EVALUATION OF FUZZY LOGIC AND PROPORTIONAL-INTEGRAL CONTROLLERS FOR HYBRID ELECTRIC VEHICLE

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https://doi.org/10.26782/jmcms.2019.12.00069

Abstract

This paper discusses the control action of various classic controllers such as fuzzy logic controllers and proportional-integral controllers. Consider the typical features of various terrains such as smooth, rough, uphill and downhill. For each type of terrain, i.e. when the local shape changes, the input parameters taken into account also change accordingly because it is adaptive, this includes all possible parameters of the vehicle. During running, the controller can perform smooth, rough, uphill and downhill driving at different speeds and terrain. The results were performed during the simulation.

Keywords: Controllers, Hybrid Electric Vehicle, Speed, Terrains, Performance

I. Introduction

The hybrid electrical vehicles¹ (HEV) are used to achieve greater fuel economy as compared to conventional vehicles and with an additional improvement of performance [II]. In the market, research is being carried out in this area to an extent whereby the complete fuel based automobile industry is replaced with electrical vehicles due to the drastic hike in prices and shortages of petroleum stores in Middle East. Most of the automobile companies across the world are working on different possibilities to perceive high efficiency and improve the performance of vehicles using HEVs.

In an attempt to obtain excellent field-regulation using hybrid excitation flux-switching (HEFS), Hua et al. experimented on brushless machines along with magnets and concentrated wings [XI]. This research identified the difficulty to regulate the air gap field produced by using only stator-magnets. In the recent times, HEVs based on P0 architectures grabbed the attention of various researchers with the
enhanced fuel efficiency and with the advantage of reduced emissions. A detailed study and discussions carried out by Sethuraman and Haris identified different causes and effects of additional hub loads on P0 electrical machines due to torsional torque [VII]. Various driving scenarios of fuel consumption by a HEVs was discussed by Veeraraghavan et al. explained the impact of different powertrain operation modes [IX]. The authors in this work proposed a unique method of using machine learning approach for improving the performance of the HEV controllers. Controlling and co-ordinating power sources is always a challenging task for the engineers designing the HEVs [V]. Real-time power hardware was proposed by Kaarthik and Pillay for parallel HEVs using mechanical and electrical parts with mathematical modelling. In this work, the authors also used power hardware-in-the-loop (PHIL) to develop the individual subsystems.

In an attempt to provide self-sustained energy management system (EMS) Solano et al. suggested the HEVs equipped with battery, ultra-capacitor system (UCS) and fuel cell system (FCS) [XII]. Only degraded operations were considered for the failures of FCS and UCS and modified the EMS for the purpose of normal operations. A flexible substation and interface device was proposed by Tong et al. to improve the flexible operation capabilities of both AC and DC hybrid power distribution [VIII]. In this work, voltage transformation and electrical isolation were achieved at the same time. A fuzzy logic estimator (FLE) was used by Wang et al. for the state of charge (SOC) estimation, which plays a vital role in most of the hybrid electric propulsion systems (HEPS) [III]. Such systems help to support the supervisory tasks as suggested by Kamal and Adouane using the fuzzy supervisory fault management to detect and possibly compensate the battery faults in HEVs [VI]. The research also revealed that the fuzzy logic controllers (FLC) are tuneable by using neural networks for the purpose of power distribution among the electric motors and internal combustion engines (ICE). However in the later stages the authors also achieve best operational performance using fuzzy controllers by regulating the vehicle subsystem set points [IV]. In this way the energy management was possible online and helped to reduce overall energy consumption as compared with other traditional methods. In a real-time environment the adaptive fuzzy logic energy management system were tested on a hybrid electric city bus by Tian et al. to learn the mechanism of various optimal state-of-charges (SOC) curves [X]. The study revealed that a fuel saving of 4.61% - 13.49 % was achieved by using trained and untrained cycles when compared with charge-depleting and charge-sustaining strategies. Earlier the similar experiment was carried out by Zhang et al. for parallel HEVs using adaptive neuro fuzzy interference system optimization algorithm.

Apart from these some research is carried out on the conventional method of proportional-integral (PI) controllers for improving the engine behaviour and power in HEVs. They are helpful in controlling the high-voltage (HV) battery power in most of the power-split HEVs. Sometimes these PI based controllers may be responsible for overshots of engine speeds and power; also they are leading to damage the settling times due to the nature of non-linearity and hence are responsible for degraded response. To solve this problem Syed et al. used the fuzzy gain scheduling to identify the suitable gains for PI systems, to eliminate overall overshoots for an approximate value of 50% faster response. In a similar experiment, Camara et al. used
a PIC18F4431 micro controller for the two dc/dc controller topology controls. Later by using the engine transient characteristics Yan et al. developed a HEV model for predictive control torque-split strategy using EM and drivers accelerator / brake using PI derivative predictive control methodology.

II. Performance of the PI Controller

The controller behaviour on different terrains by combined fuzzy decision makers (FDM) and proportional-integral controllers are analyzed in this work. In general, these terrains represent typical road conditions. The response of PI control loop from the smooth terrain shown in Fig. 1 indicates that there is a peak overshoot and a long settling time. Similarly, obtained performance repose for different terrains are given in Fig. 2 to Fig. 4 for the PI Controllers.

Fig. 1 Obtained performance response in smooth terrain for PI controller

Fig. 2 Obtained performance response in rough terrain for PI controller

The major difference between the conventional PI controller and fuzzy logic control is that in the later case it is based on the defined model of a system. However, both will be working or implements the same control rules, which in general used by a skilled expert. The Fig. 2 shows the response of a conventional PI controller for the rough terrain and uses a combined speed of 80 rad / sec. It is observed that the speed drops in this case due to the high rolling resistance. To meet the required amount of velocity the HEVs must employ a method as suggested by Kim and Lee by adopting the kinematic-based rough terrain control (KRTC).

In the uphill terrain the response of the PI controller is shown in Fig. 3 and 70 rad/s speed is achieved. However, at the time of trip the change in the rolling resistance a drastic change in speed is observed. On the other hand, for the downhill terrain response of the PI controller is shown in Fig. 4 and 58 rad/s speed is achieved.
In this process it is observed that the rolling resistance is increasing and a sharp drop in the speed is observed.

III. Analysis of the fuzzy logic controller performance

In this work, the fuzzy logic controller (FLC) is tested for different types of road conditions of India. Most of the times roads will be very narrow with heavy traffic and sometimes with lot of mud and dust due to diversified environmental conditions. The motors run with a speed of 110 rad/sec on the smooth terrain without any kind of peak overshoots and noticed a short settling time on these kinds of smooth terrains.

- Smooth Terrain

In the Indian conditions, most of the vehicles of are used between first gears to fourth gear with a speed between 40-60 km/h in the cities and it is found to be 33 km/h in urban conditions. In such conditions, state of charge (SOC) is high, the load will be very much low, with a slow speed and low acceleration. FLC speed was recorded very low when the first gear was selected in smooth terrains.
On the condition when SOC is high, low load and acceleration were observed and the speed found to be normal. However, FLC setting speed found to be very low at a time when the vehicle in second gear.

In the third gear, with SOC high, load is low, speed found to be normal with moderate acceleration. FLC setting speed also found to be low in third gear. Now in third gear with normal mode and SOC is normal, with a medium load, speed found to be normal with high acceleration. In the same conditions FLC setting speed also found to be lower. Now considering the normal mode and SOC is low, with a high load and speed along with larger acceleration. However, in fourth gear FLC setting speed is higher.

Fig. 5 Obtained performance response in smooth terrain for FLC controller

- Rough Terrain

All the four gears from first to fourth are applicable in this rough terrain for the Indian road conditions. Generally, speed of vehicles is reported to be between 20-30 km/h and overall average speed observed is to be 33 km/h.

Now by considering normal mode, SOC found to be 0.9, load as 15 with a speed of 180 rad/s. With a gear of 2.5 resulted to a FLC set speed of 65 rad/s and overall motor speed found to be 25 km/h as shown in Fig. 6. By increasing the vehicle speed by forcing the accelerator to 2.5, SOC changes to 0.9, load to 10, and speed went up to 200. However, with a gear 3.5, the FLC set speed went up to 75 rad/s and overall speed of the vehicle went up to 15 km/h. On the other hand, by applying a brake with 4.5, the speed reduced, SOC changes to 0.9, load to 100 and speed went to 200. When gear was at 3.5, FLC set speed recorded to be 50 rad/s and overall speed of the vehicle went up to 20 km/h.

- Uphill Terrain

Again the four gears from one to four are applicable for uphill terrain for the Indian road conditions. In general, vehicle speeds vary between 30-40 km/h with an overall average speed of 33 km/h are observed in city driving conditions.

Now by considering the normal mode, SOC found to be 0.5, load as 10 with a speed of 120 rad/s. With a gear of 2.5 resulted to a FLC set speed of 50 rad/s and overall motor speed to be 35 km/h as shown in Fig. 7. By increasing the vehicle speed...
by forcing the accelerator to 2.5, SOC changes to 0.5, load to 15, and speed went up to 90. However, with a gear 2.5, the FLC set speed went up to 35 rad/s and 25 km/h vehicle speed was registered. On the other hand, by applying a break with 2.5, the speed was reduced, SOC changed to 0.5, load to 10 and speed went up to 100. When gear was at 2.5, FLC set speed recorded to be 20 rad/s and overall speed of the vehicle went up to 15 km/h.

Fig. 6 Obtained performance response in rough terrain for FLC controller

Fig. 7 Obtained performance response in uphill terrain for FLC controller

- **Downhill Terrain**

By considering the downhill terrain with Indian road conditions for all four gears from one to four, the vehicle speeds were recorded between 40-50 km/h and the overall average speed found to be around 33 km/h.

Now by considering the normal mode, SOC found to be 0.75, load as 10 with a speed of 50 rad/s. With a gear of 1.5 resulted to a FLC set speed of 30 rad/s and overall motor speed to be 25 km/h as shown in Fig. 8. By increasing the vehicle speed by forcing the accelerator to 50, SOC changes to 0.79, load to 10, and speed went up to 50. However, with a gear 1.5, the FLC set speed went up to 10 rad/s and 17 km/h vehicle speed was registered. On the other hand, by applying a break with 2.5, the speed was 50 rad/s, SOC changed to 0.79, load to 10 and speed went up to 50. When
gear was at 1.5, FLC set speed recorded to be 35 rad/s and overall speed of the vehicle went up to 30 km/h.

![Graph showing performance response in downhill terrain for FLC controller](image)

Fig. 8 Obtained performance response in downhill terrain for FLC controller

IV. Performance and Role of Fuzzy Decision Maker (FDM)

So far it is seen how a PI and FLC are used as a transfer function and for the decision making. FLC considered the parameters such as SOC, load, speed, acceleration and type of terrain to derive the type of output of the FLC which has to control the speed of the vehicle. The inclusion of FLC made the electric vehicle system more efficient with respect to performance.

A simple block diagram for the speed control system for electrical vehicle with FDM is shown in Fig. 9. This arrangement was made to be along with the PI controller to the FDM. Finally, the corresponding response of the control loop with PIC along with FDM in smooth terrain shown in Fig. 10.

![Block diagram for speed control system](image)

Fig. 9 Block diagram for the speed control system for electrical vehicle with FDM
Fig. 10 the corresponding response of the control loop with PIC along with FDM in smooth terrain

It is seen that performance of traditional controllers takes longer to reach the desired destination. Here, speed error response indicates an error existing in the response and performance of FLC means that it will be able to cover longer distance in short time duration. Speed error responds smoothly.

Table 1 Characteristics of the Fuzzy Logic Controller

| Type of Terrain | Speed in Rad/Sec | Settling Time in Seconds |
|-----------------|------------------|--------------------------|
| Smooth          | 110              | 40                       |
| Rough           | 70               | 40                       |
| Uphill          | 65               | 40                       |
| Downhill        | 58               | 40                       |

Table 2 Characteristics of the PI Controller

| Type of Terrain | Maximum Overshoot | Settling Time in Seconds | Rise Time in Seconds |
|-----------------|-------------------|--------------------------|----------------------|
| Medium Hard     | 110               | 40                       | 15                   |
| Sand            | 80                | 40                       | 14                   |
| Concrete        | 130               | 40                       | 15                   |

In the proposed fuzzy logic controller, the integral squared error is smaller than the conventional controller. The following table shows the characteristics of the controller.
V. Conclusion

The FLC and PI controllers have different constraints, such as transfer function and no transfer function, and there are no fuzzy decision makers and fuzzy decision makers. The analysis is conducted separately for various Indian road conditions such as smooth, rough, uphill and downhill. It is inferred from the study that compared with the conventional controller, the proposed fuzzy logic controller has no peak overshoot and the settling time is also minimal. The final conclusion from the analysis is that compared to the analog logic controller, the performance of the electric vehicle is better than that of the classical PI controller because it has a wider winding coverage and a smaller speed error. The velocity variation and velocity
error plots of terrain response changes are obtained using two controllers. The PI and FLCs are also used in the estimation of the range of the vehicle. The performance of the fuzzy controller and the proportional-integral controller under the no-fuzzy decision-making (FDM) is studied. It has been observed that if there is no FDM, the vehicle will travel at a specific speed despite changes in the parameters during driving. For this reason, the rolling resistance increases, reducing the battery's power.

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