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The Energy Flow Management and Battery Energy Capacity Determination for the Drive Train of Electrically Peaking Hybrid Vehicle

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ABSTRACT

In this paper, the configuration of a parallel hybrid vehicle, called electrically peaking hybrid (ELPH) vehicle is introduced. Several operation modes of the engine and electric motor and different control strategies are analyzed. The results show that, with proper selection of the drivetrain parameters, the vehicle can satisfy the urban and highway driving with a small internal combustion engine, a small battery pack and a single gear transmission. Moreover, the vehicle does not need to charge the battery pack from the electricity network for keeping its battery SOC at a reasonable level.

INTRODUCTION

In recent years, increasing concern over air pollution, caused by tailpipe emissions of petroleum-based vehicles, and the dwindling petroleum resources have lead the automotive engineers and automakers to probe the possibility of the zero-emission (ZE) and ultra-low emission (ULE) vehicles. Among all kind possible schemes, electric vehicle (EV) seems to be the most attractive due to their zero emission, petroleum-free energy supply, control flexibility, and simple construction. However, pure electric vehicles suffer from other disadvantages.[5,6]

1. The heavy and bulky battery pack, with very limited energy storage, makes the EV limited in range, and load carrying capacity.

2. Long charging time limits the EV's availability.

Therefore, commercial success of the EV depends entirely on development of advanced high energy batteries. However, progress in batteries over the past several decades has not been adequate.

Hybrid configurations, in which two power sources are applied to propel the vehicles, are now holding the greatest promise. The hybrid electric-internal combustion engine drive train, if properly configured, can combine the advantages of both EV and ICE vehicles with no drawbacks.

The configuration of a parallel hybrid vehicle, called electrically peaking hybrid (ELPH) vehicle is shown in Fig. 1.[7,8,9,10] The internal combustion engine (ICE) and the electric motor are coupled by a set of match gear (or chain) into the input shaft of the transmission. The transmission would be multi-speed or single-speed depending completely on the performance requirement and drivetrain parameters selected.

When the vehicle operates on level road with constant cruising speed, relatively low power is required, but large amount of energy is consumed in a long trip. In this case, a small ICE alone is used to power the vehicle, resulting in an excellent fuel economy due to its operating point being close to the optimal point. When the vehicle experiences an acceleration or a steep hill climbing, the electric motor, functioning as a load leveling device, supplies supplementary power to the drive train to meet the performance requirement. The ELPH configuration has the ability to recover braking energy with the electric motor functioning in regenerating mode. Furthermore, when the vehicle operates with light load, such as at a relatively low constant speed or going down a slight hill,

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the engine can recharge the battery pack to maintain adequate state-of-charge. More beneficially, this enhances the engine load, for operation close to its optimal point. A well designed ELPH vehicle may never use a wall plug to charge its battery pack and can obtain an excellent fuel economy.

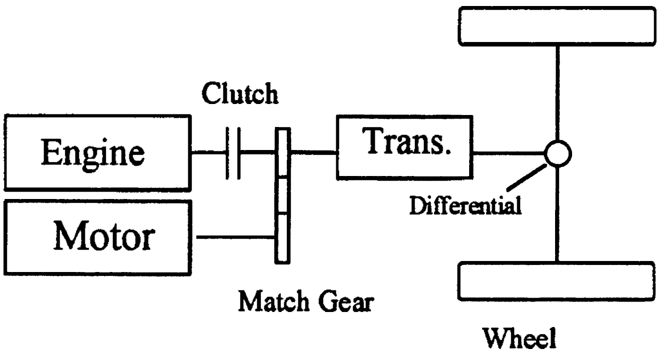

Fig. 1 The Configuration of the ELPH Vehicle

MANAGEMENT OF MOTOR AND ENGINE POWER

The operation of a vehicle can be divided into three basic modes: constant speed (cruising), acceleration (peak power) and deceleration (regeneration). In each mode, the engine and the motor operate with the appropriate behavior to meet the load power requirement and keep proper SOC on the battery.

CRUISING MODE - The cruising mode is the operation mode of the vehicle in which the engine alone can meet the load power requirement, such as operating on a level road with constant speed or with a slight acceleration or a slight hill climbing with constant speed. In this operation mode, the engine and electric motor have several operating status.

Motor-only Tractive Mode - When the speed of the vehicle is less than the speed that is limited by the minimum rpm of engine or greater than the speed that is limited by the engine maximum rpm, all the power required by the load of the vehicle is supplied by the electric motor. The engine must remain at standstill or in idling. In these cases, we have

$$P_e = 0 \quad (1)$$

$$P_m = P_l \quad (2)$$

$$P_b = \frac{P_m}{\eta_{bd}\ \eta_m} \quad (3)$$

where, P_e = power output of engine,
P_m = power output of electric motor,
P_l = load power of the vehicle,
P_b = discharge power of the battery pack,
η_{bd} = discharge efficiency of the battery pack,
η_m = efficiency of the motor.

In this operating mode. All the required energy must be supplied by battery pack.

Battery Pack Charging Mode - When the load power of the vehicle is less than the engine power with wide open throttle, engine has the extra power to charge the battery pack, if necessary. The electric motor functions in the regenerating mode to convert the engine power into electric power to recharge the battery pack. The electric motor power (as a generator), P_m, and battery pack recharging power, P_b, are

$$P_m = -(P_e - P_l) \quad (4)$$

$$P_b = P_m \eta_m \eta_{bc} \quad (5)$$

where; η_{bc} = the battery pack charging efficiency .

Negative P_m means electric motor functioning as generator.

Engine-only Mode - If the battery pack is not required to be recharged, for example, the SOC of the battery pack reaches its top line, the electric motor is idling and the engine power is equal to the load power of the vehicle, that is

$$P_e = P_l \quad (6)$$

PEAK POWER MODE - When the vehicle experiences an acceleration or a steep hill climbing, the load power is much greater than that the engine can produce. Consequently, the motor must work together with the engine to produce enough power to meet the requirement. In this case, the motor power output and battery power output are

$$P_m = P_l - P_e \quad (7)$$

$$P_b = \frac{P_m}{\eta_{bd}\eta_m} \quad (8)$$

REGENERATING MODE - When the vehicle experiences a deceleration or a hill descending, the engine is turned off or idles. The electric motor functions in regenerating mode. The electric motor (generator) power P_m, and battery charging power, P_b, are

$$P_m = \alpha P_l \tag{9}$$

$$P_b = P_m \eta_{tm} \eta_m \eta_{bc} \tag{10}$$

where α = fractional factor of power recovery,
η_{tm} = efficiency from motor to the drive wheels.

In equations (1) to (10), positive P_e, P_m and P_b mean that the engine, motor and battery pack supply powers to the vehicle. In contrast, negative P_m and P_b means that motor and battery pack absorb power from the engine or regenerating braking.

THE ENERGY CHANGE IN THE BATTERY PACK

As explained above, in the peaking power mode, the battery pack must supply energy to the vehicle. Consequently, the stored energy in the battery pack is decreased. On the other hand, when the vehicle operates at low load or in the braking mode, the battery pack absorbs energy from engine or regenerative braking. In a whole drive cycle, if the consumed energy and absorbed energy are balanced, the battery pack will never have to get energy from wall plug. Therefore the range of the vehicle is only limited by the fuel tank as in a conventional vehicle.

The amount of energy change in the battery pack at time t in the drive cycle ($t=0$ represents the beginning of the drive cycle) is expressed by

$$E = -\int_0^t P_b d\tau \tag{11}$$

The negative sign means that when P_b is positive (battery pack supplies power to the vehicle), the energy in the battery pack is decreased. If, at the end of the drive cycle, the value of E is the same as that at the beginning of the driving cycle, the battery SOC will be kept the same as at the beginning of the drive cycle. Consequently the vehicle will not need wall plug to charge the battery.

CONTROL STRATEGIES OF THE DRIVETRAIN

As explained above, at any time in driving, the sum of the engine power, P_e, and the electric motor power, P_m, should be equal to the vehicle load power P_L (except in the braking mode, in which external braking power may be applied by brake system of the vehicle). In the actual operation, the control system of the drivetrain can determine the power output of each power unit in many ways, provided the total power output meets the requirement. Different control strategies will obtain different fuel economies and different battery energy capacities.

MAXIMUM BATTERY SOC CONTROL STRATEGY - The maximum battery state-of-charge control strategy is consistent with the principle that, at any time, except the battery SOC reaching its top line, the engine should operate with full load (wide-open throttle) to produce maximum power. One part of the engine power is used to counterbalance the vehicle load power, and the remainder is used to charge the battery. This control strategy is illustrated in Fig. 2. In this figure, the segments a and a' represent the battery charging power for high-speed and low-speed gears of the transmission respectively. Similarly, b and b' represent the battery discharging power for higher and lower speed gear of the transmission. *Fig. 2* also implies that a multi-speed transmission is helpful to reduce the size of battery pack. However the penalty is a complicated construction and control system.

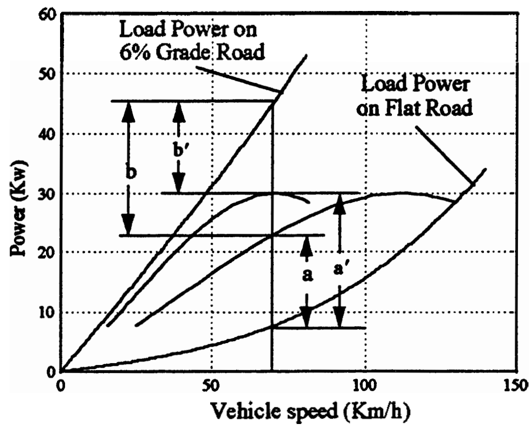

Fig. 2 Battery Charging and Discharging Power

OPTIMAL CONTROL STRATEGY - Fig. 3 shows the fuel consumption map of a typical SI engine with its optimal fuel economy operating line. If operating point of the engine is just on the optimal fuel economy operating line, the engine has a optimal operating efficiency. Fortunately, the power output corresponding to the optimal operating line is just a little smaller than the power output with a full load (wide-open throttle). This implies that, if the control system controls the engine operating on the optimal operating line, the vehicle can not only maintain the battery SOC at a certain level, but

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