Design of Series Hybrid Electric Vehicle with Auxiliary Power Unit

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ABSTRACT

This paper represents the development of a model of series hybrid vehicle with a power generator as its Auxiliary Power Unit (APU). Simulation using the model helps to provide an understanding of the interaction and flow of power. Moreover, electrical power sharing between the APU and the Electrical Storage System (ESS) is shown as a promising future direction for the transportation sector in terms of decreasing the reliance on fossil fuels while simultaneously decreasing emissions so that energy can be used for driving is fully or partially shifted to electricity leading to lower emission rates. In this case some standard equations are considered.

Keywords: Series hybrid vehicle, Auxiliary power unit, Simulation, Power share, Storage system, Emission.

1 INTRODUCTION

Transportation is a major source of energy consumption and airborne pollutants around the world. At the advent of a new millennium, the main parameters used to decide on a consumer product are not only business targets, but also rather some more important factors such as environmental pollution, sustainability, etc. While the future of a harmonious environment needed for continual existence of humankind is under a tremendous threat, continuous effort is going on to replace all the consumer products and technologies with more environment friendly technologies. One of the vastly used technologies that are not environment friendly is the IC engine. This technology is being used in several millions of automobiles in one form or another. While these automobiles are continually degrading the planet's environment, the use of gasoline as fuel is, also, not renewable.

The energy consumed by millions of vehicles on the highways accounts for the majority of petroleum usage around the globe and in this process billions of tons of airborne pollutants are introduced in the atmosphere each year. In response to concerns over environmental degradation, world’s renowned and famous associations of environment were proposed regulations, which would require a progressively increasing number of automobiles to be zero emission automobiles. After that, hybrid electric vehicle’s come to focus.

Electric vehicles are a promising technology for the long-range goal of energy efficiency and reduced atmospheric emissions. A well-designed electric motor drive can yield close to 90% efficiency and since the onboard systems in an electric vehicle are powered by batteries and electric motors, there are no toxic emissions. Some argue that the use of electric vehicles neither improves efficiency nor reduces toxic emissions. It merely shifts the energy production and pollution away from the urban centers to the areas where electricity is produced. The increase of size and resulting efficiency gains of electric generation facilities and the high efficiency of the distribution systems results in better use of natural resources when compared to conventional vehicles. According to several reports, widespread use of electric vehicles would reduce pollution not only in urban areas, but also across the rest of the country since electric utilities burn fossil fuels much more cleanly and efficiently [1]. Electric power plants can also be easily monitored for emissions since they are large stationary installations whose location is known where as an automobiles emission can only be monitors at production and intermittent state inspections. Also, since a growing proportion of electricity is being produced by non-polluting sources like hydroelectric, nuclear, solar and wind power, the pollution associated with electric power is decreasing. Despite the many beneficial aspects of the electric vehicle, many technical and social obstacles stand in the way. The most debilitating aspects of the electric vehicle are its limited range and lack of supporting infrastructure using present technologies [2]. Electric vehicles can achieve ranges of only 200-250 km before the battery is depleted. While this is sufficient for everyday use, it precludes the use of electric vehicle for long distance trips. Until an electric storage device is developed that can provide adequate range and quick recharging capabilities, the electric vehicle will have a limited role as a delivery vehicle or as a commute.

Hybrid vehicles offer higher efficiency and reduce emissions when compared with conventional automobiles, but they can also be designed to overcome the range...
limitations inherent in an electric vehicle. Hybrid vehicles utilize two distinct energy sources, usually an electric motor and an Internal Combustion Engine (ICE) to power the vehicle systems. The electric motor is used to improve the energy efficiency and vehicular emissions while the ICE provides extended range capability. Although the widespread use of electric vehicles would require a substantial investment in new infrastructure, current facilities can accommodate hybrid vehicles since the ICE runs on gasoline, diesel, or Compressed Natural Gas (CNG), which can be replenished quickly and are widely available [2]. The batteries used to power the electric motor can be either charged by the ICE or the electric machine, during regenerative braking. Hybrid vehicles provide an alternative to present automotive designs while research to develop advanced energy storage continues.

The concept of a series hybrid electric drive train has been developed from the electric vehicle drive train. As mentioned in the previous chapter, electric vehicles suffer from some serious disadvantages, mainly their limited driving range due to limited storage of energy on board in the form of batteries, limited payload and volume capacity due to the weight and size of the batteries, and also the long time it takes for the batteries to charge. In a series hybrid, an ICE/Electric generator system is added to the electric vehicle drive train, to charge the batteries on board, and thus increase the driving range.

2 DESIGN RELATED EQUATION

Traction motor characteristics shown in figure 1, the motor has a constant torque region till base speed, beyond which there is constant power region. The ratio of maximum speed of the motor to its base speed is called the factor ‘x’. As shown in figure 2, with increase in the values of ‘x’, the maximum torque of the motor also increases for the same power, thus increasing the acceleration and gradability performance (higher acceleration - higher torque; higher gradability - higher torque) and also simplifies the transmission.

\[ X = \frac{\text{Motor max. Velocity}}{\text{Motor base velocity}} \]

Fig 1: Speed torque characteristics of a traction motor.

Motor power rating: The power rating of electric motor drive in series HEV is completely determined by the vehicle acceleration requirements, motor characteristics and transmission characteristics. The motor might have been derived either from the peaking power source or the energy source; it is always equal to the tractive power. Tractive power can be defined as the power being delivered to the wheels at any instant [3]. The power rating of the traction motor can be represented as shown below [4].

\[ P_t = \frac{M_v}{2t_a} \left( V_f^2 + V_b^2 \right) + \frac{2}{3} M_v g f_r V_f + \frac{1}{5} \rho_a C_D A_f V_f^3 \]

Where,
- \( P_t \) = Traction motor power in watts.
- \( M_v \) = Total vehicle mass in kg.
- \( t_a \) = Expected acceleration time in seconds.
- \( V_f \) = Final speed of the vehicle accelerating in m/s.
- \( V_b \) = Vehicle base speed in m/s.
- \( g \) = Gravitational acceleration in m/s.
- \( f_r \) = Tire rolling resistance coefficient.
- \( \rho_a \) = Air density i.e. 1.202 kg/cubic meters.
- \( C_D \) = Aerodynamic Drag Coefficient.
- \( A_f \) = Vehicle front area.

Fig 2: Speed torque characteristics of a 60HP motor for x=2, 4 and 6.

3 ENGINE / GENERATOR

The engine/generator in a series hybrid drive train is used to supply the steady-state power, in order to prevent the peaking power source from being discharged completely. While 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 in the cities. In the long distance driving pattern, the drive train should not rely on the peaking power source 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 peaking power source at a certain level, so that enough power can be drawn to support the vehicle acceleration. At constant speed and on flat road, the power output from the power source can be calculated as [4]:

$$P_g = \frac{v}{1000 \eta_t \eta_m} (M_r g f_r + 0.5 \rho_a C_D A_f V^2) \text{kw}$$

Where, $\eta_t$, $\eta_m$ are the efficiencies of the transmission and motors respectively.

When the vehicle is driving in the stop and go pattern in urban areas, the power that the engine/generator produces should be equal to slightly greater than the average load power in order to maintain the PPS energy storage balanced. This load can be given by

$$P_{avg} = \frac{1}{T} \int_0^T (M_v g f_r + 0.5 \rho_a C_D A_f V^2) v dt + \frac{1}{T} \int_0^T M_v \frac{dv}{dt} dt$$

Where, $T$ is the total drive cycle time.

When designing for a stop and go type of system, the power capability should be greater than that needed to support the vehicle at constant speed as well as the average load power required in urban areas (figure 3). In any hybrid vehicle, due to the limitations of the battery, it is never possible to absorb all the regenerative power. This is because this power is in the form of high current for a very short time. The battery can take in only a certain amount of power in a given period of time. Similarly, the power intake is also limited by the power electronics of the traction motor. Hence, figure 3 shows the average power with full regenerative braking and partial regenerative braking; the average power with partial regenerative braking is in between the average power with full and no regenerative braking. This is the power that the engine must be able to provide.

Throughout this paper, we have considered the engine and the generator to be a single entity, and will be considered as the energy source for the power train.

### 3.1 Peaking Power Source

The peaking power source and the engine/generator jointly supply power to the traction motor, which finally provides power to the wheels. Therefore, the total power of the engine/generator and the peaking power source should be greater than or at least theoretically equal to the power of the electric motor. If the power rating of the traction motor, $P_{m, \text{max}}$, $P_{e/g}$ is the engine/generator power and $\eta_m$ is the efficiency of the motor, then the PPS (Peaking power source) power rating can be calculated as

$$P_{PPS} \geq \frac{P_{m, \text{max}}}{\eta_{motor}} - P_g \eta_g$$

The energy changes in the peaking power source can be expressed as

$$\Delta E = \int_0^T P_{PPS} dt$$

Where, $P_{PPS}$ is the instantaneous power from the peaking power source. This might be positive, zero as well as negative (charging of the peaking power source).

### 3.2 Drive cycle

Drive cycles represent typical traffic environments for a particular range of time. The drive cycle is a plot of velocity versus time. Drive cycles vary for various city at same time and same city at various times. Some typical drive cycles are shown below. Figure 4 shows the first drive cycle, characterized by repeated rapid accelerations with gradual decelerations. This studies the effect of excessive current loads on the motor temperature. After each gradual deceleration is a short interval to allow the heat generated to equalize before accelerating again.
Figure 4: Drive Cycle 1 (Rapid Accelerations)

Where:
A = time to accelerate to maximum speed  
B = time to decelerate from maximum speed  
C = time to allow heat to conduct through motor case

Figure 5 shows the second drive cycle, characterized by gradual accelerations with rapid decelerations. This studies the heat generated by the motor when used to slow the vehicle while capturing some of the energy dissipated in accelerations. The gradual accelerations are necessary to minimize the heat produced while not decelerating. A brief interval after each rapid deceleration again allows the heat generated to dissipate through the motor case.

Figure 5: Drive Cycle 2 (Rapid Decelerations)

Where:
A = time to accelerate to maximum speed  
B = time to decelerate from maximum speed  
C = time to allow heat to conduct through motor case

Figure 6 shows the third drive cycle, consisting of a gentle acceleration to a predetermined speed followed by a constant velocity output. This drive cycle ends when the amount of energy discharged through the motor is equal to that of the other two drive cycles.

Figure 6: Drive Cycle 3 (Constant Velocity)

Where:
A = time to accelerate to maximum speed  
B = time that vehicle travels at maximum speed

3.3 Transmission

The power delivered to the wheels in the case of a series hybrid comes entirely from the traction motor. The speed torque characteristics of a motor are ideally suited for traction. The speed torque characteristic of a motor has two regions (figure 2) the constant torque region and the constant power region. The constant power region shows high torque at low speed and low torque at high speeds. Since the torque speed characteristics of the motor match ideally with that of the traction requirements, an electric motor is much better suited for traction as compared to an IC. Engine. The Speed torque characteristics of an IC engine are not suitable directly for traction, hence a gearbox has to be used, which shapes the torque at various speeds and makes it suitable for traction. In the case of a series hybrid, a single gear transmission between the traction motor and the wheels is possible, since it uses electric motor for traction.

The mechanical torque generated by the motor is translated to the torque at the wheels by a gear. The torque at the wheels can be represented as a product of force exerted by the wheel on the ground (also known as tractive effort) and tire radius (Figure 7). Figure 8 shows the plot of tractive effort versus speed.

Figure 7: Torque at the wheels and the tractive effort (F_t)
Tractive effort can be derived from the following equation

\[ F_t = r \frac{T_i g \eta_t}{r} \]

Where,
- \( F_t \) = Tractive effort.
- \( \eta_t \) = Transmission efficiency
- \( r \) = Tire radius.
- \( g_i \) = Gear ratio.

The gear ratio is designed such that the vehicle maximum speed corresponds to the motor maximum speed.

\[ i = \frac{2 \Pi n_{m,\text{max}} r}{V_{\text{max}}} \]

Where,
- \( n_{m,\text{max}} \) = Maximum motor speed in RPS
- \( r \) = tire radius in meter
- \( V_{\text{max}} \) = Maximum vehicle speed in m/s

Fig 8: Tractive effort versus speed for a traction motor

Tractive effort is an important parameter in designing the grad ability of the vehicle.

4 DESIGN

For designing the hybrid electric vehicle we need to consider vehicle maximum mass, front area, maximum velocity, acceleration time, transmission efficiency, traction motor efficiency, generator efficiency, aerodynamic drag coefficient, rolling resistance coefficient, tire radius and air density. For a four passenger carry able vehicle, normally the maximum mass is 1200-1500Kg.

When a vehicle runs, then a resistance is created by air. This resistive force act against car speed is proportional to vehicle front area, aerodynamic drag co-efficient, air density and vehicle speed. To overcome from this resistive force, traction motor has to consume certain amount of its total consumed power.

Table 1: Drag coefficients for some passenger vehicles [5]

<table>
<thead>
<tr>
<th>Vehicle (class)</th>
<th>( C_D )</th>
<th>( C_D \times A_f (m^2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>VW Polo (class A)</td>
<td>0.37</td>
<td>0.636</td>
</tr>
<tr>
<td>Ford Escort (class B)</td>
<td>0.36</td>
<td>0.662</td>
</tr>
<tr>
<td>Open Vectra (class C)</td>
<td>0.29</td>
<td>0.547</td>
</tr>
<tr>
<td>BMW 520i (class D)</td>
<td>0.31</td>
<td>0.649</td>
</tr>
<tr>
<td>Mercedes 300SE (class E)</td>
<td>0.36</td>
<td>0.785</td>
</tr>
</tbody>
</table>

From this table, we can consider our vehicle’s front area is 2m² and hence drag co-efficient is approximately 0.3.

Table 2: Air density at various temperatures [5]

<table>
<thead>
<tr>
<th>( T ) in °C</th>
<th>( \rho ) in kg/m³ (at 1 atm)</th>
<th>( T ) in °C</th>
<th>( \rho ) in kg/m³ (at 1 atm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-25</td>
<td>1.423</td>
<td>5</td>
<td>1.269</td>
</tr>
<tr>
<td>-20</td>
<td>1.395</td>
<td>10</td>
<td>1.247</td>
</tr>
<tr>
<td>-15</td>
<td>1.368</td>
<td>15</td>
<td>1.225</td>
</tr>
<tr>
<td>-10</td>
<td>1.342</td>
<td>20</td>
<td>1.204</td>
</tr>
<tr>
<td>-5</td>
<td>1.316</td>
<td>25</td>
<td>1.184</td>
</tr>
<tr>
<td>0</td>
<td>1.293</td>
<td>30</td>
<td>1.164</td>
</tr>
</tbody>
</table>

For design purpose we take temperature of air is normally 25°C and so air density 1.184 kg/m³ (at 1 atm). Again another part of motor power is consumed for friction of tire with road surface. This friction is related with tire radius, rolling resistance co efficient, vehicle mass and velocity of the vehicle.

Table 3: Co efficient of rolling friction of tire [5]

<table>
<thead>
<tr>
<th>Tire Type</th>
<th>Coefficient of Rolling Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low rolling resistance car tire</td>
<td>0.006 - 0.01</td>
</tr>
<tr>
<td>Ordinary car tire</td>
<td>0.015</td>
</tr>
<tr>
<td>Truck tire</td>
<td>0.006 - 0.01</td>
</tr>
<tr>
<td>Train wheel</td>
<td>0.001</td>
</tr>
</tbody>
</table>

We consider our desired rolling co efficient is 0.01. As motor’s & generator’s efficiency are normally 80% to 90%, we consider motor efficiency as 85% and generator efficiency as 90%.

Table 4: Various types of gear with their efficiency [5]

<table>
<thead>
<tr>
<th>Name of gear</th>
<th>Efficiency</th>
<th>Name of gear</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spur Gears</td>
<td>90%</td>
<td>Helical Gears</td>
<td>80%</td>
</tr>
<tr>
<td>Sprocket Gears</td>
<td>80%</td>
<td>Bevel Gears</td>
<td>70%</td>
</tr>
<tr>
<td>Rack and Pinion</td>
<td>90%</td>
<td>Worm Gears</td>
<td>70%</td>
</tr>
</tbody>
</table>
As we select spur gear so we can take transmission efficiency as 90%.

**Parameters:**
- Weight of the vehicle, $M_v = 1500$ Kg (with 4 passenger)
- Front area of the vehicle, $A_f = 2.0$ square meters.
- Transmission efficiency ($\eta_t$) = 90%
- Traction motor drive efficiency ($\eta_m$) = 85%
- Generator efficiency ($\eta_g$) = 90%
- Aerodynamic drag coefficient ($C_D$) = 0.3
- Rolling resistance coefficient ($f_r$) = 0.01
- Tire radius = 0.3 meters
- Air density ($\rho_a$) = 1.184 kg/cubic meters

Performance specifications,
- Acceleration time (from 0 to 100 km/h) = 10 Seconds
- Grad ability is more than 5% at 100 km/h.
- Maximum speed = 160 km/h.

### 4.1 Design of Traction Motor

The power rating of the traction motor is determined by using the equation:

$$ P_t = \frac{M_v}{2t_a} \left( V_f^2 + V_b^2 \right) + \frac{2}{3} M_v g f_r V_f + \frac{1}{5} \rho_a C_D A_f V_f^3 $$

In this case, we know that

- $M_v =$ Vehicle mass = 1500 kg.
- $t_a =$ Acceleration time in seconds = 10 seconds.
- $V_f =$ Final Speed of the Vehicle in m/s = 160 km/h.
- $V_b =$ Final speed corresponding to motor base speed.

The motor base speed and the maximum speed of the motor are related by a factor ‘$x$’.

$$ X = \frac{Motor \ max.\ Velocity}{Motor \ base \ velocity} $$

The factor ‘$x$’ is arbitrarily chosen to have a value of 4.

As the motor and the wheels are connected to each other by a single gear transmission, the ratio between the motor maximum speed and base speed is also reflected on the vehicle side, the ratio between maximum vehicle velocity ($V_f$) and $V_b$ will be ‘$x$’ = 4. The Motor power thus calculated will be 82.5 KW. Hence the value of $V_b$ can be calculated. The values of $C_D$, $A_f$, $f_r$, $\rho_a$ have already been specified. The motor maximum speed is chosen to be 5000 RPM. Correspondingly the motor base speed is 5000/4 that is 1250 RPM. Knowing the motor power and the motor base speed, the rated torque of the motor is calculated by following equation.

Motor power = $2\pi \times$ Motor base speed $\times$ Rated motor torque

The motor torque thus calculated is found out to be 630 Nm.

Thus the specifications of the traction motor are as follows:

- Motor power = 82.5 KW.
- Motor rated torque = 630 Nm.
- Motor base Speed = 1250 RPM.
- Motor maximum Speed = 5000 RPM.

### 4.2 Design of Gear Ratio

As is the case of an electric vehicle, the traction motor is connected to the wheels through a single gear ratio. The reason for this is the speed torque characteristics of a motor, which are ideal for traction. Hence the gear ratio is designed such that the vehicle maximum speed corresponds to the motor maximum speed.

$$ i_g = \frac{2\pi \eta_{m,\ max} r}{V_{\ max}} $$

Where
- $\eta_{m,\ max} =$ Maximum motor speed = 5000 RPM.
- $r =$ tire radius = 0.3 meters.
- $V_{\ max} =$ 160 km/hr.

The gear ratio thus calculated is 3.53.

### 4.3 Calculation of Tractive Effort

Ttractive effort of the designed vehicle is calculated by following equation.
\[ F_t = \frac{T_p}{r} \eta_t \]

Here, rated motor torque, \( T_p = 630 \text{N-m} \)

Gear ratio, \( i_g = 3.53 \)

Transmission efficiency, \( \eta_t = 90\% \)

Tire radius, \( r = 0.3 \text{m} \)

So, rated tractive effort will be 6.2 kN

To check, if the motor is able to meet the gradability condition, the tractive effort of the vehicle is plotted with the vehicle resistance (aerodynamic drag + rolling resistance + the hill climbing).

4.4 Design of Generator

The engine generator is rated such that it supports the vehicle at regular highway speed (130 km/hr) on a flat road. Considering a 5\% grade, the engine power needed to support the vehicle at this speed, considering transmission efficiency to be 90\%, motor drive efficiency to be 85\% and the generator efficiency to be 90\%.

\[ P_g = \frac{V}{1000 \eta_v \eta_m} (M_v g f_r + 0.5 \rho_a C_D A_f V^2) \text{kw} \]

Using this equation, our desired generators power rating is approximately 29 kW.

When the vehicle is driving in the stop and go pattern in urban areas, the power that the generator produces should be equal to slightly greater than the average load power in order to maintain the PPS energy storage balanced. This load can be given by

\[ P_{avg} = \frac{1}{T} \int_0^T (M_v g f_r + 0.5 \rho_a C_D A_f V^2) V dt + \frac{1}{T} \int_0^r M_v \frac{dv}{dt} dt \]

Consider that drive cycle is about 16 hour. At this condition \( P_{avg} \) will be approximately 26.45kW. Thus, this generator will be able to support the vehicle when traveling long distance on a highway at a constant speed of about 130 km/hr. This generator will be able to maintain sufficient energy in the peaking power source when used for the urban or the stop and go type of traffic.

4.5 Power Rating of Peaking Power Source

The traction power is provided to the wheels by the traction motor. The traction motor is powered by the two power sources, the peaking power source and the generator. Naturally, the sum of the power ratings of the peaking power source and the generator should be greater than or equal to the input power of the traction motor. Since the power rating of the generator and the traction motor has been decided, the rating of the peaking power source can be easily calculated.

\[ P_{PPS} = \frac{P_{motor}}{\eta_{motor}} = \frac{82.5}{0.85} = 98kW \]

4.6 Design of Peaking Power Source Energy Capacity

The energy capacity of the peaking power source is completely designed by using the drive cycle and the control strategy. For this design the engine-on and off control strategy is chosen. As already explained, the state of charge is chosen to vary over a given range. The S.O.C is decided to vary from 0.6 to 0.4. Hence, \( \Delta SOC = SOC_{top} - SOC_{bottom} = 0.2 \).

Also, the energy capacity of the PPS is decided to vary from 1.5 kWh to 1 kWh. Hence \( \Delta E_{max} = 0.5 \text{kWh} \). Having decided how much the state of charge as well as the energy rating of the peaking power source, its energy capacity can be calculated.

\[ E_{PPS} = \frac{\Delta E_{max}}{\Delta SOC} = \frac{0.5}{0.2} = 2.5 \text{kWh} \]

5 CONCLUSION
Efforts have been underway to find a sustainable and renewable fuel, even before the current levels of gasoline use. Since there has not been an effective alternative to the IC engine which can meet the needs of a consumer automobile, the IC engine is even more popular today even though its use is strongly harmful for the environment. Research has continued to replace the IC engine and there has been some reasonable progress in some areas. Hybrid Electric Vehicle technology promises the potential for being a competitive contender to replace the use of IC engines fully at least partially in consumer automobiles. In this paper various aspects of the use of a generator and a battery have been reviewed. When more power is required for drive the vehicle then both the energy source will support it. When the vehicle run in urban area then it takes less power and this power is fully can give by the generator and during this less requirements of electrical power in the electric motor, the extra energy can be stored in the batteries. The motor can also be used as a generator during regenerative breaking in which case the batteries will also get charged.

Another strategy can take in middle stage power requirements and that is the battery supports the vehicle according to its maximum capacity and the rest less required power is come from the generator. By taking this strategy the IC engine is partially replaced by the reliable battery. One plus point for the use hybrid electric vehicle is this reduces the cost and the use of space in the car. Another important point of series hybrid electric vehicle is that it is almost same the fuel cell hybrid electric vehicle. Series hybrid electric vehicle can be converted into fuel cell hybrid electric vehicle by only replacing the IC engine with generator by fuel cell.

REFERENCES
