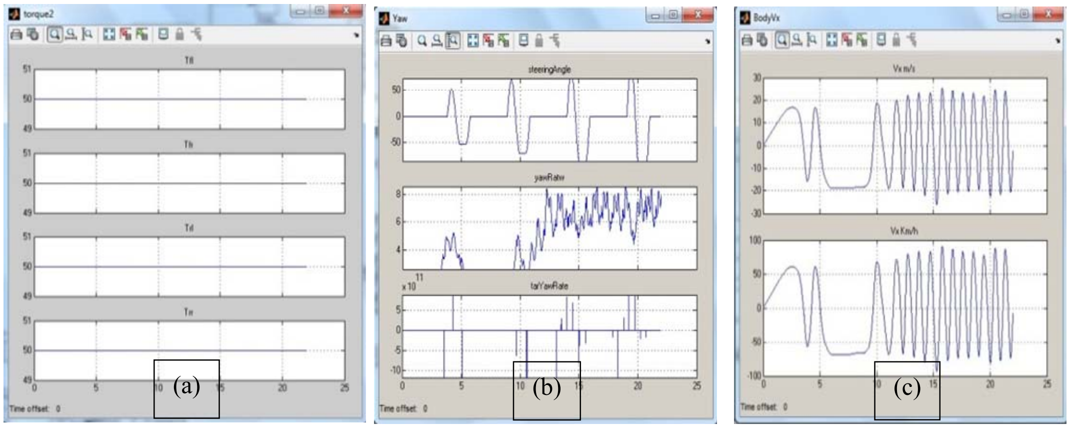

Fig.5. (a) Constant torque for wheels, (b) Steering angle, yaw rate and target, (c) vehicle velocity in m and km

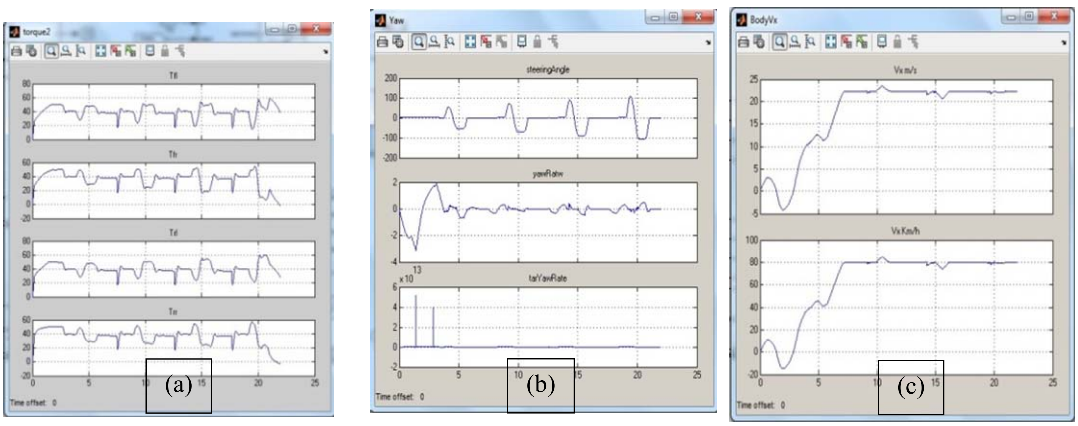

Fig.6. (a) differential torque for wheels, (b) Steering angle, yaw rate and target, (c) vehicle velocity in m and km

Apart from the In-wheel vehicle another experimental setup has been made to observe the control of wheels on the bench. Fig.8 shows an experimental setup to observe the motors behavior and to control the motors with differential torque.

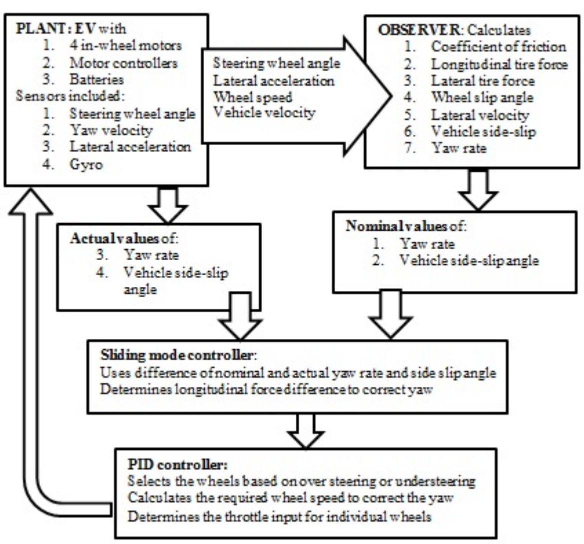

Fig.7. Closed loop control structure

Fig.8. In-wheel motor test bench

A reference model is required to have in the embedded controller to compare the actual sensor values, to include this reference model in the controller NI cRIO real time controller is chosen to be the host of reference model. LabView program is used here to create embedded reference model and control the motors.

Using this proposed In-Wheel ESC calculation of required torque can be done. As the wheel torque can be expressed in terms of wheel velocity, the controller in this test bench rotates these wheels according to the required torque properly.

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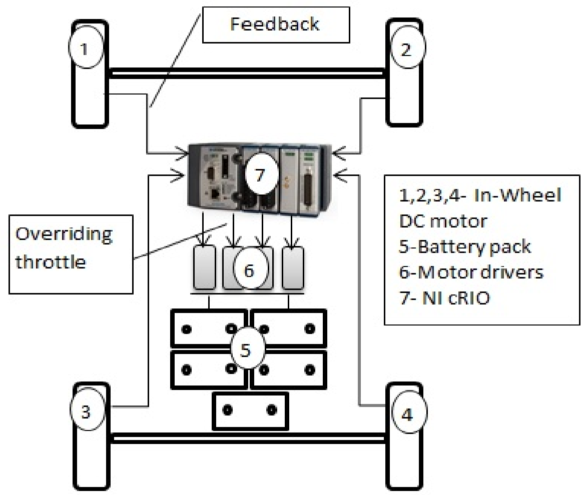

Fig.9. Hardware and controller setup in the In-wheel EV

The controller developed here is manipulated the throttle coming from the pedal for each wheel and maintaining the required wheel rotation as expected for the required torque. Controller receives throttle input from single source throttle initially, and then generates the specific throttle signal for each wheel internally in the controller after comparison of wheel speed using the sensors.

VII. CONCLUSION

A practical approach for developing an ESC for advanced 4 in-wheels EV is taken here. Initially non-linear vehicle model is developed and analyzed the yaw control for electric vehicle with four in wheel motors. Based on sliding mode control law a controller is designed to track the yaw rate. To verify the proposed controller simulation is done here that shows enhanced stability of the vehicle. Experiment has been done to find out the possibility of generation of differential torque in terms of wheel speed based on the demand from controller. The controller calculated differential torque using sensor data and reference vehicle model transformed it to wheel speed is achieved by the test bench to reduce chassis physical error, human error and cost. Simulation and experiment has shown promising result in this stage for a suitable type ESC for In-wheel motor EV to go further for real time test on the racing track in future.

REFERENCES

[1] Y. E. Papelis, G. S. Watson, and T. L. Brown, "An empirical study of the effectiveness of electronic stability control system in reducing loss of vehicle control," *Accident Analysis and Prevention,* vol. 42, pp. 929-934, 2010.

[2] S. A. Ferguson, "The Effectiveness of Electronic Stability Control in Reducing Real-World Crashes: A Literature Review," *Traffic Injury Prevention,* vol. 8, pp. 329-338, 2007/10/25 2007.

[3] J. Scully and S. Newstead, "Evaluation of electronic stability control effectiveness in Australasia," *Accident Analysis and Prevention,* vol. 40, pp. 2050-2057, 2008.

[4] M. M. Al Emran Hasan, M. Ektesabi, and A. Kapoor, "Pollution control and sustainable urban transport system - electric vehicle," *World Academy of Science, Engineering and Technology,* vol. 78, pp. 970-975, 2011.

[5] E. K. L. K. M. J. S. G. Nenninger, "Safety and Performance Enhancement: The Bosch Electronic Stability Control (ESP)," *Robert Bosch GmbH, Paper Number 05-0471,* 2004.

[6] J. Ackermann, "Robust control prevents car skidding," *IEEE Control Systems Magazine,* vol. 17, pp. 23-31, 1997.

[7] S. Zhang, T. Zhang, and S. Zhou, "Vehicle stability control strategy based on active torque distribution and differential braking," 2009, pp. 922-925.

[8] M. Canale, L. Fagiano, A. Ferrara, and C. Vecchio, "Vehicle yaw control via second-order sliding-mode technique," *IEEE Transactions on Industrial Electronics,* vol. 55, pp. 3908-3916, 2008.

[9] H. Dugoff, Fancher, P. S., Segel, L., "Tire performance characteristics affecting vehicle response to steering and braking control inputs. Final report," *Highway Safety Research Institute,* 1969.

[10] A. Van Zanten, Erhardt, R., Pfaff, G., Kost, F., Hartmann, U., Ehret, T, "Control aspects of the Bosch-VDC," *International Symposium on Advanced Vehicle Control,* pp. 573–608, 24th-28th of June 1996.

[11] R. Rajamani, *Vehicle Dynamics and Control*: Springer US, 2012.

[12] N. Picot, B. Miller, M. D. Rizzo, and T. A. Klingler, "FMVSS126 Electronic Stability Control Sine With Dwell Incomplete Vehicle Type 2 Analysis," *SAE International Journal of Passenger Cars - Mechanical Systems,* vol. 4, pp. 713-721, 2011.