NSGA-II Based Optimization Approach For Intelligent Load Sharing In Plug-In Hybrid Vehicles

Parag Jose Chacko, Meikandasivam Sachidanandam

Abstract: Plug –in Electric Vehicles (PHEV) ensures the reduction in emission levels as compared to IC engine based vehicles. The minimization of emission levels and fuel costs would lead to over utilization of the Traction battery in a PHEV. This work focuses on development of an Intelligent Energy Management System (IEMS) which optimizes the emission level and fuel costs considering the criticality of the future journey of the PHEV user. The criticality of the journey for the PHEV user regulates the decision made by the Intelligent Energy Management System. The system developed is a Parallel Hybrid system with a BLDC motor assisting the IC engine in propulsion. To validate the IEMS operation a detailed design and development of a Parallel Hybrid Vehicle considering a 150cc Petrol engine as the main propulsion source and a 3kW BLDC motor as the support propulsion source is done. The design and testing of the response of the vehicle to drive cycle is performed using Matlab/Simulink environment. The impact of the designed model on the 14 –Degrees of Freedom is performed to validate the developed model. The prototype is then developed and tested with the IEMS controller. The decision on load sharing is performed using a Non-Dominated Sorting Genetic Algorithm –II (NSGA-II) approach. The IEMS optimizes the Emission Level and Fuel costs depending on the next journey distance, altitude and the PHEV user criticality and decides the permissible Depth of Discharge (DoD ) level for the traction battery.

Index Terms: PHEV; IEMS; NSGA-II; SoC; DoD; Pareto Front.

1. INTRODUCTION

The conventional automotive industry today, is facing a major challenge. This is a high demand for providing improved and higher fuel economy. This is for the better acceptance of their vehicles in the context of rising fuel prices and depleting fuel resources. Also the challenges of increased levels of vehicle emission is adversely affecting the health and economy of the country. The high level of Air Quality Index (AQI) in metro cities in India like capital Delhi, where the AQI reached 471[1] is an indication of adapting urgent measures for controlling and reducing these emissions. These high values of AQI recorded in major cities of the country indicates how severe the situation is and how unhealthy the conditions are for the masses living in these cities in India. However, the automotive industry is in a dilemma to maintain profit, and at the same time ensure the acceptance of their vehicles by making them affordable. This leads to compromise in terms of emission levels and economy. But with the National Electric Mobility Mission Plan (NEMMP) 2020 and Faster Adoption and Manufacturing of Electric & Hybrid Vehicles (FAME) the Government of India has given clear indications for future of mobility in India. The electrification of mobility would enable the problems of emissions to be reduced to a great extend. Stringent BS-VI standards expected to be implemented early 2021 would further reduce the emission levels. However with a huge country like India with almost 3.8 million IC engine vehicles plying, it is not an easy task to convert to Electric Vehicles. The lack of Government policies for infrastructure development on a ground level and the inability of our traditional power grid to accept such a sudden influx of Electric Vehicles will slow the process. But today, the Hybrid Electric Vehicle industry is slowly emerging with higher fuel economy and reduced emissions and could prove to be a viable alternative when compared with conventional vehicles. However the process of integration of an electric motor drive into the conventional power train is a challenge with respect to packaging the Electrical & Mechanical subsystems and integrating it for control of Vehicle dynamics. Hybridization helps to downsize the IC Engine for similar vehicle performance while delivering improved fuel economy. The Hybrid Control strategies mainly primarily aiming at the parameters of improved fuel economy and reduced level of emissions. But in real time implementation, the improvement of one objective might affect the other objective adversely. Therefore, for implementing the control strategy proper weighing functions are to be defined which provides priorities to the objectives. The main issue that occurs is the non-causal nature of the strategy. The driver’s future action cannot be predicted as it varies based on driving conditions. The driver can accelerate at any time and the control strategy should withstand this parameter while defining the objective function. Therefore charge sustaining control strategy are also to be considered. The control strategy would determine the operating points of an engine or a motor based on efficiency and emission characteristics while maintain the battery SoC. The novel methods for Energy Management System where in the trip schedule based intelligent control is devised are being researched[2], [3] The parallel architecture makes use of a motor and an IC Engine to propel the vehicle. A power split is provided to enable parallel operation as per requirement of the system.[4] The implementation of the hybrid architecture is usually performed either by using a mechanical coupling device or through an electronic coupling mechanism. In the mechanical power split mode the fuel flow rate is determined by the power required for the propulsion. The power requirement corresponds to the accelerator pedal input. The load torque will be controlled by the generator by a torque control mechanism [5]. In Electronic control mode the electrical generator is coupled to the IC Engine through a fixed gear mechanism. The motor is coupled directly to the wheels through another fixed gear mechanism. The utilization of a Planetary gear system in the series-parallel architecture provides more flexibility. It operates in series mode while in low speed region, behaving like a parallel system while in high speed region. When the vehicle climbs up an inclination

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where more torque is required the motor acts up as the main propeller and provides majority of the power through the battery and generator. During EV mode the engine is kept at stand still. In HEV energy management two main approaches are utilized for optimizing the operation. It includes offline and online optimization approaches. In offline optimization approach the road profile is determined before hand and an optimized path is charted for operation while in online the data is taken in real time and the operation optimized.[6] But online optimization will be complex and difficult as the power train cannot be so dynamic in responding to the optimization profile designed by the Energy Management System. [7] GPS based Energy Management Systems are discussed in different literatures, [8],[9],[10] however the utilization of Altitude to create a driving profile is new. Egor et.al presented a novel method of GPS-track data processing to obtain the tangential and normal acceleration and the elevation angle data of a vehicle based on its travel route. The paper presents a new algorithm that makes the GPS data acquisition more accurate. [11] Liu et.al has prepared a controller design based on Dynamic Programming (DP) involving an optimization algorithm based on State of Charge. [12] In section II the detailed modelling and validation of the Parallel Hybrid Power train with the modelling performed for a 150cc petrol engine and a 3kW BLDC motor is discussed. Section –III discusses the development of the NSGA-II based optimization model and the Intelligent Energy Management System. Section –IV showcases the Results of the model and the performance analysis.

2. POWER TRAIN MODELLING AND VALIDATION

The modeling of Parallel PHEV model has been performed using ADVISOR software. The model has been subjected to a WLTC Class –I drive cycle. The Class-I WLTC drive cycle is for Indian scenario with the power to mass (PMR) ratio less than 22 W/kg. The modelled parallel PHEV with a 150cc petrol engine and the 3kW BLDC motor power train is compared with an Electric Vehicle model of 15 kW powertrain. For the same drive cycle the performance in terms of SoC level of the traction battery is checked and the results have been validated in Fig.1. It shows that for the same drive cycle and the same power rating the PHEV is consuming lesser SoC as compared to the EV. This would be because of the presence of IC Engine as the main propulsion source. Therefore the emission levels of the modelled PHEV is also compared with the BS-IV standards applicable in India. The results shows comparable values with respect to BS-IV standards as shown in Table –I.

![Fig.1: (a) Battery Pack SoC depletion for EV (b) Battery Pack SoC depletion for PHEV](image)

**Table-I : Emission levels comparison for modelled vehicle using ADVISOR with standards**

<table>
<thead>
<tr>
<th>Exhaust Component</th>
<th>Designed Level (g/km)</th>
<th>BS-IV standards (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>1.81</td>
<td>1</td>
</tr>
<tr>
<td>NOx</td>
<td>0.10</td>
<td>0.125</td>
</tr>
<tr>
<td>HC</td>
<td>0.09</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The modelled power train is then tested for impact of variation in the steering angle on the 14 DoF and validation on the response of the sprung and unsprung masses. The fig 2 shows the effects of variation of the steering angle on the 14 DoF. Fig.2 (a) shows the effect on the Yaw Angle, the Roll and lateral acceleration. The roll angle is found to be 1.56° while the lateral acceleration is found be 0.05 m/s² on an average. The yaw rate follows the steering angle. Fig.2 (b) shows the vertical deflection forces acting on the wheels. The impact of the steering angle causes more force to be acted upon the front wheels as compared to the rear wheels as seen in the figure. The HEV Model Analysis/4 and HEV Model Analysis/5 are the effect on the two front suspensions of the HEV while HEV Model Analysis/6 and HEV Model Analysis/7 are the effects on rear suspension. This shows that the deflections are synchronized and the effect of the deviation in steer angle is uniform on the set of front wheels and the set of rear wheels based on the direct impact. The set of rear wheels which follow the motion are having lesser deflection forces acting. The variation in the slip angles of the front and rear wheels is shown in fig 2(c). The analysis shows that all the forces caused due to sprung and unsprung masses on the wheels are equally distributed and the model satisfies the design considerations.

![Fig.2: Effect of variation in steering angle on 14 DoF](image)
3. INTELLIGENT ENERGY MANAGEMENT SYSTEM (IEMS) CONTROLLER

3.1 Terrain based Load Sharing

The creation of a GPS-Gradient database follows an offline optimization pattern. A database would be created where the Latitude and Longitude of the path to be taken is mapped with the gradient of the road with minute samples. The user when keys in the next destination to travel in the GPS unit the entire route is extracted from the GPS unit to the database along with the altitude of the terrain. This would then be divided into nodes ranging from 1 to n. The load sharing Energy Management framework therefore is operated for the data between the nodes. Before the commencement of the journey the IEMS would have the information regarding the most optimum path and also about the gradient of the road. Based on the road gradient feature the IEMS would decide upon managing of power flow from the IC Engine and the Motor. The advantage of this approach is that it prepares an offline optimized operating mode even before the journey and so the IEMS could bring about changes as planned. The only interruption factor that would be effective is the road traffic conditions which would be viewed as disturbances in the charted path. The Questar model G702-001UB GPS unit is used to track the actual GPS coordinates while in operation. The current GPS location is compared with the database data and the current node of operation is identified. Based on the mapping done already the terrain data in the current node of operation is determined and the corresponding optimized load sharing ratio is enabled by the Energy Management Controller. The response to traffic conditions are logged and the information is transmitted through the ESP12-NodeMCU to the cloud platform. This information is used to update the database and the Energy Management System updates the optimized load sharing for that particular node.

Fig.1: Flowchart for IEMS Control

The operation of the IEMS system is shown in Fig.1. This approach ensures that the optimized load sharing level decided by the IEMS could be updated to a new value in the event of an interruption in the form of traffic conditions. This ensures that for the current node where the vehicle is operating the load sharing is dynamically updated thereby ensuring the objectives of minimization of fuel cost and emission levels are maintained. With increase in altitude there occurs variation in atmospheric pressure which causes reduction of air density. This would affect the Air/fuel ratio of the engine. Consequently, there is an enrichment effect to the combustion mixture with an increase in altitude. If an engine tuned at sea level is operated at high altitude, there will be a reduction in power and fuel economy. Moreover, severe Carbon Monoxide and Hydro Carbons exhaust emissions are expected. Various tests conducted on a vehicle equipped with a sea-level carburettor would experience some 6 percent enrichment in air/fuel ratio upon driving from sea level to an altitude of 1200 m[13]. The enrichment in air/fuel mixture at altitudes substantially increased the bsfc of the engine. The sample case study has been done for a journey of 5 km between Kengeri and Varahasandra, Bangalore, India, as shown in Fig.3. The elevation profile has been obtained from the Google Earth map and is used to create and test the database. The entire distance profile and the corresponding elevation profile for the distance of 5 km is divided into 100 nodes. Therefore, the load sharing for each of the node is predetermined by the IEMS to facilitate dynamic operation of the vehicle.

Fig.2: Impact of Steering angle variation on (a) Yaw Rate, Roll angle and Lateral Acceleration (b) Vertical Deflection forces acting on the wheels (c) Slip Angles on the tyres
the vehicle, \( e_i \) represents the emission levels of the fully loaded vehicle, \( e_{\text{empty}} \) denotes the emission levels when the vehicle is empty, \( V \) represents the Volume of the vehicle, \( c_i \) represents the fuel cost between nodes \( i \) and \( j \) while \( x_{ij} \) represents the distance between the nodes \( i \) and \( j \). Based on the road gradient profile developed from the GPS gradient database the optimized operating point of the IC Engine is determined for each node by considering the emission levels and the fuel cost involved for operating the distance and the road altitude for that particular node. The criticality of the next journey also plays an important role in determining the operation point. If the criticality is low then more traction motor is used to maintain the emissions as low as possible. For medium criticality the emissions levels are more higher since traction battery is preserved more for future driving and if the criticality is high then more traction battery SoC is preserved thereby producing more emission levels. For every increase in 10% of road gradient the engine share of power increase by 2%. This would lead to an increase in emission levels and the fuel consumed thereby. The various combinations of fuel levels and the fuel cost is used as the individuals in the sample population. An predetermination for 100 generations are done for each node and the emission level is determined. This value from the database is used to determine the level of load sharing between the IC Engine and the traction motor.

The proposed model is a pseudo dynamic system. The fig. 3(a) shows the distance profile of the entire journey of 5 km. Fig. 3 (b) shows the elevation profile of the road considered for the journey. For the evaluation of the developed IEMS a small region of the entire profile is taken into consideration. The considered region is divided into four nodes, namely region between node 0 -1, represented by \( X_{01} \), region between node 1 -2, represented by \( X_{12} \) and region between node 2 -3, represented by \( X_{23} \).

### 3.2 NSGA-II based Optimization model

Non Dominated Sorting Genetic Algorithm –II (NSGA-II) is found to be the best for BNH type multi objective problems which gives rise to convex pareto optimal front.[14] This includes two objective minimization problem governed by constraints. The GPS database provides the terrain data to the Energy Management system which resolves the entire distance into \( n \) equally spaced nodes. The nodes are used to evaluate the level of load sharing expected based on the permissible level of emissions and fuel cost determined by the optimization approach. The objective is to minimize the emission levels and the fuel cost. The objectives identified are, \( f_1 = d \times (\frac{\text{e}_i + \text{e}_{\text{empty}}}{V}) \times L + \text{e}_{\text{empty}} \) and \( f_2 = \sum_{i=0}^{n} \sum_{j=0}^{n} c_{ij} x_{ij} \) where \( f_1 \) is the objective specifying the emission levels while \( f_2 \) denotes the fuel cost objective.\( d \) represents distance between the source and destination, \( L \) represents the load on

\[ \text{Pareto Optimal Front} \]

**Fig.4: Pareto Optimal front for distance between node-0 and node-1, } X_{01} \text{ obtained with NSGA-II approach}**

The pareto optimal front obtained for the distance between node-0 and node-1, \( X_{01} \) is as shown in Fig.4. This is for a distance of 5 m of the next journey. With respect to the evaluation, it can be inferred that the emission levels and fuel cost are non-dominated by each other. However for further operation of the controller an optimized single operating point has to be obtained. Since the pareto optimal front obtained is a convex front a knee function approach is used to determine the best operating point for the given criticality. An angle based focus approach [15] is used for the determination of the knee point. This helps in determining the best fit function for the two objectives of Emission levels and Fuel cost. The emission level is then calculated and then evaluated with respect to the sfc curve developed for the engine under consideration. This derivation of the IC Engine torque (\( T_{\text{eng}} \) required is then evaluated with respect to the reference torque (\( T_{\text{r}} \) calculated from the GPS-database data. This is
turn gives the Electric Motor torque expected, \( T_{EM} \)
\[ T_{EM} = T_r - T_{eng} \]
Based on the Torque calculated at the measured speed (\( w_{EM} \)), the Power sharing expected from the Electric Motor, \( P_{EM} \) is determined.
\[ P_{EM} = T_{EM} \cdot w_{EM} \cdot n_{EM} \]
where \( n_{EM} \) represents the motor efficiency. Based on the power share expected from the Traction motor the expected SoC level of the battery pack could be accurately determined.
The measured speed (\( w_{EM} \)) is then used to calculate the Power sharing expected from the Electric Motor, \( (P_{EM}) \). The SoC level (\( SoC_{st} \)) is estimated,
\[ SoC_{st} = SoC_i - 100 \times \frac{\int_0^T l(t)dt}{Q} \]
where \( Q \) is the charge flow rate, \( SoC_i \) is the initial SoC measured and \( l(t) \) is the current demand. Considerations like Battery ageing, Charging discharging cycles the battery is subjected to is used to update the estimated SoC (\( SoC_{st} \)) to an accurate SoC level which would be the actual remaining SoC. \( SoC_i = \left[ \frac{\Delta SoC_{st}(\alpha-\beta T+\gamma T^2)}{100} \right] \). \( \alpha, \beta, \gamma \) and \( \zeta \) represents the fitting constants [17].

Fig.5 (a) shows the optimized emission levels for a low criticality condition while Fig.5(b) shows for medium criticality condition and Fig.5(c) for high criticality condition. The emission levels obtained for these conditions are 0.721g/km, 0.8291g/km and 0.9733 g/km respectively.

Based on the observed emission levels the load sharing is determined for the journey through Node-1. Similarly the evaluation is done for all the 1000 nodes and the level of load sharing is decided.

4. HYBRID POWER TRAIN CONTROL

The Hybrid Power Train controller is evaluated for the regions between node-0 to node-3. The input to the IEMS would be from the GPS database as directed by the PHEV user and also the criticality of the journey. The IEMS could then perform decision based on the constraints and objectives to be achieved.
Fig. 6 shows the proposed controller where the load sharing is performed between the IC Engine and the Traction Motor. A load test is done on the IC Engine to map the throttle position and the Torque generated for a standard loaded condition. This mapping is important to regulate the IC Engine to operate in the optimum operating point. The IEMS regulates the throttle position by a drive by wire control mechanism. To implement the drive by wire mechanism a 20kgf dc servo motor is used. The traction motor is regulated to give the remaining torque. This is performed by controlling the BLDC controller. The specifications of the entire system is shown in Table I. The model developed considers only longitudinal dynamics. The Indirect coupling effects due to vertical and lateral motions are neglected. Simplified versions of the transient characteristics of the powertrain actuators are represented. This is important because the actuators’ internal controls which has a considerable impact on the transient behaviours of the actuators are not accurately known. The torsional flexibilities of all the shafts and gears are considered to be very high. The frictional properties due to the road surface are assumed to be acting uniformly on all tires. The drivetrain losses are represented by lumped efficiency and friction models. Frictional losses of driveline components due to effects such as gear meshing and bearing friction are not modelled individually. The impacts of environmental factors such as temperature are not taken into consideration in the component models. The control logic is initially simulated in the Matlab/Simulink environment. The power drive train is divided into two sections which are the Electric drive train and the IC Engine drive train. The IC Engine drive train is connected to the Sun gear of the planetary gear. The Electrical drive train consists of the Brushless motor and is connected to the Ring Gear of the planetary gear system. The Energy Management system based on the information from the Fuzzy controller decides the share of Generator, Motor and the IC Engine. Torque actuators are used to monitor the power transferred by the Electric and the IC Engine drive trains. Based on the altitude, the Energy Management system develops the Reference torque which has to be maintained by the Generator and the Motor.

Table II: Simulation Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC Engine</td>
<td>14 kW, 150cc Yamaha R15 engine</td>
</tr>
<tr>
<td>Brushless DC Motor</td>
<td>3 kW</td>
</tr>
<tr>
<td>Gear System</td>
<td>Planetary gear system</td>
</tr>
<tr>
<td>Battery Pack</td>
<td>48 V, 8Ah</td>
</tr>
</tbody>
</table>

In the case of the IC Engine the requirement is in terms of the throttle control of the IC Engine. The operation modes depends upon various factors including the altitude gradient and the Torque requirement. The produced power is fed to the wheels through a Planetary Gear arrangement. In the proposed system a speed coupling mechanism is sued and so the speed from the IC Engine and the Electric Power train can be independently controlled but the torques are dependent.

To monitor the speed of the Motor, and the IC Engine speed sensor are used at the coupling point of these units with the Drive Shaft. The wheels are modelled based on the nonlinear tire model proposed by Pacejka [16]. The Final drive is coupled to the planet gears. This mechanical coupling ensures that the speed of the IC Engine and the Traction motor could be different but their torques match. Fig.7 shows the parallel PHEV configuration. The system is having an IEMS system which monitors and performs the decision to operate. For the simulation, a lookup table has been developed which has the mapped data of the coordinates and the elevation and the distance profile. A fuzzy-based approach is used to evaluate each of the nodes and the information is transferred to the IEMS unit. The unit then performs the NSGA-II based optimization approach for the considered node and gives its output in terms of optimum emission level and the fuel cost. This data is used to determine the torque output from the IC Engine with respect to the Actual torque demand of the vehicle. Once the decision is made regarding the engine torque $T_{eng}$, the share to be taken by the motor is decided and the BLDC motor is regulated accordingly. After the load test conducted on the IC Engine and the fuel economy performance was evaluated the torque range for the best sfc region for the rated load condition was found to be ranging from 4.375 Nm to 6.36Nm.
The case study for the distances between four nodes is performed here. The distance between node-0 and node-1 is $X_{01}$, the distance between node-1 and node-2 is $X_{12}$, and between node-2 and node-3 is $X_{23}$. During $X_{01}$ region the torque requirement ($T_r$) is ranging from 0 Nm to 6.3 Nm. Therefore during this mode the IC Engine alone is operated. The throttle position is placed at 26% of the TPS (Throttle position sensor) value. During $X_{12}$, when the torque required, $T_r$ increases and reaches above 6.36 Nm then the traction motor started operating. Due to the increase in the terrain profile the torque required, $T_r$ also increases. During this mode therefore the IC Engine load share is reduced and it starts to operate in the best sfc region. The extra torque required is taken up by the traction motor. By the end of $X_{12}$ the torque required, $T_r$ comes back to 7.2 Nm and therefore the traction motor is turned and the IC Engine takes up the torque requirement. During $X_{23}$ operation the Torque requirement, $T_r$ increases and the engine and the motor feeds the required torque. The implementation of the planetary gear system ensures that the torque matching happens between the IC Engine torque, $T_{eng}$ and the Motor torque, $T_m$. The net propulsion power provided by the Motor and the IC engine is shown in Fig.9. The net power is sufficient for meeting the tractive power required for the vehicle propulsion considering the various resistive forces acting on the Vehicle while moving up a gradient during the four node operation considered. The power is shared between the 14kW capacity IC Engine and the 3kW BLDC traction motor.

![Net Propulsion Power](image)

**Fig.9: Net propulsion power together from Motor and IC Engine**

The IEMS was implemented and tested using a prototype controlled by a Raspberry Pi based Controller. Fig.10 shows the implemented system. In the prototype model the 150cc Engine represents the IC Engine while the 9kW BLDC motor is the traction motor. A 48 V, 8 Ah Li ion battery pack is used to do the prototype testing. The look up table used in the simulation is used to feed in the already mapped data to test the setting. Based on the data the IEMS the regulated the performance of the engine and the motor. The engine throttle was regulated through the drive by wire mechanism developed using the servo motor. The scenario of traffic interruption was introduced using variable rheostat. This caused the reduction of speed given by the motor. This was interrupted as decrease in torque demand. The ESP12-NodeMCU transfers the data back to the RPi. The RPi then updates the torque profile and then from the look up table captures the load sharing required. Based on the decision made the throttle of the IC Engine is regulated using the drive by wire mechanism.

![Implemented Prototype model](image)

**Fig.9: Implemented Prototype model**

5. CONCLUSIONS

The paper introduces an Intelligent Energy Management System with the capability of creating a pseudo predictive drive cycle for the Vehicle even before the commencement of the journey. The distance to be travelled for the next journey, the expected elevation profile of the road and the criticality of the next journey are the factors used to make the decision. The division of the entire journey into nodes enables to have micro level regulation of the IC Engine and load share level with the traction motor. To validate the IEMS, the modelling of a Parallel PHEV is done based on a 150cc IC Engine and a 3kW BLDC motor. The modelling is performed through ADVISOR software. The modelled vehicle is then subjected to 14 DoF analysis to validate the model. The IEMS is then incorporated to the model and testing is done. Based on the performance of the modelled PHEV to the developed IEMS, the hardware prototype was implemented. The developed parallel configuration PHEV system with the IEMS is capable of providing a minimal emission, minimal fuel cost operation based on the criticality of the journey of the PHEV User.

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