

MATLAB-Simulink based Tool Development for Early Stage Design of Electric Powertrain during Conversion of Conventional Vehicle into Plug-In Hybrid Electric Vehicle

Pritam Keshavdas Gujarathi^{1*}, Varsha A. Shah², Makarand M. Lokahnde³

1, 2- Department of Electrical Engineering, Sardar Vallabhbhai National Institute of Technology, Surat, Gujarat-395007, India.

Email: pritamgujarathi@rediffmail.com¹ (Corresponding author), vas@eed.svnit.ac.in²

3- Department of Electrical Engineering, Visvesvaraya National Institute of Technology, Nagpur, Maharashtra-440010, India.

Email: makarandlokhande@gmail.com³

Received: March 2018

Revised: June 2018

Accepted: July 2018

ABSTRACT:

Electric Vehicles (EV) are becoming more popular due to an environment friendly approach. However, due to the dominance of fossil fuel-based conventional vehicle on road, emission reduction is a crucial task. In spite of continuous efforts to keep emission under control with alternative fuels, emissions are not under control. Conversion of Conventional Vehicle (CV) into Plug-In Hybrid Electric Vehicle (PHEV) is a promising solution to keep emissions under control of present vehicles running on the road as per norms. However, performance is limited by the size of an electric powertrain. Size of electric powertrain and its control strategy decided the fuel economy and emissions of vehicle i.e. the right size of the powertrain components is essential to fully exploit the benefits of the hybridization. The trend of electric powertrain design is from driving cycle. This will give better performance at that particular route only. Hence values are misleading for any other route and this design value cannot be generalized. The paper provides driving cycle independent generalized tool for the design of electric drivetrain during conversion of the conventional vehicle into the plug-in hybrid electric vehicle by fundamental force analogy method to get better performance of the vehicle. The MATLAB-Simulink tool is developed to size electric drivetrain parameters. The design parameters can be given as the input which will size the electric powertrain i.e. the size of motor and battery. In addition, the tool can be used to size battery of new PHEV. The obtained results have confirmed the effectiveness of proposed tool and compared to designed values of the vehicle. The size of electric powertrain can be utilized as early stage design during conversion of the conventional vehicle into the plug-in hybrid electric vehicle.

KEYWORDS: Electric Powertrain Plug-in Hybrid Electric Vehicle, Sizing, Software.

1. INTRODUCTION

PHEV is composed of an Internal Combustion Engine and Electric Machine (EM) which is usually powered by a battery through power electronics converter. Furthermore, the possibility to combine pure electric operation within no emission zones with the range capabilities of conventional vehicles makes converted PHEV the stepping stone towards the development of the electric mobility. Conversion of CV into PHEV is promising solution towards sustainable transportation for vehicles running on road, however there is less attention in terms of research on conversion of CV into PHEV as it is an ongoing challenge due to the limitation of space for fitting electric drivetrain, change in mechanical drivetrain components, size and weight constraint of electric drivetrain along with its energy management and control strategy. Few papers are published related to

conversion to HEV/PHEV mostly on conversion aspect and energy management strategy with stress on fuel economy [1-15]. Mostly electric powertrain is designed considering driving cycle only, which will give better performance only to considered driving cycle. There is no contribution in sizing of the electric drivetrain in a generalized way (sizing can be used for any driving route). As a matter of fact, PHEVs operation can be strongly affected by the selected component size. Therefore, once the mission of the vehicle is to the design of the electric powertrain with a fully electric mode for better performance of the converted plug-in hybrid electric vehicle (CPHEV) with a moderate range of the vehicle. Also, the design values should be driving cycle independent. The paper contributes towards MATLAB-Simulink based tool development of generalized electric powertrain design.

The paper is organized as below:

Section 2 provides details of proposed MATLAB Simulink tool. Section 3 gives a methodology for modeling of power required to size electric powertrain with vehicle dynamic approach. In section 4 results are provided for sizing of electric powertrain during conversion of the conventional vehicle into the plug-in hybrid electric vehicle along with battery sizing for market available PHEV followed by conclusion in section 5.

2. PROPOSED MATLAB-SIMULINK TOOL

The layout of the proposed tool can be seen in Fig. 1. It can be seen that design parameters are given as input at input side, and the size of motor and battery are outputs. The black box tool does the calculation required using fundamental vehicle dynamic approach by force analogy.

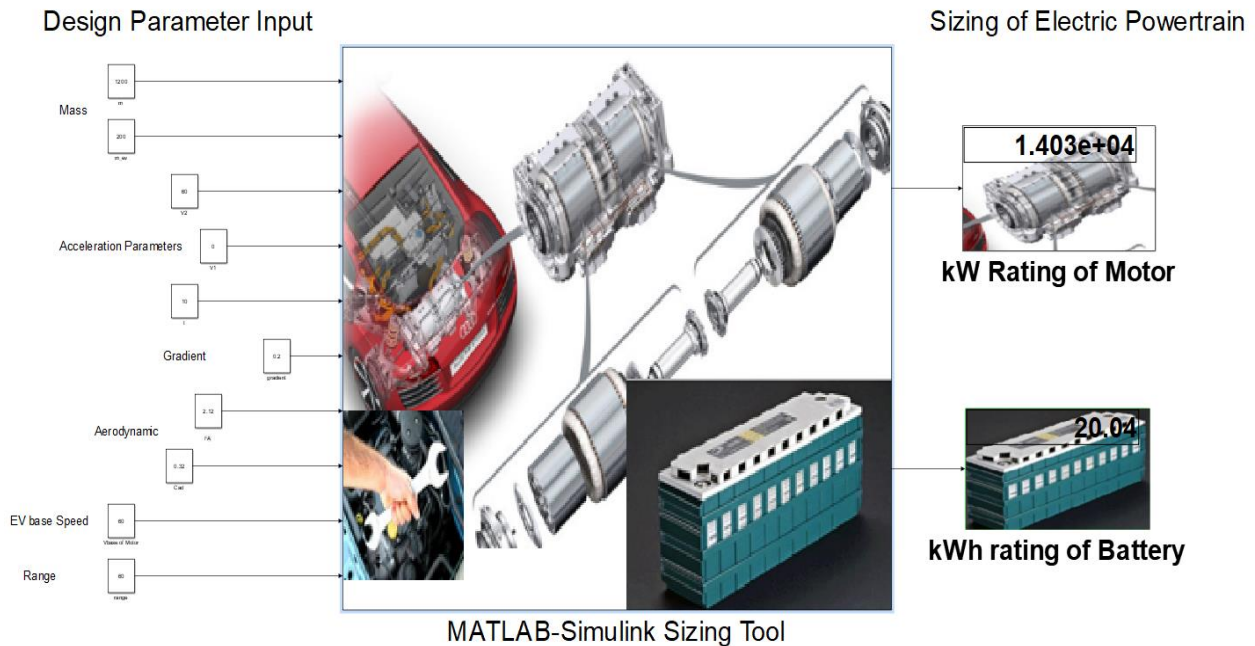


Fig. 1. MATLAB-Simulink Sizing Tool Layout.

The input parameters required are

1. Mass of vehicle in kg (including passenger and luggage).
2. The additional mass of the electric powertrain in kg.
3. The frontal area of the vehicle in m^2 .
4. The range of vehicle (electric) in km.
5. The speed of vehicle corresponding to base speed of the motor in km/hr.
6. Performance required (Acceleration details) e.g. 0 to 60 km/hr. in 10 secs. (Required speed in km/hr. and time in sec. to attain a required speed).

The output is the size of an electric drivetrain which is the size of the motor in kW and size of the battery in kWh.

3. METHODOLOGY

Electric powertrain is mostly sized from standard Driving Cycle (DC). Moreover, standard DC approach is misleading as it will give optimum performance for a specific route and the performance obtained cannot be

generalized. Hence fundamental approach of the vehicle dynamic needs to be considered for the design of electric powertrain. Hence in this work for sizing tool development, the fundamental vehicle dynamic approach is used.

The minimum sizing of the electrical motor is done by comparing following powers modeled.

1. The power required for acceleration of the vehicle at the start is modeled by the power required to overcome inertia and rolling resistance. The power required to overcome rolling resistance at the time of starting is modeled using fundamental equations considering worst unpaved road condition. The inertia power is determined by modeling accelerating performance requirement of the vehicle.

2. The power required to overcome gradient is modeled by the power required to overcome rolling resistance and weight component for a low speed of the vehicle. The force required to overcome rolling resistance is modeled considering the normal value of the coefficient of rolling resistance and weight component is considering maximum grading

requirement condition.

3. The power needed at a base speed of the electric motor is modeled by considering force required to overcome rolling resistance and aerodynamic drag. The normal values of coefficient of rolling resistance and aerodynamic drag can be considered.

The motor sizing has done by comparing these three-power requirements and considering the efficiency of transmission between wheel and motor. The size of motor can be increased to improve regenerative capability with the limitation of space for fitting.

The battery sizing solely depends on a range of vehicle per charge and the power corresponding to the speed of vehicle corresponding to the base speed of the motor.

When the default values are considered, design input requirements are;

- μ_{max} -coefficient of rolling resistance=0.05,
- ρ -air density in $kg/m^3 = 1.224$,
- g - acceleration due to gravity in $m/s^2 = 9.81$.

The specification of two passenger car is considered for study as shown in Table 1 below.

Table 1. Vehicle Specification of CPHEV.

Vehicle	Hatchback [16]	SUV [17]
Gross Weight	1400 kg	1860 kg
Engine Type	4 Cylinder Turbo Intercooled	4 Cylinder
Displacement	1405 cc	2494 cc
Fuel Type	Diesel	Diesel
Maximum Power	70 bhp @ 4500 RPM	100.57bhp@3600rpm
Maximum Torque	135 Nm @ 2500 RPM	200Nm@1400-3400rpm
Mileage (ARAI)	19.1 kmpl	12.99 kmpl
Frontal area of vehicle	2.12 m ²	2.632 m ²
Battery	Li-ion	Li-ion
Motor	3 Ph. Induction Motor	3 Ph. Induction Motor
Base Speed	60 km/hr.	60 km/hr.
Range/charge	60 km	60 km
Acceleration	1.667 m/s ² (0-60 km/hr. in 10 sec.)	1.5873 m/s ² (0-100 km/hr. in 17.5 sec.)

4. RESULTS

The results of sizing of an electric powertrain for specifications of the vehicle are given in table 2.

Table 2. Early Stage Design Values.

	Hatchback	Hatchback [16]
Battery Capacity	23.66 kWh	22.76 kWh
Motor Capacity	16.56 kW	15.78 kWh
	SUV	
Battery Capacity	30.26 kWh	
Motor Capacity	21.26 kWh	

Note: Results are with consideration of the efficiency of battery-0.8, State of charge utilization of 0.7 and efficiency of transmission between motor and wheel as 0.8 as in [16].

In addition, the effect of variation in range and speed of vehicle corresponding to the base speed of motor on motor rating and battery capacity can be plotted.

The battery capacity in kWh for variation in range

per charge for a hatchback for the constant base speed of vehicle of 60 km/hr. is shown in Fig. 2.

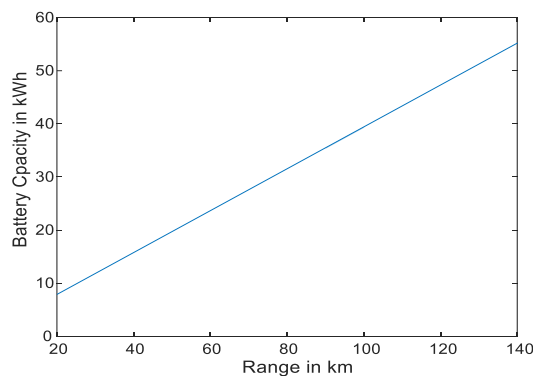


Fig. 2. Battery Capacity in kWh vs. Range in km.

If the vehicle is running with rated power, then battery capacity increases with range as shown in Fig. 2.

The effect of variation in vehicle speed corresponding to the base speed of the motor on

minimum motor size and battery capacity is plotted, for a hatchback, as shown in Figs. 3 and 4.

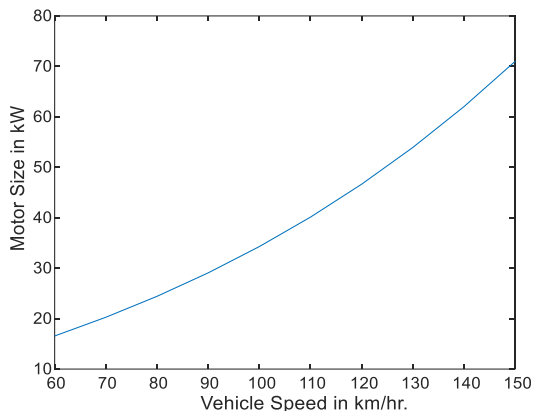


Fig. 3. Motor Size in kW vs. Vehicle Speed in km/hr.

In addition, this software tool has tested for sizing of a battery of PHEV available in the market. The motor size is not possible as new PHEV is designed with smaller engine size with a higher value of motor rating. The parameters used for sizing of the battery are shown in Table 3.

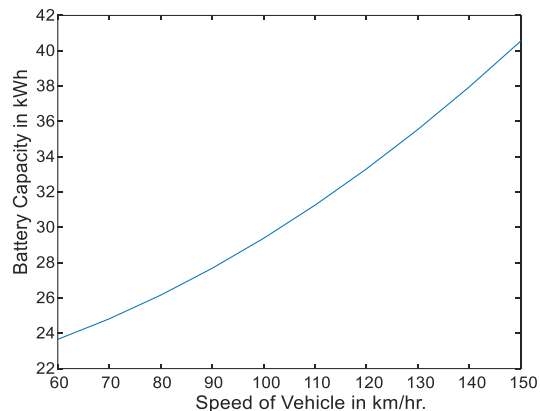


Fig. 4. Battery Capacity vs. Vehicle Speed in km/hr.

It should be noted that the values given by company are under idle condition. Under reality, it is not possible to get the range for given value of the battery. In the actual case for the range given the value of battery capacity required is more.

Table 3. Specifications of Market available PHEV.

	Ford Fusion Energi-SE [18] 2017	Honda Accord PHEV [20] 2017	Mahindra e20 plus [22] 2017
Curb Weight	1775 kg	1723 kg	937 kg
Gross Weight	1950 kg	1900 kg	1257 kg
Frontal area of vehicle	2.32 m ²	2.3 m ²	2.12 m ²
Top Speed (projected)	135 km/hr.	100 km/hr.	80 km/hr.
Range/charge	35 km	21 km	60 km
Acceleration	1.827 m/s ² (0-100 km/hr. in 15.2 sec.) [19]	6.63 m/s ² (0-100 km/hr. in 6.63 sec.) [21]	1.97 m/s ² (0-60 km/hr. in 14.1 sec.)
Battery capacity	7.6 kWh	6.7 kW	13.44 kWh

The parameters given above are used as input for a tool developed and the size of battery required are given in table 4.

Table 4. Early Stage Design Values

Battery Capacity	Software tool	Actual
Ford Fusion Energi	10.55 kWh	7.6 kWh
Honda Accord PHEV	9.971 kWh	6.7 kWh
Mahindra e20 plus	23.64 kWh	13.44 kWh

The default value of efficiency of the battery is considered as 80 %. However regenerative energy captured and SOC utilization range is not considered.

The value given by fundamental strategy is more as expected compared to given value. In addition, as per team BHP review, Mahindra Reva e20 plus tested extensively for two real-world driving patterns in typical Mumbai conditions [23]. The results are given below.

Table 5. Case 1/Day 1: Single Driver (with a lot of flyovers and mild climbs)

1 person - 80% of the time, 2 people - 20% of the time
 Air-conditioning - OFF
 50% of the driving was done at night with the headlights on
 Entertainment screen was on for 30% of the time

Boost mode used for 25% of the driving

Range obtained: 87 km Company Specified-140 km

Table 6. Case 2/Day 2: Extremely rigorous (20% of the journey was spent going up and down steep hills)

3 people - 30% of the time, 2 people - 30% and 1 - 40%

Air-conditioner - ON for 100 % and 20 minutes of the A/C running when parked

Boost mode- used for 25% of the driving

Entertainment screen & music playing- ON for 100% of the time

Headlights- ON for 30% of the time

Range obtained: 60 km Company Specified-140 km

Hence the range of vehicle during the real-time driving cycle is only 87 km in case 1 and 60 km in case 2 compared to a specified range of 140 km on the website.

5. CONCLUSION

The early stage design tool using MATLAB-Simulink is demonstrated for sizing of battery and motor of an electric powertrain. In addition, plots of base speed and range variation on sizing can be studied by the proposed tool. The proposed tool has also used to size battery of new PHEV available in market. The obtained results show that the EV industry needs to be more mature regarding proving proper electric range for specified battery capacity as the values are misleading. The variation observed by real-time testing done by team BHP for Mahindra e20 plus is 62.14 % of specified range in case 1 and less than 50 % as low as 42.85 % of specified range in case 2. Hence driving cycle design of electric drivetrain trend should be shifted to a fundamental vehicle dynamic approach for the design of electric powertrain to get better performance of the vehicle under any driving condition.

REFERENCES

- [1] Reza Ghorbani, Eric Bibeau, and Shaahin Filizadeh, "On Conversion of Hybrid Electric Vehicles to Plug-In", *IEEE Transactions on Vehicular Technology*, Vol. 59, No. 4, May 2010, doi: 10.1109/TVT.2010.2041563.
- [2] Saiful A. Zulkifli, Nordin Saad, Syaifuddin Mhd, A. Rashid A. Aziz, "Development of Split Axle Parallel Hybrid Electric Vehicles with in Wheel-Motor", 2012, *4th IEEE International Conference on Intelligent and Advanced Systems (ICIAS2012)*.
- [3] Sudhir Gupta, "Experimental Analysis and Feasibility Study of 1400 CC Diesel Engine Car Converted Into Hybrid Electric Vehicle by Using BLDC Hub Motors", *4th International Conference on Advances in Energy Research*, 2013, ICAER 2013, Energy Procedia 54 (2014) 177 – 184, doi:10.1016/j.egypro.2014.07.261.
- [4] Mushtak Talib Al-Atabil and Talal F. Y u d, "Experimental Investigation of a Single Cylinder Diesel Engine as A Hybrid Power Unit for a Series Hybrid Electric Vehicle", *IEEE. Student Conference on Research and Development Proceed-ings, Shah Alam, Malaysia*, 2002.
- [5] Steven Jenkins and Mehdi Ferdowsi, "HEV to PHEV Conversion Compatibility", *IEEE Vehicle Power and Propulsion Conference (VPPC)*, September 3-5, 2008, Harbin, China.
- [6] Michael L. McIntyre, Maegan Young, Robert Kessinger, "On Conversion of Hybrid Electric Vehicles to Plug-In Hybrid Conversion: As a Capstone Project and Research", 2010, *IEEE*.
- [7] Saiful A. Zulkifli, Nordin Saad, Syaifuddin Mhd, A. Rashid A. Aziz, "Split-Parallel In Wheel-Motor Retrofit Hybrid Electric Vehicles", *IEEE International Power Engineering and Optimization Conference (PEOCO2012), Melaka , Malaysia*, 6-7 June 2012.
- [8] Nisai H. Fuengwarodsakul, "Retrofitting a used Car with Hybrid Electric Propulsion System", 2009, *IEEE*.
- [9] G.Rizzo, M.Sorrentino, C.Speltino, I.Arsie, G.Fiengo, F.Vasca, "Converting Conventional Cars in Mild Hybrid Solar Vehicles", *International Federation of Automatic Control (IFAC)-18th IFAC World Congress Milano (Italy) August 28 - September 2, 2011*.
- [10] Steven Jenkins and Mehdi Ferdowsi, "Urban Bus Fleet Conversion to Hybrid Fuel Cell Optimal Powertrains", *EWGT2013 – 16th Meeting of the EURO Working Group on Transportation, Procedia - Social and Behavioral Sciences 111*, pp. 692 – 701, doi: 10.1016/j.sbspro.2014.01.103, 2014.
- [11] Ehsan Tara, Soheil Shahidinejad, Shaahin Filizadeh, Eric Bibeau, "Battery Storage Sizing in a Retrofitted Plug-in Hybrid Electric Vehicle", *IEEE Transactions on Vehicular Technology*, Vol. 59, No. 6, July 2010.
- [12] Reza Ghorbani, Eric Bibeau, and Shaahin Filizadeh, "Influence of Motor Power and Efficiency On fuel Consumption Of Retrofit –Conversion Split Parallel Hybrid Electric Vehicle", 2013, *IEEE*.
- [13] Frank Zeman, Randall Lewis, "Retrofitted plug-in hybrid vehicles: Results of NYIT drive share program", *Transportation Research Part D 17*, pp. 514–518, 2012.
- [14] Sanjaka G. Wirasingha, Nigel Schofield, Ali Emadi, "Feasibility analysis of Converting a Chicago Transit Authority (CTA) Transit Bus to a Plug-in Hybrid Electric Vehicle", *IEEE Vehicle Power and Propulsion Conference (VPPC)*, September 3-5, Harbin, China, 2008.
- [15] Sunarto Kaleg, Abdul Hapid , M. Redho Kurnia , "Electric Vehicle Conversion Based On Distance, Speed and Cost Requirements", *2nd International Conference on Sustainable Energy Engineering and Application, ICSEEA 2014*, Energy Procedia 68 (2015) 446 – 454, doi: 10.1016/j.egypro.2015.03.276.

- [16] Gujarathi P. K., Varsha A. Shah and Makarand M. Lokhande, “**Design, Modeling, Simulation and Analysis for Conversion of Conventional Tata Indica Car into Plug in Hybrid Electric Vehicle**”, *The 28th International Electric Vehicle Symposium and Exhibition (EVS28)*, KINTEX, Korea, May 3-6, 2015.
- [17] <https://www.cardekho.com/toyota/toyota-innova-specifications.htm>, (accessed on 02/03/2018).
- [18] <https://www.ford.com/cars/fusion/models/fusion-hybrid-se/?gnav=vhpnav>, (accessed on 02/03/2018).
- [19] <https://www.caranddriver.com/reviews/2017-ford-fusion-energi-tested-review>, (accessed on 02/03/2018).
- [20] https://en.wikipedia.org/wiki/Cadillac_ELR, (accessed on 02/03/2018).
- [21] <http://www.hybridcars.com/how-gm-amped-up-the-2016-cadillac-elr/>, (accessed on 03/03/2018).
- [22] <http://www.mahindraelectric.com/e2oPlus/>(accessed on 03/03/2018).
- [23] <http://www.team-bhp.com/forum/official-new-car-reviews/134857-mahindra-reva-e2o-official-review.html> (accessed on 03/03/2018).