DESIGN STUDIES OF A SERIES HYBRID HEAVY-DUTY TRANSIT BUS USING V-ELPH 2.01

Z. Rahman, K. L. Butler, M. Ehsani

Applied Power Electronics Laboratory
Department of Electrical Engineering
Texas A&M University
College Station, TX 77843-3128 USA
email: klbutler@ee.tamu.edu

Abstract – Series hybrid transit buses reduce significant fuel consumption and exhaust emissions as a result of regenerative braking and uniform engine operation. This study discusses the steps involved in designing series hybrid propulsion for a full-sized transit bus with simulation results for fuel consumption and emissions for urban drive cycle. The HEV research group in Texas A&M University has developed a computer simulation tool, V-ELPH, to facilitate the design and analysis of electric and hybrid vehicles. In this paper a design example for a 40′ series hybrid heavy-duty transit bus is given in detail, from design specifications to complete design, using V-ELPH with supporting illustrative graphs.

I. INTRODUCTION

The high degree of auto dependency is causing air pollution in urban areas. Introduction of zero or low emission electric (EV) and hybrid electric vehicles (HEVs) can reduce this problem. In early days, trolley buses capable of operating from overhead wires were used. However, the route coverage was limited by the availability of overhead wires. In addition, vehicle electric breakdowns or unanticipated blockages of the route can cause serious service problems. Hybrid propulsion systems (HPS) permit route extension and route flexibility without attendant extension of the electrical distribution system. Transit buses are considered to be the best candidates for hybrid application because they normally operate on predictable routes with frequent starts and stops. HPS is also better suited for transit buses than private cars because they have lower speed, limited acceleration, less road grades and ample space available for batteries. Many prototype hybrid transit buses are currently running to test the different configurations of propulsion systems [1, 2]. Among many different hybrid configurations, the two generally accepted classifications are series and parallel. The parallel hybrid is more efficient satisfying high road power demands (high speed or acceleration), while series is more efficient for large energy demands. For public transportation purposes, where large weight is of more concern than high acceleration, the series propulsion strategy becomes more efficient and simpler.

In this paper, we present a methodology to design a series hybrid heavy-duty transit bus. We also introduce the 'V-ELPH 2.01' [3] EV-HEV computer simulation package developed in Texas A&M University (TAMU) and show its various features and functions.

II. BASICS OF HEV

A. HEV Concept

An HEV has more than one energy source and energy converters among one of which are electric traction. The two commonly used energy sources in HEV are petroleum fuel and battery pack and the two energy converters are the internal combustion engine (ICE) and electric motor (EM), respectively. The EM in HEV propulsion system minimizes vehicle emissions and improves overall system efficiency while the ICE provides extended range capability. There are two HEV configurations depending on the pattern of energy flow from the two sources: Series and Parallel. In series hybrid drive-train, the EM propels the vehicle while the ICE and generator generate electric power. In parallel structure, either the EM or ICE or even both can drive the vehicle.

B. Series HEV Architecture

The series hybrid structure has two energy converters, ICE and generator, connected in series. The ICE-generator combination is often referred to as auxiliary power unit (APU). The EM propels the vehicle. Here, the battery pack delivers electric energy to the motor and the APU assist the battery on energy supply. The EM can function as either motoring or generating machine for propelling and regenerative braking. Figure 1 shows a series HEV architecture.

0-7803-5565-2/99/$10.00 © 1999 IEEE

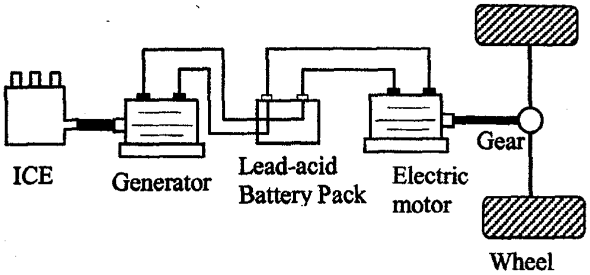

Figure 1. Series HEV architecture.

The advantage of series HEV is its simple structure and uncomplicated energy management strategy. Since there is no mechanical connection between the ICE and load, the engine speed and torque is completely independent of vehicle load. Therefore, the engine can run at its optimal efficiency region all the time and minimize the engine emissions. Also, special attention can be paid to design the ICE to run efficiently at a fixed operating point.

III. DESIGN METHODOLOGY

The main design parameters in a series hybrid are the selection and sizing of the EM and APU. Design methodology for a series hybrid consists mainly of sizing the propulsion motor to provide the desired performance and then choosing a generator and storage device to provide the required range on a specific drive cycle.

A. Performance Specifications

The dimensions of a typical 40′ transit bus and its performance goals outlined in the Baseline Advanced Design Transit Coach Guidelines (White Book) are summarized from three different resources [4-6]. The specifications are as follows:

Bus data:

1. Weight, M: 10,900kg (without battery pack).
2. Frontal area, A_f: 5.9 m^2.
3. Drag coefficient, C_d: 0.6.
4. Rolling resistance coefficient, f_r: 0.03.
5. Tire radius, r: 0.45 m.

Performance data:

1. Acceleration: i) 0-30 kph in 10 secs.
   ii) 30-42 kph in 5 secs.
   iii) 42-49 kph in 5 secs.
   iv) 49-54 kph in 5 secs.
   v) 54-80 kph in 35 secs.
2. Gradeability: i) 0% at 80 kph.
   ii) 2.5% at 70 kph.
   iii) 16.5% at 11 kph.
3. Range: Independent of battery energy storage.

B. Motor Size Estimation

The size of the propulsion motor for the series hybrid is estimated by the power required driving the vehicle under different grade angles. The equation for the total power demanded by the vehicle from its power plant is expressed as:

$$P = \frac{v(f_r Mg + \frac{1}{2}\rho C_d A_f v^2 + M\delta \frac{dv}{dt})}{\eta_t} \tag{1}$$

where, P is vehicle power demand in watts, v is velocity of the car in m/s, f_r is coefficient of rolling resistance, M is vehicle weight in kg, g is acceleration of gravity in m/s^2, ρ is air density in kg/m^3, C_d is coefficient of air drag, A_f is frontal area of the vehicle in m^2, δ is mass factor which includes the effect of rotational inertia, η_t is transmission efficiency. We simulate equation 1 with grade angles of 0%, 2.5% and 16.5% with η_t = 0.92, δ = 1.035 and ρ = 1.202kg/m^3. For the time being we assume the weight of the battery pack to be 600 kg. Figure 2 shows the simulation result.

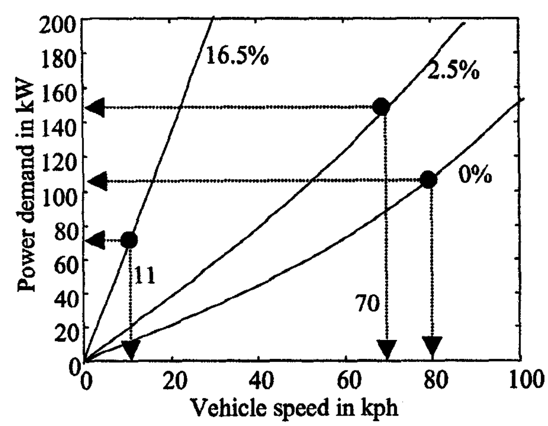

Figure 2. Vehicle power demand with vehicle speed.

From the figure, we determine the size of the motor to be 150 kW. Assuming a demand of 10 kW power for air conditioning, lighting and other auxiliary loads, then a 160 kW electric motor is required.

C. Battery Size Estimation

The size of the battery pack is determined by the power requirement of the motor. We choose 12 volts lead-acid batteries because of its availability and high power density. These batteries have power density of 280 w/kg and energy density of 34 w-hr/kg. A 160 kW motor requires 570 kg of battery, which is almost 25 battery cells. We consider 26 battery cells with two 13 cells series wired strings connected in parallel. This gives a nominal voltage rating of 156 volts. We assume the charging and discharging efficiency of the battery pack to be 80%.

D. Determination of Gear Ratio

The equation of gear ratio from motor to drive wheel is expressed as follows:

$$i_t = \frac{\pi n_{max} r}{30 v_{max}} \qquad (2)$$

where, i_t is the gear ratio, n_{max} is the maximum speed of EM in rpm, r is wheel radius in meters and v_{max} is maximum vehicle speed in m/s. We choose a 160 kW DC motor with base speed of 2000 rpm and maximum speed of 7500 rpm. For v_{max} = 80 kph, the gear ratio is found to be 15.9. We verify this value by plotting in figure 3 the vehicle force demand curve (F=P/v) at different grades with EM traction curve at a gear ratio of 15.9. The figure shows that the vehicle satisfies the three gradeability conditions mentioned in the performance specifications.

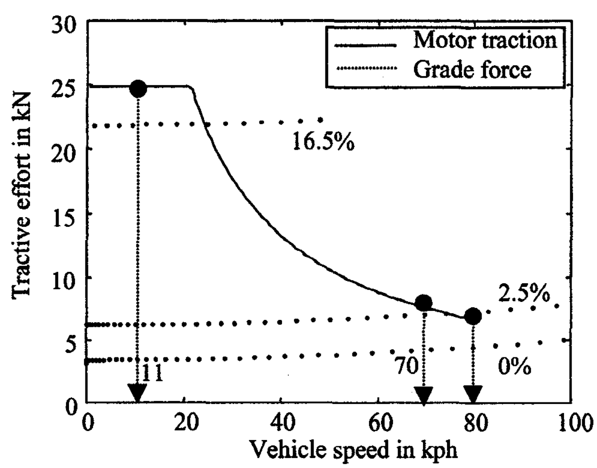

Figure 3. Motor traction force with a gear ratio of 15.9 and grade forces.

E. Acceleration Performance

To observe the acceleration performance of the vehicle we simulate an electric transit bus with the motor, battery pack and gear ratio obtained from the previous three sections. The EM is operated at its available capacity of 150kW as 10 kW power is reserved for auxiliary units. Figure 4 shows the performance comparison of the simulated electric bus with the White Book specification. The electric bus gives better acceleration results than the requirement.

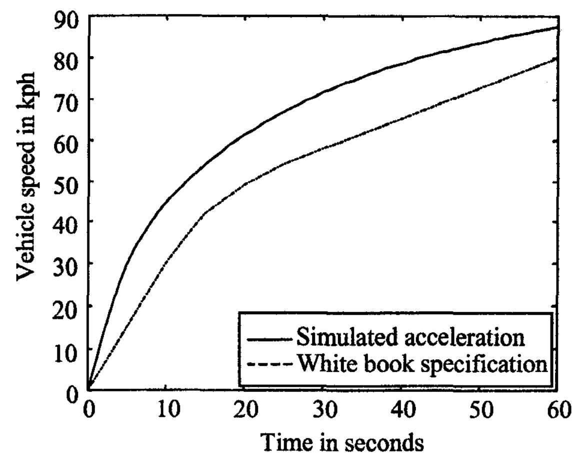

Figure 4. Acceleration performance of the electric bus.

F. APU Size Estimation

The sizing of the APU is done by calculating the energy capacity requirement of the vehicle. We select the EPA Urban Dynamometer Driving Schedule for Heavy Duty Vehicles (HUDDSHDV) for this purpose [7]. The electric bus created in the section D is used to measure the total energy consumption by the bus in HUDDSHDV driving profile. From the vehicle energy demand curve of figure 5 we see that 45 MJ of energy is consumed during 1060 seconds. The battery delivers this energy. To obtain a charge sustainable series hybrid bus we require the battery to maintain the same state of charge (SOC) in the beginning and at the end of the drive cycle. To do so, the APU should recharge the exact total energy that the battery has discharged through out the drive cycle. Assuming a recharging efficiency of 80% for the battery pack, the total APU energy output should be 56.25 MJ. If we consider the APU to continuously produce electric power through out the drive cycle, then the APU energy production curve becomes a straight line with the gradient

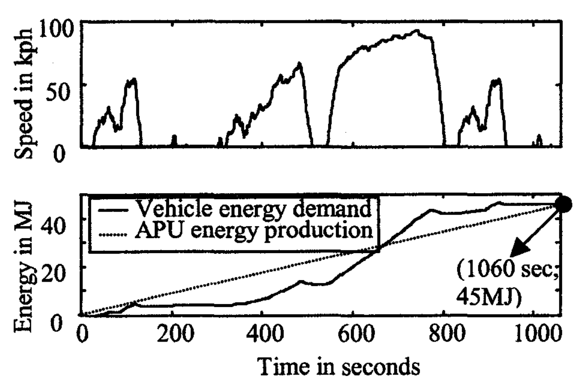

Figure 5. Vehicle energy consumption and APU energy production on HUDDSHDV drive cycle.

equal to APU power output. This is shown in figure 5 with dotted line. Thus, the output power from APU is calculated as (56.25MJ/1060sec=) 54 kW. Assuming a generating efficiency of 85% and the coupling efficiency of 95% we compute the ICE power as 67 kW.

To optimize system efficiency, we require the engine to operate at its maximum efficiency region. We select a 3.5 litre gasoline fueled spark ignition engine. The efficiency map of the engine is given in figure 6. From the figure we see that the ICE will deliver 70 kW of power at 3000 rpm while running near its maximum efficiency point.

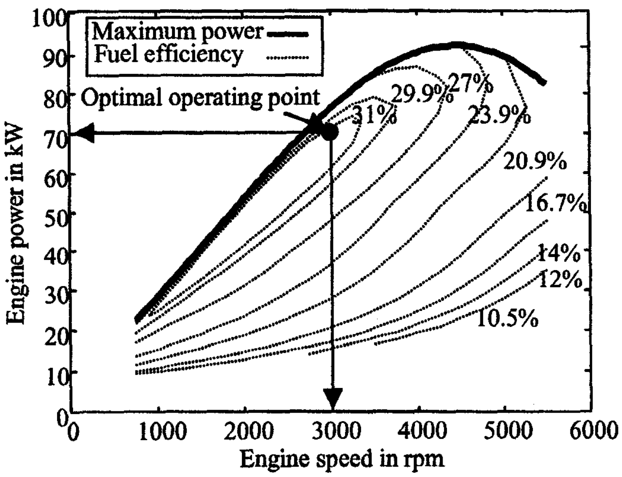

Figure 6. Efficiency mapping of the engine.

IV. DESIGN SUMMARY AND RESULTS

After estimating the component parameters and sizes for the transit bus power plant, we simulate its performance. We use an imperical battery model, steady-state DC motor model, steady-state DC generator model and the dynamic engine model for our simulation. The component parameters and gear ratios used for the simulation are summarized in table 1. Figure 7 shows the battery SOC, EM and APU power output for the HUDDSHDV drive cycle with the APU running continuously at its optimal point. The figure shows that over the drive cycle the depth of discharge (DOD) of the battery is almost zero. This indicates the charge sustainability of the series bus.

V-ELPH has a data summary table, which shows the simulation results in a tabular form. We present the summary of our result in figure 8 and discuss some of its key features regarding the simulation. The engine emissions presented in the figure were calculated using the empirical equations provided by Prabhakar [8]. The battery charging and discharging efficiency was found to be 84% and 80% respectively, which is close to what we

Table I. Summary of component parameters.

Components	Rated specification
ICE	Operating speed: 3000rpm Power output: 70kW Efficiency: 32%
Generator	Operating speed: 7500rpm Power output: 56kW Efficiency: 85%
Coupler	Gear ratio: 2.5 Maximum torque: 250 Nm Maximum speed: 7500 Nm Efficiency: 95%
Motor	Base speed: 2000rpm Maximum speed: 7500 rpm Power rating: 160kW
Differential	Gear ratio: 15.9 Efficiency: 92%
Battery	26 twelve volts lead-acid two 13 cells series wired strings connected in parallel

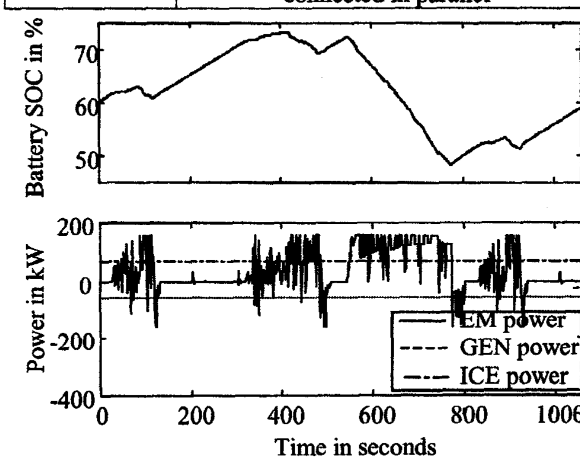

Figure 7. Time history of Battery SOC, EM and APU power output.

initially assumed in sizing the APU. The battery used 34.29MJ during discharge and gained 32.94MJ in recharging. A deficit of 1.35MJ of energy has caused the battery DOD to be 0.98%. Total charging energy supplied by generator and motor (during regeneration) is (60.63+6.079=) 66.71MJ and total energy drawn by the motor is 54.48MJ which gives a difference of 12.23MJ of charging energy. The total battery charging energy is also found (41.16-28.91=) 12.25 MJ. This verifies the energy conservation in the simulation. The ICE burns 236.6 MJ of fuel to produce 75.11MJ of mechanical power of which 71.35MJ is available to the generator due to 95% of coupling efficiency. We find the system output from the drive train to be 45.1 MJ which verifies our simulation result obtained from figure 5. The energy input to the system was calculated by adding the energy of fuel burnt (236.6MJ) and the energy deficit in the battery pack

(1.35MJ). An overall system efficiency of 18.95% was obtained. The fuel economy was obtained 0.3256 km/litre.

V. CONCLUSION

We have shown the series of steps involved in designing a series hybrid transit bus with simulation results starting from its performance specification. The designed vehicle was able to meet all the requirements of the White Book. Based on the results we expect series hybrid buses to attain decreased fuel consumption and lower emissions, thus increased system efficiency. We have also shown the capability of the V-ELPH software package in designing hybrid vehicles and analyzing their performance. There are not many HEV design software packages publicly or commercially available, partly because this area of research is newly evolving and mostly due to the trade confidentiality within the automotive industries. The V-ELPH 2.01 can provide valuable assistance to vehicle designers and significant understanding to researchers in the area of hybrid vehicles.

VI. ACKNOWLEDGMENTS

The authors affirm their appreciation to all the students and faculty persons in the HEV research group of TAMU in developing V-ELPH 2.01. Support for this work was provided by the Texas Higher Education Coordinating Board Advanced Technology Program (ATP) and the Office of the Vice President for Research and Associate Provost for Graduate Studies, through the Center for Energy and Mineral Resources, TAMU.

REFERENCES

(1) Bass E.A., Ullman T.L., Owens E.C., "*The Challenges of Developing an Energy, Emissions, and Fuel Economy Test Procedure for Heavy-Duty Hybrid Transit Vehicles*", SAE 952610.

(2) Mutch, G., Drozdz, P., Ramsay, M., " *Duty Cycle Simulation for Near Term Hybrid Electric Transit Buses*", pp. 587-596, Windsor workshop, June 1993, Toronto, Canada.

(3) Butler K.L, Stevens K.M., Ehsani M., "*A Versatile Computer Simulation Tool for Design and Analysis of Electric and Hybrid Drive Trains*", SAE 970199.

(4) Levinson H.S., Abrams-Cherwony and Associates, Lea, Elliot, "*Characteristics of Urban Transportation Systems*", Technical Report DOT-T-93-07, Federal Transit Administration, U.S.A.

(5) Gilbert A.T., Rehn R. L., "*Electric Drivetrain for Hybrid Electric Bus*", SAE 920446.

(6) Arthur Wu, "*Hybrid Electric Drives for Heavy Duty Transit Buses*", SAE 951932.

(7) http://www.epa.gov, *Code of Federal Regulations*, 40 Part 86 Appendix 1 (d).

(8) Prabhakar R., Citron S.J., Goodson R.E., "*Optimization of Engine Fuel Economy and Emissions*", Technical report 75-WA/AUT-19, ASME, 1975.

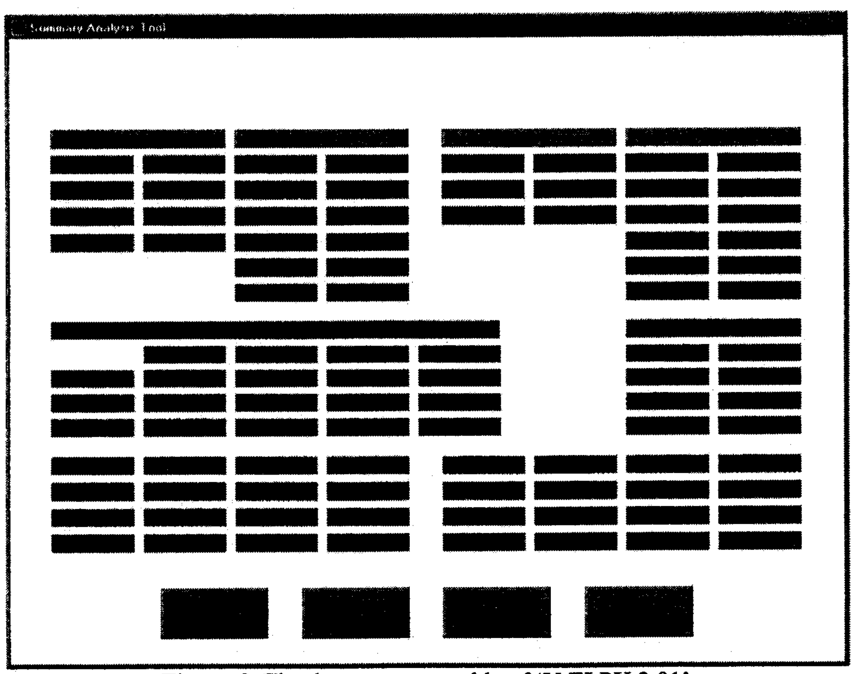

Figure 8. The data summary table of 'V-ELPH 2.01'.