Design of Hybrid and Electric Vehicles

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Background about Hybrid Electric Vehicles

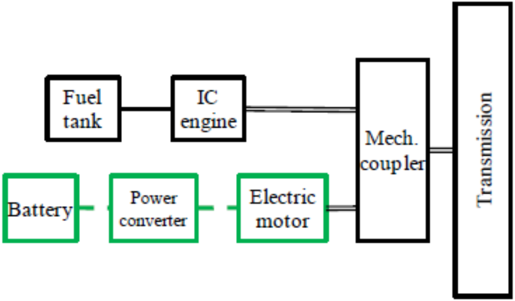

Figure 4c: Parallel hybrid [1]

Background about Hybrid Electric Vehicles

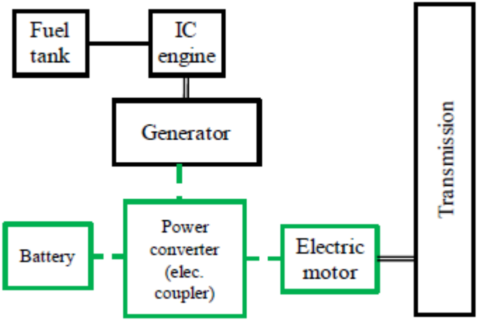

Figure 4a: Series hybrid [1]

Topics

1. Definition of Hybridness
2. Hybrid Design Philosophy
3. Optimization and Hybridness

Hybridness

- The definition of hybridness, H, is

$$H = \frac{\text{Sum of power of all traction motors}}{\text{Sum of traction motor+Engine power}}$$

- Some hybrids have more than one motor/generator (M/G).
- Example of hybridness

  Consider a light delivery van with the propulsion:
  Diesel engine: 110 kW at 3000 rpm
  Electric motor: 23 kW; maximum torque 243 N-m at 500 rpm

Hybridness

- $H = \frac{23}{23+110}$ =0.17
- As a note of caution, the sum of component power (23 + 110) kW = 133 kW is not the maximum hybrid power. The maximum electric motor torque and engine torque occur at different rpm.
- H defines micro, mild, and full hybrids.
- As will be seen $H = 17\%$ is a mild hybrid.

Design Philosophy

- Efficiency of Gasoline Engine is low-around 25%
- Efficiency of MGs is higher -above 90%
- Battery efficiency is moderate- round trip in/out efficiency is $70 - 80\%$
- Batteries must be cooled to improve efficiency

Design Philosophy

Overall hybrid design philosophy has three parts

- Operate electric motor first (less emissions/less fuel consumed)
- Add gasoline engine only when needed.
- Operate gas engine at the best rpm and throttle setting, that is, operate on minimum fuel consumption line in engine map.

Range Extender

- A range extender is a fuel-based auxiliary power unit (APU) that extends the range of a battery electric vehicle by driving an electric generator that charges the vehicle's battery.
- R_0 is the range without engine-generator, $R = \frac{R_0}{H}$
- R is the range with engine-generator
- increment in range $\Delta R = R - R_0 = R_0 \frac{1-H}{H}$

Range Extender

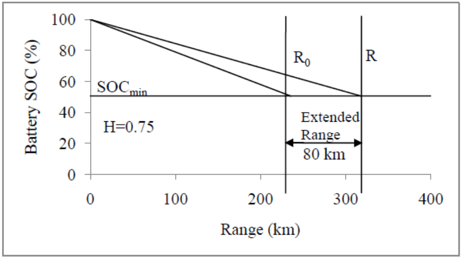

Figure 3. Extension of range due to a small gasoline-powered generator recharging the battery. [1]

- $R_0 = 240$ km, $H = 75\%$, $R = 240\text{km}/0.75{=}320$ km
- The gain in range is 80 km

Hybridness

- Mild Hybrids - $0\% < H < 40\%$
- Full Hybrids - $40\% < H < 50\%$
- Plug-in hybrids -$50\% < H < 100\%$

Battery Power and Electric Motor Power

- Battery size is determined by - Battery Energy=(power of M/G)(run time)
- The equation assumes the battery power equals the power of M/G
- For mild and full hybrids, as H increases, the battery power and energy increases hand in hand.
- For the plug-in hybrid, the M/G power no longer needs to grow. The M/G has sufficient power to move the vehicle. However the battery energy must grow to gain more range

Battery Power and Electric Motor Power

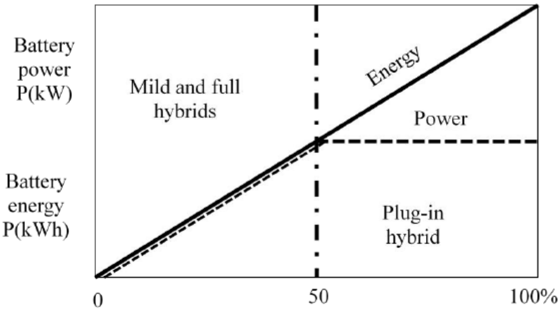

Fig.4.Variation of battery power and battery energy as a function of hybridness. [1]

Interpretation of Ramps

- Capability of hybrids to exploit regenerative braking
- For a mild hybrid,$H = 15\%$, regenerative braking is possible but only about 38% of kinetic energy can be recovered
- The limitation is due to the small generator.
- The ramp ends at $H = 40\%$ for which a hybrid has a generator large enough to enable high-efficiency regenerative braking
- For a full hybrid, $H = 50\%$, more than enough generating capability exists for regenerative braking.

Interpretation of Ramps

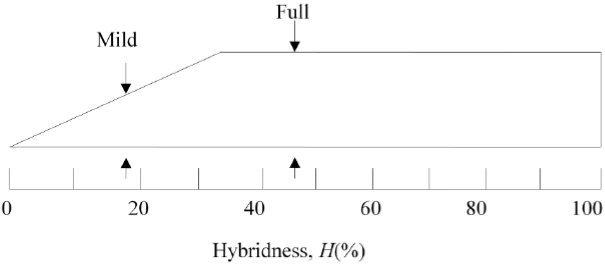

Fig.1. Interpretation of the ramps [1]

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Techniques to enhance Hybrid Performance

<u>START-STOP</u>

- Engine-off during stops in traffic affords a saving in fuel.
- The usual 12 V starter does not have the power to restart the engine without delay, noise, and vibration.
- With the more powerful electrical motors, even in mild hybrid, the engine rpm can be quickly increased.
- Once smoothly and quickly up to starting rpm, the fuel injection can be activated.

Damping Driveline Oscillations

- Another way that fuel consumption can be reduced is to shut off fuel flow whenever brakes are applied.
- Abrupt-sudden turn off of fuel can cause shudder and unpleasant oscillations of the engine and of driveline.
- Damping by the electrical motor can decrease the unpleasantness to an acceptable level.

Vehicle Launch

- An engine at low rpm has little torque.
- At launch, torque is essential. An electric motor, even a small one, has high torque at low rpm.
- The motor fills in the torque hole at low rpm. A small motor can contribute significantly to the initial launch.

Motor Assist

- Vehicle launch is part of motor assist, but applies to very low speed.
- Motor assist covers a broader range of speed and vehicle operations such as hill climbing and driving in snow.
- More power and a larger electric motor are required. Hybridness, H, of 50% yields enough power from the electrical motor to overcome the power deficiencies of the downsized engine.

Electric-only Propulsion

- Electric-only propulsion means the gasoline engine is shut down and does not consume fuel. Electric-only operation improves mpg.
- To achieve performance goals, the motor must have adequate power. At $H = 50\%$, the traction motor is as large as the engine.
- Alone, the traction motor yields the desired performance. Another reason that electric-only operation is desirable is the fact that emissions are zero or near zero. Stringent emission requirements may be met by electric-only operation.

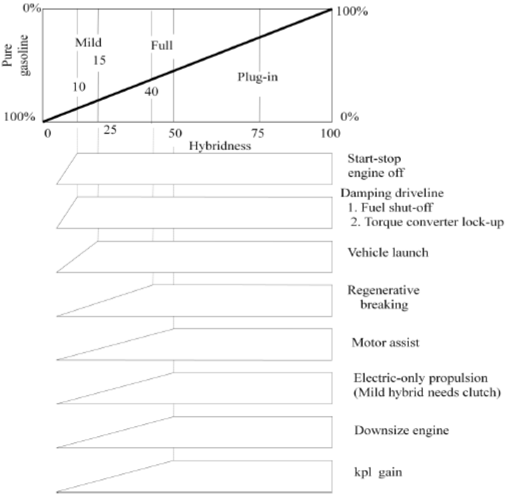

Fig.2. Availability of various techniques to enhance hybrid performance as a function of hybridness and resulting mpg gain. The bar below the hybridness graph has a ramp which extends from $H = 0\%$ to a value of H for the particular technology. For start–stop, the ramp ends at $H = 10\%$. The flat bar beyond indicates that for all values of $H > 10\%$, that feature is available to the hybrid designer. [1]

Mild or Micro Hybrid Features

As a result of being a mild hybrid, certain features follow.

- The M/G serves as the starter/alternator combined.
- Mild hybrids have limited regenerative braking. The battery and installed M/G may be large enough to provide low speed motor assist or to provide low speed launch assist.
- Other possible design features include fuel cutoff at deceleration, idle shutoff etc.

Plug-in-Hybrid

- The plug-in hybrid can be viewed as an EV but with a small engine to extend range.
- Features of a plug-in hybrid include a large, heavy, expensive battery.
- Additional equipment is needed to connect to external "wall plug" electrical source for recharging. Since batteries are high voltage, the voltage of the charging source must be even higher. Inductive rechargers prevent exposure to high voltage.
- For people willing to undertake the recharging chore, the plug-in offers fantastic mpg.

Power Train and Drive Cycle

- The power train of EVs and HEVs consists of Electric Motor (EM) and the Internal Combustion Engine (ICE).
- The first step towards the design of the power train is to determine the power ratings of the motor used in the EV and HEV drivetrain is to ascertain the motor specifications.
- These specifications are determined making use of the drive cycle the vehicle operates on and the vehicle dynamic equation for tractive force calculation.

Design Constraint of the Power Train of the Vehicle

The design constraints of power train of the vehicle are listed below.

- Initial acceleration.
- Cruising at rated vehicle speed.
- Cruising at maximum vehicle speed.
- Retardation.

Operational Regime of a Vehicle

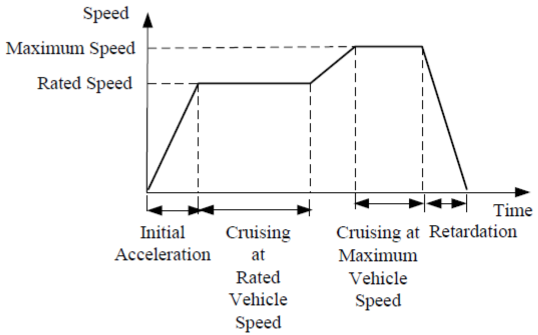

Figure 1: Operation regimes of a vehicle [1]

Drive Cycle and its detailed Analysis

In order to size the components of the vehicle properly, it is necessary to understand the drive cycle properly. The various drive cycles used are:

- New York City Cycle (NYCC)
- Japanese (JP-10-15)
- Extra Urban Driving Cycle (EUDC)
- Federal Test Procedure (FTP-75)
- New European Driving Cycle (NEDC)

Dynamic Equations

The dynamic equations of the vehicle are used to analyse the impact of drive cycle on the vehicle performance. The dynamic equations of the vehicle give the force required to move the vehicle and this force is given as:

$$F_{resistance} = Mgf_r \cos(\alpha) + \frac{1}{2}\rho A_f C_D V^2 + Mg\sin(\alpha) + \lambda M\frac{dV}{dt}$$

Rolling resistance, aerodynamic drag, grading resistance, acceleration resistance

$$F_{resistance} = F_r + F_w + F_g + F_a$$

Dynamic Equations

The sizing of the components of HEVs and EVs is usually done in terms of power.

$$P_{resistance} = P_r + P_w + P_g + P_a$$

where

$$P_r = F_r V,\ P_w = F_w V,\ P_g = F_g V,\ P_a = F_a V$$

V = speed of the vehicle in m/s

Parameters of the Test Vehicle

Table 1: Parameters of the test vehicle

Mass of vehicle [Kg]	5300
Coefficient of rolling resistance	0.01
Gravitation acceleration constant [m/sec^2]	9.81
Air density [kg/m^3]	1.3
Aerodynamic drag coefficient of vehicle	0.5
Frontal area of vehicle (m^2)	5.65
Road angle [degrees]	0
Radius of the wheel [m]	0.21

New York City Cycle

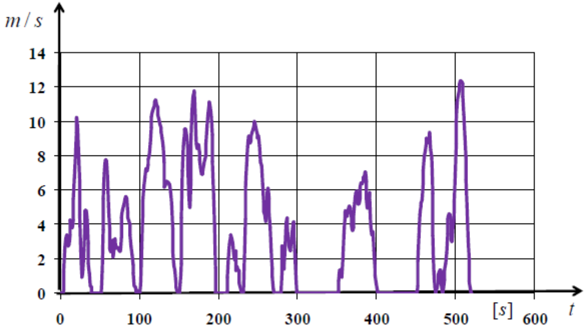

Figure 2: Speed versus time curve for NYCC

New York City Cycle

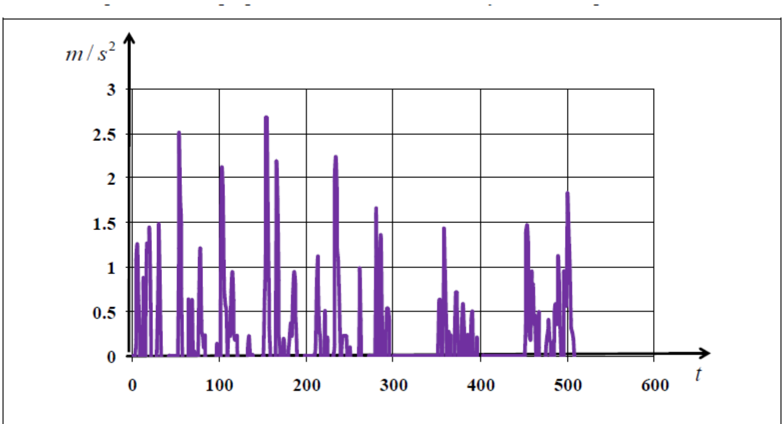

Figure 3: Acceleration versus time curve for NYCC

New York City Cycle

Table 2: Parameters of NYCC

Average speed	3.63 [m/s]	Maximum deceleration	2.6 [m/s^2]
Maximum speed	12.4 [m/s]	Maximum power	85 [kW]
Maximum acceleration	2.7 [m/s^2]	Maximum braking power	89 [kW]

NYCC

- The maximum power required to move the vehicle on this drive cycle is about 85kW, hence, the prime mover (combination of ICE and EM in case of HEVs and EM in case of EVs) should be able to deliver the required power.
- The maximum braking power is about 89kW and a fraction this power can be recovered by using regenerative braking.
- The vehicle is subjected to frequent start-stop. Since the ICEs tend to be very fuel inefficient for such frequent start-stop operation, it is wise to use only EM as the prime mover.

Extra Urban Driving Cycle

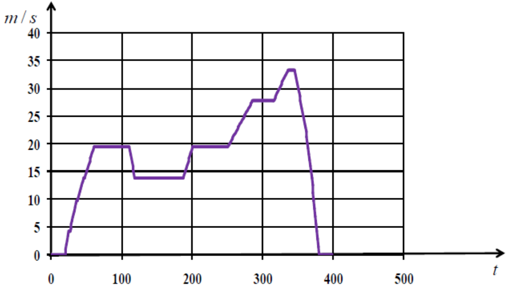

Figure 6: Speed versus time curve for EUDC

Extra Urban Driving Cycle

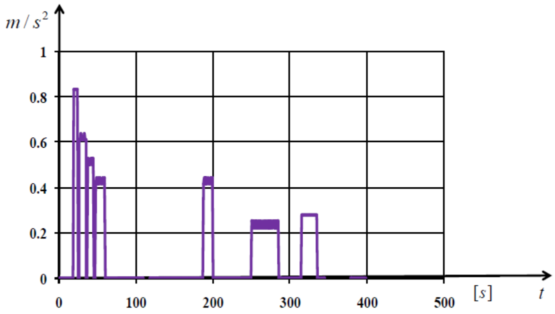

Figure 7: Acceleration versus time curve for EUDC

Extra Urban Driving Cycle

Table 4: Parameters of EUDC

Average speed	6..53 [m/s]	Maximum deceleration	1.33 [m/s^2]
Maximum speed	33.33 [m/s]	Maximum power	115 [kW]
Maximum acceleration	0.83 [m/s^2]	Maximum braking power	101 [kW]

EUDC

- The maximum power required to move the vehicle on this drive cycle is about 115 kW, hence, the prime mover (combination of ICE and EM in case of HEVs and EM in case of EVs) should be able to deliver the required power.
- The maximum braking power is about 101 kW and a fraction this power can be recovered by using regenerative braking.
- The maximum and minimum acceleration that the vehicle experiences are 0.83m/s2 and 1.33 m/s2. Since this drive cycle does not involve start-stop operation, the ICE can be used to supply the required power.

Choice of Electrical Machine (EM)

An EM is at the core of HEV drivetrains. Most EMs used in HEV or EV drivetrains have speed limit of 12000 rpm due to following reasons:

- At very high rpm, the centrifugal force acting on the rotor increases and it is possible that the rotor might fail mechanically.
- The control algorithms of the EM involve determination of rotor position and this becomes very difficult at high rotor rpm.

Performance of EM

The performance of EM is measured by following quantities

- Torque and Power cabability
- Constant Power Speed Ratio

Peak Torque and Power

The EM capability curves for torque and power define the peak operating capability of the HEV.

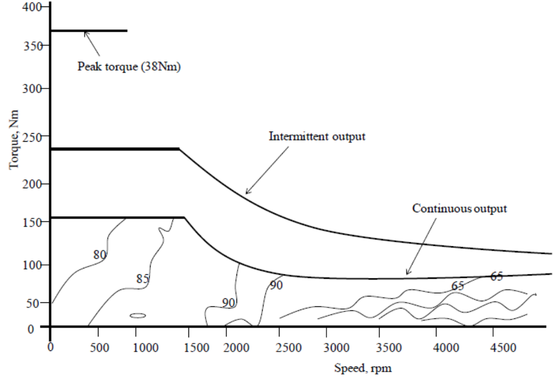

Figure 2: Torque versus speed curve of an EM [2]

Peak Torque and Power

Three Curves

- Continuous Rating - The EM can be operated in its continuous rated region
- Intermittant Overload Operation- The EM can operate in this regime for short duration (typically < 30 s)
- Peak Overload Operation- The EM can operate in this region for a very short duration (typically $<$1-2 s)

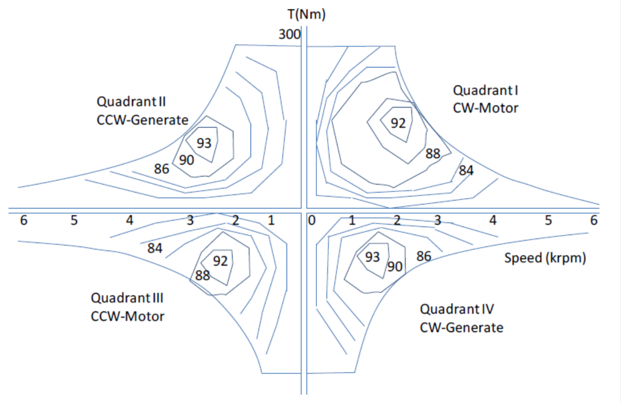

Figure 3: Torque versus speed curve of an EM for four quadrants [2]

Change of Quadrant in Operations

- The shift of EM's operation from one quadrant to the other is generally very fast but it depends on the previous and new operating points.
- For example: A transition from motoring at 2500 rpm and 100Nm of torque to generating at 2500 rpm and -100Nm of torque can be achieved a simple change in sign in the controller.
- Since the EM's transient electrical time constant is much smaller than the mechanical system, the torque change is viewed as occurring nearly instantaneously.

Change of Quadrant in Operations

- The driver wishes to overtake some vehicle and at that instant the EM is operating in motoring mode at 2500 rpm and producing a torque of 100Nm.
- After overtaking the driver slows to re-enter the traffic. When the driver slows, the EM has to decelerate and it acts as a generator and produces -100Nm of torque at a reduced speed, for example, of 1500 rpm.

EM Sizing

The EM is physically sized by its torque specification. Since, EM torque is determined by the amount of flux the iron can carry and the amount of current the conductors can carry, and can be expressed as

$$T = kABD^2L \tag{1}$$

where k is proportionality constant, A is total ampere-turns per circumferential length [A/m], B is the Magnetic flux density [T], D is the diameter of the rotor [m] L is the length of the EM [m]

EM Sizing

- The two fundamental sizing constraints on the EM are: i. Electric loading ii. Magnetic loading
- The EM design is constrained by a mechanical limit -rotor burst condition

Sizing the Power Electronics

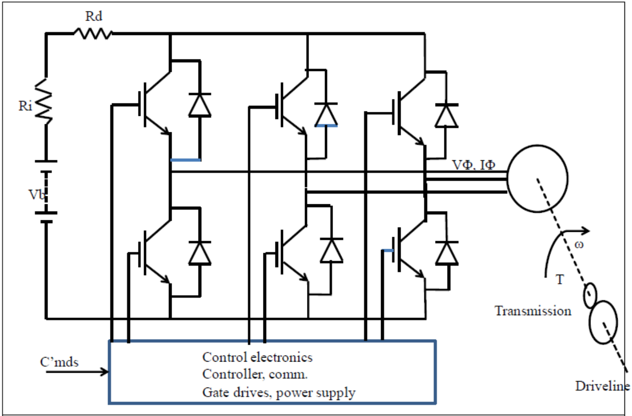

Figure 4: The HEV drivetrain with on board energy storage [2]

Power Electronics

- Power Electronics -equivalent to gearbox that processes mechanical energy to match the ICE to the road requirements
- Power processing capability of the power inverters are directly related to DC voltage available.
- For hybrid propulsion, voltage in excess of 150 V are advisable.
- With recent advances in power electronics switches, it is possible to move beyond 300 V.

Power Electronics

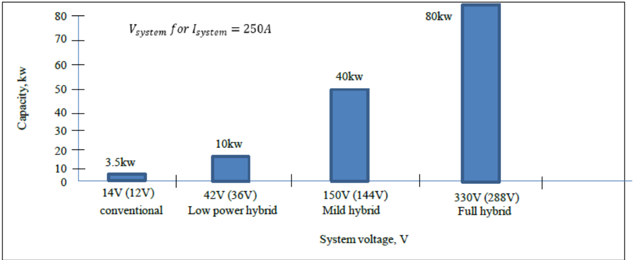

Figure 5a: Automotive voltage trend [2]

Power Electronics

- Most of the hybrid propulsion systems such as Toyota Hybrid System, Honda IMA, etc are clustered along the 100 A trend line.
- Power semiconductor device range in voltage withstanding capability from 2kV to 6.5kV and current magnitudes from 3kA to 4.5kA.
- Thyristors have the highest kVA rating but are generally slow switching.
- The gate turn off thyristor (GTO) is capable of handling 3kA at 4.5kV but can switch at only 700Hz.
- The IGBTs have made enormous progress in both the voltage and current ratings, with some IGBTs being capable of handling 6.5kV and 3.5kA and have switching frequency up to 100kHz.

Power Electronics

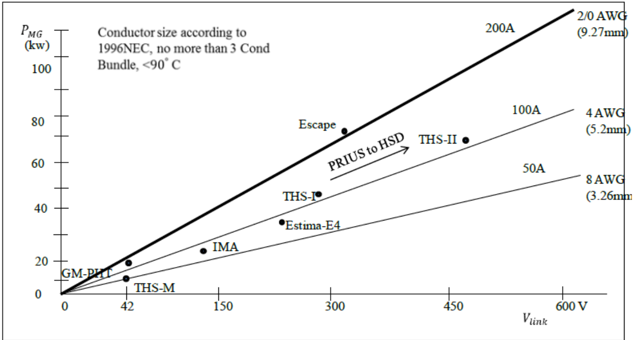

Figure 5b: Voltage levels of different hybrid drivetrains [2]

References

1. NPTEL Course by IIT Guwahati - Introduction to Hybrid and Electric Vehicles

Thank You