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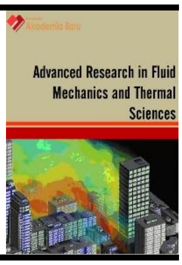

Energy Management System in Series-Parallel Hybrid Solar Vehicle

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ABSTRACT

In this paper, the study on energy management in a hybrid solar vehicle is presented. The proposed system consisted of five main energy conversion components i.e. internal combustion engine, electric motor, electric generator, battery, and photovoltaic. The energy management system in hybrid solar vehicles aims to select the best mode of operation corresponding to the driving conditions and the state of charge of the battery. In this study, the proposed energy management system applied a specific energy balance equation for each mode of operation of the vehicle as the basis of the decision-making algorithms. The algorithms are then simulated on a model of series-parallel hybrid solar vehicle system to investigate the power supplied by each component, the fuel consumption of the vehicle, and the efficiency of each component. The results show that the fuel consumption of an internal combustion engine on a hybrid solar vehicle is about 30% less than the conventional vehicle, in which up to 0.6 % contributed by the photovoltaic cells.

Keywords:
Energy management; series-parallel hybrid solar vehicle; fuel consumption

1. Introduction

From the late 19th century to the present day gasoline and diesel have become the primary choices as the fuel of conventional vehicles [1,2]. According to the current development, the needs of the limitations of oil fuel reserves, the impact of exhaust emissions, and global warming lead to the demand on a more environmental-friendly vehicle which can also increase the use of renewable fuel [3-6]. To answer these needs, the efforts to develop internal combustion vehicle technology through the development of injection systems on conventional vehicles [7] and the use of biofuel like ethanol [8-11] and biodiesel [12] have been done. However, this is considered not enough that experts continue to seek other solutions. The alternatives to be developed continuously are hybrid and electric vehicles [5,13,14]. The development of these vehicles is supported by the very rapidly growing battery technology that they become alternative conventional vehicles of combustion fuel

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[15]. The driving range of electric and hybrid vehicles has increased significantly, and they significantly reduce exhaust emissions as well as the use of fossil fuels. Experts predict that hybrid vehicles are a transition before electric vehicles will later be the primary choice in transportation [2,3,16].

Solar energy is abundantly available. Various technologies of solar energy are possible to be applied in the field of buildings [17,18] and transportation to reduce the use of fossil fuels. Photovoltaic utilization in electric vehicles has long been cultivated [6,19-21]. Photovoltaic are appealing because they are lightweight and not noisy, need little maintenance, and work continuously. Today photovoltaic with 20% efficiency is available on the market while in laboratory its efficiency has reached 44%.

An initial implementation of photovoltaic on a hybrid vehicle was conducted by Sasaki [20]. Photovoltaic were attached on a car roof and hood when the car was parked as well as on the roof of the building used for charging the battery. The combination of these three parts of photovoltaic contributed significant energy. The use of photovoltaic on the roof in vehicle charging also reported by other researchers [22-24]. Arsie *et al.,* [25] developed type series of hybrid solar vehicle. In this study, the power contribution of photovoltaic was not much, compared to power from batteries and motor fuel. Significant fuel savings were mainly due to hybrid series energy management that keeps the internal combustion engine operating around its maximum efficiency area. Giannouli and Yianoulis [26] and Rizzo *et al.,* [27] introduced the use of solar cells on parallel hybrid vehicles. In that study, Sasaki *et al.,* [20] and Giannouli and Yianoulis [26] did not discuss their energy management strategy in detail.

Further study on energy management in hybrid solar vehicles is interesting as it involves more than two energy sources that can increase the use of renewable energy sources that further reduce the use of fossil fuels as well as exhaust gas emissions. Energy management in a hybrid solar vehicle is more complex than a hybrid system consisting of only two sources of energy, and therefore, it should be studied more specifically. The system also can be applied in the shipping field where solar cells can be installed in much larger areas.

In this study, the investigation on energy management in a series-parallel hybrid solar vehicle in the form of electrical energy is conducted. The management strategy of hybrid solar vehicle energy is to determine the working mode of propulsion and battery charging adjusted to the conditions of driving power needed and battery State of Charge (SOC). The energy management investigates further on the energy balance equation for each mode of operation of the vehicle. The series-parallel hybrid energy management implemented is not just a simple type of thermostat management based on the conditions of battery SOC. It is then simulated on a series-parallel hybrid solar vehicle system. The simulation is conducted to see the fuel consumption in the vehicle. In this study, the ratio of power contribution provided by each available energy source is investigated.

2. Methodology

Figure 1 provides a block diagram of a series-parallel hybrid solar vehicle. The main components of the energy conversion source were the Internal Combustion Engine (ICE), batteries (BAT), and photovoltaic (PV). ICE got its energy from burning gasoline, PV from the Sun, while battery got it from three sources: electric generator, regenerative braking, and PV. Generator served to convert mechanical energy output from ICE into electrical energy. Next, the electric motor (EM) as a driver of vehicle wheels received electrical energy from those three energy sources. During the braking process, the electric motor could provide electrical energy to the battery through the regenerative braking process. The flows of mechanical and electrical energy from those three sources are presented in Figure 1.

2.1 Energy Balance

Driving power needed must always be met by an electric motor that gets its energy from the battery, electric generator, and PV. This type of vehicle can be operated in three main modes, depending on the conditions of driving power and battery SOC, namely: (1) The wheels are driven by electric motors whose energy is supplied by batteries and or PV while ICE is off. (2) The wheels are driven by electric motors whose energy is supplied by batteries and or PV and or generators while ICE is on. (3) With the PV provided, battery charging when the vehicle is parked outdoors during the day is possible.

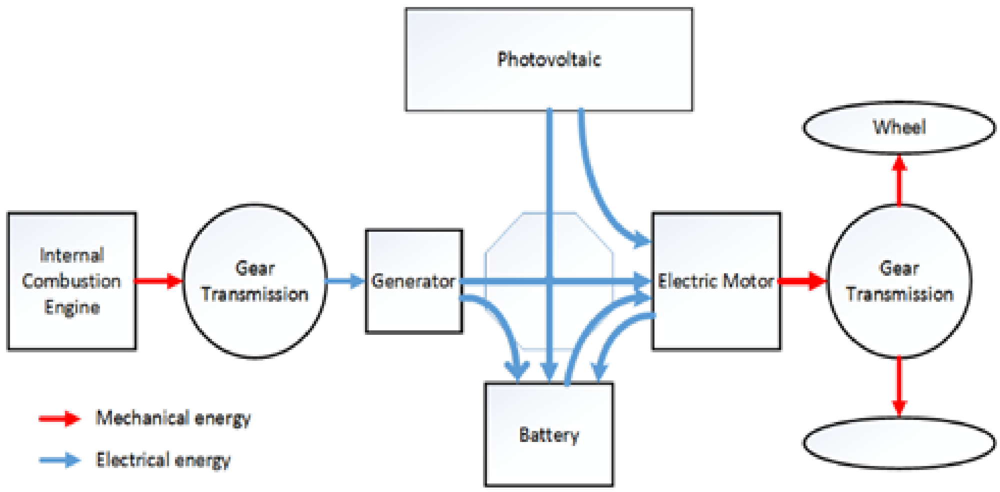

Fig. 1. Block Diagram of Hybrid Solar Vehicle

Despite the energy conversion losses between and within each component, the energy balance equation describing the mode of operation of the hybrid solar vehicle between energy needs and supply can be presented as follows:

i. P_{driver} = PEM, in which $P_{EM} = P_{BAT} + P_{PV}$; that is when the wheels are driven by electric motors whose energy is supplied by batteries and or PV while ICE is off, for instance, when the SOC condition is safe, i.e., between lower and upper limit, and driving power is low. In this situation:
    a. If $P_{driver} = 0$, P_{PV} can be fully used for battery charging.
    b. If $P_{PV=0}$, the EM energy is fully supplied by the battery when the solar radiation condition is completely zero.
    c. If $P_{BAT} = 0$, EM energy is fully supplied by PV. In most normal-sized vehicle systems, this is not possible because the installed PV capacity is usually not very large. However, this mode is possible on the design of special vehicles such as small-sized vehicles with sufficient power capacity of installed PV or applications in the field of shipping.

ii. When $P_{driver} = P_{EM}$, in which $P_{EM} = P_{BAT} + P_{PV} + P_{generator}$ and $P_{generator} = P_{ICE}$, the wheels are driven by electric motors whose energy is supplied by batteries and or PV and or generators while ICE is on to drive the generator.

The amount of output power of ICE-generator can be designed in such a way that it is only for charging the battery and or a part of which is directly to drive the electric motor. Examples of the implementation of this case are:

a. The need for driving is low while SOC is low that battery charging occurs until it reaches the upper limit of high SOC.
b. The need for driving is medium, when ICE has been on before, so the battery charging process even exceeds the upper limit of high SOC. The battery charging limit is SOC = 1.
c. The need for driving is high at any level of SOC condition that ICE is automatically on to start the generator for increasing energy supply to EM.

2.2 Energy Management Strategy

The three sources of energy in a hybrid solar vehicle should be used synergistically to generate fuel consumption saving. Therefore, it is necessary to apply energy management strategy with the principles that (i) the energy balance between the need for driving power and energy supply to the electric motor must be met and maintained at all times. (ii) ICE and EG are operated in their optimum condition. (iii) The battery is maintained at safe SOC range conditions during operation. (iv) Photovoltaic can be utilized as much as possible for battery charging within safe limits. Battery charging can be done by means of three sources, namely: PV, regenerative braking and electric generator current driven by ICE. Battery charging is set as follows:

a. Battery charging from PV can be done as long as solar radiation still allows to generate electrical energy and the battery is still in safe level for electric charging.
b. Battery charging from regeneration braking can be done during the braking process and energy can be saved if battery SOC is still possible to do charging.
c. Battery charging from the electric generator depends on the battery SOC level condition and the need for driving power.

Battery SOC levels are classified into low, medium and high. The amount of driving power is also divided into three ranges: low, medium, and high. Based on the classifications of the driving power range and the SOC range of batteries, different working methods of a hybrid solar vehicle will be applied to ensure that the needs for driving power are always met. Also, it is useful to determine when the battery charging process starts, takes place or stops. The following are examples of settings based on SOC and the needs for driving power levels:

a. The need for driving power is low. Under these conditions ICE will be on when battery SOC reaches the lower limit of low SOC and the battery charging will take place until the upper limit of high SOC is reached, and then ICE will turn off again.
b. The need for driving power is medium. In the case of medium load, if in the initial condition ICE is off,it will remain in the off condition, and then it will be on soon after the lower limit of low SOC is reached. Meanwhile, if ICE is already on, the initial condition of ICE is on, ICE will be allowed to be on although the upper limit of high SOC has been reached. The maximum charging limit is SOC=1.
c. The need for driving power is high. In the case of high load, ICE will be positioned on at any level of SOC battery. In this case, the maximum charging limit is SOC=1.

The minimum limit of P_high determination is the driving power level in which the total energy losses of conversion from the ICE output to the Generator to EM is lower than that when the energy conversion process is done through the ICE-Generator-EM- batteries where the ICE is at its optimum efficiency condition.

d. The battery is not allowed to drive EM by itself when the SOC level is under SOC_low.

e. Overall, the energy management strategy or working mode arrangement of the series type of hybrid solar vehicle, considering the needs for driving power and SOC battery conditions, is presented in the flowchart of Figure 2.

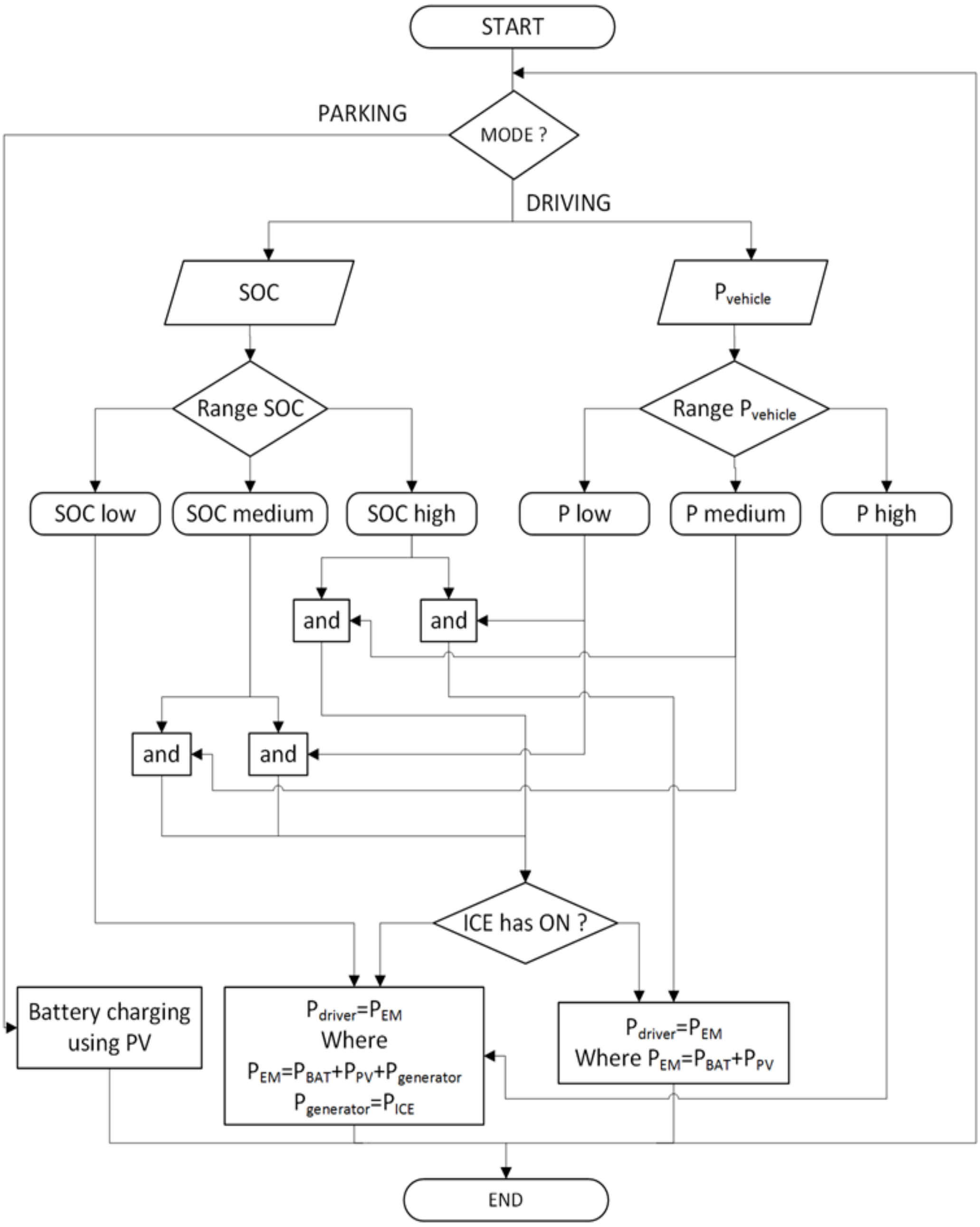

Fig. 2. Flow chart of strategies of energy management

3. Results and Discussions

The simulation conducted by using the NEDC driving cycle as presented in Figure 3. The performance of the power of the vehicle, electric motor, battery, electric generator, internal combustion engine, and photovoltaic during the driving cycle presented in Figure 4. The needs for driving power always met by electric motor power, so it seems that both have a profile similar. The electric motor power is slightly larger than the driving power. At the time when driving power is under zero, EM will serve as a generator. Battery power also has a profile similar to electric motor power, but at the time of charging by the generator, after 400th seconds, there is a significant energy input from the generator to the battery.

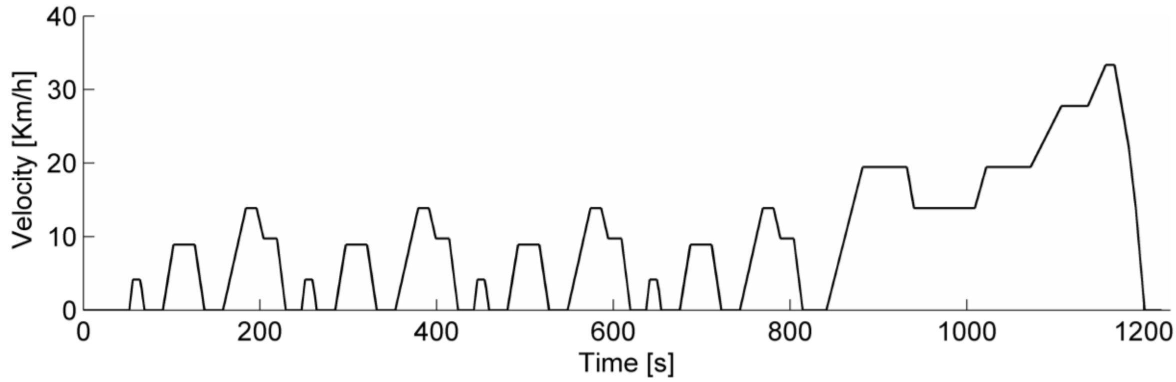

Fig. 3. NEDC driving cycles

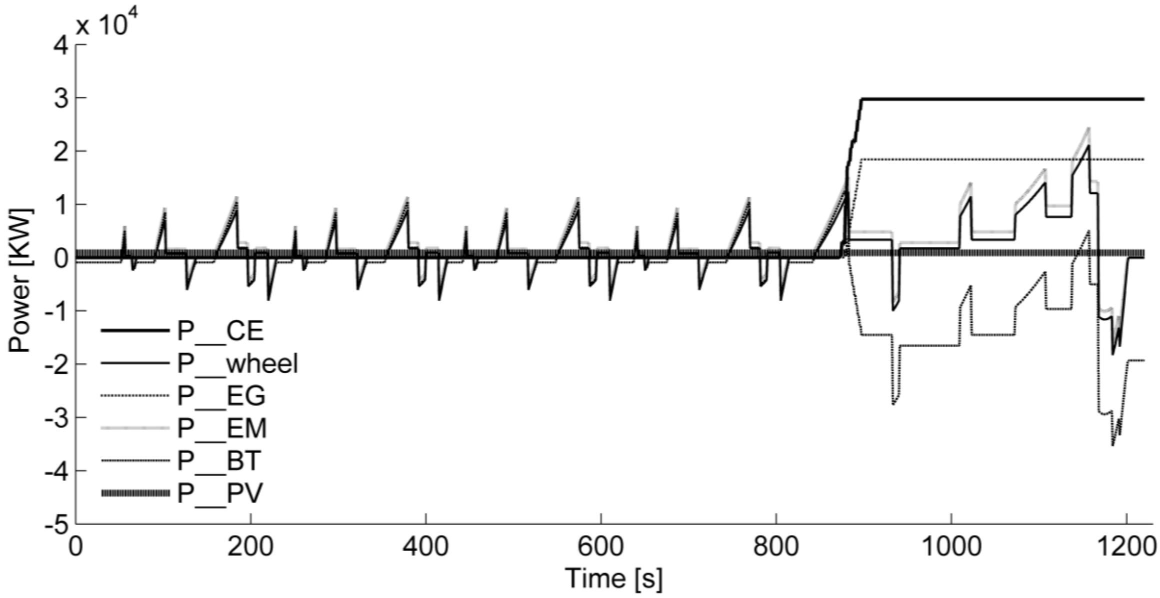

Fig. 4. Power of main components

The battery gets its energy from the generator, solar cells, and the regenerative braking process. Battery charging from the generator depends on the energy management strategy in determining the time to start the battery charging. If initial SOC is 0.41, Before 400th seconds, the battery was charged both by regenerative braking and PV while it supplied energy to the EM. Then, after 400 seconds, the battery was charged by EG, PV and regenerative braking while it supplied energy to the EM. The battery charging from the generator starts at the second of 400 because SOC battery at that time has touched the lower limit of charging. In this simulation, some initial SOC inputs to test energy management strategies tested. At SOC of 0,2; 0,7; 0,9 it seems that the process of battery charging by the generator occurs at different times, Figure 5.

When initial SOC is 0.2, that is under SOC low generator will automatically be on since the beginning of the driving cycle. It will be on until the upper limit of charging reached and or driving power is at a high level.

When initial SOC is 0.7, that is between SOC low and SOC high, ICE will be on in the second of 1137 although battery SOC has not reached SOC low. It is so because driving power is at a high level as in the previous case.

When initial SOC is 0.9, that is above SOC high; battery charging still takes place in the second of 1137 although battery SOC has not reached SOC_low. It is so because the driving power is at a high level that the generator starts.

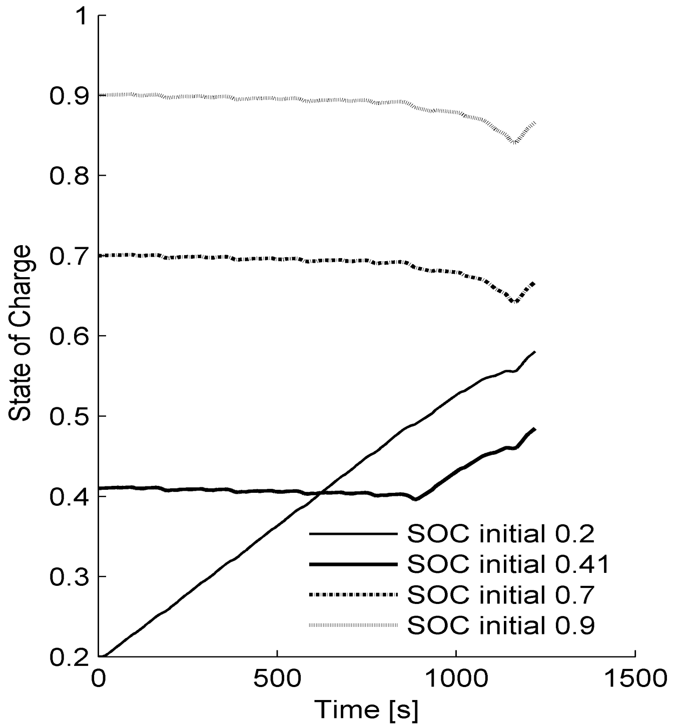

Fig. 5. SOC of battery

The energy input of solar radiation is directly proportional to the level of received radiation. In this simulation, the received radiation is assumed to be constant at the available period of times. Electrical energy from PV is received and converted during the driving cycle takes place, as seen in Figure 4.

During a period of times of 1200 seconds under daylight conditions, assumed that the output energy of PV is constant. The contribution of solar energy is about 3%. In the hybrid solar vehicle, electrical energy obtained from PV is cultivated for battery charging and or driving an electric motor. It takes place as long as PV is directly exposed to solar radiation when the vehicle is in use or is parked. Assuming the current solar cell efficiency level is 20%, the limits area of the solar cell to be used are on the available top area of the vehicle. Thus, if significant power contribution of the solar cell needed, hybrid solar vehicle management should be applied to very light vehicles or the shipping field. Another interesting thing in the use of PV is that solar energy can continuously be received even when the vehicle has been off, for example, while being parked. Today the realisation of solar cell charging facilities on regular use, which placed in the parking area is the most feasible option. It will increase the charging capacity significantly. Also, it can be safe and available throughout the year in tropical countries like Indonesia.

As the driving force of the vehicle, EM operates at a relatively stable efficiency that is around 70%-90%. Figure 6 and Figure 7 show that in acceleration mode, EM converts electrical energy of a battery into mechanical energy while in deceleration mode, EM serves as a generator and supplies electrical energy to the battery. In HSV, it is possible to combine the energy of the accumulated generator, battery and PV driving the EM together. It is a combination of parallel energy supply in the form of electrical energy for EM. The implementation of this strategy makes it possible to choose smaller battery power capacity than that of EM. The selection of parallel methods in the form of electrical energy is also simpler in design than that of mechanical-electric.

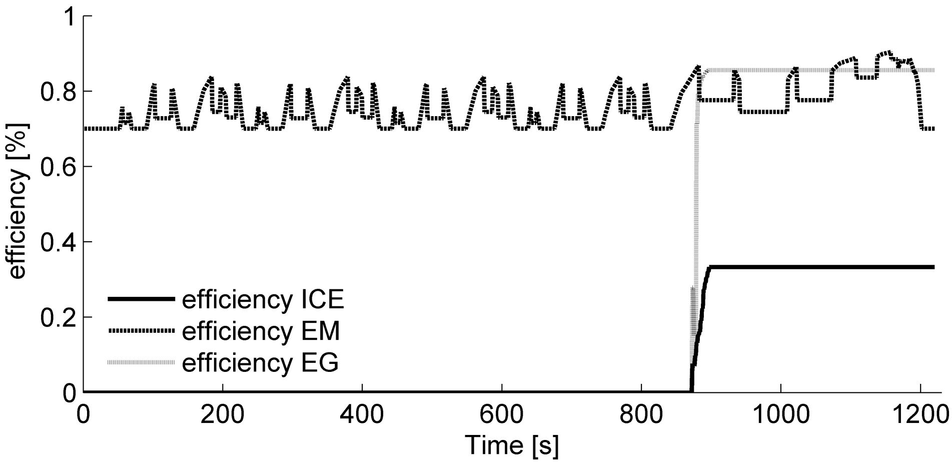

Fig. 6. The efficiency of ICE, EM, and EG

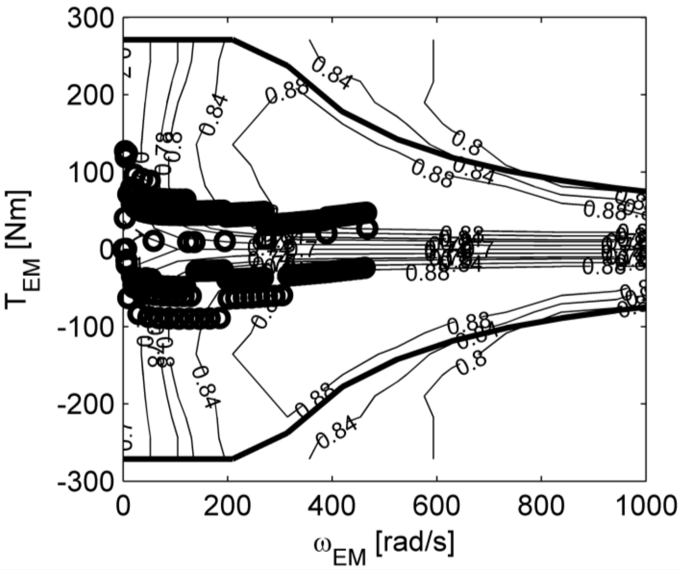

Fig. 7. Electric motor efficiency map

Figure 8 shows maps efficiency for ICE in HSV. The energy management regulates that when it is on, ICE always operates at its optimum cycle, which is at the efficiency of 34%. The ICE output will be converted to electrical energy by a generator that operated at approximately its optimum efficiency at around 85%, Figure 9. The ICE power capacity must be balanced with the generator power capacity so that both potentials can synergize as much as possible. Generator capacity is chosen to be able to perform the battery charging process as well as to move the EM on a relatively significant driving power. The generator combined with the battery and the PV must be able to drive the EM at its maximum capacity.

Conventional vehicles operate met the driving cycle speed profile so that it is often operated not at its maximum efficiency, Figure 10. Fuel consumption in a conventional car is 8.7 L/100 km. Table 1 shows the fuel consumption in the proposed HSV.

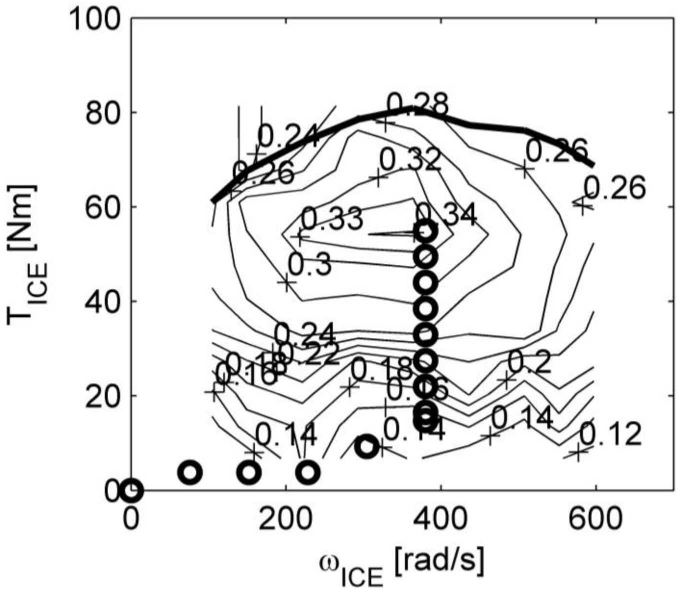

Fig. 8. Internal combustion engine map

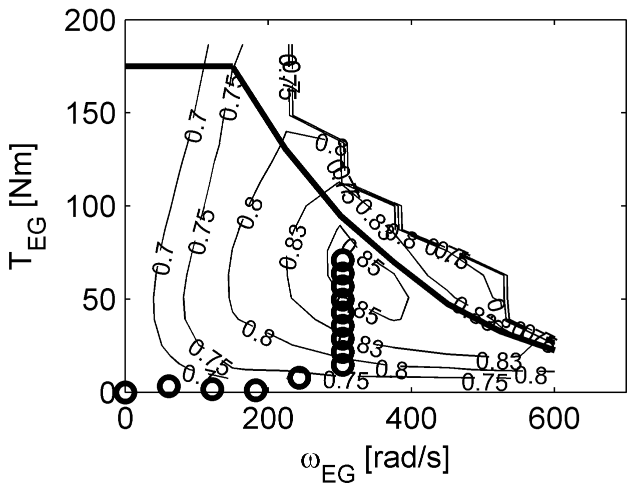

Fig. 9. Electric generator map

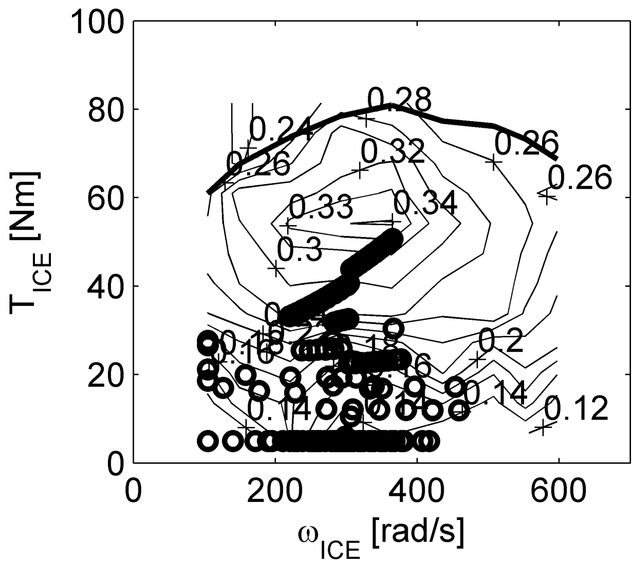

Fig. 10. Conventional vehicle engine map

Table 1
The Fuel consumption and SOC of the battery of HSV

Initial SOC	Hybrid Solar Vehicle (Power of PV = 900 Watt)	
	Fuel Consumption L/100 km	SOC at the end of Driving Cycle
0.20	10.3	0.55
0.41	2.8	0.48
0.70	0.5765	0.66
0.90	0.5765	0.86

This fuel-saving in the HSV system because of the ICE in HSV system always operates in optimum efficiency. The average fuel saving is about 30% depending on the initial SOC of battery conditions. Then, the fuel-savings also because of regenerative braking and additional power from PV. The PV contribute about 0.6% during the driving cycle. The contribution of PV can increase if we use a bigger size of PV but the area of vehicle is the limit. However, PV will continue charging the battery as long as the car gets solar radiation even the car just in parking condition.

4. Conclusions

In this article, the performance of hybrid solar vehicles has investigated. The development of the implementation of PV on vehicles is interesting.

Energy management of hybrid solar vehicle is more complex than that of an ordinary hybrid vehicle. The former has more options in saving fuel consumption than conventional or ordinary hybrid vehicles. Three main things about the potential saving of fuel consumption in a hybrid solar vehicle are related to the setting of the working modes of the internal combustion engine at its optimum working efficiency, regenerative braking and the use of PV at its maximum efficiency so that the fuel consumption saving reaches 30% compared with a conventional vehicle. The PV delivers 0.56% power supplied.

Photovoltaic can be applied to all driving modes when solar radiation is sufficiently available. Even when the vehicle is parked PV can still be enabled for charging the battery. Adding installation of PV on the roof of the parking area is an attractive option to speed up the battery charging.

The configurations of the electrical series-parallel system are relatively simpler and more in line with the typical use of photovoltaic in vehicles and also with the direction of the development of automotive technology in which electric vehicles have significant increases.

Energy management of hybrid solar vehicle considering the need for driving power and battery SOC ensures the system to be more reliable than considering just the battery SOC.

Although the efficiency of solar cells in the market continues to increase, their lack of implementation in the field of vehicles and the limited use of PV due to the little energy density makes their contribution is relatively little compared to other energy sources. To increase the contribution of solar energy, a very large extent is still needed, but it is often not feasible on land-based applications for cars.

Pollution potential is low as a result of the operation of ICE in its optimum area. The use of PV does not produce pollution. Furthermore, it reduces the energy losses using regenerative braking technology.

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