Development of Control Strategy Based on Fuzzy Logic Control for a Parallel Hybrid Vehicle

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Abstract

This paper presents a fuzzy logic based control strategy development for a parallel hybrid electric vehicle. A hybrid electric vehicle (HEV) has the internal combustion engine (ICE) with at least an additional electric motor (EM) for the traction of the vehicle system. A Matlab model of a parallel HEV which has been developed to simulate the fuzzy control algorithm will be mentioned as well with the simulation results. The control algorithm is based on power distribution between the ICE and the EM in an efficient way, to control the charging and discharging of the batteries, to optimize the ICE and EM working states according to the driver's requests and road conditions.

1. Introduction

Hybrid Electric Vehicle (HEV) technology has been drawing attention of vehicle manufacturers for the last decades with the traffic seizure and increasing demand of vehicle usage causes exponential increase on the environmental pollutions. Exhaust emissions releases on the atmosphere and the increasing ratio of CO and CO_2 according to these emissions caused greenhouse effect and climate change and also the reduction of the fossil fuels with rising prices of barrels brought up the idea of high efficient energy usage. Literal meaning of the word HYBRID is the combination of two or more different things, aimed at achieving a particular objective or goal. For vehicles, hybrid means a vehicle can be run with ICE and EM for traction. Higher energy efficiency with better performance with electric traction, lower emissions for greening, recapturing energy with regenerative braking for energy saving and silent mode drive for urban usage capabilities are some of the major advantages of HEVs over conventional vehicles. The size of the main energy source of the vehicle ICE will be reduced and can be controlled to work on the most efficient line to reduce the usage of fossil fuels in the transportation sector and reducing emissions.

HEV CONFIGURATIONS - The best configuration for a vehicle with zero emission and noise consideration is fully electric vehicle. Battery technology is a challenging topic especially for this kind of pure electric drive type vehicles. The need of fuel economy and the energy storage which cannot supply the demand of the fully electric traction for a reasonable duration, revealed the technology of hybrid vehicles, where the word hybrid means the mixture of two or more species. For vehicles the meaning of hybrid is having two or more different type of power sources or drive system for traction.

Basically hybrid vehicle configurations can be classified into three groups. These are,

- Series hybrid electric vehicle
- Parallel hybrid electric vehicle
- Series – Parallel hybrid vehicle

Series Hybrid Electric Vehicle (SHEV) - SHEV configuration is like fully electric vehicle for traction. The vehicle is driven by only EM but it contains ICE for generating electrical power to keep the batteries charged and propel the vehicle by the means of the electrical power through the generator when the State of Charge (SOC) of batteries is low. In this configuration there is no mechanical connection between ICE and wheels.

Parallel Hybrid Electric Vehicle (PHEV) - In PHEV configuration both EM and ICE are connected together to the transmission line where both of them or one by one can propel the vehicle. The batteries can be charged by ICE where EM acts as a generator or by regenerative braking.

Series-Parallel Hybrid Electric Vehicle (SPHEV) – Beyond SHEV and PHEV configurations, there are hybrid vehicles which have properties of both SHEV and PHEV called Series – Parallel hybrid electric vehicle with the advantages of both configurations. In this configuration SPHEV can charge the battery packs in the idle mode from ICE.

Any powertrain system of an HEV configuration consists of subsystems like energy production unit, energy storage system(s), electric machine(s) and related power electronic circuits more than a commercial vehicle. Most of these subsystems have their own controller units, but there must be a master controller which has to capability of controlling all of them according to the data collected from the subsystems and the requests of the driver. In this paper, development of a control strategy based on fuzzy logic for a parallel hybrid vehicle will be mentioned. Parallel hybrid vehicle will have the topology as in Fig. 1. where ICE is connected to the front wheels and EM is connected to the rear wheels and where idle loads of the vehicle are ignored and start/stop can be applied to ICE [1, 2, 3].

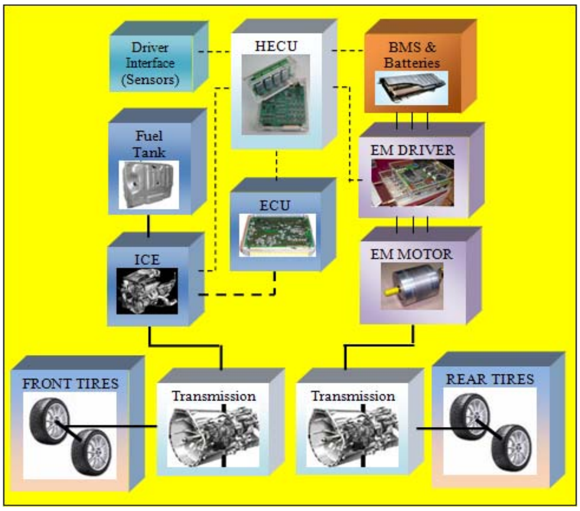

Fig. 1. Parallel hybrid vehicle configuration that the control strategy build for

2. Fuzzy Logic Control (FLC)

The basic of a fuzzy logic is a rule based problem-solving control system methodology that formulates human knowledge and reasoning, which can be represented as a collection of if–then rules, in a way that can also be simulated on and applied by a computer or controller. In this paper the control algorithm will be modeled and simulated on the fuzzy engine MATLAB Fuzzy Logic Tool-BOX. A typical fuzzy control system can be divided into the main sections below as illustrated in Fig. 3.;

i. Fuzzification: the inputs and their membership functions are formed in this section. The membership function is a graphical representation of the magnitude of participation of each input and output.

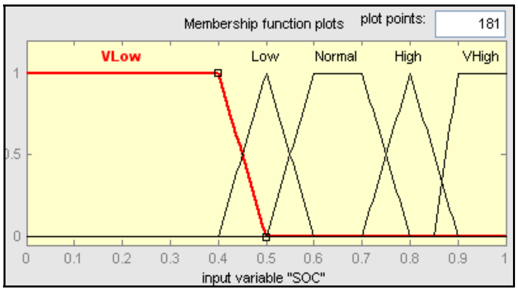

Fig. 2. Example to a membership functions of the input State of Charge of the batteries used for simulation

ii. Rules: Simple, plain-language IF X AND Y THEN Z rules are used to describe the desired system response in terms of linguistic variables rather than mathematical formulas. Linguistic rules describing the control system consist of two parts; an antecedent block (between the IF and THEN) and a consequent block (following THEN). There are 2 types of FLC according to the consequent part of the rules defined. The first one is Sugeno-Takagi type where the user will define the consequent part of the rules (control actions) as a crispy – single value. And the second type is Mamdani type where the consequent part is defined as fuzzy sets as antecedents part of the rules. A Mamdani type FLC is used in the control system.

iii. Degree of membership: All the degree of memberships of antecedent of each rule is computed using fuzzy logic operators. The linguistic definitions NOT, OR and AND operators of boolean logic exist in FLC.

$$NOT = (1 - \mu_{Low}(x)) \tag{1}$$

$$AND = \min(\mu_{Low}(x), \mu_{Low}(y)) \tag{2}$$

$$OR = \max(\mu_{Low}(x), \mu_{Low}(y)) \tag{3}$$

iv. Inference: In this section If-Then implication and aggregation is made for Mamdani FLC. The degree of fulfillment of the antecedent of each rule is used to modify the consequent of the rule accordingly. Inference is taking the strength of antecedents over consequent of the rules.

v. Defuzzification: This is the last step where we get back to crispy values of output of the fuzzy control application. The defuzzification of the data into a crisp output is accomplished by combining the results of the inference process and then computing the "fuzzy centroid" of the area. The weighted strengths of each output member function are multiplied by their respective output membership function center points and summed. Finally, this area is divided by the sum of the weighted member function strengths and the result is taken as the crisp output [4, 5, 6, 8].

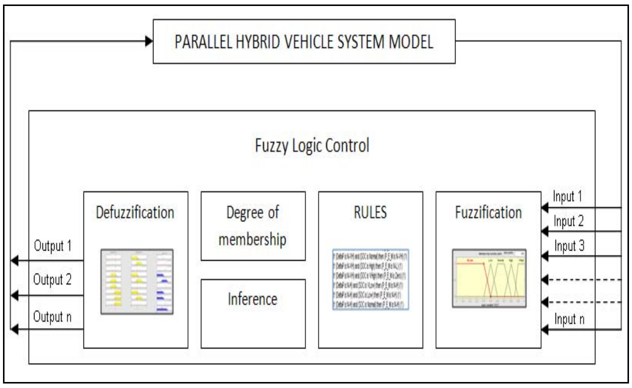

Fig. 3. FLC block diagram

3. Control Algorithm

The control algorithm developed in this paper is fuzzy based power distribution between ICE and EM to operate these units as possible as on the most efficient operating points according to the driver's requests and situations of the other components like batteries. A simple vehicle simulation is designed by using MATLAB\Simulink with basic features to show how efficient PHEV over the conventional configuration. For both configurations of vehicle, simulation model will be simulated in same driving cycles to compare. Operating points of engine on efficiency map of torque versus ICE speed for both configurations will be also given.

Basic longitudinal vehicle dynamics is included in simulation where the related power request is calculated with the road loads on the vehicle. These loads are generated with the cause of the external forces acting on the vehicle. These are aerodynamic drag force (F_a), acceleration force (F_{acc}), and rolling resistance force (F_r). These forces can be found by the formulas below.

$$F_a = 0{,}5.c_r\delta.A_f V^2 \tag{4}$$

$$F_{acc} = \lambda.m.a = \lambda.m.\frac{dv}{dt} \tag{5}$$

$$F_r = f.m.g \tag{6}$$

Where c_r is drag coefficient, δ is air density (kg/m3), A_f is vehicle frontal area, V is vehicle speed (m/s), λ rotating mass factor (1.1), m is the mass of the vehicle, a is vehicle acceleration (m/s^2) and equal to the derivation of vehicle speed of time, f is rolling resistance coefficient (0.011) and g is gravitational acceleration (9.81). Total external force on the vehicle is sum of these forces [2, 3]:

$$F = F_a + F_{acc} + F_r \tag{7}$$

With multiplying this force with the velocity of the vehicle, the requested power (Preq) demand will be found in kW as;

$$P_{req}(kw) = \frac{F \times V}{1000} \tag{8}$$

The gear estimation according to the vehicle speed change is as in Fig. 4.

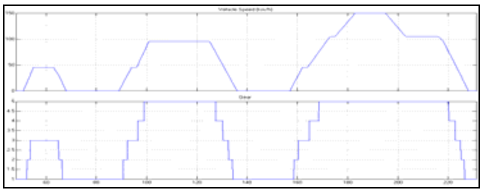

Fig. 4. Gear estimation according to speed

Form the vehicle speed data the engine speed is calculated because the engine is connected directly to the tires with differential. So from ICE speed in RPM (n_{ice}) is;

$$n_{ice}(RPM) = \frac{diffratio * 60}{2\pi.r} * gear\ ratio \tag{9}$$

According to the ICE speed (n_{ice}(RPM)) optimum power that the ICE must be operate will be checked from the look-up table in Fig. 5. which is provided from the manufacturer of the ICE.

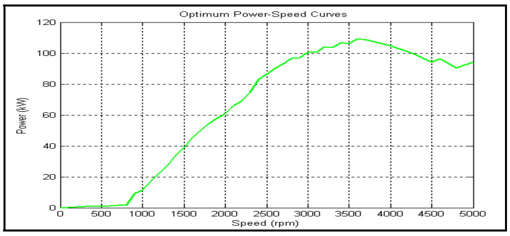

Fig. 5. Optimum Power vs ICE Speed curve

The difference of optimum power from requested power will give DeltaP.

$$DeltaP = P_{req} - P_{opt} \tag{10}$$

Battery model for Li-ion battery consisting of nominal 3.6V and 27Ah cells are used, which is the equivalent circuit model of;

$$V_{bat} = V_{OC} - I.R_{\text{int}} \tag{11}$$

Where V_{OC} is open-circuit battery voltage, R_{int} is battery internal resistance and V_{bat} is terminal voltage. In the battery model you can set the initial SOC value. Positive power input for battery model means discharging where negative power input is used for charging the battery. According to the power of EM (Pem) and the R_{int} values for charging and discharging given by manufacturer, SOC of the batteries were calculated.

In the algorithm the batteries SOC wanted to be used between the range of 0.6 and 0.8 which is the efficient range of the batteries. The SOC values that are not in the range will damage the batteries. So if the SOC value gets the lower limit, ChargeFlag will be high which means that until the SOC value gets the higher limit value of 0.8, ICE will start on and charge the batteries while propelling the vehicle.

SOC, ChargeFlag, Preq and DeltaP will be the inputs of the FLC block that will be used and power of EM (Pem) and ICE$_{on\text{-}off}$ flag are the outputs of the FLC. Flowchart of the control algorithm is as in Fig. 6.

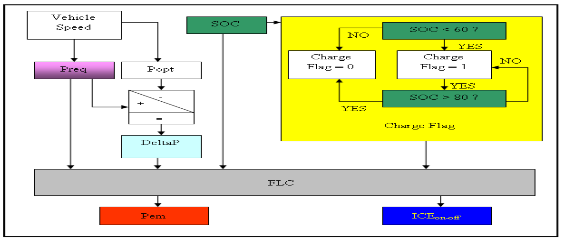

Fig. 6. Flowchart of the control algorithm

According to the given information a PHEV model with FLC is designed as in Fig. 7.

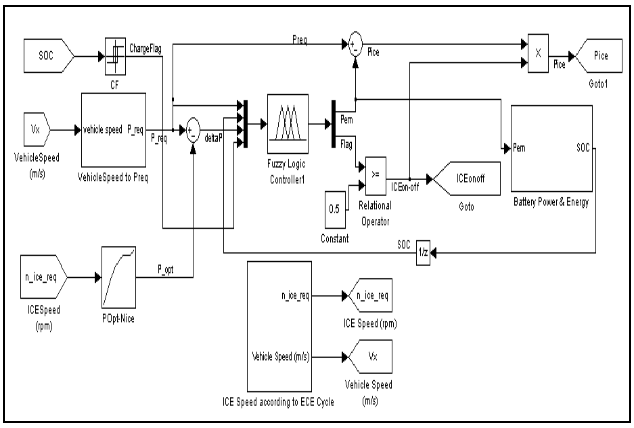

Fig. 7. PHEV Model with FLC

As in the model the power of ICE (Pice) is also the output of the FLC relative to the Pem and ICE$_{on\text{-}off}$ outputs. In fact it always calculates the Pice as in Eq. 12, but if ICE_{on-off} output is zero then Pice is zero which means ICE is off.

$$P_{ice} = (P_{req} - P_{em}) \times ICE_{on-off} \tag{12}$$

Mamdani type FLC with AND method of MIN, OR method of MAX, inference of MAX-MIN and defuzzification type of “fuzzy centroid” is used as the FLC of the simulation.

75 kW EM motor is chosen as EM motor of the hybrid vehicle where the most efficient motoring and generating power areas are nearly 30 kW as in Fig. 8. So the FLC will range its power response for EM under 30 kW. And response of (-) means work in generating mode and charge the batteries.

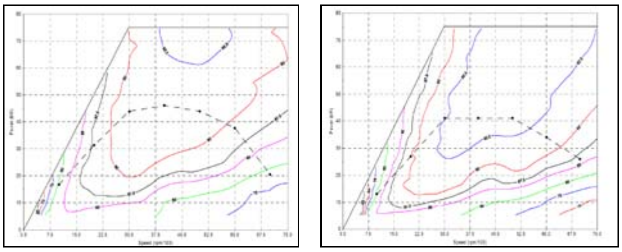

Fig. 8. Power - EM speed – Efficiency graph of the EM used for motoring and generating modes [7].

If ICE_{on-off} flag is off vehicle is driven by EM only and if ICE_{on-off} is on then both EM and ICE is working. In the condition of both ICE and EM are working, if the DeltaP is positive (Preq is higher than the Popt) according to the membership functions of DeltaP and SOC for that position, FLC gives Pem relative positive output to overcome the difference as EM can. And the Pice output will be closer to the Popt of ICE. If the DeltaP is negative then again according to the membership functions of DeltaP and SOC for that position, FLC gives Pem relative negative output where the ICE will also charge the batteries while propel the vehicle and increases the Pice operating point to reach the Popt. The flowchart of FLC is as in Fig. 9.

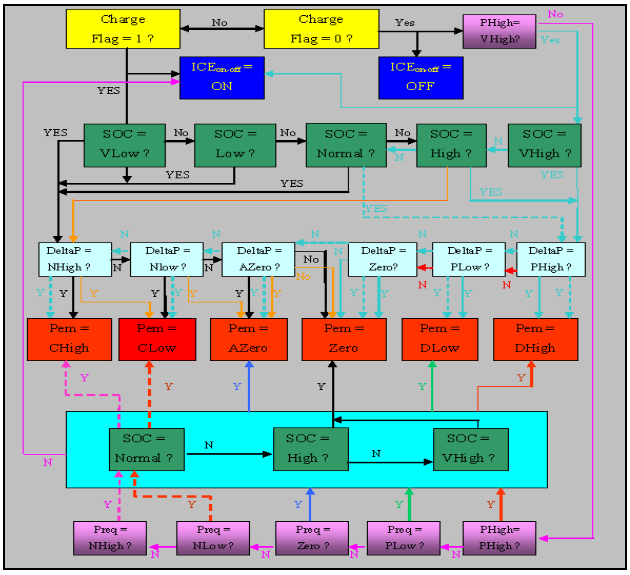

Fig. 9. The flowchart of FLC.

FLC first checks if the ChargeFlag is high or low. If the CharFlag is high it means that the batteries SOC is lower than the threshold value of 0.60 where if it goes under that it will damage the batteries and means keep charging the batteries until it gets the higher value of 0.80 where the range 0.80> SOC > 0.60 is the best range to use the Li-ion batteries. If the condition of ChargeFlag is high then for any conditions of requested power (Preq) the FLC looks the difference of the Preq and optimum power (Popt) for the related vehicle speed (DeltaP = Preq-Potm) and SOC of the batteries. According to these antecedents FLC gives adaptive related power consequent for the EM (Pem) if the ChargeFlag is KeepCharging. And also if DeltaP is > 0 it means Popt is lower than the Preq so send no Pem.

If the ChargeFlag is Low, there are 2 conditions. The first one is if 30KW> Preq> -30KW. FLC can discharge and charge batteries according to Preq, DeltaP and SOC, if SOC is not below 0.6. If Preq is in the efficient range of the power that EM motor can meet then according to rate of SOC FLC gives Pem output to meet the request of the driver. The second condition is the condition that Preq is higher than 30 KW which is the range that EM cannot support efficiently. In this condition ICEon-off flag is On which means open the ICE and according to DeltaP FLC gives Pem output and this is added to Pice which means if DeltaP < 0 then charge the batteries according to the magnitudes of DeltaP and if DeltaP > 0 then supply the difference P until the range Pem can meet [8].

4. Simulation Results

The simulation results of the PHEV and conventional vehicle configurations will be given in this chapter for the New European Drive Cycle (NEDC) because the requested power values will be more proper for the FLC algorithm to show all operating conditions. Vehicle speed and the power requirement for the related vehicle speed loads for the NUDC driving cycle is calculated in the model and given in Fig. 10.

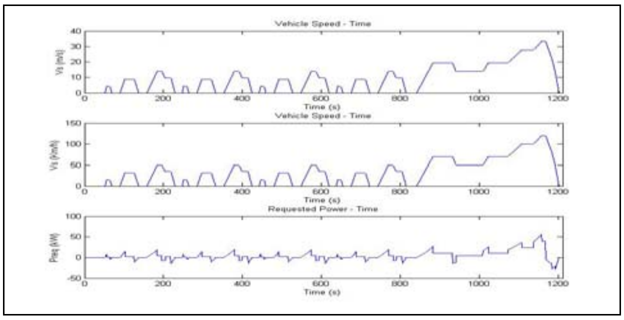

Fig. 10. Vehicle Speed - Time and Preq – Time graphs for the related speeds for ECE driving cycle.

In this driving cycle the Preq is higher than 30kW for some periods where although the Charge Flag is low because of the EM would not reply the requested power the ICE starts working where it can be seen in Fig. 12. subplot 8. The FLC looks the value of the DeltaP and SOC and tries to work the ICE in more efficient operating points. In the Fig.12 it can easily be seen that after the 1100 second the power demand is more than 30 KW and DeltaP is very high so FLC sends charge request to EM and these load also added to the requested value of power. It can also be seen that SOC value gets higher when the ICE starts to propel and to charge the batteries. In Fig. 11. Subplot 1 shows the efficiency of the operating points of the PHEV where subplot 2 shows the efficiency of operating points if it was working in conventional configuration for NEDC driving cycle and it can be easily seen that while the ICE is working in PHEV it is working on more efficient operating points [8].

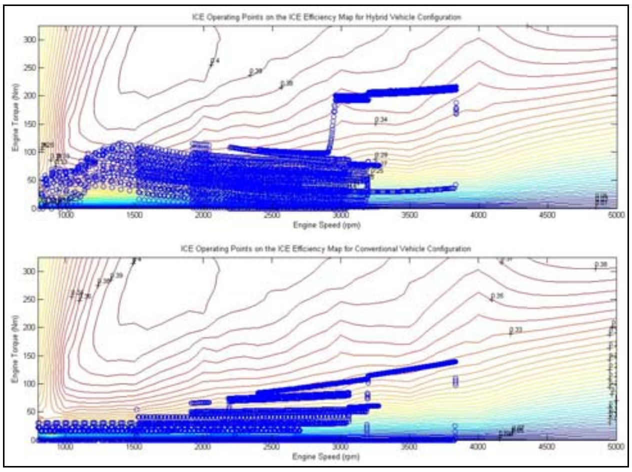

Fig. 11. Operating points for PHEV and conventional configuration for the NEDC driving cycle on the efficiency map

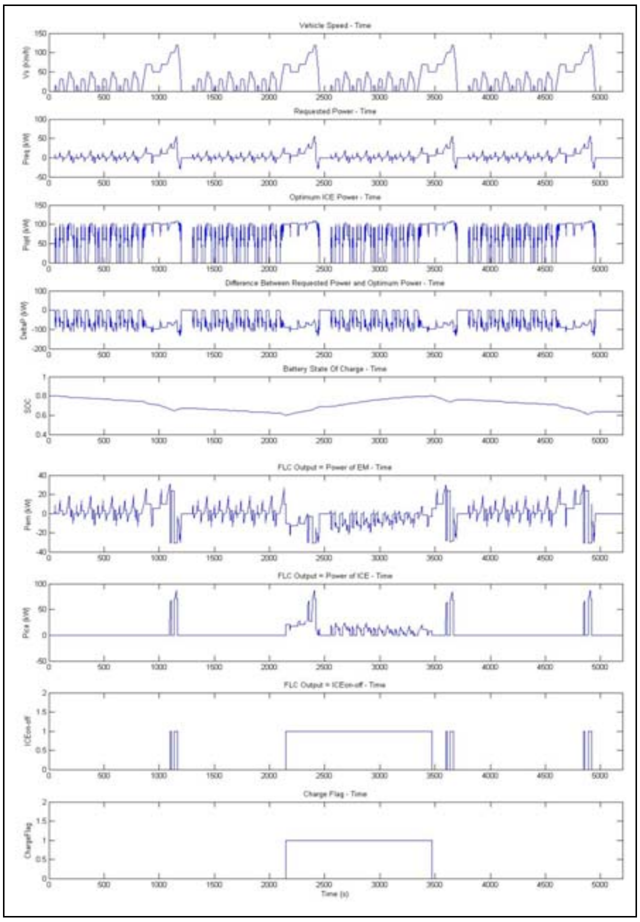

Fig.12. Simulation results for NEDC driving cycle where Preq gets higher than 30 kW

5. Conclusions

FLC tries to response to the drivers request from EM until EM can cover but if the requested power is higher than the ranges, FLC sets ICE on and covers the required power from the ICE and according to the difference between the requested power and the optimum power that ICE has to work, to work in the most efficient level; FLC charges the batteries with using the EM as generator. Related to the efficient range of EM it can only cover the maximum of 30 kW to charge the batteries. Although the ICE is working in better efficient levels and works less than conventional configuration, ICE cannot reach the most efficient operating points. The reason of this is new drive cycles especially drive cycles for urban transportations requests very lower powers as compared to power supplied by the ICE. So while hybridization of vehicle, to make more efficient vehicles, the ICE must be down-sized according to what cycles is the HEV will be driven [8].

6. References

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