BASICS OF ELECTRIC VEHICLE TECHNOLOGY AND A DESIGN STUDY ON A SERIES HYBRID ELECTRIC VEHICLE POWERTRAIN

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ABSTRACT

This paper starts with the basics of electric vehicle technology and introduces design principles of series hybrid electric vehicle. A series hybrid electric vehicle powertrain design study has been presented and a previously developed MATLAB/Simulink model has been used to simulate the designed vehicle in two drive cycles using a soft hybrid energy management strategy. Also performance simulations have been conducted for all electric drive mode and results have been compared with the measurements taken from an experimental vehicle.

INTRODUCTION

It is known that electric vehicle (EV) technology has been gaining importance at both military and commercial vehicle systems for the last decades. Despite they have higher cost, their higher energy efficiency, lower emissions, regenerative braking and silent mode drive capabilities are major advantages over conventional vehicles. Better performance of electric traction, suitability for future weapon systems, stealth mode, silent watch and reduced signature are some of the reasons for the growing interest on combat electric vehicles.

This paper introduces electric vehicle technologies and basic design principals of series hybrid architecture. Performance of the designed vehicle is obtained using previously developed simulation environment.

ELECTRIC VEHICLE CONFIGURATIONS

Basically electric vehicle configurations can be classified into three groups. They are,

- All electric vehicle
- Series hybrid electric vehicle
- Parallel hybrid electric vehicle

As shown in Figure 1, electric energy storage systems such as battery, flywheel and supercapacitor can be used as power supply system in all electric vehicles. In this configuration, the range of the vehicle is limited by the stored electrical energy. Today, this is the most important drawback of EVs as a result of the weight of energy storage systems.

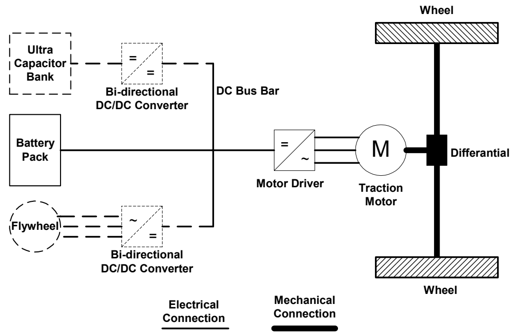

Figure 1. All Electric Vehicle Powertrain

Any vehicle having two or more different type of power sources or drive system is called hybrid vehicle. Series hybrid electric vehicle (SHEV) is hybridization of power supply system [2]. At series hybrid configuration, an ICE-generator set is placed additional to all electric system (Figure 2). The generator set (genset) may act as electrical energy storage system state of charge (SOC) controller or as the main power unit. When used as main power supply, it covers average power demands and the energy storage system supplies peak loads. During deceleration or low power drive, energy storage system is charged by regenerative braking or genset.

Parallel hybrid electric vehicle (PHEV) is the hybridization of drive system. In parallel hybrid electric vehicles, both ICE and electrical machine can propel the vehicle. For example, at low speeds, electric machine drives the car to use energy more efficiently. For better performance at long distance travels, ICE operates for traction. Electric machine can also act as a generator to charge energy storage systems if torque demand can be supplied by only ICE. One of the parallel-hybrid configurations is shown in Figure 3.

Beyond these two different hybrid configurations, as in Toyota Prius example, some other drive concepts have been studied like dual hybrid vehicles, which have properties of both SHEV and PHEV.

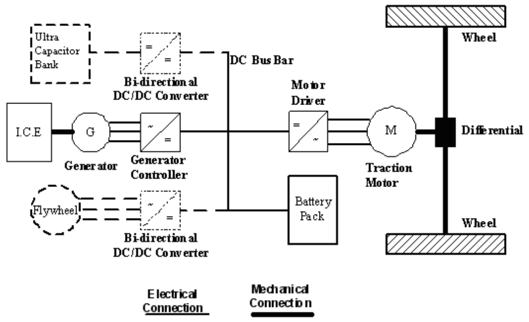

Figure 2. Series Hybrid Electric Vehicle Powertrain

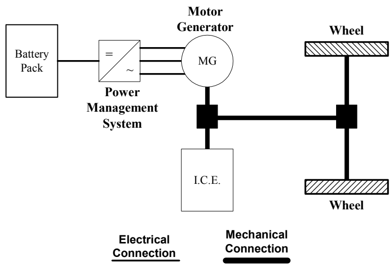

Figure 3. Parallel Hybrid Electric Vehicle Powertrain

TECHNOLOGIC TRENDS ON SUBSYSTEMS

Power system of an HEV consists of energy production unit, energy storage system(s), electric machine(s) and related power electronic circuits.

Present studies accept AC induction and permanent magnet synchronous machines as possible alternatives for electric drive applications. Switch reluctance motors may be another interesting alternative. DC machines are not preferred anymore, as they need brush and commutator maintenance.

Having robust construction, low production cost and low maintenance requirement, induction machine has been common selection for experimental electric vehicles. Modern control techniques like field-oriented control properly provide necessary speed control function for induction machines.

Permanent magnet synchronous machines have high efficiency, low-weight, high power density and high speed possibilities. So far, in all commercial hybrid electric vehicles, permanent magnet motors have been used due to certain advantages defined above.

Fuel cells are the most promising technology for power generation, which convert the chemical energy of a fuel directly to electrical energy. When they take hydrogen as fuel, they produce only heat and steam as emission. Although there are several types of fuel cells, proton exchange membrane fuel cell (PEMFC) seems the most promising choice for electric vehicle applications as it has relatively small dimensions and low operation temperature (50-100°C).

However, fuel cells have some serious disadvantages like high manufacturing, hydrogen production and storage costs. For today, usage of fuel cells as energy production unit in commercial hybrid vehicles is not yet feasible.

On the other hand, conventional energy production method, electric generator, takes mechanical energy and produces electrical energy. Mechanical power source can be a diesel engine, a gas fuel engine or a gas turbine. AC induction or permanent magnet machines can be used as generator.

As mentioned before, the worst problem in front of electric vehicle technology is the energy storage. Until now, lead acid (PbA) batteries have sustained the leadership despite their low specific energy and power ratios. Reliability and ability to withstand rough conditions are some reasons for that. In addition, advanced PbA battery technologies like spiral wounded AGM (absorbent glass mat) or VRLA (Valve regulated lead acid) batteries are able to provide higher specific power ratios up to 400 W/kg.

Table 1. Battery Comparison

	Specific Energy Ratio (Wh/kg)	Specific Power Ratio (W/kg)	Cycle Life at %80 DOD (cycles)
PbA	30-45	150-400	300-550
NiMH	60-70	150-1300	800-1300
Li-Ion	90-130	250-1400	500-1200

Studies on both nickel metal hydride (NiMH) and lithium ion (Li-ion) batteries are going on. Higher specific energy and power ratios, better charge absorption during regenerative braking and longer cycle life are some of the promised attributes of these advanced technologies. In commercial hybrid vehicles like Toyota Prius and Honda Insight, NiMH batteries are used.

Although some data has been given in Table 1, it should be noted that these parameters are only for indicative purposes since the data may have wide variations among different battery manufacturers and these data always change with the advancement of battery technology.

As flywheels, mechanical energy storage system, have high specific power ratio but low specific energy ratio, they cannot be used as main energy storage devices but can be a good alternative for short-term peak power demands. Another alternative for supplying peak loads is super capacitor. However, these systems also bring cost and reliability issues.

POWERTRAIN DESIGN

As mentioned before, power system of SHEV consists of traction motor, power generation unit, energy storage system and associated power electronics.

Choosing proper traction motor and its supply system are the main issues. Series hybrid electric vehicle power system design starts with choosing the traction motor. Vehicle specifications like weight, friction force, desired nominal velocity, acceleration and gradability affect this choice. The selected electric motor has to overcome several forces, which are wheel friction force (Ft), air friction force (Fr), slope friction force (Fe) and force due to vehicle inertia (Fa). The required power from traction motor is $P_m = F_{total}.V$.

Forces acting on to the vehicle;

$$Ft = c_t.m.g.\cos\alpha \quad (1)$$
$$Fe = m.g.\sin\alpha \quad (2)$$
$$Fr = 0.5.c_r.\delta.A_f.V^2 \quad (3)$$
$$Fa = m.dV/dt \quad (4)$$

Ft, Fe and Fr are used to calculate the continuous power requirement from electric motor and Fr is used to determine the additional power for acceleration. Total power that should be transferred to the wheels is obtained by multiplying the total force(F_{tot}) and vehicle speed (8). Total wheel torque(Ttot) is the product of force and wheel radius (9).

$$Fp = Ft + Fe + Fr \quad (5)$$
$$Fd = Fa \quad (6)$$
$$Ftot = Fd + Fp \quad (7)$$
$$Ptot = Ftot \,.\, V \quad (8)$$
$$Ttot = Ftot \,.\, r \quad (9)$$

Reduction gear ratio and mechanical efficiency is also considered while selecting the traction motor specification. If direct drive is applied, transmission efficiency (μ_{teff}) may also be omitted.

$$Pm = Ptot / \mu_{teff} \quad (10)$$
$$w_{tire} = V / r \quad (11)$$
$$w_{rotor} = w_{tire} \,.\, GR \quad (12)$$
$$Tm = Pm / w_r \quad (13)$$

Gradability target is one of the most important parameter for the nominal torque requirement and maximum motor speed is one of the parameters determining the maximum vehicle speed.

Power supply system(Pss) of hybrid electric vehicle is configured considering energy management strategy and power requirement of consumers such as traction motor, cooling system(Pc) and auxiliaries(Paux).

$$Pss = Pgenset + Pbat = Pm / \mu_{meff} + Pc + Paux \quad (14)$$

Load sharing between power generation and energy storage devices and total energy that should be stored are influenced by the energy management system. Longer silent drive range requires higher energy storage. The other way is that generator set covers the average load and energy storage device supply short-term peak power.

Table 2 Formula constants

Variable	Description	Unit	Variable	Description	Unit
m	Total vehicle mass	kg	α	Road slope	°
c_t	Wheel friction coefficient	-	c_r	Air friction coefficient	-
g	Gravity 9.81	m/s^2	δ	Air density	kg/m^3
A_f	Vehicle frontal area	m^2	V	Vehicle speed	m/s

The proposed design activity is conducted on the series hybrid electric vehicle power train architecture shown in figure 4.

Table 3 Vehicle constant

Constant	Value	Constant	Value
ct	0.01	cw	0.3
δ (km/m^3)	1.17	Af (m^2)	3.1
nt	% 90	rw (m)	0.325
mt (kg)	1600	g (m/s^2)	9.81
GR	5.7276		

Using equations given in (5) to (12), forces acting on the vehicle were modeled and given in Figure 5. Using the vehicle constants in Table 3, to be able to determine the specifications of traction motor, input signals, speed and slope, were applied to the model and following power-speed, torque-speed graphics were calculated.

0 to 90 km/h acceleration in 25 seconds at straight road input signals were applied to the model and power-motor angular velocity and torque-motor angular velocity values were plotted. Pivme and Psabit show power requirement during acceleration and requirement at constant speed drive respectively.

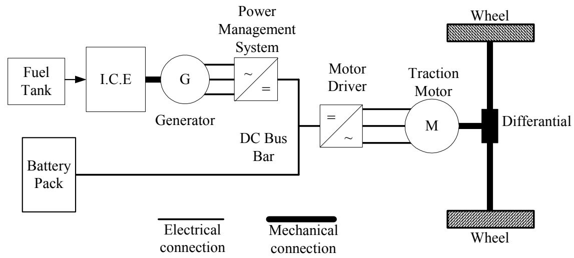

Figure 4 Power train of series hybrid vehicle

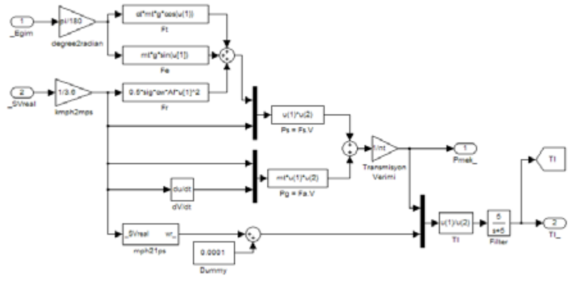

Figure 5 Vehicle load model

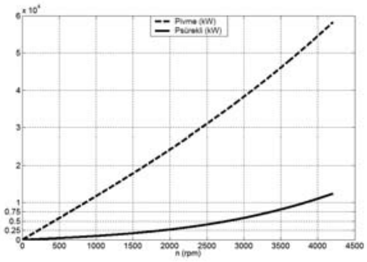

Figure 6 Maximum speed power requirement

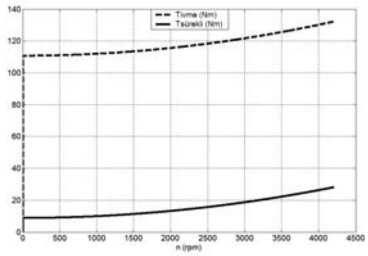

Figure 7 Maximum speed load moment

The same model was run for acceleration to 50 km/h in 25 seconds but this time at %10 slope and outputs were plotted in figure 8 and figure 9.

The graphs show that for this vehicle an electric motor having 250 Nm maximum torque at low speed (0-2000 rpm) and 50-60 kW maximum power between 2000-5000 rpm is needed.

For SHEV, the electric power supply system design is a more complex problem then the drive system. Selected power management method influences the parts of it. There are two basic energy management strategy called like soft hybrid and power assist [3, 4]. In the first one, battery pack may act as the main supplier and genset may be used as the battery SOC controller. In the other method genset is the main supplier for average power requirement and batteries are used for supplying peak loads.

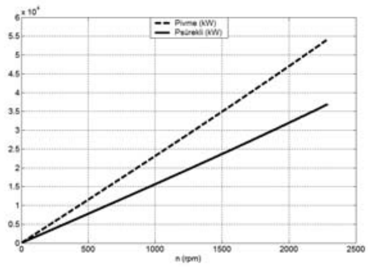

Figure 8 %10 slope power requirement

For this study, power management is selected as soft hybrid. Battery pack can supply all required power from traction motor. When battery pack state of charge decreases under a certain limit, generator set starts to supply electrical energy to recharge the battery pack.

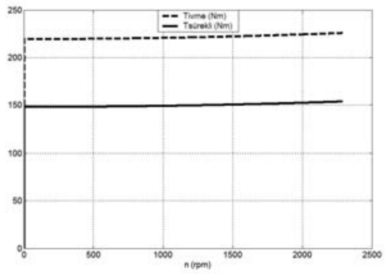

Figure 9 %10 slope load moment

In this context, battery pack should be able to supply at least 60 kW. 300 V DC bus bar, which seems suitable for power electronics at this power level, can be composed by 25 x 12 V lead acid batteries in series.

Capacity of the battery pack should be selected considering both maximum current supply capability and silent mode drive range of the vehicle. Selecting silent drive range as 150 km at 50 km/h constant speed, analyzing the calculations conducted before, brings the requirement of 18 kWh total stored energy. Division of maximum discharge power to total capacity results in 3.3 C discharge rate, which may be allowable for advanced lead acid batteries.

Generator set should be able to supply recharging power when the SOC decreases predefined ranges and also supply power for the traction at moderate speed drive. Selecting 9 kW nominal recharge power as the half of total capacity and taking 5 kW power requirement for 50 km/h drive into consideration, genset is selected at 15 kW power level.

In the soft hybrid energy management strategy, battery pack SOC level is divided into various operating modes, such as given in figure 9.

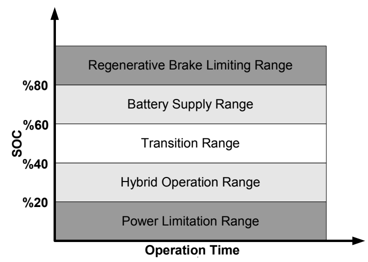

Figure 10 SOC operation bands

One wants to operate in the %20 - %80 SOC range. This is mainly because of the high internal resistance of battery pack behind those limits. So, above %80 SOC, regenerative braking is simply omitted or limited to avoid over charge and below %20 SOC, power limitation for traction is applied to avoid deep discharge. When SOC is in the %60-%80 range, required power is supplied only by battery pack till SOC decreases to %40. At this point, genset starts to supply power to the dc bus until SOC reaches %60. While driving down hill battery pack may increase upto %80.

Designed vehicle has been simulated using previously developed MATLAB/Simulink environment [1]. The first drive cycle applied is Urban Dynamometer Drive Schedule (UDDS) of USA federal test procedure FTP-75. The second one is the US06 highway cycle of USA test procedure.

In the urban drive cycle, only battery pack supplied the dc bus and genset didn't operate. At the end of 23 minute drive cycle, vehicle traveled 12 km/h distance and the battery SOC decreased %8. Seeing that the traction motor power was usually under 20 kW, 15 kW generator set would be sufficient to keep battery SOC between the required operation band.

In figure 11, urban drive simulation result has been given representing respectively drive cycle, battery pack voltage, battery pack current and SOC.

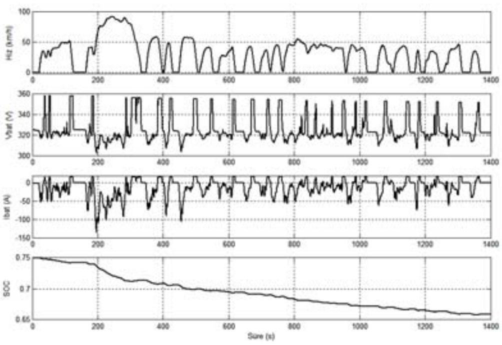

Figure 11 UDDS cycle simulation results

In the high-speed drive cycle, after 25 km drive, battery pack SOC decreases around %35 and dc bus bar voltage floats between 250 V - 360 V.

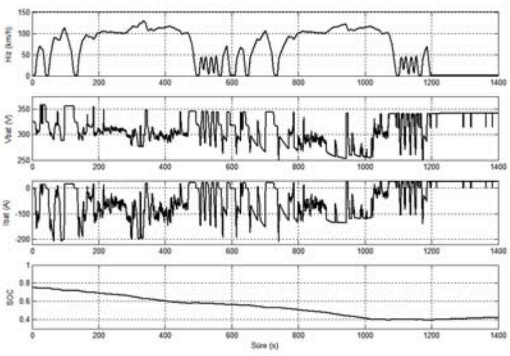

Figure 12 US06 drive cycle simulation results

COMPARISON OF PERFORMANCE SIMULATIONS AND REAL CASE

For the pure electric mode drive, acceleration and constant speed power consumption simulations were conducted and the results were compared with an experimental electric vehicle. Simulations were conducted under 35 kW power supply limitation to compare the results with the real case. Figure 13 shows that vehicle accelerates to 60 km/h in 13 seconds in the simulation mode. Experimental vehicle accelerated to the same speed in 14.4 seconds.

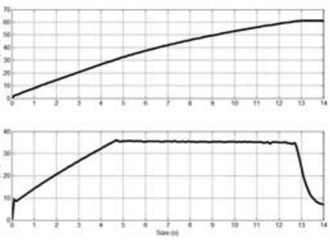

Figure 13 Acceleration to 60 km/h and power consumption

The simulation showed that power consumption at 50 km/h is 5 kW. In the real case power consumption was measured as 5.9 kW. Reasons for the difference between the simulation and real case are thought to be the uncertain vehicle parameters and efficiency values used in the model.

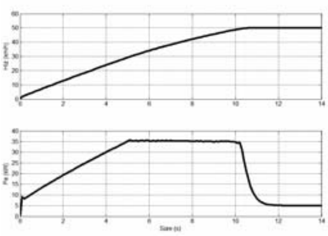

Figure 14 Power consumption at 50 km/h

CONCLUSION

In this paper, basics of hybrid electric vehicle technology have been presented. Also a series hybrid electric powertrain design study has been conducted.

The designed vehicle has been simulated using previously developed MATLAB/Simulink model.

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