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SIMULATION ANALYSIS OF A HYBRID ELECTRIC VEHICLE ASSISTED BY A SOLAR PANEL FOR SPEED CONTROL USING A FUZZY LOGIC CONTROLLER

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Abstract

Transportation is a major sector which contributes to pollution at a global level. And, road transportation is the biggest source of pollution in the transportation sector. The prevailing global energy and climate conditions clearly suggest that less polluting vehicles must be used for transportation to curb carbon and other harmful emissions like SOX and NOX. An Electric Vehicle (EV) is a good option to combat pollution but its driving range is low. Thus, a Hybrid Electric Vehicle (HEV) is a well-suited option in this regard as it produces low tailpipe emissions and provides a long driving range. Integration of a solar panel with the onboard battery bank to power a HEV helps further in this regard as solar energy is a renewable form of energy. In this paper, a solar-assisted HEV is analyzed for speed control using a Fuzzy Logic Controller (FLC). The FLC performs throttle control of the Internal Combustion (IC) engine and torque control of a Permanent Magnet Synchronous Motor (PMSM) drive to achieve the control of the speed of the HEV. The modelling and validation of results through simulations is carried out using the software package MATLAB/Simulink.

Keywords:

Fuzzy Logic, Hybrid Electric Vehicle, Solar Panel, Speed Control, Throttle Control, Torque Control

1. INTRODUCTION

According to the Global Fuel Economy Initiative (GFEI) report published in the year 2016, one of the main contributors to the global carbon footprint is the transport sector (23%) and most of it (74%) is due to the road vehicles only. It is projected that by the year 2050 there will be more than 2 billion vehicles plying on the road [1]. Thus, less polluting vehicles must be developed and used for transportation. Global car manufacturers like Tesla, Nissan, Chevrolet, Volkswagen, BMW, Toyota, Maruti, Tata etc. are actively involved in the research and development of Electric Vehicles (EVs) as these produce zero tailpipe emissions. But, one of the biggest roadblocks in the development of EVs is that the driving range of EVs is short [2]. Hence, an extension of the driving range of EVs is an important area of research. An alternative solution is to develop HEVs which provia de long driving range and produces less pollution. Therefore, developing various control strategies for HEVs is also a major area of research. This is the theme of the presented paper. Also, a solar panel can be added to an HEV to further increase the driving range. The solar panel, apart from the onboard battery bank, will provide some additional energy to the HEV to help in extending its driving range [3]. The modelling of HEVs for simulation study and test of various control strategies can be easily carried out using MATLAB/Simulink [4-5]. The modelling of a solar panel can also be carried out easily using the software package MATLAB/Simulink with the help of the dynamic equations of a solar cell [6]. In EVs and HEVs, AC motors are always preferred over DC motors owing to the inherent properties of the AC motors. EVs and HEVs require variable speed operation, therefore, mostly a Permanent Magnet Synchronous Motor (PMSM) drive is used in EVs and HEVs [7]. PMSMs are efficient and robust AC motors which provide high torque-to-current and power-to-weight ratios [8]. Boost converters are required to match the voltage levels of the onboard battery bank and the PMSM drive. These are also required for matching the voltage levels of the solar panel output and the output of the onboard battery bank. In the presented work a bidirectional dc-dc converter is used. However, other DC-DC boost converters are also found in the literature [9]. The control of HEVs by various artificial intelligence and other techniques can be found in the literature. Techniques like Genetic Algorithms, Neural Networks, $H\infty$ control etc. have been exhibited in the past [10]-[12]. In this paper, the speed control of the solar-assisted HEV is realized using a Fuzzy Logic Controller (FLC). The FLC controls the throttle of the IC engine and the torque of the PMSM drive.

The presented paper contains four sections. In section 1 the introduction and the literature survey on the research title are presented. Section 2 gives details of the HEV and the solar panel models. Section 3 presents all the results of the simulation along with analysis. Section 4 concludes the presented paper.

2. MODEL DETAILS

In the presented work the parallel configuration of HEV is chosen where the torque outputs of the IC engine and the PMSM drive are mechanically added in parallel with the help of planetary gear to sum the power outputs of the IC engine and the PMSM drive. Two solar panels with a combined capacity of 282.6 W assist the onboard battery bank. The voltage output of the panel is boosted to the output level of the battery bank by the dc-dc converter. The dc bus voltage is set at 288 V. The solar panel and the battery bank are electrically in parallel and provides electrical energy to the motor via torque controller. The FLC provides the setpoints to the torque and throttle controllers according to the desired speed of the HEV. The throttle controller controls the fuel injection into the IC engine. The torque controller controls the firing angle of the dc-dc converter between the electrical source, which is the combination of the onboard battery bank and the solar panel, and the PMSM. The block diagram of the HEV is shown in Fig.1.

The modelling details of each component shown in Fig.1 are discussed in detail hereafter.

2.1 SOLAR CELL

A solar cell is represented as a dc current source and the output current of the cell is proportional to the solar insolation. Solar insolation is defined as the flux of solar radiation per unit of horizontal area for a given locality. The equivalent model of a solar cell is shown in Fig.2.

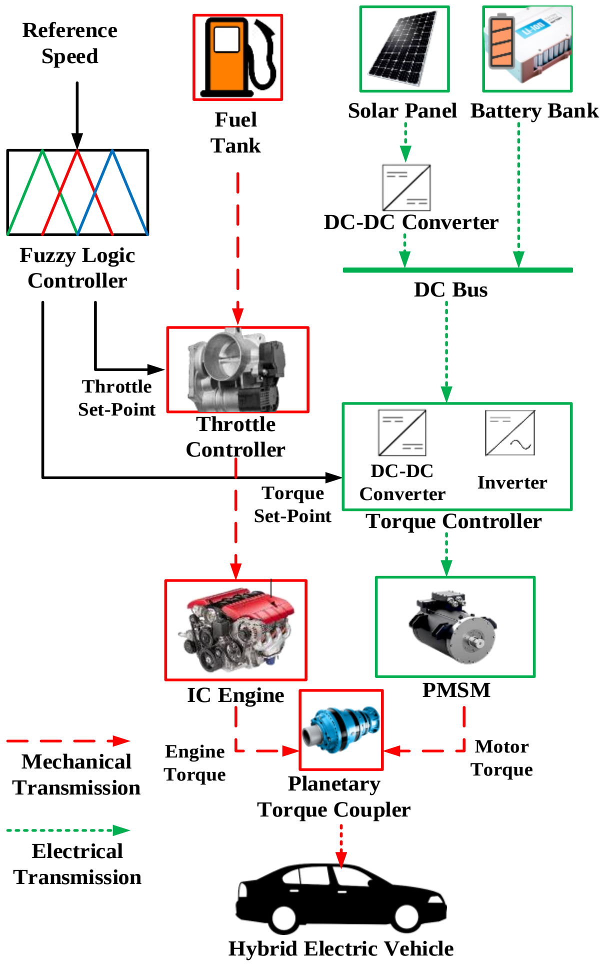

Fig.1. HEV Block Diagram

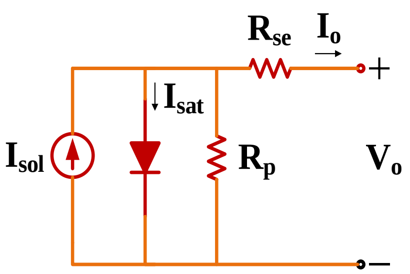

Fig.2. Dynamic Model of a Solar Cell

The dynamic equations [6] of the cell are given by Eq.(1) and Eq.(2):

$$I_o = I_{sol} - I_{sat}\left(e^{\frac{q(V_o+R_{se}I_o)}{nkT}} - 1\right) - \frac{V_o + R_{se}I_o}{R_p} \tag{1}$$

$$I_{sol} = \left[I_{sol\,n} + K_i\left(T - 298\right)\right]\frac{G}{1000} \tag{2}$$

where, I_o-output current of the solar cell, I_{sol}-solar-generated current, I_{sat}-diode reverse saturation current, q-electron charge, Vo-output voltage of the solar cell, R_{se}-series resistor, R_p-parallel resistor, n-diode ideality factor, T-cell temperature k-Boltzmann constant, I_{soln}-nominal solar-generated current, K_i-solar current coefficient and G-solar insolation.

The solar cell is modelled using a dependent current source in MATLAB/Simulink with input value equals to

The values of R_{se} and R_p are calculated by an iterative method as proposed in [6]. The values of I_o and V_o are continuously measured and fed to a MATLAB Function block which computes the value of I_{inp}. These updated value ids are fed to the dependent current source block. A solar panel with a maximum power output of 141.3 W has been selected. The peak voltage and peak current at maximum power are 18.3 V and 7.72 A respectively. The panel is able to give 22.3 V in open circuit conditions and 8.39 A in short circuit conditions. The parameter values are calculated for G = 1000 W/m^2 and T= 25° C. The output voltage of the solar panel is boosted to 43.2 V to match the voltage level of the onboard battery bank.

2.2 BATTERY

The inbuilt generic battery model of MATLAB/Simulink is used in the proposed work. Six modules of type Lithium-Ion with a nominal voltage of 7.2 V are connected in parallel to provide a nominal voltage of 43.2 V combined.

2.3 TORQUE CONTROLLER

The torque controller consists of two parts: dc-dc converter and an inverter to control the output of the PMSM drive. A generic dc-dc boost converter is used to increase the voltage level from 43.2V input to 288V output. It is to be noted that the input voltage value may vary due to variation in insolation and battery state-of-charge. A PID controller is used to change the duty cycle of the firing pulses to control the dc-dc converter. To control the output of the PMSM drive inbuilt PWM inverter block of MATLAB/Simulink is used. Two control loops are used. The inner loop regulates the motor stator currents. The outer loop controls the motor speed. The fuzzy logic controller provides the speed reference to the outer loop.

2.4 PMSM

The equations for the modelling of the Permanent Magnet Synchronous Motor (PMSM) drive are given as:

$$\frac{d}{dt}i_D = \frac{v_D - R_{iD} + \omega_R L_Q i_Q}{L_D} \tag{3}$$

$$\frac{d}{dt}i_Q = \frac{v_Q - R_{iQ} + \omega_R L_D i_D - \omega_R \lambda_F}{L_Q} \tag{4}$$

$$\frac{d}{dt}\omega_R = \frac{\tau_E - \tau_L - B\omega_R}{J} \tag{5}$$

$$\frac{d}{dt}\theta_R = \omega_R \tag{6}$$

$$\tau_E = \frac{3}{2}\frac{P}{2}\left\{\lambda_F i_Q + \left(L_D - L_Q\right)i_D i_Q\right\} \tag{7}$$

where v_D-the d-axis voltage, v_Q-the q-axis voltage, i_D-the d-axis current, i_Q-the q-axis current L_D-the d-axis winding inductance, L_Q-the q-axis winding inductance θ_R-angular position of the rotor,

ω_R-angular speed of the rotor, τ_E-electromagnetic torque and τ_L-load torque.

The generalized model of a PMSM is shown in Fig.3.

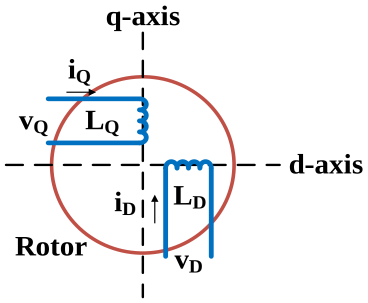

Fig.3. Generalized Model of a PMSM

A 100 kW, 8 poles, 288 V PMSM is selected. It is able to give a maximum speed of 12500 RPM. The armature resistance is 830 mΩ and the direct axis and quadrature axis inductances are 174.18 µH and 292.65 µH respectively.

2.5 IC ENGINE MODEL FOR THROTTLE CONTROL

The throttle control action is explained in Fig.4. The throttle controller basically controls the fuel input of the IC engine. The torque output produced by the IC engine is dependent on the amount of fuel provided to it for combustion.

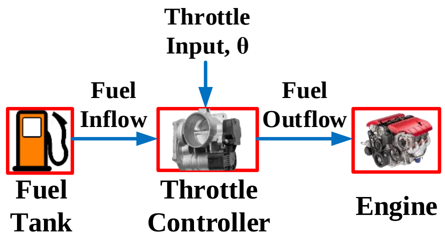

Fig.4. Throttle Control Action

The modelling equation of the IC engine for the throttle control [10] is as follows:

$$\frac{d}{dt}F_E(\theta)=\frac{1}{\tau_E}\left(-F_E(\theta)+f_I+\gamma\sqrt{\theta}\right) \tag{8}$$

where τ_E-time constant of the engine, θ-throttle angle, γ-force constant of the engine, $F_E(\theta)$-the engine force and f_I-the engine idle-force. The engine force constant is set at 12500 N. The engine idle force is kept at 6400 N and the engine time constant is 0.2 sec.

2.6 PLANETARY TORQUE COUPLER

The ideal planetary gear block available in MATLAB/Simulink is used to add up the torque outputs of the PMSM drive and the IC engine. The combined torque is then applied to the vehicle for propulsion.

2.7 VEHICLE BODY MODEL

The vehicle body model takes into account the torque input provided to it and the deaccelerating agents: gravity and air drag. The effect of gravity is only pronounced when the vehicle is ascending or descending an incline. The effect of air drag is dependent on the vehicle's body shape. The generic modelling equation of the vehicle body with all these factors taken into account is given by:

$$M_V\ddot{x}=F_p-\alpha_D\dot{x}^2-F_G \tag{9}$$

where M_V-the vehicle mass, α_D-coefficient of the aerodynamic drag, F_G-forced produced by the gravity, F_P-propulsion force and $\dot{x}$-velocity of the vehicle and $\ddot{x}$-acceleration of the vehicle. The dynamic model of the vehicle body is shown in Fig.5. The vehicle body mass is 1860 kg. The coefficient of the aerodynamic drag is 0.25 N/(m/s)^2 and forced produced by the gravity is set at 30% of the vehicle body mass.

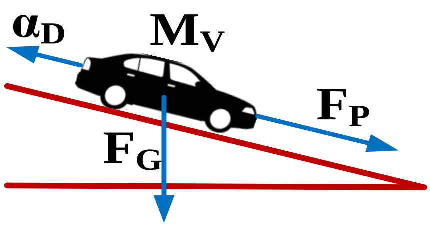

Fig.5. Vehicle Body Dynamics

2.8 FUZZY LOGIC CONTROLLER (FLC)

Firstly, the FLC performs fuzzification on the input. Fuzzification is the process of converting a crisp value into a fuzzy value. Then the inference system gives the fuzzy output according to the set membership functions and if-then rules. Mamdani inference system is used in the presented work. Finally, the fuzzy output undergoes defuzzification. Defuzzification is the process of obtaining the crisp value from the fuzzy value. This process is also explained in the Fig.6.

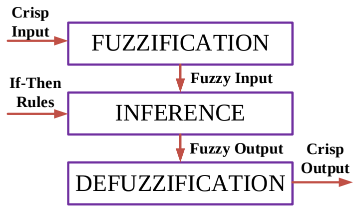

Fig.6. Fuzzy Logic Controller

In the proposed model, the Fuzzy Logic Controller (FLC) controls the working of both the throttle controller and the torque controller. The inputs provided to the FLC are:

- The error in speed i.e., the difference between the desired speed of the HEV and the actual speed of the vehicle.
- The rate of change of the error in speed

The output of the FLC is the setpoints for the throttle controller and the torque controller. The setpoint for the throttle controller is the throttle angle θ. The throttle controller controls the fuel injection into the IC engine and is modelled using Eq.(8). The setpoint for the torque controller is the speed reference for the outer loop of the PWM inverter. The torque controller controls the PMSM through vector control and is modelled using Eq.(3)-Eq.(7).

2.9 FUZZY LOGIC CONTROLLER VS PID CONTROLLER

The proposed fuzzy logic controller has been compared with a conventional industrial controller, the PID controller. PID controller is used to improve the closed loop response of a system. The error signal is fed to the PID controller and the PID controller generates necessary control signals to control the system response. PID is simple in construction and function. Also, PID is very robust. Thus, PID is the most used controller in the control industry. The Fig.7 shows the block diagram of a closed-loop system with PID.

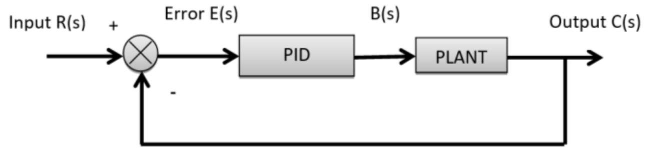

Fig.7. Closed Loop System with PID

The error signal e(t) or E(s) is the input to the PID and the controller output is b(t) or B(s). PID is composed of three elements Proportional, Integral and Derivative, thus the name PID. The output of this element is proportional to the error signal, $b_P = K_p e(t)$, where K_p is the proportional gain constant. The output can be adjusted by tuning K_p. The proportional element is used to make the response faster, but it always leaves an offset in the output. The output of this element is proportional to the integral of the error signal, $b_I = K_i \int_0^t e(t)\,dt$, where K_i is the integral gain constant. The output can be adjusted by tuning K_i. The integral element is used to eliminate the offset in the output, but it causes high overshoot and delayed settling of the output. The output of this element is proportional to the derivative of the error signal, $b_D = K_d \frac{d}{dt} e(t)$, where K_d is the derivative gain constant. The output can be adjusted by tuning K_d. The derivative element is used to reduce overshoot and settling time, but it is not causal. Thus, the combined output of the PID can be shown by Eq.(10).

$$b(t) = K_p e(t) + K_i \int_0^t e(t)\,dt + \frac{d}{dt} e(t) \tag{10}$$

Fuzzy logic controller is an intelligent controller. Intelligent controllers are Artificial Intelligence (AI) based controllers. Artificial Intelligence (AI) is a term that in its broadest sense would indicate the ability of a machine or artifact to perform the same kind of functions that characterize human thought. The term AI has also been applied to computer systems and programs capable of performing tasks more complex than straightforward programming.

The vehicle performance is compared for two cases, first when a PID controller is employed and second when the proposed fuzzy logic controller is used.

2.10 WORKING FLOW OF THE SPEED CONTROL PROCESS OF THE HYBRID ELECTRIC VEHICLE

The speed demand is provided by pressing the accelerator on the vehicle. Then this reference speed is compared with the actual speed of the vehicle. If the actual speed is not equal to the reference speed, then the throttle controller and the torque controller are activated. Set-points for the engine and the PMSM are generated by the controller. The throttle control acts upon the set-point and adjusts the engine fuel flow such that the engine torque output meets its demand. Also, the torque controller adjusts the firing angle of the dc-dc converter such that the PMSM torque output meets its demand. This process is also described using a flowchart in Fig.8.

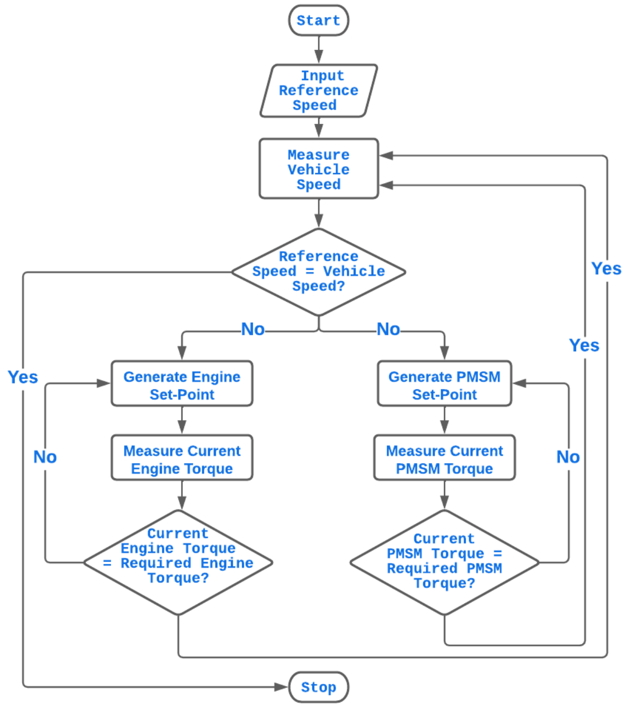

Fig.8. Flowchart of the Control Process

3. RESULTS AND DISCUSSIONS

First of all, the solar panel was modelled and simulated using the dynamic Eq.(1) and Eq.(2). Then the model was validated by measuring various parameters at Standard Test Conditions (STC): G = 1000 W/m^2 and T = 25ºC. The IV curve of the panel at different solar insolation is shown in Fig.9, it is evident that the solar-generated current increases with the solar insolation if the cell temperature is maintained constant. The IV curve of the panel at different cell temperatures is shown in Fig.10, it is evident that the solar-generated current and the open-circuit voltage both are affected by the cell temperature even if the solar insolation is constant.

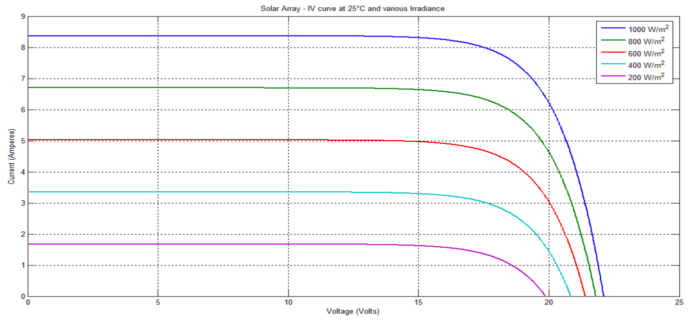

Fig.9. IV Curve at different Solar Insolation

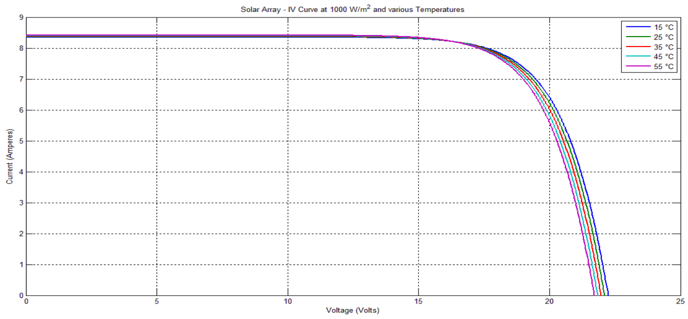

Fig.10. IV Curve at different Cell Temperatures

The PV curve of the panel at different solar insolation is shown in Fig.11, it is evident that the output power of the solar panel increases with the solar insolation if the cell temperature is maintained constant. The PV curve of the panel at different cell temperature is shown in Fig.12, it is evident that the output power of the solar panel and the open circuit voltage both are affected by the cell temperature even if the solar insolation is constant.

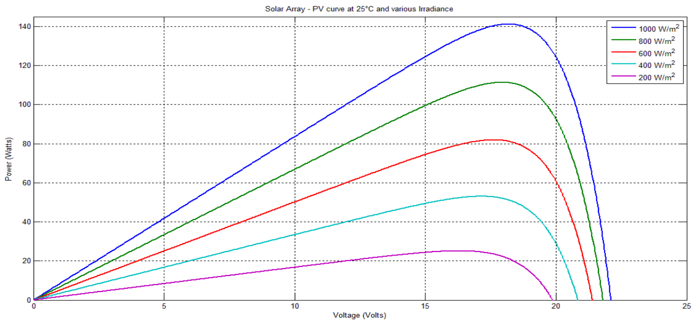

Fig.11. PV Curve at different Solar Insolation

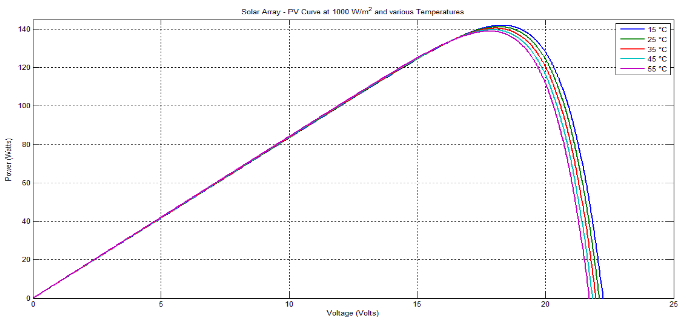

Fig.12. PV Curve at different Cell Temperatures

The Fuzzy membership functions for throttle control is shown in Fig.13. The Fuzzy membership functions for torque control is shown in Fig.14.

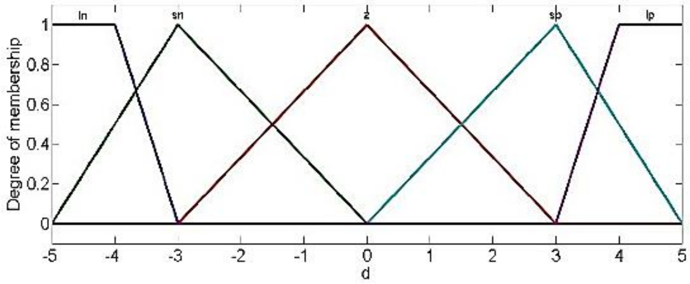

Fig.13: Fuzzy Membership Functions for Set-Point of IC Engine Throttle Control

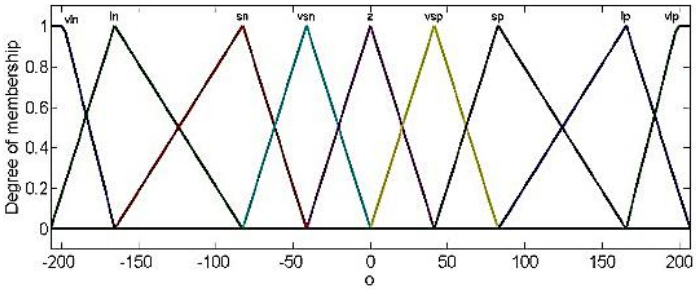

Fig.14. Fuzzy Membership Functions for Set-Point of Torque Control of PMSM

The open-loop response of the HEV is shown in Fig.15. It is clearly evident that a controller is required for speed control as the time taken to reach a steady state is around 50 sec, which is unacceptable. Firstly, a hand-tuned PID controller is used for the speed control of the HEV. The step-input response in this case is shown in Fig.16. It is observed that the output exhibits overshoot and the settling time is large. Then an FLC is used for the speed control of the HEV. The step-input response in this case is shown in Fig.17.

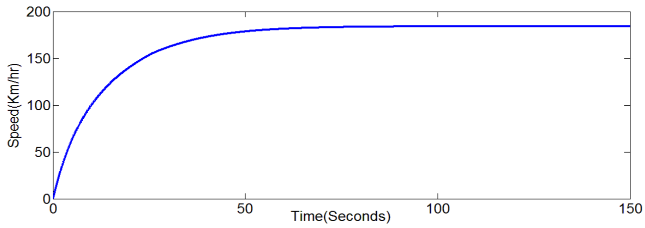

Fig.15. Open-Loop Speed Response of the HEV

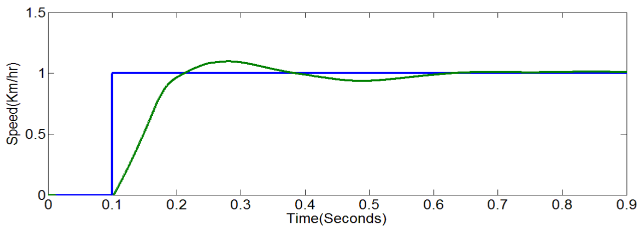

Fig.16. Closed-Loop Speed Response of the HEV for Step-Input using PID Controller

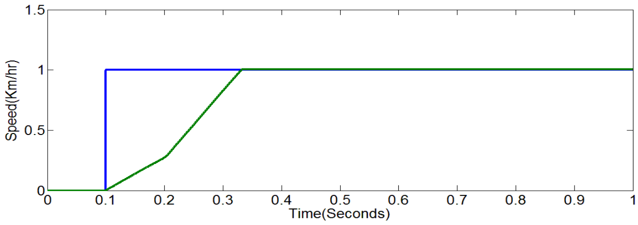

Fig.17. Closed-Loop Speed Response of the HEV for Step-Input using FLC

It is observed that both the overshoot and the settling time are significantly reduced and thus the performance of the HEV is improved. The performance of both the controllers are compared in Table.1.

Table.1. Controller Performance Comparison

Controller	PID	FLC
Overshoot	35%	0%
Rise-Time	0.1 sec	0.2 sec
Settling-Time	0.4 sec	0.2 sec

The developed FLC is then tested for a standard test speed input, the Indian Drive Cycle as shown in the Fig.18. It is then observed that the FLC controller satisfactorily controls the speed of the HEV, the output is shown in Fig.19.

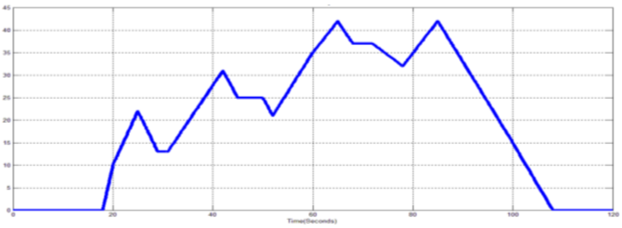

Fig.18. Indian Drive Cycle (IDC)

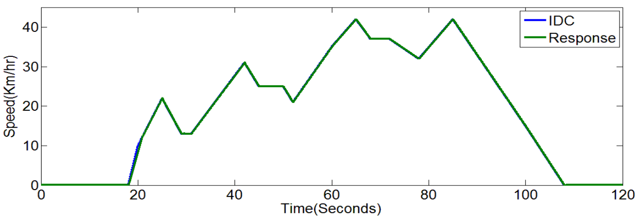

Fig.19. Closed-Loop Speed Response of the HEV for IDC Input using FLC

4. CONCLUSION

It is pivotal that fewer polluting vehicles are used to combat the extensive pollution levels. EVs and HEVs are helpful in this regard, thus development of mature EV and HEV technologies is need of the hour. In the development of EVs, short driving range is a big hurdle, hence this attracts extensive research work. One way to handle this problem is to use HEVs. Integration of a solar panel to the HEV helps in extending the driving range of the HEV and it also has environmental benefits as it works on renewable solar energy. The simulation results satisfactorily show that the speed control of HEVs can be easily achieved using FLC.

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