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Power Management For A Series Hybrid Electrical Vehicle Via On-off Control Strategy

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Abstract Hybrid electric vehicles (HEV) powered by internal combustion engine (ICE) and energy storage device are now being given more and more attention because of their inherent advantages over the conventional vehicles (i.e. increased fuel economy, reduced harmful emissions and better vehicle performance). Most common HEV types are series hybrid electrical vehicles (SHEV) and parallel hybrid electrical vehicles (PHEV). As the HEV improvement highly depends on the management of power flow between the different parts of the vehicle, an attempt will be made through this paper to study the on-off control strategy for a SHEV with the help of Matlab/Simulink. In the on-off control strategy, the IEC is operated at its optimal operating point which is based on minimization of fuel consumption or minimization of emissions or even a compromise on both. The overall efficiency of the SHEV under the on-off control strategy will be investigated and the effect of the initial state of charge (SOC) of the battery on the overall efficiency will be considered.

Key words: Hybrid Vehicles, On-off Strategy, Driving Cycle, State of Charge.

إدارة الطاقة للمركبة الكهربائية الهجينة عبر استراتيجية التحكم في التشغيل والإيقاف

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الملخص هناك المزيد من الإهتمام مؤخراً بالمركبات الكهربائية الهجينة (HEV) والتي تعمل بواسطة محرك الإحتراق الداخلي (ICE) والبطاريات بسبب مزاياها على المركبات التقليدية (مثل زيادة الإقتصاد في استهلاك الوقود وتقليل الإنبعاثات الضارة وتحسين أداء السيارة). أكثر أنواع HEV شيوعاً هي المركبات الكهربائية الهجينة المتوالية (SHEV) والمركبات الكهربائية الهجينة المتوازية (PHEV). نظراً لأن تحسين HEV يعتمد بشكل كبير على إدارة تدفق الطاقة بين الأجزاء المختلفة من السيارة ، فسيتم إجراء محاولة من خلال هذه الورقة لدراسة إستراتيجية التحكم في التشغيل والإيقاف لـــ SHEV بمساعدة Matlab / Simulink. خلال هذه الاستراتيجية يتم تشغيل IEC عند نقطة التشغيل المثلى والتي تعتمد على تقليل استهلاك الوقود والإنبعاثات. سيتم التحقيق من الكفاءة الكلية لـــ SHEV في إطاراستراتيجية التحكم في التشغيل والإيقاف وسيتم النظرفي تأثير حالة الشحن الأولية (SOC) للبطارية على الكفاءة الكلية.

الكلمات المفتاحية: المركبات الهجينة، استراتيجية التشغيل، دورة القيادة، حالة الشحن.

Introduction

In a conventional vehicle, an internal combustion engine (ICE) provides power and matches the load at all times. The conventional engine should ideally have high efficiency when the vehicle is starting, accelerating and cruising .This is hard to fully achieve and therefore the average ICE efficiency is much lower than its peak efficiency .Also, when the ICE follows transient loads emissions will increase[1].

In a hybrid electric vehicle (HEV), however, one or more additional sources of power are used and can support the ICE. The ICE is taken as the primary source (steady state source) and the battery-electric motor are taken as the secondary power source (dynamic power source). The battery can be replaced by flywheels or ultrcapacitors [2].

This gives the chance to operate the ICE more efficiently and transients could be avoided. Also, most hybrid vehicles have the ability to regenerate some of the vehicle's kinetic energy at the time of decelerating [3].

The main advantages of HEVs over the conventional vehicles are lower fuel consumption as a result of higher system efficiency and energy regeneration in addition to Lower emissions as a result of the lower fuel consumption and avoidance of emissions formed by ICE transients [1], [4].

The configuration of a hybrid vehicle is defined as the connection between the components which define the energy flow routes and control ports.

System Modelling in Matlab/Simulink

The SHEV can be decomposed into two parts: the battery charge and the traction system. The battery charge is composed of a combustion engine, a generator and a power converter. The traction system is composed of a power converter, a motor unit, a gearbox, a mechanical differential, four wheels and the vehicle chassis [5]. Fig.1 illustrates the block diagram of the SHEV.

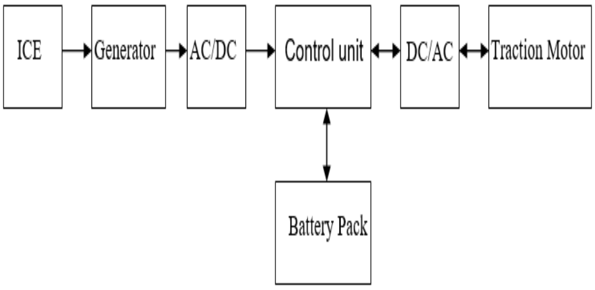

Fig. 1: SHEV block diagram

The vehicle components and control logics are modelled in Matlab/Simulink. Some of the Matlab/Simulink subsystems are described below.

Engine/Generator Unit

The engine/generator in a SHEV is used to supply steady-state power in order to prevent the battery from being discharged completely. When calculating the power of the engine/generator, two conditions should be considered, one is driving for a long time with constant speed, such as highway driving between cities, and other is the driving with frequent stop-go driving pattern, such as driving inside the cities which is the case considered for this paper. In the long distance driving pattern, the drive train should not rely on the battery to support the operation at a certain high speed, say 130 km/h or 80mph. The engine generator should be able to provide enough power at this high speed. For the stop-go pattern, the engine/generator should provide sufficient power to maintain the energy storage of the battery at a certain level, so that enough power can be drawn to support the vehicle acceleration. In this study, diesel combustion engine and three phase induction generator type are used. For this control strategy, the engine is to operate only at it is best efficiency which is 31.895 % at engine output 50KW. [6]

Battery Unit

An important factor in the performance, durability and long term reliability for the SHEV is the energy storage system being utilized (i.e. In this case, it is a battery). In this study a lead-acid battery is utilized and it is represented by its current voltage charging and discharging characteristic shown in fig. 2.

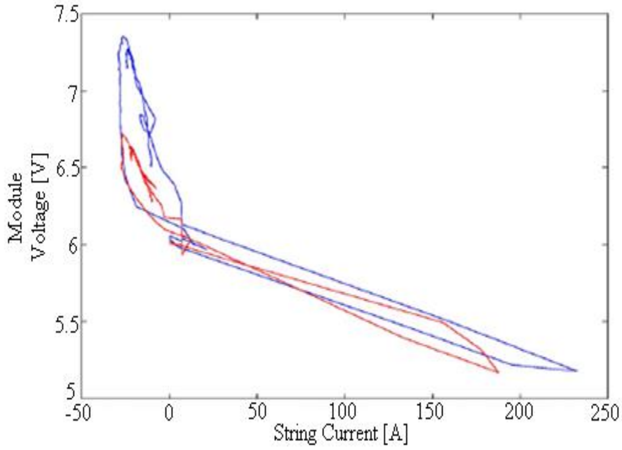

Fig. 2: Current–voltage plots for one module of a 36V [7].

The above curve has been modified to suit the requirements of this application where nine modules have been connected in series to implement 324V nominal voltage and 10Ah capacity.

Finally the current-voltage characteristics have been entered into a lookup table for further Matlab/Simulink construction. Fig.3 depicts the battery subsystem in the Matlab/Simulink model.

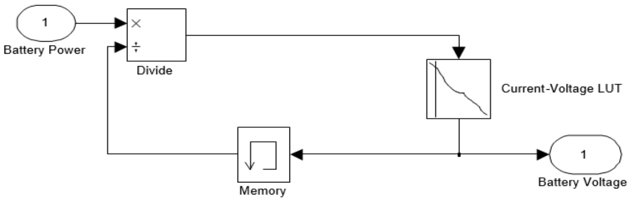

Fig. 3: Battery subsystem in the Matlab/Simulink model

In most systems that use a battery, an important point is the knowledge of the state of charge (SOC) of the battery or more simply: how long does it take before the battery stops working?

SOC of a battery is defined as the ratio of the present charge of a battery to the maximum charge that can be possibly stored in a battery. A fully charged battery would have a state of charge as one while a completely discharged battery would have a state of charge as zero [8].

In order to determine the SOC of the battery, the energy consumed or generated is calculated at each time step and would be added to or subtracted from the available energy in the previous time step. The new energy value would then be stored in memory to be used for the next time step. Equation (1) shows that the battery SOC is calculated by dividing the current energy value by the maximum energy capacity of the battery [7].

$$SOC_{[i]} = SOC_{[i-1]} - \frac{Pt \times \Delta t}{3600 \times P_f}$$

(1)

Where:

P_t = battery power (watt)

P_f = maximum energy capacity of battery pack (kWh)

Δt = the time period at which the SOC is calculated = 0.005s.

The maximum energy capacity of the battery is calculated by multiplying the rated capacity (10Ah) and the rated voltage (320V) of the battery.

Maximum energy capacity =10 × 320 = 3.2kWh.

Fig. 4 depicts the SOC calculation subsystem in the Matlab/Simulink model.

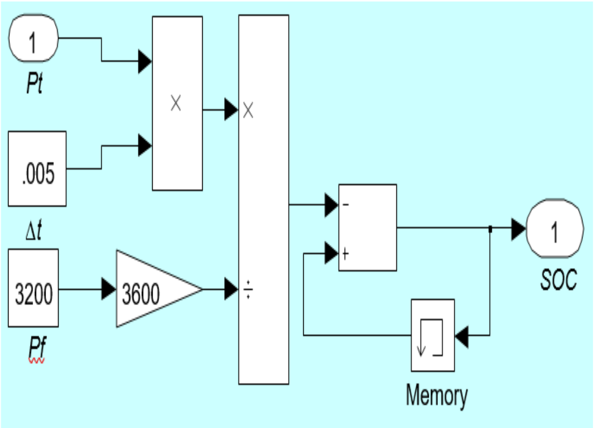

Fig. 4: SOC calculation subsystem

To calculate the charging and discharging efficiency of the battery, it is assumed for simplicity that the internal resistance of the battery is fixed at 1.5Ω.

Motor Unit

A permanent-magnet type synchronous traction motor is adopted to achieve higher performance, higher reliability and downsizing. In order to provide drivers with a smooth feeling during operation and to achieve high system efficiency it covers a wide driving range from low speed high torque to high speed low torque. When the brakes are applied, the motor converts kinetic energy to electric energy and stores it in the battery [9].

The motor characteristics are based on the efficiency data obtained from [10] and shown in fig. 5 where the power electronic losses are also included.

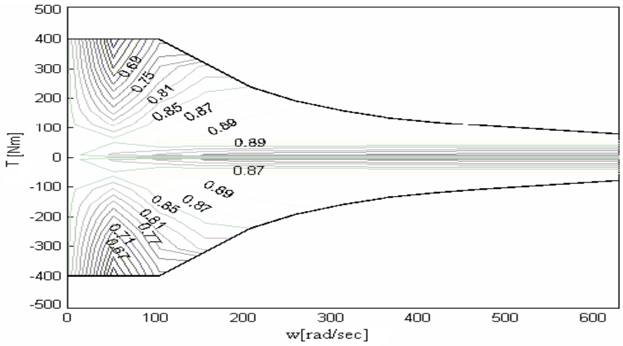

Fig. 5: Efficiency map of electric motor (including power electronic efficiency) [10]

As mentioned earlier, the traction motor must be sized for the maximum power requirement since it is the only power plant propelling the vehicle and hence a 50kW traction motor is used to suit the requirements of the New European drive cycle (NDEC) shown in fig. 6.

Drive cycle

In order to help with the simulation and analysis of the SHEV, certain typical driving schedule has been used. This driving schedule represents typical traffic environment for a particular range of time. The drive cycle is a plot of velocity and mechanical power demanded versus time. A (NEDC) shown in fig. 6 has been used for this purpose.

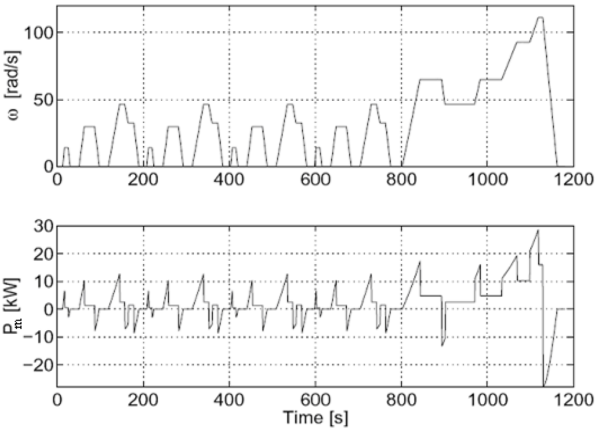

Fig. 6: Vehicle drive cycle [11]

The drive cycle subsystem shown in fig. 7 contains the time history data for the calculated demanded electrical power where it is modelled as a look-up table.

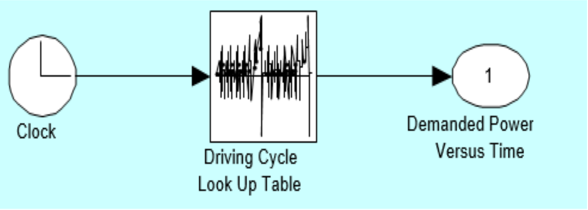

Fig. 7: Drive cycle subsystem in Matlab/Simulink model

On-Off Control Strategy

Generally, the engine should be controlled such that it always operates at its optimal operation point, in which the fuel consumption and the emissions of the vehicle are minimized.

A well-proposed on-off control strategy is very important for optimal performance of the drive train. It ensures that the engine runs at its optimal efficiency point and that the battery state of charge is maintained between its upper and lower limits through out the drive cycle [8].

In this control strategy, the operation of the engine is completely controlled by the SOC of the battery. When the SOC reaches its upper limit, the engine is turned off and the vehicle is propelled by the battery alone. When the SOC reaches its lower limit, the engine is turned on and the battery is charged by the engine/generator unit, thus enabling the engine to always operate at its optimal operating point. Fig. 8 describes how the engine is turned on and off depending on the SOC.

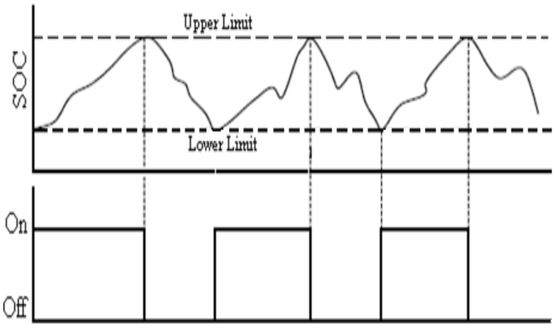

Fig. 8: Engine on-off control [8]

Fig. 9 shows the Simulink file used for the on-off control strategy

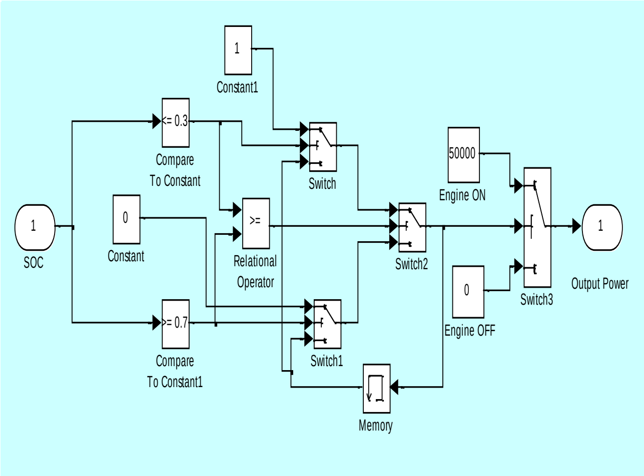

Fig. 9: Engine on-off control Matlab/Simulink subsystem

In fig. 9, the SOC is compared to preset upper and lower limits (i.e. 0.7 and 0.3). If SOC is less than 0.3 the engine will start running at its optimal operating point supplying the system with 50 KW. Once the battery is charged and the SOC reaches 0.7 the engine is switched off and the vehicle is only propelled by the battery. Fig. 10 indicated the overall Matlab/Simulink file.

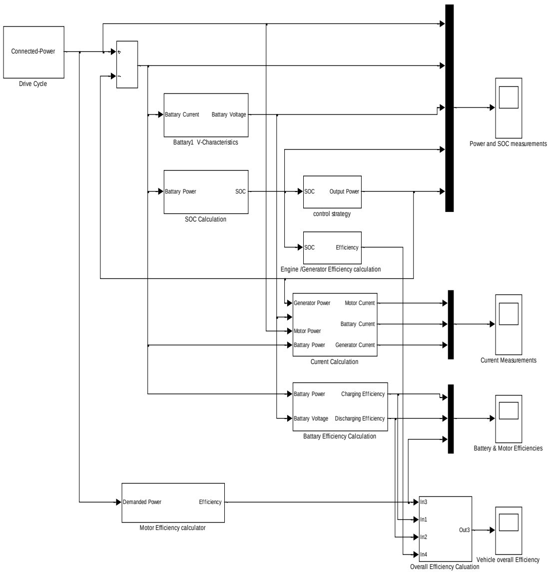

Fig. 10: Overall Matlab/Simulink File

Results and Discussions

After the design had been completed, the vehicle was simulated for its performance over the New European drive cycle of 1200 seconds for the on-off control strategy. The results of the simulation are as shown in fig. 11. One can easily see the engine turning on and off as the SOC varies between 0.3 and 0.7. The battery power flow is negative when the engine is on which means that the battery is being charged. Fig. 11 (e) indicates battery instantaneous voltage against time. For illustration purpose, the simulation period has been repeated for one more cycle.

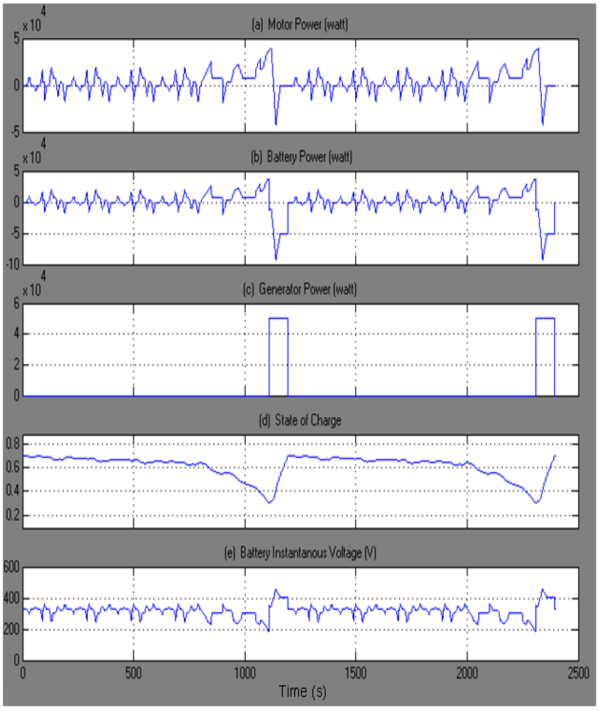

Fig. 11: (a) Motor electrical power (b) Battery power (c) Generator power (d) State of charge (e) Battery instantaneous voltage

Another goal is to find the overall efficiency of the vehicle. It has been achieved by firstly simulating the individual efficiency for each component of the vehicle (i.e. the engine/generator unit, Battery unit and the motor unit) and then according to the operating modes, the interacting efficiencies were calculated and finally the average efficiency value was taken. Battery charging efficiency, battery discharging efficiency and the motor efficiency are shown in fig. 12.

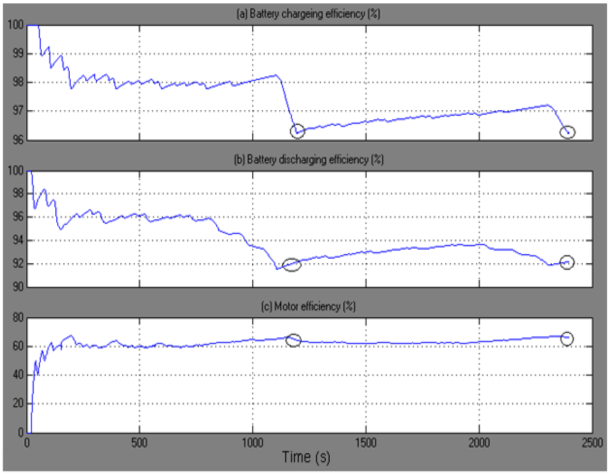

Fig. 12: (a) Battery charging efficiency (b) Battery discharge efficiency (c) Motor efficiency

Although the overall efficiency of the vehicle is taken as the average of the previous four cases, it can be said that taking the average is not a very accurate way to find the overall efficiency because the four cases do not last for the same time. Fig. 13 shows the overall efficiency.

As mentioned earlier the efficiency of the series hybrid vehicle has to be much higher than that of the conventional vehicle due to running the engine at its optimal operating point and the use of the battery system and the regenerative energy.

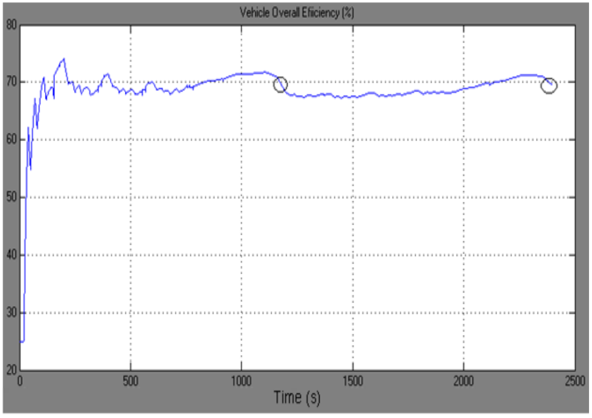

Fig. 13: Vehicle overall efficiency

All the previous simulation was done using an initial SOC value of 0.7 which would not always happen in practice. Therefore, the effect of having different initial values of SOC has been analysed by simulating the system using 0.3 and 0.5 as initial values of SOC.

Table (1) shows the overall efficiencies over different initial SOC values.

Table 1: Overall efficiencies against SOC

	On-off strategy		
SOC $_{initial}$	0.3	0.5	0.7
η (%)	68.1	69.1	69.60

It is clear that the higher the initial SOC the higher the efficiency because more initial energy is assumed to be already stored in the battery and hence less input energy is consumed leading to an increase in the overall efficiency.

Conclusion

Several benefits can be achieved by using the hybrid technology, whereas this introduces some issues. For example, a hybrid vehicle is more complex than a conventional vehicle as it includes some components such as power electronics, battery packs and electrical machines. Some of these components are quite expensive and also an increase in number of components may increase the risk of failure. Additionally, if hybrid vehicles become more common, car repair shops must be able to handle the electrical drive system. However, the hybrid technology is one way to reduce the fuel consumption and the emissions of vehicles.

The key design parameter in a SHEV is how to select the suitable size of the generation and storage devices. Measuring of energy storage in batteries presents the most difficult problem in designing a SHEV. Also life cycle of the battery has an effect on both the cost of the vehicle and the control strategy chosen. System design involves deciding the power of each component, so that these components would work together to generate motion, and satisfy the performance conditions of the user with minimum fuel consumption and emissions. Therefore, on-off control strategy has been developed for a SHEV.

It is clear that for different kinds of driving cycle and power demand, different control strategies are needed to get the optimal performance. This could be a suggestion for a further study.

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