Robust throttle control of Hybrid Electric Vehicle

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Abstract. In recent past years, growing carbon emission caused by vehicle and scarcity of oil resources gives attention of all researchers to investigate low pollution, improved fuel economy type vehicle such as Hybrid Electric Vehicle (HEV). In this paper nonlinear hybrid electric vehicle speed control using different control techniques has been employed to improve the efficiency of vehicle by throttle position control. The controller like Proportional-Integral-Derivative (PID), Artificial intelligence based fuzzy controller, robust controller (H∞) and their comparative performance analysis has been done on the basis of rise time, settling time, and zero steady error in MATLAB-Simulink.

Keywords—Hybrid Electric Vehicle (HEV), H∞, Fuzzy Logic, Robust Control

1. Introduction

In recent decade our environment, economy and various oil resources are dwindling at an alarming rate. Due to heavily use of fuel in automobile sector, the severe carbon monoxide, hydrocarbon and nitrogen oxide stimulated in the environment and result in worsening air quality and global warming [1-2]. This type of problem attract researcher to investigate and found the solution from the all-petroleum vehicle. The optimized vehicle system such as Hybrid vehicles. The main and the foremost reason behind all this is the use of classical Internal Combustion Engine Vehicles (ICEVs). The exhaust emission system used in these classical combustion engines releases poisonous and hazardous air pollutants. These ICEVs are not only playing a major role in urban pollution but is also leading to greenhouse effect which in turn results in global warming [3]. Other issues related to such type of internal combustion are that neither it is economically stable nor it has efficient energy conversion mechanism and thus making electric vehicles ubiquitous. EV has some advantages over ICEV in terms of wide speed range, high efficiency and torque generation which are also EVs special requirement. Moreover, the power source used in batteries of EVs can be easily produced via non-conventional source of energy which is ecofriendly. [4-6] Contrary to the internal combustion emission there is hardly any emission of hazardous gases through EVs thus eradicating the pollution problem [7].

Based on the special requirements of EVs researchers have proposed many technologies. basically, these technologies are divided into 1) Conventional controller such as PID controller [2,7] 2) Artificial controller like Fuzzy controller, neural, GA controller etc and[8-9] 3) Robust technique[7-9]. Although some of the conventional controllers are insufficient in providing steady state speed but many new techniques have evolved to vague unknown disturbances [2]. As discussed earlier that the definition for a good controller is to accomplish effective resistance towards disturbance further utilizing low energy and giving high performance. The above mentioned point enlightens us to the description of control problem of H infinity theory one of the technique which we will use
[10-11]. H-infinity theory has been into existence since early 80s having a wide scope in motor control, LED lighting [12-14]. Among these new controllers one such controller is Fuzzy Logic Controller which also helps in eradicating such problems. The main advantage of using fuzzy logic is that it highly efficient in managing inexact information i.e., it extract an algorithm from the uncertain knowledge provided. Like the other controllers Fuzzy controller lacked behind in providing features of adaptive controller. The next feedback controller introduced was LQR which came with stupendous features which helped in improving dynamic and steady state characteristic [1]. The basic fundamental rule to control the speed factor in HEVs is to control the servo motor which in turn will help in controlling the throttle position thus resulting in good torque– speed characteristics and efficiency [15-17].

This paper involves the systematic observation of pros and cons of various controllers suggested thus bringing into notice the superior among all of them.

2. Mathematical Analysis

Given below is the diagram of the throttle control. This diagram also shows the various controllers which is controlling a DC servo motor [1].

![Throttle Control Diagram](image)

The equations used for the derivation of the transfer function are given as:

\[ m \frac{dv}{dt} F_e(\theta) - av^2 - F_g \]  
\[ \tau_e \frac{dF_e(\theta)}{dt} = -F_e(\theta) + F_{eI}(\theta) \]  
\[ F_{eI}(\theta) = -F_i + \gamma \sqrt{\theta} \]  

Where, \( F_e \) = Engine force, a throttle position function.
\( F_g \) = Gravity induced force, a road slope function.
\( \theta \) = Position of throttle
\( v \) = Speed of Vehicle

The values of the various constant used in above equation are described below in the table which will help in further evaluation of the transfer function [1].

| System Parameter                   | Symbol | Value (SI Unit) |
|------------------------------------|--------|-----------------|
| Mass of the Vehicle                | m      | 1000 kg         |
| Drag coefficient                   | \( \alpha \) | 4 N/(m/s)²      |
| Coefficient of engine force        | \( \gamma \) | 12500 N         |
| Idle engine force                  | \( F_i \) | 6400 N          |
| Time constant of engine            | \( \tau_e \) | 0.2 second      |

Thus after implementing the values in above three equations we get the state variable equation which is as follows:
The values of the various constant used in above equation are described below in the table which will help in further evaluation of the transfer function.[1]
Also while assuming the numerical values of the different constant some of the following assumptions have been made:

1. Here the Fg i.e., the induced force is considered to be 30% of the weight of the vehicle.
2. The range between which the engine constant lies is 0.1 to 1 but we assume it to be 0.2 sec.

By using equation (1), (2) and (3) and putting the parameter from table the transfer function obtained is [1]:

\[
\frac{V(s)}{\theta(s)} = \frac{8.29*10^5}{s^2 + 5s}
\] (4)

3. PID Controller
The proportional integral derivative (PID) controller is a classical feedback control mechanism. It adjusts the control variable which further determines the reaction to present, past & possible future values of error, processes it and ultimately minimizes it. Equation (5) shows the PID controller mathematical equation. The weighted sum of three parameters can be calculated as:

\[
u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}
\] (5)

Where Kp, Ki & Kd are proportional, integral and derivative coefficients of controller parameters respectively. Since in the conventional PID controller, error coefficient tuning by Ziegler Nichols (ZN) is not applicable for all time-varying nonlinear system. Hence, a trail and error method is apply for error control. [4,7]

4. Fuzzy Logic Controller
In complex system structure such as HEV where accurate mathematical model formulation is not easy or it’s too difficult for system model analysis. In such cases PID controller is not a feasible solution for error control. The system in which uncertainty and nonlinearity found fuzzy controller is more suitable. The fuzzy controller, introduced by Prof. Lotfi Zadeh in 1965, based on fuzzy set theory. The fuzzy set theory which is a knowledge based where input variable taken as a crisp values and convert in to linguistic variable. Figure (2) shows the basic fuzzy logic controller (FLC) structure. This fuzzy control structure consist of fuzzification unit where input variable convert in to fuzzy set. A fuzzy logic inference unit which convert crisp fuzzy value to a linguistic variable. A rule-base, and a defuzzification unit for converting inferred fuzzy control action to a crisp control action.
For Non-linear nature system, it is difficult to find accurate gain value for tuning of fuzzy logic controller (FLC) shown in Figure (2). In this paper mamdani type FLC having two-input error (e) and error dot (ce), divided into seven states and one-output (u) has been taken. Since the fuzzy controller performance completely depends upon membership function, fuzzification and adopted rule base. So, for this FLC design 7 input and 7 output taken which gives 49 fuzzy if then rule given in table no.2.

In fuzzy controller rule designing, the linguistic variable BN assign as “Big Negative”, MN “Medium Negative” SN “Small Negative”, EZ “Error Zero”, SP “small Positive” MP “Medium Positive”, BP “Big Positive”.

| Error Dot | BN | MN | SN | EZ | SP | MP | BP |
|-----------|----|----|----|----|----|----|----|
| BN        | BN | BN | BN | BN | BN | MN | EZ |
| MN        | BN | BN | BN | BN | MN | EZ | MP |
| SN        | BN | BN | BN | MN | EZ | MP | BP |
| EZ        | BN | BN | BN | EZ | MP | BP | BP |
| SP        | BN | MN | EZ | MP | BP | BP | BP |
| MP        | MN | EZ | MP | BP | BP | BP | BP |
| BP        | EZ | MP | BP | BP | BP | BP | BP |

5. Robust Controller \((H^\infty)\)

When the system is linear, its stability analysis is easy to check but for nonlinear system due to presence of noise, parameter uncertainty or disturbance the classical control law difficult to apply. In order to solve such type of problem robust control technique \((H^\infty)\) is a better way as compared to its analogue counterpart.

The general open-loop interconnection of system for \(H^\infty\) as shown in (Fig.3)

And the generalized state equation of this system is

\[
\begin{pmatrix}
z \\
y
\end{pmatrix} = \begin{bmatrix}
P_{11} & P_{12} \\
P_{21} & P_{22}
\end{bmatrix}
\begin{pmatrix}
w \\
u
\end{pmatrix}
\]

(6)

Where \(w\) is disturbance, \(z\) is controlled variable (\(z=e=V_{ref}-V_o\)). \(u\) is the controller output signal. \(y\) is measurement output signal that enter in the controller.

The system \(P\) interconnected in such a way with all the subsystem from multiple output multiple inputs (MIMO) to single output single input (SISO) system. The system resultant will give matrix as under:

\[
P = \begin{bmatrix}
A & B_1 & B_2 \\
C_1 & D_{11} & D_{12} \\
C_2 & D_{21} & D_{22}
\end{bmatrix}
\]

(7)
The general $H_\infty$ controller formulation with system interconnection from equation (6) and (7) gives a robust closed loop connection as shown in Fig.(4) will gives $w$ to $z$ is $S(P,K) = S(P,K)$

Where

$$\gamma > \gamma_{\text{min}}$$

(8)

Where,

$$\|F_i(P,K)\| = \max_{\omega / |\omega|} \left( \frac{|z(\omega)|}{|w(\omega)|} \right)$$

(9)

Since robust and optimal solutions are too difficult to achieve, therefore to obtain controller value $K$ which satisfies

$$\|F_i(P,K)\| < \gamma$$

(10)

Where $\gamma > \gamma_{\text{min}}$ and $\gamma_{\text{min}}$ should be predefined. The above process for finding controller value $K$ through iteration which satisfy inequality constraint for shaping singular values over specific frequency to specified transfer function.

5.2 MIXED SENSITIVITY APPROACH ($\bar{H}_\infty$ PROBLEM):
Using several combinations of closed loop system, the primary aim is to find controller with mixed sensitivity (MS) approach. In the mixed sensitivity approach controller output gives desired output with sensitive function $S = (1+GK)^{-1}$ with complementary sensitivity function $T = GK(GK)^{-1}$ respectively.

It is difficult to find balance between $S$ and $T$ function due to confliction of nature the general approach to design controller is to minimize its weight factor.

$$\frac{Sw_i}{Tgw_o}$$

where $w_i$ is weight of error due to input reference, $w_o$ is the noise weight of and $w_c$ is control weight of the system. All the weight function, controller, and system interconnection with plant is shown in Fig.(5). In Fig. (5) the $w_i$ and $w_o$ are weight function respectively $w_c$ and $w_o$.

Hence, with association of weight function the plant $P$ is defined as:

$$P = \begin{bmatrix} W_p & -W_cG \\ 0 & W_c \\ I & -G \end{bmatrix}$$

(11)
The main property of internally stable controller is to follow the following condition. For nominal performance and stability the $S$ over $KS$ should satisfy following inequalities.

$$\left\| \frac{W_p S(G_n)}{W_c KS(G_n)} \right\|_{\infty} < 1$$

(12)

Where, $S(G_n) = (I + G_n K)^{-1}$ nominal system sensitivity function

and for robust performance,

$$\left\| \frac{W_p (I + G K)^{-1}}{W_c K (I + G K)^{-1}} \right\|_{\infty} < 1$$

(13)

6. Simulation and Result

In this section, the time domain stability analysis is carried out. Moreover, it also shows the different controller technique applied on system and their output responses. Fig.6 shows the open loop response of HEV system. From figure 6 shows the system’s instability as it is not converging.

![Open loop response of HEV](image)

Figure 6. Open loop response of HEV

The PID controlled response of HEV is shown in figure.7. From below figure the maximum overshoot of controlled system is 30%.

![PID Controller response for HEV](image)

Figure 7 PID controller closed loop response of HEV

From above PID controlled output its clear that conventional controller makes system stable under certain condition. Fig.8 and 9 shows the system response using fuzzy logic controller with and
without external disturbance respectively. In Fig.8 the settling time of output response is 1 sec while the max. overshoot become zero.

![Figure 8. FLC closed loop response of HEV](image)

Figure 8. FLC closed loop response of HEV

![Figure 9. Disturbance rejection response of FLC](image)

Figure 9. Disturbance rejection response of FLC

Figure (10) and (11) shows the system response with $H_\infty$ controller with and without external disturbance applied on the system.

![Figure 10. $H_\infty$ controller response of HEV](image)

Figure 10. $H_\infty$ controller response of HEV

![Figure 11. Disturbance Rejection of $H_\infty$ controller](image)

Figure 11. Disturbance Rejection of $H_\infty$ controller
Figure 11. Disturbance rejection response of $H_\infty$ controller

Figure (12) is a comparative performance of PID, Fuzzy and $H_\infty$ controller. From Fig.12 the response of robust $H_\infty$ controller gives better then the fuzzy and PID in term of rise time maximum overshoot, steady state error which is shown in table 3.

**Figure.12 Comparison of PID, Fuzzy and $H_\infty$ controllers**

**Table 3.** Performance comparison table of various Controllers

| Types of controller | Controller Performance Index |
|---------------------|-----------------------------|
|                     | rise time (Sec.) | Overshoot Mp (%) | settling time | steady state error (Ess) |
| PID                 | 1.3               | 3.4              | 1.7          | 1-2%                     |
| FLC                 | -                 | 0                | 1            | 0                        |
| $H_\infty$          | -                 | 0                | 0.07         | 0                        |

**REFERENCES**

[1] Yadav, A.K., Gaur, P., Jha, S.K., Gupta, J.R.P., Mittal, A.P. Optimal speed control of hybrid electric vehicles. J. Low Power Electron. 11(4), 393–400 (2011)
[2] Vasak, M., Baotic, M., Petrovic, I., Peric, N.: Hybrid theory-based time-optimal control of an electronic throttle. IEEE Trans. Ind. Electron. 54(3) (2007)
[3] Ali Emadi, Young Joo Lee, and Kaushik Rajashekara, “Power Electronics and Motor Drives in Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicles”, IEEE Transactions on Industrial Electronics, Vol. 55, No. 6, pp. 2237-2245, June. 2008
[4] S. K. Jha, A. K. Yadav, Prerna Gaur, H. Parthasarathy, and J.R.P. Gupta, “Robust and Optimal Control Analysis of Sun Seeker System,” Journal of Control Engineering and Applied Informatics, vol.16, no.1, pp. 70-79, 2014
[5] Rastogi, S., S. K. Jha, and R. Oberoi, “Robust Stability Analysis of Sun Seeker System byArguon's Theorem,” in Proc. of Fifth International Conference on Advanced Computing and Communication Technologies (ACCT), Haryana, India, Feb. 2015.
[6] Anil Kr.Yadav, Dr.Prerna Gaur, Sandeep Tripathi, “Design and Control of an Intelligent Electronic throttle Control System,” in Proc. IEEE international Conference on Energy Economics and Environment (ICEEE) , Noida, India, Mar. 2015, pp 1-5
[7] Tripathi S.K., Panday H, Gaur P, “Robust control of Inverted Pendulum using fuzzy logic controller,” in Proc. of IEEE Students Conference on Engineering and Systems (SCES), Allahabad, India, Apr. 2013, pp 1-6.
[8] J. Lam, “Control of an Inverted Pendulum”, University of California, Santa Barbara, 10 June 2004
[9] Yanmei Liu and Zhen Chen, Dingy Xue, Xinhe Xu “Real-Time Controlling of Inverted
Pendulum by Fuzzy” Proceedings of the IEEE International Conference on Automation and Logistics Shenyang, China August 2009.

[10] Ricardo S. Sanchez-Pena and Mario Sznaier, Robust systems theory and applications, John Wiley & Sons, 1998.

[11] Amin S. Meghani, Haniph A. Latchman, “$H_\infty$ Vs. Classical Methods In The Design of Feedback Control Systems” Department of Electrical Engineering University of Florida, Gainesville January 16. 1992.

[12] Zhou K. and Doyle J., (1998), Essentials of Robust Control, Prentice Hall, New Jersey

[13] Amit Agrawal, Ashish Shrivastava, Kartick C. Jana, “Uniform Model and Analysis of PWM DC-DC Converter for Discontinuous Conduction Mode”, IETE journal of Research, Vol. 64, issue-4, 2018, pp. 569-581.

[14] Ashish Shrivastava and Bhim Singh, “Power factor-corrected DCM-based electronic ballast,” Electrical Engineering, vol. 95, no. 4, pp. 403-411, Dec 2013.

[15] D.-W. Gu, P. Hr. Petkov and M. M. Konstantino Robust Control Design with MATLAB®.

[16] Tsui Chia-Chi, “Robust Control System Design,” Marcel Dekker, Inc., 1997.

[17] Robust control design by Skogestad, S., and Postlethwaite, I., 1996, Multivariable Feedback Control: Analysis and Design, John Wiley and Sons, New York