Development of an Intelligent Power Management Strategy for Hybrid Electric Vehicle Based on Permanent Magnet Electrical Variable Transmission

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Abstract

In this paper, a power management control strategy for Hybrid Electric Vehicle (HEV) based on Permanent Magnet Synchronous Machines-Electrical Variable Transmission (PMSM-EVT) is developed. This method introduces an intelligent strategy for vehicle's power distribution, during driving and braking, between the system's plants by Fuzzy Logic Control (FLC). This has been investigated throughout two main aspects. The first is the optimum power splitting between the Internal Combustion Engine (ICE) and the PMSM-EVT machines that controls the throttle angle degree of the ICE in order to make it work in a high efficiency region; and the second is optimizing the vehicle' energy capture at braking or deceleration. These goals have been accomplished by two FL controllers. Designing of these controllers are mainly based on the function and power ratings of each plant. Because of the EVT machines make the operation strategy of this type of HEVs different from the others, the building of the fuzzy variables (fuzzy rules, membership functions, boundaries and limits) is different. The fuzzy logic controllers were designed based on the state of charge of battery, vehicle's velocity and the vehicle's power. The strategy is validated by Energetic Macroscopic Representation (EMR) simulation model strategy based on the software Matlab/Simulink. The results show that the energy management strategy is effective to control the engine's operating points within the highest efficiency region as well as to sustain the SOC of the battery while satisfy the drive ability. The vehicle's performances have been analyzed throughout a combined trip driving cycle that represents the normal and the worst operating conditions.

Keywords

permanent magnet electrical variable transmission, hybrid electric vehicle, fuzzy logic regenerative, global control strategy, energetic macroscopic representation

1. INTRODUCTION

Energy management in vehicles is an important issue because it can significantly influence the performances of the vehicles and component sizing. Improving energy management in the Hybrid Electric Vehicles (HEVs) can deliver important benefits such as reducing fuel consumption, decreasing emission, lower running cost, reducing noise pollution, and improving driving performance and ease of use. In addition, the intelligent energy management methods can observe and learn driver behavior, environmental and vehicle conditions, and intelligently control the operation of the HEV.

Electrical Variable Transmission (EVT) is the powertrain of the studied HEV. Many efforts have been developed for researching and discussing different aspects of this series/parallel HEV using Induction Machines (IM-EVT) [Hoeijmakers and Ferreira, 2006; Cui et al., 2008; Cheng et al., 2008; Chen et al., 2009; Cheng et al., 2009]. Permanent Magnet Synchronous Machines (PMSM) has been researched as the strongest candidate as an EVT power train for the HEV [Xu, 2005; Fan et al., 2008; Cheng et al., 2010; Cheng et al., 2011]. Also, the PMSM-Dual Mechanical Port (DMP) as an energy conversion device has been introduced as an alternative to the Toyota Hybrid System (THS) transmission in [Chen et al., 2009a]. In which a comparison between the two kinds of series-parallel HEVs was presented.

Since driving conditions and vehicle loads are highly nonlinear and cannot be explicitly described, intelligent controllers have been proposed in several studies for HEVs' control. There have been two general trends dealing with control strategies: rule-based and optimization strategies [Salmasi, 2007]. Rule-based power follower control strategy was presented and simulated for the EVT based HEV in [Chen et al., 2008; Cheng et al., 2008; Abdelsalam and Cui, 2011]. The rule-based revised control strategy has been used to coordinate the power distribution process between the components of HEV. On this strategy, the Internal Combustion Engine (ICE) operates on its maximum efficiency region and drives the vehicle with the base required power such that the ICE turns ON and OFF depending on the terminate limits of the State of Charge (SOC) of the battery.

Due to the multi-domain, nonlinear, and time-varying nature of the HEVs powertrain, many researchers have investigated the implementation of Fuzzy Logic Control (FLC) as a solution. Instead of using deterministic rules, the decision making property of the FLC can be adopted to realize a real-time power-split controller [Salmasi, 2007; Abdelsalam and Cui, 2011]. The FLC has been successfully applied in HEV areas of energy management strategy [Hyeoun and Seung-Ki, 1998; Schouten et al., 2002; Zhonghao and Wang, 2005; Travis et al., 2008; Zhang et al., 2009; Khoucha et al., 2010; Zheng et al., 2010].

In this paper, a fuzzy logic global control strategy for PMSM-EVT-HEV system has been developed. This is considered as an initiative research work about using FLC for this system. This strategy guarantees the operation of the ICE within its maximum efficiency region, saves the power ratings of the PMSM-EVT machines and battery. Also at braking, maximum power has been captured by using a regenerative strategy. Finally, the requirements of the driver at normal and worst driving conditions have been accomplished. To validate the robustness of the developed global FL control strategy, a combined reference driving cycle, incorporating the modified 10.15 Prius and UDDS is derived.

The paper is organized as follows: Section II explains the basics of the studied PMSM-EVT-HEV, and also briefly describes the Energetic Macroscopic Representation (EMR) simulation model with the typical data of the Toyota prius HEV powertrained by PMSM-EVT instead of the THS transmission. Then, the implementation of the power management strategy is presented describing the proposed fuzzy logic controllers in section III. Finally, the vehicle performance and the power flow through the ICE, PMSM-EVT machines, and the battery are analyzed and discussed via the simulation results at different driving cycles in Section IV.

2. DESCRIPTION OF THE STUDIED HEV

2.1 Construction of the HEV based on PMSM-EVT

PMSM-EVT, ICE, battery, and final gear are the main components of the studied HEV as shown in Figure 1. Double rotor PMSM (EM1), normal PMSM (EM2) and two power converters are the components of the split PMSM-EVT unit. The inner rotor of EM1 is connected mechanically to ICE and has distributed windings (stator 1) that are connected to battery via inverter 1 across the brushes and slip-rings. The rotor of EM2 is connected to the final gear of the vehicle and to the outer rotor of EM1; while the windings of stator (2) are connected to the battery via inverter 2. Vector control with field weakening strategy is used to drive the PMSM-EVT machines. More details about the local control strategy for the PMSM-EVT have been presented on the previous research work [Abdelsalam and Cui, 2011]. Therefore, using the global intelligent power management strategy, the PMSM-EVT is exploited to optimize the ICE operation via covering the speed and torque differences between the vehicle requirements and the optimized output power of the engine.

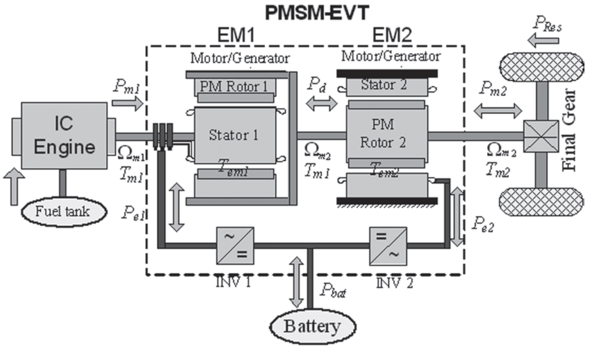

Fig. 1 Hybrid electric vehicle driven with PMSM-EVT

2.2 EMR global simulation model

Since HEVs are energetic systems, the energy consideration should be emphasized. EMR is an energy-based graphical description that gives insights into the real energy operation of the system and allows a deep understanding of its potentialities from a dynamic point of view [Chen et al., 2009b; Chen, 2010]. EMR is used in the global modeling and strategy simulation for the EVT based HEV; and a control scheme is deduced from the EMR models using specific inversion rules. The systems' plants, PMSM-EVT machines (EM1 & EM2), ICE, inverters, battery, transmission and vehicle dynamics, are modeled by EMR as depicted in Figure 2. It indicates the global modeling of the PMSM-EVT-HEV components with their local and global controllers. More details about the model of these plants and their controllers could be found in [Chen et al., 2008; Cheng et al., 2008; Abdelsalam and Cui, 2011].

3. IMPLEMENTATION OF THE FUZZY LOGIC POWER MANAGEMENT STRATEGY

The EVT based HEV system is too complex especially from points of nonlinearity, functionality, and switching structure. Also, it needs to be controlled by an intelligent controller accurately to meet vehicle's needs with smooth operation, guaranteeing stability,

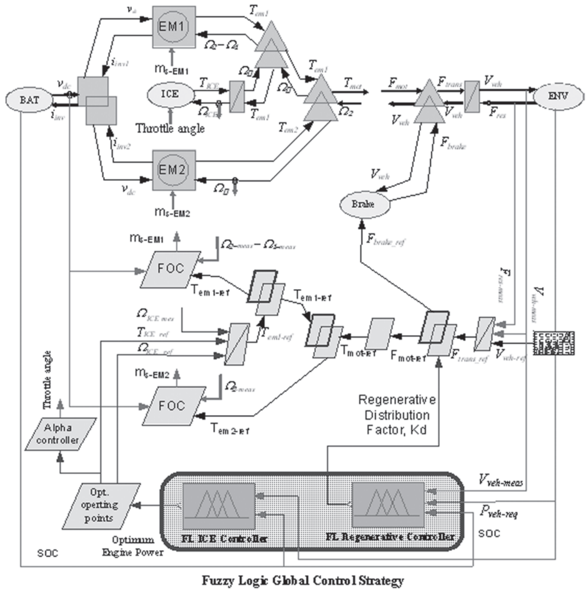

Fig. 2 The EMR of PMSM-EVT-HEV managed by FLCs

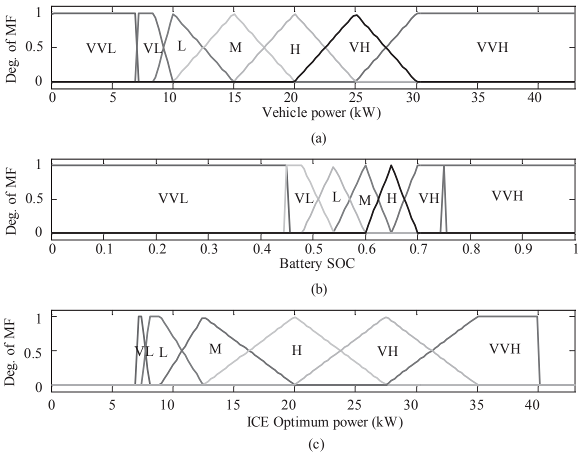

Fig. 3 Membership functions of the ICE fuzzy controller: (a) vehicle power, (b) SOC of battery, (c) power of ICE

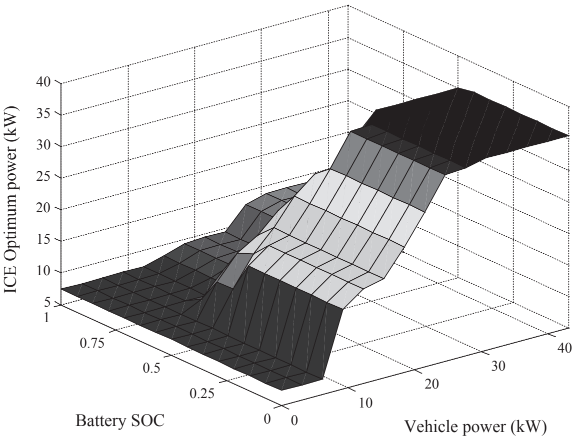

Fig. 4 Surface plot of the ICE fuzzy logic variables

and saving the power sizing of the systems' components. The proposed FLC strategy for this system is different because of the structure and functionality of the PMSM-EVT based HEV is different to the other types of HEVs.

As noticed in the lower part of Figure 2, there are two FL controllers. The first is responsible for distributing the power of the vehicle between the ICE and the EVT such that the engine operates at its maximum efficiency region. On another side, at braking or/and deceleration instances, the amount of the regenerative power is adaptively controlled by the second FL controller to maximize the captured power.

3.1 ICE Fuzzy logic control strategy

The ICE-FLC strategy is responsible to guarantee the operation of the engine at its maximum efficiency region. Using the EVT machines for driving HEVs neglects the proportionality between the velocity of the vehicle and the optimum power delivered by the ICE. Hence in this type of vehicles, the optimum power of the engine, as the output of the FLC, is determined only according to the power of the vehicle and SOC of the battery, as the inputs of the controller. The Membership Functions (MFs) and the fuzzy logic rules are designed carefully according to plants' ratings and the proposed driving strategy.

3.1.1 Input/output membership functions

The proposed MFs are developed based on the limits of vehicle performance, PMSM-EVT machines and battery's SOC. The MFs of the input and output variables are described in Figure 3. The demanded power calculated from the vehicle velocity and acceleration is first estimated, and then classified into {VVL; VL; L; M; H; VH; VVH} which represent the vehicle power demand from the minimum value of 0 kW to the maximum value of 43 kW. As shown in Figure 3 (a), the most operating power of the vehicle is divided into five concourses with overlapping starting from 7 kW to 30 kW; whereas the power blow 7 kW and the power behind 30 kW represent the lowest and highest requested powers respectively. The battery SOC is classified into {VVL; VL; L; M; H; VH; VVH}; which could reflect SOC from 0 to 1 dividing the permitted operating range into five concourses starting from the lower value of 0.45 to the higher value of 0.75 with the target value of 0.6 as depicted in Figure 3 (b). Also, the output optimum power of ICE is classified into {VL; L; M; H; VH; VVH}, Figure 3 (c). These concourses represent the engine power from the minimum optimal value of 7kW to the maximum optimal power of 40 kW. The overlapping between the concourses guarantees the smooth transition within the optimum operation region. According to engineering expertise and insight, the fuzzy control rules are constructed as shown in Figure 4.

3.1.2 Fuzzy logic rules

FLC of the ICE is designed to optimize the power split between the ICE and battery; at the same time to guarantee the operation of the engine within its optimum power range, form 7 kW to 40 kW. This power is enough to drive the vehicle at cruise velocities, and also for charging the battery at hybrid driving mode. The rule base is presented in Table 1 and it can be described as:

- At low, medium and high power requested at the vehicle's wheels, the ICE turns OFF when SOC exceeds the high limit value (0.75) to work as EV mode.
- At very low power and when the SOC becomes lower than the minimum limit of 0.45, the ICE turns ON and develops at least the minimum optimum vale of the engine of 7 kW to work as ICE charging mode.
- When the vehicle's power becomes very high, the ICE develops its maximum optimum power and then decreases its output with increasing the SOC of the battery and also with decreasing the vehicle's power.
- The optimum speed and torque of the ICE is estimated from the optimum power of the engine.
- EM1 is controlled to develop the engine optimum torque at steady state at the same speeds; and the throttle angle of the engine is determined from the optimum engine power.

Table 1 Rule base of the ICE fuzzy logic controller

Vehicle Power (kW)	SOC (State of Charge)						
	VVL	VL	L	M	H	VH	VVH
VVL [0-7]	L	L	VL	VL	VL	VL	VL
VL [7-10]	M	L	L	L	VL	VL	VL
L [8.5-15]	H	M	M	L	VL	VL	VL
M [10-20]	H	H	H	M	VL	VL	VL
H [15-25]	VH	VH	VH	M	L	L	L
VH [20-30]	VVH	VH	VH	H	M	M	L
VVH [25-43]	VVH	VVH	VVH	VH	VH	H	M

3.2 Regenerative fuzzy logic control strategy

Regenerative braking is commanded whenever the torque is less than zero across the vehicle speed range and the battery SOC range. Therefore, it is important to properly distribute the braking force between regenerative and friction braking to maximize energy capture while maintaining safety of the vehicle and healthy operation of components (motors, inverters, and battery). In order to achieve this goal, this section uses the fuzzy logic control strategy to distribute braking torque to regenerative braking as much as possible.

The captured force, as regenerative part, to the total brake force is defined as a regenerative braking factor K_d. Using a fixed K_d is not suitable for the whole driving. At low vehicle speeds, K_d has to be increased to charge the battery more. But, at high speeds, increasing this factor will increase the regenerated power from EM2 and may exceed its limits. Therefore, a braking distribution strategy is developed intelligently via FLC which designed carefully to control the regenerative amount of power according to the effective variables. The SOC of the battery, the total brake power, and the vehicle velocity are the most effective variables used for determining the recovered power from the vehicle.

The total vehicle reference force F_{trans_ref} is estimated from the velocity reference v_{veh_ref} and the disturbance forces F_{Res_mes} as described in (1).

$$F_{trans\_ref} = C(t)\,(v_{veh_{ref}} - v_{veh_{mes}}) + F_{Res\_Mes} \tag{1}$$

with $C(t)$ the velocity controller as seen in Figure 2. The output of fuzzy controller is the regenerative braking factor K_d, so the regenerative braking force F_{mot_ref} and friction braking force in the axle F_{brake_ref} can be obtained as

$$F_{mot\_ref} = K_d F_{trans\_ref} \tag{2}$$

$$F_{brake\_ref} = (1 - K_d)\, F_{trans\_ref} \tag{3}$$

3.2.1 Input/output membership functions

The proposed MFs are developed based on the pre-calculated limits of vehicle performance, PMSM-EVT machines and battery's SOC. Figure 5 shows the input and output variables describing their boundaries and depicts the shape and ranges of the concourses. Also, the brake power calculated from the vehicle velocity and deceleration is first estimated, and then classified into {VL; L; M; H; VH} which represent the vehicle power stored from the minimum value of 0 kW , at stopping, to the maximum negative value of 40 kW as shown in Figure 5 (a). The vehicle velocity range is divided into five overlapped levels {VL; L; M; H; VH} which represent the velocity from 0 Km/h to the

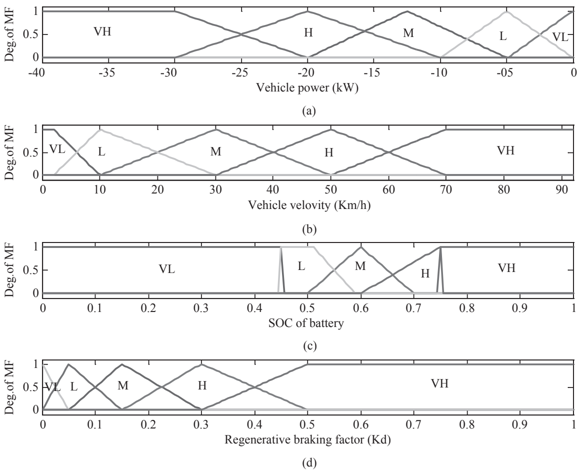

Fig. 5 Membership functions of the regenerative fuzzy logic: (a) vehicle power, (b) velocity of vehicle, (c) SOC of battery, and (d) regenerative distribution factor

maximum velocity of 90 Km/h as seen in Figure 5 (b). The battery SOC is classified into {VL; L; M; H; VH}; which could reflect SOC from 0 to 1 dividing the permitted operating range into three concourses starting from the lower value of 0.45 to the higher value of 0.75 with the target value of 0.6 as depicted in Figure 5 (c). Finally, Figure 5 (d) displays the regenerative braking factor which classified into five concourses {VL; L; M; H; VH}. These concourses represent the range of K_d from the minimum value of 0 to the maximum of 1. For K_d, the concourse VL means no regenerative power $K_d = 0$; while VH means all kinetic stored power on the vehicle will be recovered to battery via the EVT machines $K_d = 1$.

3.2.2 Fuzzy logic rules

The proposed fuzzy rule base was developed from three inputs: the vehicle speed, the vehicle's stored power, and the battery state of charge (SOC). These inputs are fuzzified and then fed into the fuzzy controller. The optimal rule base was found from experimentation with the system. The regenerative factor K_d is the output variable of the defuzzification process. In turns, this factor determines the magnitude of the regenerative torque for the EVT machines as illustrated in down part of Figure 2. The performance of the FLC depends heavily on its fuzzy rules. The rule base for the 125 rules is built to relate the three inputs with the output factor. Each of the inputs and output has 5 linguistic variables. The relation between the input and the output variables can be clearly related in the surface plot as shown in Figure 6. These rules for managing the regenerative process are explained briefly below.

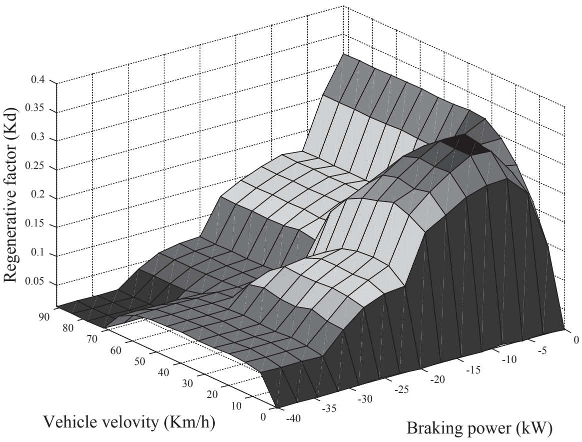

Fig. 6 Rules of fuzzy logic control for braking torque distribution

If SOC is very high (VH), i.e. $SOC \geq SOC_{high}$, the engine is turned OFF and K_d is very low (VL) i.e. $K_d = 0$ (no regenerating power required from the EVT machines) whatever the velocity and stored braking power are.

If SOC is (VL), i.e. $SOC \leq SOC_{low}$, the engine is turned ON and K_d is VH i.e. $K_d = max$ (maximum power is recovered from the braking power via the EM2 machine and no friction braking), this for all velocities and for stored braking power except two cases: the first exception is when the vehicle runs at very low velocity, K_d has to be decreased because it is not preferable to operate the EVT machines as generators at very low speeds. The second exception is when the vehicle runs at very high speed, K_d has to be changed from H to VL gradually according to the SOC and the braking power.

4. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

Using EMR and its inversion-based control, the PMSM-EVT-HEV system and the proposed control strategy have been modeled and simulated, based on the software Matlab/Simulink as depicted in Figure 2, to validate the power management strategy proposed in this paper. Based on the design and control principles discussed in the previous sections, a Toyota Prius vehicle driven by EVT instead of THS has been simulated in the combined two driving cycles: a modified Toyota Prius and UDDC as listed in Table 2. It is important to notice that, comparing with the data of Toyota Prius HEV [ADVISOR, 2002], the used trip cycle has larger velocity, larger acceleration and deceleration to validate the maximum ratings and testing the operation of the power plants at the worst operating conditions. And hence, the model of ICE, battery,

Table 2 Specifications of the used driving cycles

CYC	Max. Velocity (Km/h)	Max. Acceleration (m/s^2)	Max. Deceleration (m/s^2)
1015-6PRIUS	70.75	1.19	1.45
Modified-015-6PRIUS	90.56	1.5	1.9
UDDS	91.25	1.48	1.48

Table 3 Specifications of the used EVT machines

Machine	Parameter, Unit	Value
EM1	Maximum power, kW	17.65
	Rated power, kW	7.4
	Maximum torque data, Nm/rpm	103.5 @ 0-1623
	Rated torque data, Nm/rpm	70 @ 0-1384
	Maximum speed, rpm	2483
EM2	Maximum power	21.5
	Rated power, kW	10
	Maximum torque data, Nm/rpm	120 @ 0-2000
	Rated torque data, Nm/rpm	60 @ 0-2000
	Maximum speed, rpm	4000

power inverters, vehicle dynamics and transmission have been accomplished according to the typical data of the well-known Toyota prius HEV obtained from the ADVISOR. These plants have been modeled and simulated via EMR; and the parameters of the EVT machines simulated are listed in Table 3.

4.1 Vehicle performance

The simulation results for the vehicle are presented and analyzed in Figure 7. The simulation results show that the simulation speed can tracking the driving cycle profile, in a way which indicates that the drive ability is satisfied. In this figure, the power requested at the wheels is also presented showing the driving and regenerative powers.

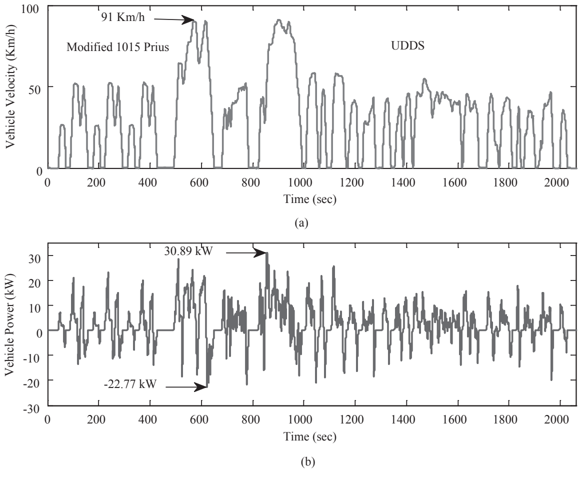

Fig. 7 Vehicle performance (a) vehicle velocity and (b) vehicle power required at the wheels

4.2 ICE Performance

Figure 8 shows the simulation results of the engine torque, speed and power. It can be seen that the torque, speed and power of the ICE with the proposed FL control strategy varies into the predefined optimum ranges. Also seen in Figure 9, the ICE operating points indicating that the engine, all of time, operates in its high- efficiency area.

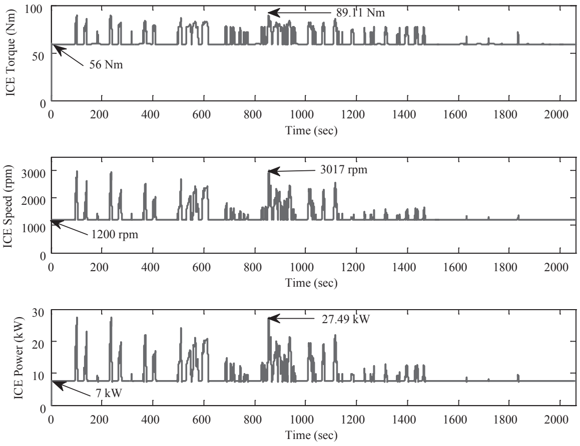

Fig. 8 Torque, speed and power flow on the ICE

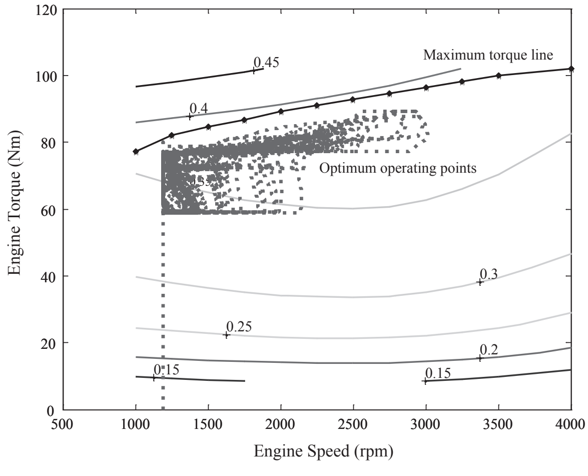

Fig. 9 Engine operation points

4.3 EM2 Performance

Figure 10 shows the torque, speed and power flow of the outer PMSM (EM2) on the EVT. It is noted that the developed positive or negative torque can be determined according to the torque of ICE and vehicle requested torque. Seen in the same figure, the speed

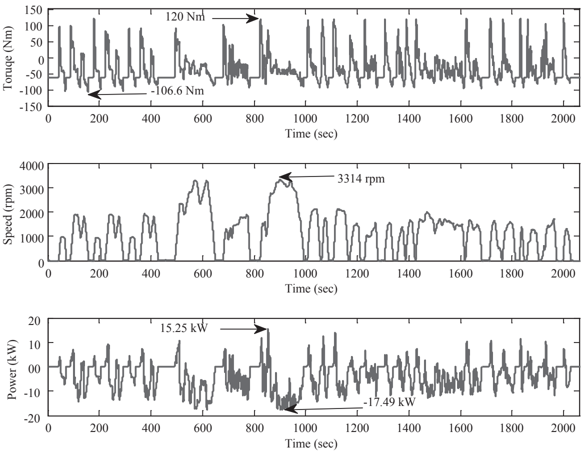

Fig. 10 Torque, speed and power flow on the EM2

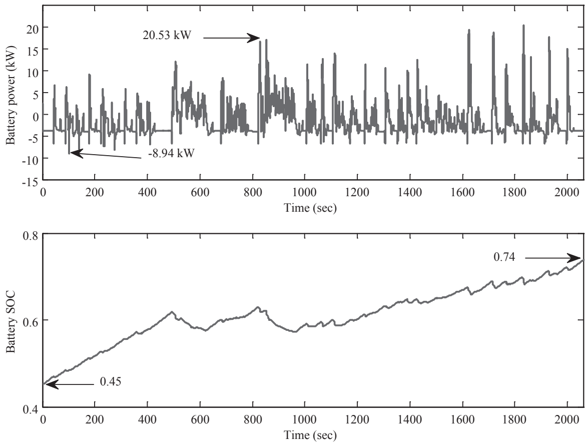

Fig. 12 Power and SOC of the battery

of EM2 proportionally aligned to the vehicle velocity. Also, it can be seen that the motor/generator, EM2, most of the time, works in generating mode because of the ICE and then EM1, all times, develops positive torque.

4.4 EM1 Performance

Figure 11 shows the torque, speed and power flow of the inner PMSM (EM1) on the EVT. It is noted that the developed torque is positive and slightly larger than the ICE torque because of the dynamic inertia. Also, it can be seen that the speed of EM1 equals to the difference between the ICE and EM2 speeds. Positive or/and negative speed is related to the vehicle's velocity and ICE operation. Also, it can be seen that the peaking power in the figure occurs at the maximum vehicle speed of 91.25 Km/h.

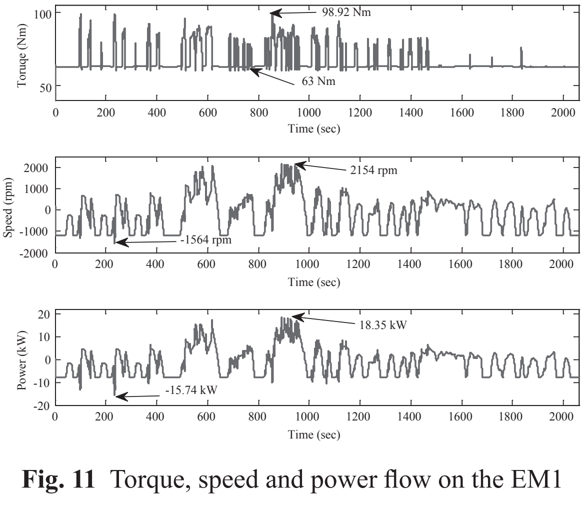

Fig. 11 Torque, speed and power flow on the EM1

4.5 Battery performance

The simulation results for the battery are presented and analyzed below. As for this simulation, the initial SOC value is set to 0.45. The favorable range of SOC is set between 0.55 and 0.75. Shown in Figure 12, the SOC is sustained in the desired range. In this figure, the value of battery power is also presented. It is noted from the figure and from Table 2 that the power rating of the battery is saved. Also, the graph of battery SOC adequately shows charging state by regenerative braking during deceleration.

4.6 Regenerative power distribution

The variation of the regenerative factor K_d is depicted in Figure 13. It is noticed that this factor varies from 0 to 1 according to the driving cycle requirements. Also it can be seen that the most effective range of the factor is from 10 to 40 % of the total power; that percentage depends mainly on the power rating of the electric machines.

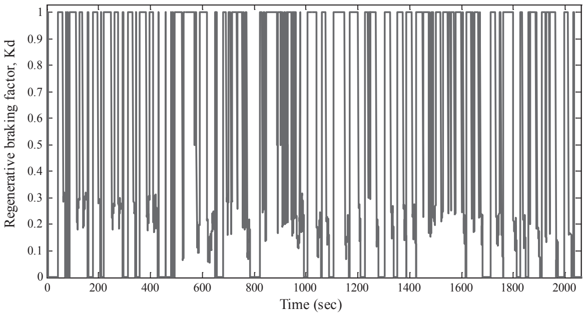

Fig. 13 Regenerative braking factor

5. CONCLUSION

In this paper, the performance simulation for EVT based HEV equipped with FLC strategy was conducted. The main contribution of this paper is the development of an intelligent global control strategy on HEV system considering the structure and functionality of the EVT machines. This strategy has the ability of dealing with the HEV system with the EVT at different modes of operation and different operating conditions.

Driving and regenerative processes are adopted with the guarantee of robust operation for each power plant on the system. Also, the power ratings of the electrical plants (EM1, EM2 and battery) are saved. The simulation results with the driving cycles of Toyota prius-UDDC modes showed that the EVT-HEV equipped with the proposed FLC strategy can regenerate the braking energy and operate the engine at its maximum efficiency region. Also, comparing with the simulation results for the Prius vehicle on the ADVISOR, the power ratings of the electrical machines, battery, and also the ICE have been decreased using the proposed FLC strategy. Succinctly, this work can be considered as an initiative research on EVT based HEV system that uses fuzzy logic controllers as a global power management strategy.

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