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Hybrid Fuzzified-PID Controller for non-linear Control Surfaces for DC Motor to Improve the Efficiency of Electric Battery Driven Vehicles

Rashmi Bhardwaj, Aashima Bangia

Abstract**:** ***The paper intends to deliver a structure of speed-control for electric DC motor widely being used in the electric rechargeable-battery vehicles. Electric vehicles are the need of the hour due to increasing environmental concerns and the dependency on fuels and oils. So as to promote this hybrid and electric vehicle technology and ensure its sustenance, the Ministry of Heavy Industry and Public Enterprises in the Gazette of India on 13th of March, 2015 approved the Scheme for Faster adoption and manufacture of (Hybrid &) Electric Vehicle in India referred as FAME-India under National Electric Mobility Mission (NEMM). This scheme intends to encourage the hybrid/electric motor driven vehicles in the market and also its manufacturing for the betterment of eco-system to be implemented over a period of six years till 2020. Electric-battery driven vehicle is sourced on the restricted electrical-energy delivered by the battery in circuit. Major contribution of this work is to propose control-strategy through Fuzzified-PID controller so that the performances of the electric vehicle is comparable to that of an internal combustion-engine vehicle. Feedback is the foundation of PID control. The target or the set point is compared with the resultant of the process. Then, correction is computed and applied for the difference identified. This procedure is carried on till the time recalculation is required. PID refers to the combined computation of proportional-integral-derivative. Controllers, in general do not apply all three mathematical functions. Maximum processes were being handled through the proportional-integral-terms. However, addition of derivative control for fine control plus to avoid overshoot are required. Following models: PID controller, hybrid Fuzzified-reasoning PID controllers for linear surfaces and non-linear control surfaces using n-D Lookup-Table data have been designed for a comparative study. It has been observed that hybrid model designed for non-linear control-surfaces provided better speed response and have zero steady state error. The simulation of these models is carried out using SIMULINK under varying state conditions.***

Keywords**:** ***Electric-motor, Fuzzified-PID Controller, Lookup-Table, SIMULINK***

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I. INTRODUCTION

Proportional Integral Derivative(PID) control describes set of rules for control which have been most extensively into the industry. It has been gradually acknowledged in the industrial control across the globe. PID-algo basically encompasses of three elementary coefficients: proportion, integration & derivation which have been improved for optimal outcome. Proportional checks on the possibilities of error; the integral prevents the growth of error plus derivative term monitors the current error versus error in the last iteration or simulation. It is be sure that contents of the paper are fine and satisfactory.

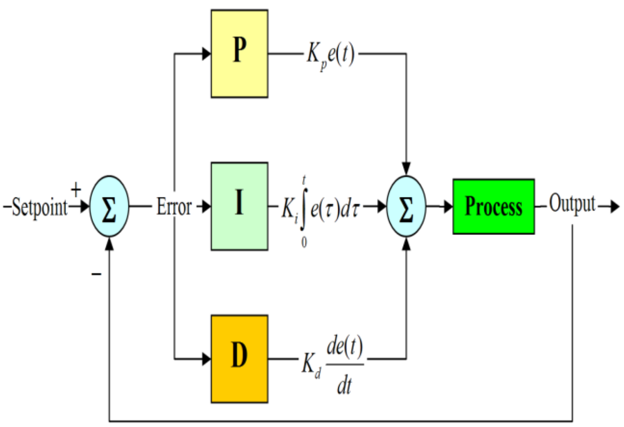
The elementary notion towards PIDcontroller is that first read measuring device, next calculate anticipated actuator outcome through simulating proportional; integral; derivative-responses then finally adding up together these mechanisms for calculating results. Proportional control implies the correction factor to be determined through size of difference between target point and the measured value. Longer the variation in target to actual value, difference increases with the increase in size of correction factor computed. So, the delay in the response to the correction makes way for overshoot thereby subsequent oscillation about set point. Purpose for derivative-function is to overcome this delay. This keeps a check at rate of change being accomplished, gradually transforming correction-factor for decreasing the outcome gradually as target advanced.

Proportional constituent based on the difference between target with process variable. The difference is Error term. Ratio of outcomes for error signal is the proportional gain (K_p). Speed of the control system is in direct proportionality to advances i.e. gain. But, if gain is very large, the process variable oscillates which perhaps leads to unsteadiness. *Integral function* sums error term with respect to time. Integral increases slowly due to the small error term. The integral response gradually increases with respect to time till the error is zero which converges the error towards zero. Integral setup phenomenon happens when integral action saturates controller devoid of the error indicator converging towards zero.

The *derivative* part leads outcome to decrease if the outcome is increasing at a fast rate.

The derivative response taken proportionate towards changing rate of outcomes. Increasing derivative time (T_d) parameter lead to control-scheme to react powerfully towards the variations in error term and will increase speed of overall control scheme. Usually, control systems involve epsilon derivative time (T_d), as Derivative response tends to grow complex to noise in to outcome.

Electric battery driven vehicles employ traditional-controller which are PID-controller. This mechanism works only in case of specific set of given considerations i.e., capacity considerations. But, sometimes capacity considerations through given standards lead to deterioration of the performance of closed-loop scheme. This results as higher overshoot, higher rise time, extensive settling times, perhaps, unstable. Usually, PID-speed-controller can be fine-tuned in accordance for a definite degree in order to attain a desirable performance under a specific set of operating conditions. On applying variable operating considerations, the performance deteriorates. Therefore, these situations require various controllers that can account for non-linearities plus are to some extent adaptive for fluctuating considerations in real-time-domain. Other approaches, such as fuzzification, are now being employed to achieve desired performance level.



Al-Mashakbeh [1] discussed the brushless DC motor through proportional-integral and derivative controller. Astrom *et al* [2] studied non-convex optimization for designing PI controllers. Badri and Tavazoei [3] tuned fractional-order proportional derivative controllers forclass of such fractional-order systems. Bahgaat *et al* [4] improved the PID controllers used in the power systems of load frequency control through Particle Swarm Optimisation and ANFIS methodologies. Bettayeb and Mansouri [5] developed PID fractional-order filter controller design for integer-order systems. Bhardwaj and Bangia [6-7] studied the complexity of meditating body via mathematical modelling of differential equations. Also, developed a conjunction model using Neuro-fuzzy for analysis of NSE for the period of Demonetization. Cominos and Munro [8] described various tuning methods and designs for various specifications of PID controllers. Durai and Bhardwaj [9] applied statistical-bias for corrected output for forecasting system for maximum and minimum temperatures in India. Gaing [10] studied Particle Swarm Optimisation Approach for designing PID controllers in AVR Systems. Goodwin et al [11] explained in detail about the classical PID control in the book Control system design. Huh *et al* [12] urbanised narrow-width inductive power transfer arrangement for the benefit of electrical automobiles. Jantzen [13] explained the tuning of fuzzified-PID controller in the technical report. John *et al* [14] discussed PID controls of continuous processes in the book Programmable Logic Controllers. Kandiban and Arulmozhiyal [15] studied controlling of speed of BLDC motor with the help of adaptive-fuzzy PID-controller. Khuntia and Panda [16] simulated automatic multi-area power-system monitoring via ANFIS approach. Li *et al* [17] designed two-degrees of freedom fractional-order PID controller of the fractional-order progressions using dead-time. Luo *et al* [18] developed stabilized & robust fractional-order PI-controller synthesis of first-order with time-delay systems. Mohanty *et al* [19] studied differential evolution algorithm based automatic generation control for interconnected power systems with non-linearity. Mudi and Pal [20] schemed a robust self-tuning for PI and PID fuzzy controllers. Neath *et al* [21] explained an ideal PID-controller for bi-directional inductive power transfer scheme with the help of multi-objective genetic algorithm. O'Dwyer [22] discussed the PI and PID-controller tuning rules. Pan *et al* [23] tuned an optimal fuzzy PID controller using stochastic algorithms for networked control systems with random time-delay. Passino [24] discussed biomimicry for optimization, control and automation. Pinuela *et al* [25] maximized DC for loading efficiency for inductive power transfer. Qiao and Mizumoto [26] studied PID controller with fuzzy and parameter adaptive methods. Sahu *et al* [27] developed the innovative hybrid of LUS-TLBO-fuzzy-PID controller towards load frequency controlling for multi-power system. Shah [28] explained in detail the fractional PID controller. Wang *et al* [29] determined the real-time state of rechargeable batteries through a patented procedure. Xu *et al* [30] described the parallel structure plus tuning for fuzzy-PID controller.

As per the literature survey carried based on various sources, none of the authors reported the structure of speed-control for the electric DC motor being used in the electric vehicles widely. No articles reported the comparison among the three models that have been prototyped and simulated separately and then hybridized into a single Simulink model for a comparable study of the outcomes.

II. METHODOLOGY

A. Creating State Space Prototypes

Generally, state-space prototypes are time-domain representations for LTI structures:

$$\frac{dj}{dt} = \alpha\, j(t) + \beta l(t)$$

$$k(t) = \gamma\, j(t) + \omega l(t)$$

j(t)- state vector; *l(t)*- input vector; *k(t)*- output trajectory;

This prototype built with the help of *nj* states, *nk* outputs, *nl* inputs with:

$$\alpha - nj \times nj\ (real\ /\ complex - valued)\ matrix$$
$$\beta - nj \times nl\ (real\ /\ complex - valued)\ matrix$$
$$\gamma - nk \times nj\ (real\ /\ complex - valued)\ matrix$$
$$\omega - nk \times nl\ (real\ /\ complex - valued)\ matrix$$

State-space models are derived from differential equalities describing system dynamics.

It has been attempted to control-speed for DC-motor through diverse Simulation models developed using PID-controller with Fuzzification. Hybridization is designed for both linear and non-linear control surfaces. For better observation, simplified closed-loop model without PID-controller is considered which the Test Model is. Then, three forms of PID-controllers have been designed and implemented in closed-loop model for speed-control for DC-motor. After that complete layout for the three controllers are executed in discrete time parallel form.

The equation is discretized which converts it from continuous to discrete form so that discrete time PID controllers can be applied in parallel form with advances K_p, K_i and K_d. The discrete form electric motor is referred as Plant system. Discrete-time PID controller (PID(t)) in parallel form which is written as:

$$PID(t) = K_p + K_i \frac{Ts \times z}{z-1} + K_d \frac{z-1}{Ts \times z}$$

K_p = -0.0406, K_i = 0.162, K_d = 0.00254, sample time, Ts = 0.25. The input signal is the sine wave whose amplitude - 100, frequency - 1, bias - 10.

B. Algorithm for design with implementation of three forms of PID Controllers

Designing fuzzified-PID-controller encompasses designing fuzzified inference system(FIS) then, setting four-parameters: Gains at response E(GE), Gains at response CE(GCE), Gains at control outcome(GCU) and Gains at outcome (GU).

In this case study, following design measures are pragmatic:

1. Prototyping traditional linear-PID-controller
2. Prototyping comparable linear -fuzzified PID-controller
3. Modify FIS so as to design the nonlinear -control-surface
4. Fine-Tune this non-linear fuzzified-PID-controller

Step-1: Prototyping *a Conventional PID Controller*

This PID-controllers are modelled for discretized period through Backward Euler in this case. It is applied to both integral & derivative methodologies. Regulator advances are K_p; K_i; K_d. Then, controller can be implemented to produce a controlled output as compared to the input.

Step-2a: Prototyping a Comparable Linear-Fuzzified-PID-Controller

Configure FIS then, select four scaling factors: GE;GCE;GCU&GU. Attain linear-fuzzified-PID-control which implements exact control-performance as conventional-PID controller. To identify scale factors, approximate span of each plant responses and outcomes into the units.

First, construct Mamdani-fuzzification scheme such that yielding linear-control-surface through responses: E and CE leading to outcome.

Next, regulate parameters GE; GCE; GCU & GU through K_p, K_i and K_d advances utilized through traditional-PID controller.

Step-2b: Apply Fuzzified-Inference-System

Fuzzified-controller has two responses: E and CE plus zone outcome (*u*) that have to be substituted with the 2D-lookup table. Fuzzified-PID controller exhausting 2-D lookup-table is implemented. When control-surface is linear fuzzified-PID controller through 2-D lookup-table that yield exactly the similar performance similar to fuzzified-controller.

Step-2c: Simulating

Simulink prototype involves diverse sub-systems, i.e., Conventional-PID; Fuzzified-PID; Fuzzified-PID through Lookup-Table controls plant. Closed-loop responses towards Sine reference change displayed in the scope and three response curves overlap each other.

Step-3: Prototyping Fuzzified PID Controller via Nonlinear Control Surface

Subsequently, corroborating linear fuzzified-PID controller gets accurately planned, modify FIS surroundings like the membership functionals and rule-base to achieve the preferable nonlinear control surface. Fig.4. sketches 3-D non-linear control surface below. Before initiating simulations, apprise lookup-table with modified control surface parameters. As surface is non-linear, break points for attaining adequate approximation are increased in number.

III. Simulation Models

The following plant in Fig.1 have been modelled without the PID controller to compare the behaviour.

The following prototypes in Fig. 2, 3 and 4 are Simulink models on which simulations have been carried out for three forms of PID Controllers:

1. Conventional PID-Controller
2. Fuzzified-PID Controller
3. Fuzzified-PID Controller with Lookup-Table

Now, the Simulink model is designed for comparison for control performance for these PID Controllers and improve the reference tracking performance. Target referred as set point input is the Sine wave. Plant requires single-input/output scheme depending on discretized-time which is taken as the LTI structure in this paper. The output is plotted on the Scope.

Designing the model without PID controllers

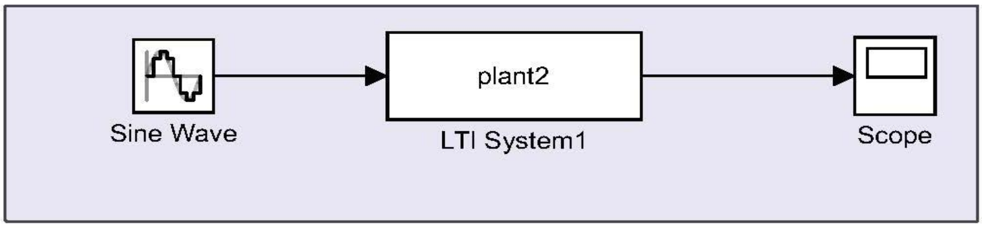


Fig.1.Simulink Model without PID Controller

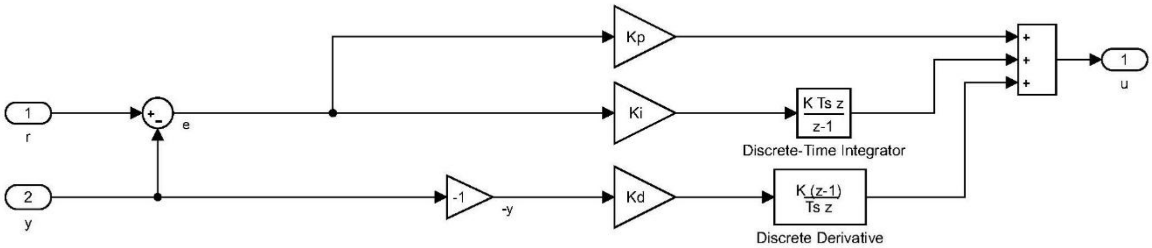


Fig.2.Simulink-Prototype of Conventional PID Controller

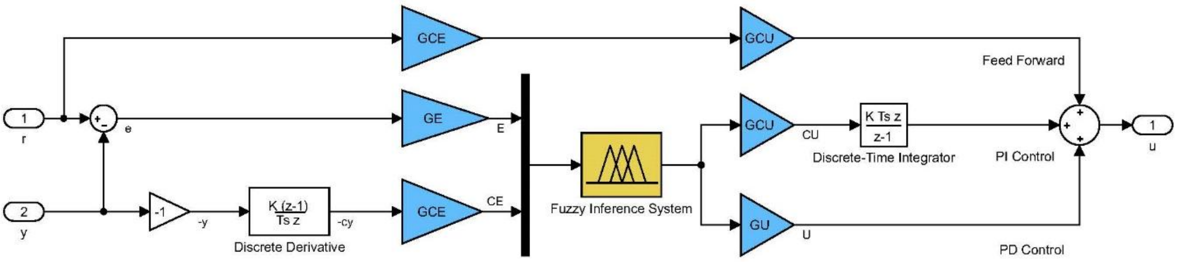


Fig.3.Simulink-Prototype of Fuzzified-PID Controller

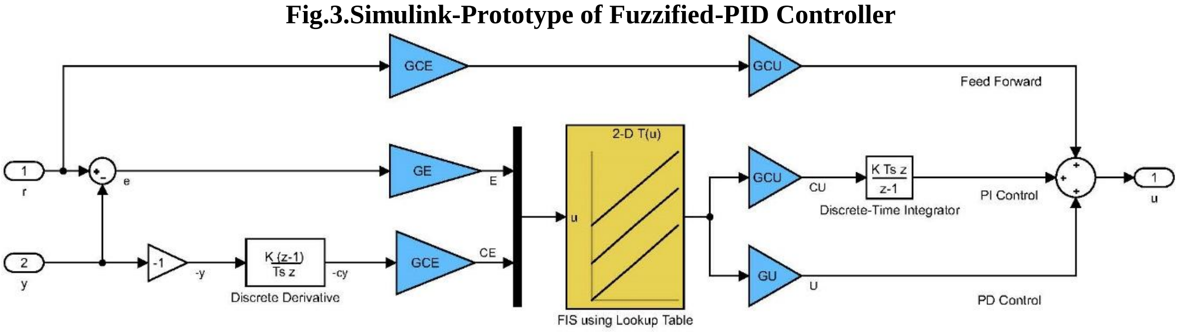


Fig.4.Simulink-Prototype of Fuzzified PID Controller using Lookup Table

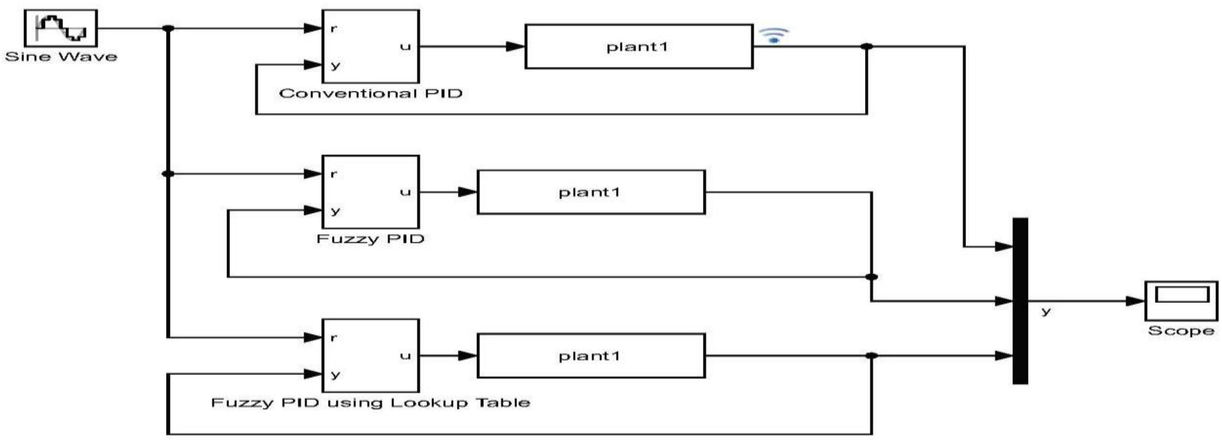


Fig.5.Simulink-Model for the comparison for all three types of Controllers as subsystems

Table I: Comparison of results of two different Simulink Models

Simulation Name	Test Model	Comparison Model
Simulation Mode	Normal	Normal
Start Time	0	0
Stop Time	12	12
Solver Name	Variable-Step	Variable-Step
Solver Type	Variable Step Discrete	Variable Step Discrete
Initialization Time	2.639367	0.968885
Execution Time	0.473026	0.147995
Termination Time	0.004004	0.199001
Total Elapsed Time	3.116397	1.315881

Table II: Comparison of gain response of three Controllers

Parameter	Speed of Response	Stability	Accuracy
Conventional PID	Increases as compared to non-controller models	Quiet Stable	Improved as compared to non-controller models
Hybrid-Fuzzified PID (for linear control surface)	Increases as compared to traditional PIDs	Steady state error converges to zero	Improved as compared to traditional PIDs
Hybrid-Fuzzified PID exhausting Lookup Tables (for non-linear control-surface)	Noticeable increase as compared to other models discussed in this study	Steady state error tends to zero faster	Less difference as compared to linear fuzzified-PID model

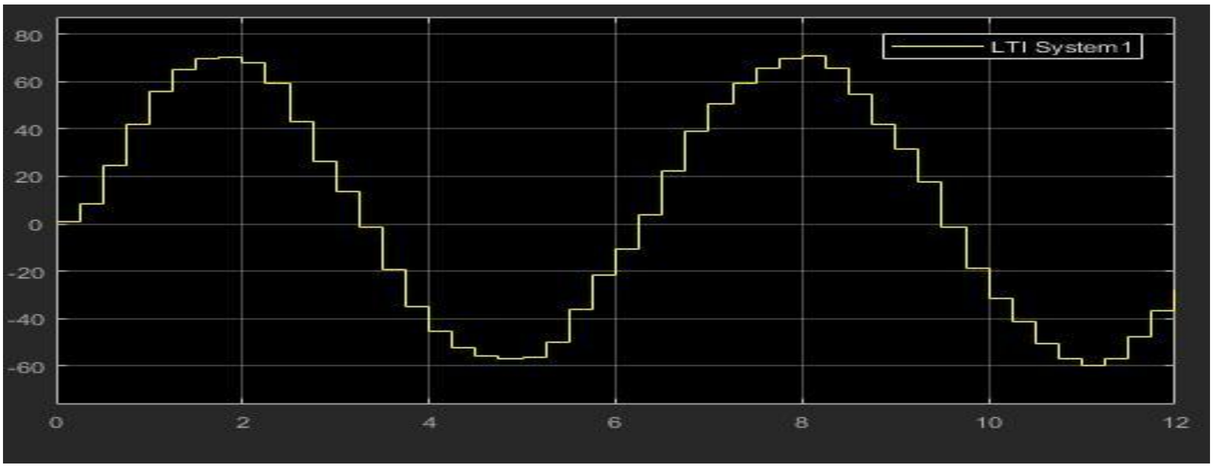


Fig.6.Output Signal of Test Model in comparison to models with Controllers as subsystems

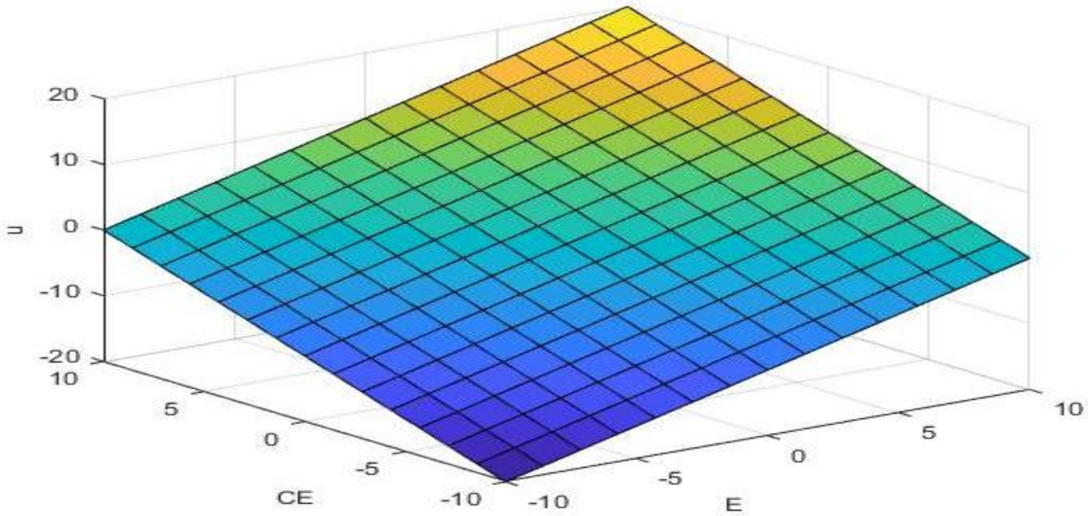


Fig.7.FIS Surface of Linear-Fuzzified Control-Surface

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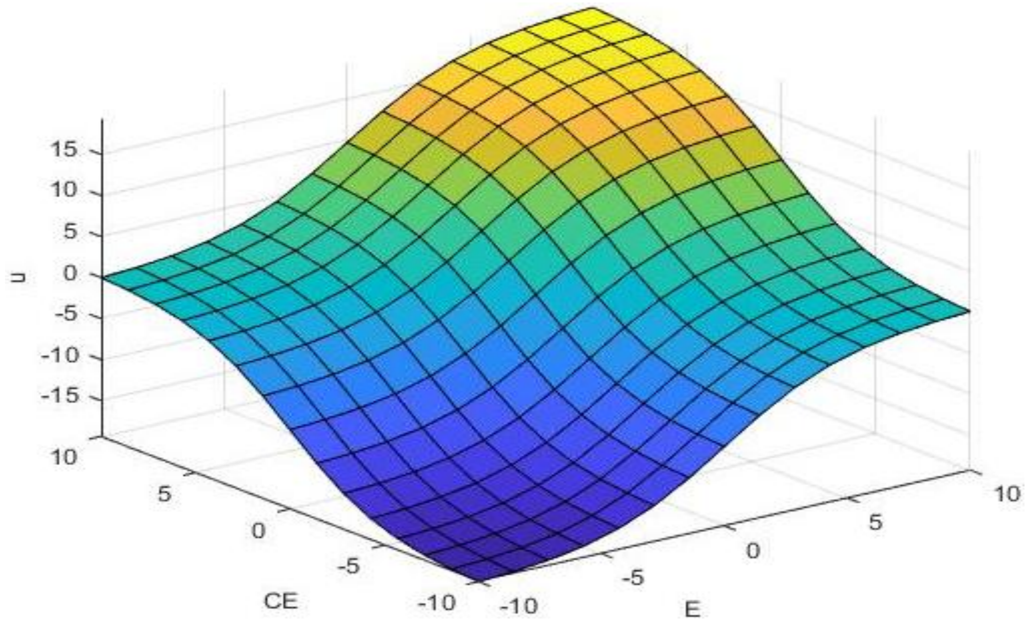

Fig.8.FIS Surface of Non-Linear Fuzzified Control-Surface

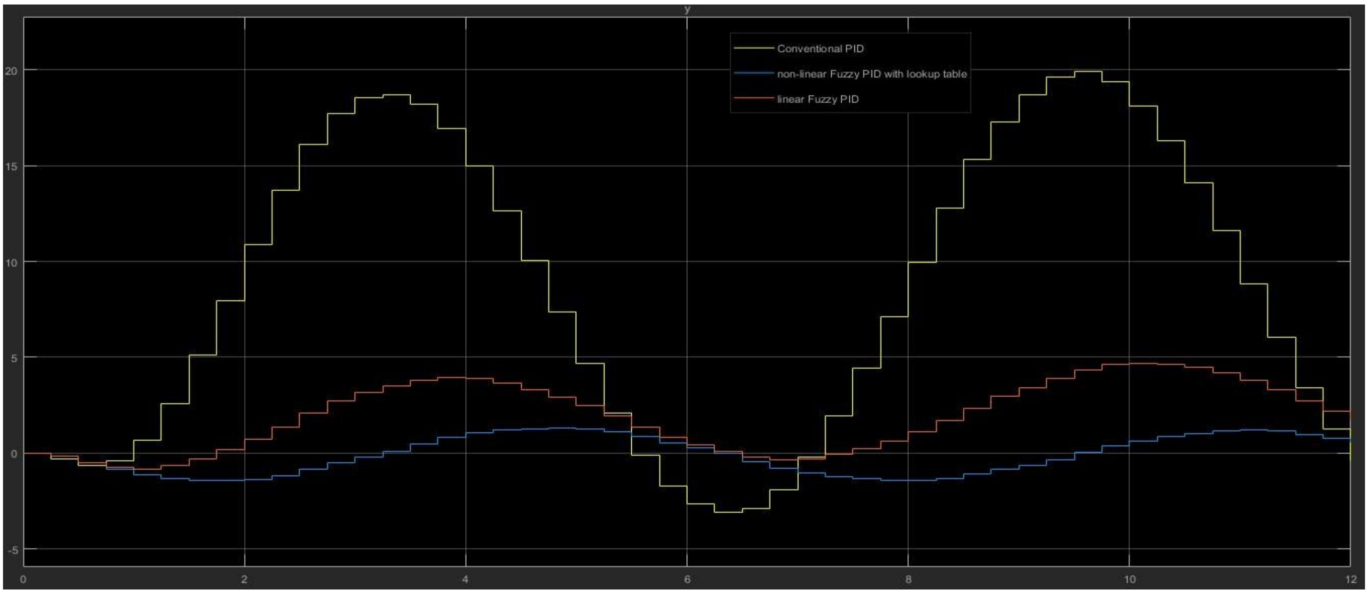

Fig.9.Output Signal of Comparison Model to compare the three types of Controllers

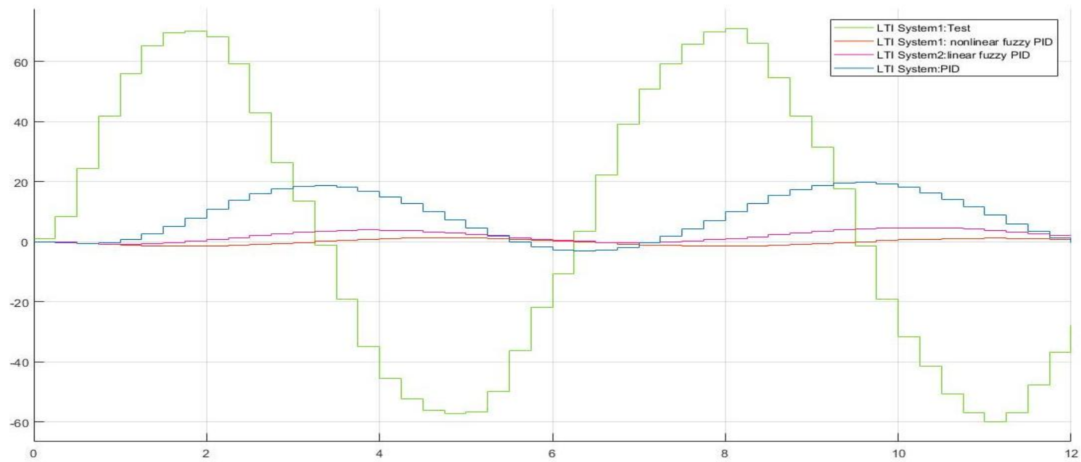

Fig.10.Comparison of output all three types of Controllers with the output of model without controller

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IV. RESULT AND DISCUSSION

In this study, the state-space form standards based on [10], [26], and [27]:

$$\frac{dj}{dt} = \alpha j + \beta i , \quad \alpha = \begin{bmatrix} 0 & 1 \\ -5 & -2 \end{bmatrix}; \beta = \begin{bmatrix} 0 \\ 3 \end{bmatrix} \qquad (1)$$

$$\phi = \gamma j + \omega i, \quad \gamma = [1\ 0]\ ;\ \omega = [0] ; i = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad (2)$$

$$j = \begin{bmatrix} \phi \\ \frac{d\phi}{dt} \end{bmatrix} \qquad (3)$$

j(t)- state vector; *i(t)* - driving current (input); ϕ *(t)*- angular displacement of the outcome

$$\alpha = \begin{array}{cc} & \begin{array}{cc} j_1 & j_2 \end{array} \\ \begin{array}{c} j_1 \\ j_2 \end{array} & \begin{bmatrix} 0 & 1 \\ -5 & -2 \end{bmatrix} \end{array} \ ; \beta = \begin{array}{cc} & j_1 \\ \begin{array}{c} i_1 \\ i_2 \end{array} & \begin{bmatrix} 0 \\ 3 \end{bmatrix} \end{array}$$

$$\gamma = \begin{array}{cc} & \begin{array}{cc} j_1 & j_2 \end{array} \\ \phi_1 & \begin{bmatrix} 0 & 1 \end{bmatrix} \end{array} \ ; \omega = \begin{array}{cc} & i_1 \\ \phi_1 & \begin{bmatrix} 0 \end{bmatrix} \end{array}$$

Simulink Models have been designed to study the state space of the second-order ordinary differential equation of electric DC-motor. Two types of Simulink Models have been created:

1. Test Model: Simulink model without any form of PID Controller
2. Comparison Model: Simulink model with three types of PID controller

Fig.1 sketches Simulink-prototype without PID-controllers. Fig.2 depicts Simulink-prototype of conventional PID controllers. Fig.3 depicts Simulink-prototype of Fuzzified-PID controllers. Fig.4 shows Simulink of fuzzified-PID Controller using Lookup-Table. Fig.5 sketches Simulink Model for the comparison of all three types of Controllers as subsystems. Fig.6 has output signal of Test Model in comparison to models with Controllers as subsystems. Fig.7 graphically shows FIS surface of linear fuzzified control-surface. Fig.8 shows FIS-surface for non-linear fuzzified control-surface. Fig.9 shows output signal of Comparison model to compare the three types of Controllers. Fig.10 compares output all three forms of controllers with the output of model without controller. Table-I tabulates comparison of results of two different Simulink models: Test Model and Comparison Model. Simulation mode for both is taken to be normal. Start time is zero seconds and stop time is 12 seconds are same for both the prototypes. Also, they are solved with same solver type i.e. discrete variable step. Initialization time (in seconds) of the solver for test model is 2.639367 and that of the comparison model is 0.968885. Execution time (in seconds) required by the solver as recorded for test and comparison prototypes are 0.473026 and 0.147995 respectively. Termination time (in seconds) for the solver implemented to these two prototypes are 0.004004 and 0.199001. So, the total elapsed time (in seconds) recorded for the test and comparison prototypes are 3.116397 and 1.315881. Table-II shows comparison of gain response of three controllers for speed of response, stability and accuracy. There is noticeable increase in speed of responses from conventional PID to Hybrid models of Fuzzified-PID for linear control and non-linear control surfaces respectively. Conventional-PID scheme is quiet stable. Fuzzified-PID hybrid for linear surface has steady state error tending to zero whereas Fuzzified-PID hybrid prototype for non-linear control converges to zero faster. Compared to non-controller prototypes, the accuracy of conventional PID improved. Further, hybrid prototype for linear control has more accuracy than conventional one. The most accurate was observed to be the Hybrid prototype for non-linear control-surfaces. Thus, hybrid of fuzzified-PID using lookup table for non-linear control surfaces provides the best results for driving electric-DC-motors in battery-driven green vehicles.

V. CONCLUSION

Mathematical model of electric motor is discretized so as to design three different types of discrete time-PID Controllers for improvement of the outputs through controllers. These models are then compared with the model devoid of PID controller. On observing response curves of traditional-PID controller and nonlinear-fuzzified-PID controller, it had reduced over shoot via sizeable amount of around 50%. Further, the response curves of linear and non-linear Fuzzified-PID controller had very close output values. So, *n*-D lookup table proved to approximate fuzzification with very less error. Also, the initialization time and execution time have improved from 2.639367 to 0.968885 and 0.473026 to 0.147995. It can be observed that Hybrid prototypes for non-linear control-surfaces performs best in terms of response speed, most stable and accurate. It can be concluded that on replacing Fuzzified-Controller by *n*-D Lookup-Table, a fuzzified-controller could be arranged through generated-code plus improved execution speed. In addition, there have been improvement in numerical quality of the optimization and state estimation calculations. Finally, the speed can be controlled by using Proportional Integral Derivative(PID) Controller and assistance of fuzzy-based estimation through 2-D Lookup-Table data for the speed and rotor position.

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