Design, Modeling, Simulation and Analysis for Conversion of Conventional Tata Indica Car into Plug in Hybrid Electric Vehicle

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Abstract

Indian transportation sector is growing very fast. Import of crude oil, fluctuation in fuel prices and depletion of fossil fuel is concern to worry about. Metro cities in India have crossed the emission standard set by vehicle regularity board. Hybridisation of conventional vehicle can be the first necessary step in reducing the environmental impacts of automobile use without losing comforts, performance, storage room and extended driving range.

In this paper efficient and sustainable personal transportation solution is provided by presenting design, modelling, simulation and analysis for conversion of conventional Tata Indica car into Plug in Hybrid Electric Vehicle (PHEV). A study of conventional vehicle dynamics for designing an electric powertrain is carried out. Design of electric powertrain is carried out by considering urban utility and local characteristics with minimum change of existing power train component using plug in parallel hybrid topology. Mathematical modelling and simulation of a power plant is presented in different modes using Matlab-Simlink. The focus of the model is on detailed assessment of different subsystem components and their dynamic models. Results of modified Plug in Hybrid topology simulated are presented.

Keywords: Dynamics, Modelling, PHEV, Simulation

1 Introduction

Automobiles have made great contribution to growth of Modern Society. The rapid development of Automotive Industry has incited the progress of human beings by satisfying needs for mobility in everyday life to highly developed industrial one. The economic growth of a country extensively depends on transportation via road, rail, sea and air. Foremost among them is road transport. At present almost all vehicles relay on fossil fuel based transportation i.e. most on Petrol (Spark plug ignition IC engines) and Diesel (Compression ignition IC engine). These pollutes atmosphere by emission of greenhouse gases & causes global warming. Also an increase in fuel prices and depletion of fossil fuel is concern to worry about. From 2006 to 2030, the global energy consumption is likely to rise by 53% and about three quarters of the projected increase in
oil demand will come from transportation [1]. As per IEA report of 2013, fossil fuel based transportation is the second largest source of CO2 emissions globally [2]. The transport sector contributes 22% of the total CO2 emissions in the world which is second highest followed by electricity and heat accounted 41% according to the latest estimates of the International Energy Agency [3].

The top 10 emitting countries account for nearly two-thirds of the world CO2 emissions as shown in Fig.2. India stands third with CO2 emission of 1.726 billion Mt [4].

Unlike other countries the Vehicle to people ratio is very high, however population is more. The number of vehicles along with growth for different types of vehicle as on is given in fig.3 [3].

Indian transportation sector is growing very fast. The gap between domestic crude oil production and consumption is widening. India is a country which imports around 70% of Oil required per year [5]. Increases in the price of fossils fuel affect the economy of Country. This poses a serious challenge to Indian energy security. For emerging economies like India, sustainable mobility is also accentuated by rapid economic development which is accelerating the demand for transportation. Metro cities in India have crossed the emission standard set by vehicle regularity board. Therefore, all measures need to be taken for lessening the dependence on fossil fuels for the country’s energy requirements and reducing pollution. The basic information on Indian transportation is summarized in table 1.

Table 1: Basic Information of Indian transportation

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<td>2.</td>
<td>Vehicle to People Ratio</td>
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<td>3.</td>
<td>Per Capita energy</td>
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<td>4.</td>
<td>GHG emissions</td>
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Figure 1: World Sector wise CO2 Emissions
*Other includes commercial/public services, agriculture/forestry, fishing etc.

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Figure 3: Indian Growth & Statistics of Vehicle

Due to urbanization and decentralization of city area, a rapid increase in personal vehicles has been observed. Looking into number of present vehicle, increase in transportation along with growing concern of pollution and depletion of fossil fuels, hybridisation of conventional vehicle can be one of the necessary steps. Compared to available sources, hybrid electric combination provides better and efficient option which combines an IC engine with electrical power.
driven motor to provide benefits of conventional & electric technologies. The on board electric motor serves as a device to optimize the efficiency of the IC engine, as well as recover the kinetic energy during braking or coasting of the vehicle. Electrification is the best way for clean and efficient transportation. Hence conversion of conventional vehicle to PHEV/HEV can be one of the efficient, viable and better solutions for Indian transportation system.

In this paper a study for conversion of conventional vehicle into PHEV is carried out. The details of vehicle under consideration, proposed structure and operating strategy is discussed in section 2 and 3. Modelling & Simulation of conventional vehicle longitudinal dynamics is considered as base for designing electric drivetrain and is presented in section 4. The electric powertrain design and simulation of proposed PHEV is presented in section 5 and 6 with results.

2 Vehicle under Consideration

Conversion of Conventional Vehicle into Plug in Hybrid Electric is considered for the Tata Indica Diesel Car whose specifications are given in table 2.

Table 2: Indica Vista [2012-2014] LX TDI BS-III Technical Specifications

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<th>Dimensions &amp; Weight</th>
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<td>Length</td>
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<tr>
<td>Width</td>
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<tr>
<td>Height</td>
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<tr>
<td>Wheelbase</td>
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<td>Ground Clearance</td>
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<td>Kerb Weight</td>
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<td>Engine Type</td>
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<tr>
<td>Displacement</td>
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<tr>
<td>Fuel Type</td>
</tr>
<tr>
<td>Max Power</td>
</tr>
<tr>
<td>Max Torque</td>
</tr>
<tr>
<td>Mileage (ARAI)</td>
</tr>
<tr>
<td>Valve/Cylinder (Configuration)</td>
</tr>
<tr>
<td>Fuel System</td>
</tr>
</tbody>
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Curb mass = 1045 kg, considering the addition of a driver, passenger and a luggage, the mass considered is $m = 1400$ kg.

The tyre radius for front and rear tyre is given as 175 / 70 R13, by standard calculations comes to be $r = 0.2876$ m.

3 Proposed PHEV Structure and Operating Strategy

The proposed converted PHEV Structure is shown in fig. 4 below.

![Proposed PHEV Structure](image)

The proposed structure will be parallel plug in hybrid with option of independent or combine operation. Plug in facility for charging along with engine dynamo charging in running condition is possible; however the rating of dynamo needs to change. The option is with driver to operate the vehicle in one of following three modes specified as IC Engine. Mode-Conventional IC engine driving EV Mode- EV mode will supply power to Wheels only by motor can be preferred in city. Plug in facility is given to charge battery with range of around 60 km.

Hybrid Mode-In hybrid there can be three modes 1. The EV mode is preferred in city or where speed of vehicle is less than 60 km/hr. 2. Between 60 to 120 km/hr., IC Engine is preferable and 3.
Above 120 km/hr., hybrid operation can be performed.

When switch is put to hybrid mode EV will supply power to Wheels up to 60 km/hr. using simple centrifugal switch engine can be automatically connected at 60 km/hr. up to 120 km/hr. If speed goes above 120 km/hr. using speed sensor motor can be started and it will operate in assisted mode. However if SOC is less than 30 % it will run with Conventional IC engine and also charge battery.

4 Modelling and Simulation of Vehicle

The force propelling the vehicle forward i.e. the tractive effort has to accomplish the following:

- overcome the rolling resistance;
- overcome the aerodynamic drag;
- provide the force needed to overcome the component of the vehicle’s weight acting down the slope;
- accelerate the vehicle, if the velocity is not constant.

![Figure 5: Forces acting on Vehicle](image)

The total tractive effort is the sum of all these forces:

\[ Ft = F_{rr} + F_{ad} + F_{hc} + F_{la} + F_{ωa} \]  \hspace{1cm} (1)

Where,

- \( F_{rr} \) is the rolling resistance force,
- \( F_{ad} \) is the aerodynamic drag,
- \( F_{hc} \) is the hill climbing or grading force
- \( F_{la} \) is the force required to give linear acceleration
- \( F_{ωa} \) is the force required to give angular acceleration to the rotating motor,

\[ F_{la} + F_{ωa} \] can be combed together as mentioned above and can be written as \( F_{La} \)

The tractive effort available for acceleration can be

\[ F_{La} = Ft - ( F_{rr} + F_{ad} + F_{hc} + F_{ωa} ) \]  \hspace{1cm} (2)

We should note that \( F_{La} \) and \( F_{ωa} \) will be negative if the vehicle is slowing down, and that \( F_{hc} \) will be negative if it is going downhill.

Where, \( Ft = \) tractive force available at tyre or vehicle out which can be converted to tractive torque by multiplication of tyre radius \( r \). The above equation can be written as

\[ m \frac{dV}{dt} = Ft - (f_{rr} mg \cos(ψ) + ½ \rho A C_d V^2 + mg \sin (ψ) + I /r^2 a) \]  \hspace{1cm} (3)

Where, \( m \) - mass of vehicle in kg, \( Ft \) - tractive force in N, \( f_{rr} = U_r \) - coefficient of rolling resistance, \( ψ \) - gradient angle, \( ρ \) - air density in kg/m³, \( C_d \) - air drag coefficient, \( V \) - Speed of Car, \( I \) - inertia of car in kg-m².

Now to accelerate vehicle total tractive force \( Ft \) should be supplied by engine and or motor, however some lost in transmission i.e. \( Ft \) tractive force supplied by engine and or motor after overcoming loss in transmission.

Simulating this equation the tractive forces required at staring, resistances offered for movement of vehicle, different coefficients and their variations, their effects etc. can be studied and plotted in view of understanding and designing electric drive train for conversion to PHEV. The results considering data given in section 3 can be shown in figure 6 and 7.

Fig 6(a), shows force required to overcome rolling resistance and total tractive force required for different road conditions i.e. \( U_r \) is varied from 0.01(smooth road) to 0.05 (unpaved road condition). \( Ft \) is plotted for a speed of 60 km/hr. with aerodynamic drag coefficient of 0.2 for flat road.
The rolling force is linear with rolling coefficient and the maximum rolling force required for unpaved road can be 687 N. The tractive force required for a speed of 60 km/hr. for above condition comes to be around 753 N.

Fig 6(b) shows force required to overcome gradient and total tractive force required for change in gradient from 0 to 30 %. Ft is plotted for a speed of 20 km/hr. with aerodynamic drag coefficient of 0.2 and coefficient of rolling resistance of 0.01.

The force required for maximum gradient with speed of 20 km/hr. with cd=0.2 and Ur = 0.01 is around 4050 N. If Ur is increased to 0.05 with decreased in speed to 10 km/hr., the maximum tractive force required would be around 4600 N.

The aerodynamic force and total force required when speed varies from 0 to 180 km/hr. with flat road for Cd=0.2 and Ur = 0.01 is shown in figure6(c).
The aerodynamic force and total force required when speed varies from 0 to 180 km/hr. with flat road for Cd=0.2 and Ur = 0.01 is around 600N and total force required is around 730 N.

Simulation results gives detail understanding of forces required and its behavior at different conditions and coefficients variations, which will help us for designing electric drive train targeted to operate efficiently up to 60 km/hr. It is observed that driving vehicle on gradient needs highest force followed by aerodynamic drag.

The analysis of forces at starting, accelerating and maintaining top speed for electric drivetrain design can be summarized as below.

If electric vehicle need to accelerate from 0 to 60 km/hr. in 10 sec then the acceleration would be 1.667 m/s². The inertia force can be accelerating weight force which will be around 2670 N and the maximum force required to overcome the rolling resistance is 785 N. (assuming increase in weight of electric drive train of 200 kg.)

\[
\text{The total force at starting} = F_{rr} + F_{\text{inertia}} = 785 + 2670 = 3455 \text{ N.}
\]

Total force at base speed of 60 km/hr.

\[
F_{60} = F_{rr} + F_{\text{ad}} = 785 + 67 = 852 \text{ N.}
\]

Due to electrification weight the increase in inertia force is around 335 N. where as force required to overcome frictional resistance increases by 115 N.

The force required for different top speed is plotted as shown in figure 7 below and varies between 852 to 970 N for speed range of 60 to 100 km/hr.

The tractive force should be provided by engine and or electric drive train i.e. motor.

If Engine: The engine power (Pe) is the product of its torque (Te) and angular velocity (ωe):

\[
Pe = Te \omega e
\]

The whole is not available for use, some will get lost in transmission system and remaining is available for acceleration (Pt). We can call it as tractive power available at wheels for movement of vehicle.

\[
Pt = Ti \omega t = \eta_t Te \omega e = Pe (1 - \eta_t)
\]

Where, \( \eta_t \) - efficiency of transmission system, \( T_t \)- Tractive torque and \( \omega t \) - required angular speed can be calculated by using proper gear ratios whose data is known. From which \( F_t \) is calculated as

\[
F_t = T_t /r
\]

If motor (V < 60 km/hr. or in between 120 to 180 km/hr.): The motor power (Pm) is the product of its torque (Tm) and angular velocity (ωm)

\[
Pm = Tm \omega m
\]

This power is available and required speed can be obtained by using single gear. However amount of power available depends on efficiency, type of motor along with control strategy etc.

If Hybrid operating in combine mode and power is supplied by both engine and motor.

\[
P = Pm + Pe
\]

The energy is lost in braking can be recovered in hybrid and EV mode which is shown simulation results.

5 Electric Powertrain Design

The electric drive train is designed for operation up to 60 km/hr. with capacity to start and accelerate to deliver approximately same performance like conventional IC Engine for base speed. If vehicle need to drive at 60 km/hr. for a range of 60 km
then the capacity of battery required to maintain range will be

\[ \text{Batt Capacity} = \frac{F \times \text{Range}}{3600} = 14.2 \text{ kWh} \]

Considering efficiency of 80%, the capacity can be 17.75 kWh. Only 70% of this capacity is used to maintain SOC, thermal limit etc. and the battery capacity can be 22.6 kWh.

The peak and continuous rating of motor is different. Normally chosen peak rating is 1.6 times of continuous rating. Rating of motor required to maintain top speed of 60 km/hr. will be around 14.2 kW. If efficiency is considered as 80% (including controller), the rating comes to be 17.75 kW. The peak value, thermal factors consideration needs higher capacity of motor although depends on driving cycle, controller etc. or otherwise 14.2 kW rating is multiplied by 1.6 to get rating of motor of 22.72 kW. One of the other way to calculate the rating of motor from driving cycle. However which will give optimum performance for specific route.

There are various choices available in electric motor along with variety of well proved control strategies. Robust well proved v/f control of Induction motor is considered for these work, latter on detail assessment along with design will be carried out.

6 Simulation and Results of Proposed PHEV

The Simulation is done to get real feel of Vehicle. User or Driver will have choice to select mode of operation. When car is started using key, the clutch is pressed by driver and gear is shifted, now accelerator and brake positions will be input for driving and direction is controlled by steering. So drivers pedal position and brake is considered as input. Clutch and Gear operation is not considered to reduce complexity and taken care in engine management/engine characteristics. The Vehicle Simulation is shown in fig. 8.

The Simulation is divided into input, vehicle (Conventional IC Engine and or Electric Vehicle) and output as shown. To start car on/off switch is provided. Once car is started clutch and gear along with accelerator, brake and road condition will be input.

Normally while driving vehicle pedal is pressed in range of 0 to 45 0. Hence input pedal position for accelerator and brake is considered as 0 to 45 0. Depending on mode selected the IC engine and or electric motor will run and speed will be displaced at output. The results are divided in to three parts.
6.1 PHEV in IC Engine Mode

The PHEV Simulation model in Conventional IC engine mode is divided into engine management, vehicle dynamics and output. When acceleration pedal position and brake position is pressed by legs to change speed as per road profile and speed requirement, the engine management block will take care of Engine characteristics, transmission system, power, torque delivered etc. by engine as per input position. Using real time engine characteristics the torque and speed delivered by engine is calculated using look up table. The power supplied by engine, engine rpm and the force delivered by engine is calculated further by using radius of crankshaft. Vehicle dynamic deals with longitudinal dynamics and divided into tractive force calculator and speed calculator. Tractive force calculator model calculate force required, whereas speed calculator block calculates speed, braking power available for regeneration. Care has been taken that brake and accelerator shouldn’t press together. Some of the results are shown in fig.9 and 10.

Figure 9: Input random pedal position driving cycle and the Speed output.

Figure 10: Energy available for regeneration from braking
6.2 PHEV in EV Mode

A v/f controlled induction motor rated 15 kW, 1500 rpm induction motor is simulated using single gear ratio. The battery pack used with rating 20 kWh. The voltage and frequency ratio is controlled by input position of pedal and brake.

The results for different positions of Accelerator and brake positions are shown with respect to time in fig.11, 12 and 13.

![Figure 11: Vdc, Vac, Speed and Torque for input pedal position of 80 % without application of brake.](image)

![Figure 12: Vdc, Vac, Speed and Torque for input pedal position of 100 % with brake position of 30 %.](image)

It is observed that as per accelerator position speed will settle to required value i.e. 48 km/hr. in fig. 11 and 42 km/hr. in fig.12. Also there is slight drop in battery voltage with starting stress in both cases as shown. The staring transients torque required in fig. 11 is more than fig. 12 as per accelerator demand. The PWM output line voltage of Inverter is also shown as VL.

The random signals are generated for accelerator and brake pedal position to create driving cycle as shown in fig. 13 as Input signal and brake signal. The driving cycle seems like urban traffic driving style.

![Figure 13: Input Pedal and Brake Signal, Vdc, Vac, Speed, and Torque with time](image)
It can be seen that there is little fluctuations in battery voltages whenever speed demand rises e.g. at time of around 1.6 sec and 2.8 sec. There is also large torque demand and hence transients are observed in electromagnetic torque developed at the same time. The available regenerative energy can be seen on speed profile below zero, which can be captured. The variable voltage and frequency of inverter can be seen clearly from line voltage plotted. The electromagnetic torque developed is also shown in figure above.

6.3 PHEV in Hybrid Mode

The driving cycle as accelerator pedal position input in between 0 to 45° applied by driver is shown in fig 14 and the response as vehicle speed is shown in fig.15.

![Figure 14: Driving Cycle as Input Pedal Position 0 to 45° with time](image)

![Figure 15: Speed response for driving cycle input](image)

It is observed that whenever pedal position is less than 30°, EV mode will be in operation with speed of maximum 60 km/hr. as shown in fig 15. During 30° to 38°, IC engine alone will operate between speed of 60 to 120 km/hr. and both will operate for pedal position greater than 38° as shown in fig 15.
7 Discussion and Future Work

In the Simulation the regeneration captured by electrical vehicle for battery charging is not considered along with SOC Control. Also the emission and fuel economy data will give more practical feel which can be the next course of action with the study of electric drivetrain details and perform in depth simulation of electrical drivetrain along with optimum control strategy which may be used for actual retrofitting of vehicle. However due to limitation of pages selected simulation details and results are shown.

Conclusion

In country like India, conversion of conventional vehicle to plug in hybrid technology can be one of the effective steps in reducing emissions and dependence of fossil fuel. Retrofitting means of conversion to plug in hybrid electric vehicle is one of the promising, viable and efficient option.

In this paper a preliminary study for conversion of Tata Indica car into plug in hybrid parallel topology has carried out with simulation. Detail assessments of Force requirement with effect of all parameters are shown. A stress on dynamic study of vehicle necessary for designing electric drive train has presented. The design and modelling of electric drivetrain is presented for conversion. A minimum designed values of motor (15 kW) with battery capacity (14.2 kWh) for range of 60 km with top speed of 60km/hr. by electric drive train are considered for simulation.

The simulation of proposed plug in hybrid with three modes of operation with practical approach is carried out and results are shown for the vehicle operation in EV mode for speed less than 60 km.hr. IC engine and hybrid mode for all speeds. The result shows the effectiveness and desired operation for selected mode as per operating strategy.

References


EVS28 International Electric Vehicle Symposium and Exhibition 11