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Design and Implementation of a Series-Parallel Light Commercial Hybrid Electric Vehicle

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Abstract

This paper presents a series-parallel hybrid electric vehicle design procedure from design stage to implementation. Firstly, the architecture of the designed vehicle and its main properties are presented. Sizing the components such as electric motor, battery and internal combustion engine are specified. Then modeling procedure of the series-parallel hybrid electric vehicle is presented. After the illustration of the hybrid architecture implementation including packaging and driver interface, design of the optimum power split and regenerative braking algorithm are given. Finally, simulation results are shown for different modes of operation.

Keywords: HEV (hybrid electric vehicle), modeling, efficiency, instrumentation.

1 Introduction

This paper is on the design and implementation of the Ford Transit series-parallel hybrid electric light commercial vehicle. Hybrid electric vehicles are the intermediate term solutions to the increasingly harder to satisfy emissions regulations mandated by governing bodies worldwide. A downsized internal combustion engine is paired with one or more electric motors and a battery pack to power these electric motors in hybrid electric vehicles. In order to modify the conventional powertrain of a vehicle to a hybrid powertrain, following steps are committed: mechanical and electrical adaptations, designing signal interfaces between hybrid and conventional components, evaluation of lower level controllers and a supervisory hybrid control algorithm. Conventional version of the vehicle used in this study is a Ford Transit, with 100PS 4 cylinder diesel engine. Emissions and performance specifications based on a chosen drive cycle are determined first. The hybridized vehicle is modeled and a design study is conducted to size and select all the additional components. Performance evaluation and engineering work for performance and operation enhancement follow the production of the prototype hybrid electric vehicle.

The organization of the rest of the paper is as follows. Sizing and selection of the components used in hybridization of the base vehicle is presented in section II. Modeling and simulation is presented in section III followed by the implementation of the designed system in section IV. Hybrid electric vehicle supervisory control system and the experimental results regarding to the different modes of operation are presented in section V. Finally paper ends with the conclusions.

2 Determination of Hybrid Powertrain Architecture and Sizing of Components

The used hybrid configuration given in Fig.1 includes 3 electric motor(EM)/generator: Front axle traction motor, EM1, rear axle traction motor, EM2 and a starter motor directly coupled to the internal combustion engine (ICE), EM3. EM1 has regenerative braking, parallel charge and front axle traction ability, EM2, has regenerative braking, through the road parallel charging and rear axle traction ability. Finally, EM3 has series charge and engine starting capability.

With the selected 3 electric motor configuration, vehicle has series and parallel charging capability, 4x4 performance and rear and front axle regenerative braking. Series charging while 4x4 drive is a characteristic feature enhanced with this configuration. The complexity of the configuration which has numerous operation modes, while bringing some difficulty in the design procedure of the control systems results with more optimal solutions in terms of fuel consumption and emissions.

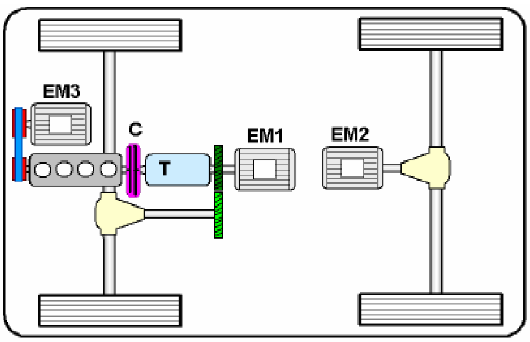

Fig.1: Selected Vehicle Architecture

The main components of a hybrid electric vehicle (HEV) which is going to be sized in this section are the internal combustion engine (ICE), electric motor (EM)/generator (EG) and battery. Sizing processes are the key points for energy efficiency and performance of the vehicle.

2.1 Electric Motor Sizing

The criteria that took into account for sizing EM1 and EM2 is maximum regenerative braking power in a specified drive cycle[1, 2]. Required power from wheels and vehicle acceleration values for European Drive Cycle (ECE) cycle is given in Fig.2. According to the simulations, 32kW is the total brake power requirement from wheels.

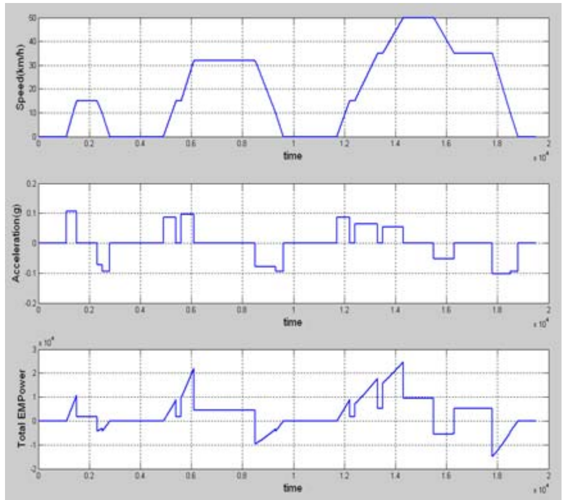

Fig. 2: Required Power and Vehicle Acceleration Values for ECE Cycle

Vehicle dynamics constraints are considered while distributing of this total brake power in front and rear axles. Therefore, the ideal brake torque ratio of conventional Ford Transit vehicle, 1.87, is reestablished choosing EM1 and EM2 power values greater than **20.85kW** and **11.15kW** respectively.

EM3 which is normally used for series charge has a totally different design procedure depending on the combined efficiency map of EM3 and ICE. A generic EM efficiency map is scaled for different power values and combined with our ICE efficiency map.

Maximum normalized combined efficiency versus EM power graphic is illustrated in Fig. 3. It can be seen that slope of the curve decreases with the increasing EM3 power. Graphically, 27.07kW is selected as EM3 power since further increases in power values has minor effect on combined efficiency values.

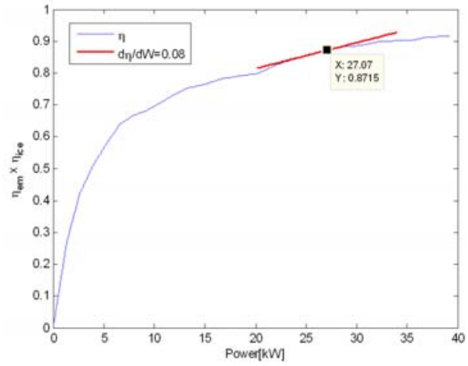

Fig.3: Selected Combined Efficiency versus EM3 Power

2.2 Battery Sizing

Battery sizing has to be done in terms of maximum charge/discharge power and maximum energy capacity.

The battery pack should provide the peak power requirement (charge/discharge) of the given drive cycle which is "ECE" in this study. Power requirement from batteries is illustrated in Fig. According to the simulations, battery pack should provide at least **27.26kW** discharge power and **13.35kW** charge power which can be seen in Fig.4

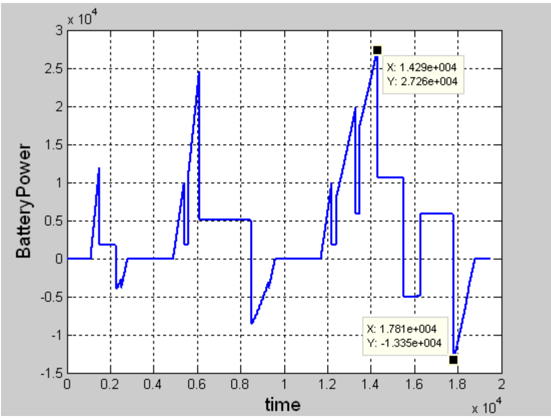

Fig.4: Battery Power in ECE Cycle

Another criterion in sizing battery pack, is to select battery energy capacity such that the vehicle must run specified number of ECE drive cycle in pure electric mode.

Our design parameter for this study is 80km range in ECE cycle. According to the simulations 182.2Wh energy is required for 1 ECE cycle which is illustrated in Fig.5 Considering that one ECE cycle is 1.018km, following equation gives the battery energy capacity(E_{bat}):

$$E_{bat} = \frac{80*182.2}{1.018} = 14318Wh \qquad (1)$$

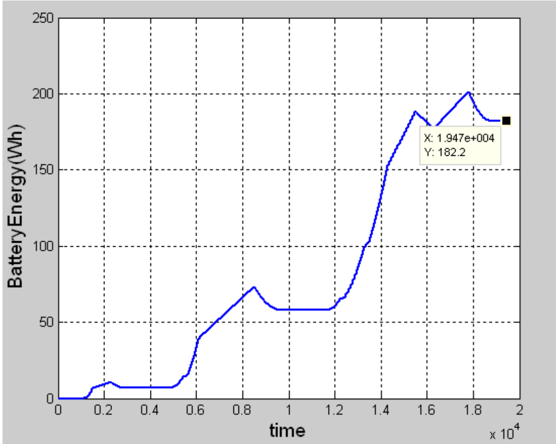

Fig.5: Battery Energy in ECE Cycle

2.3 ICE Sizing

After sizing the EM1 and EM2, size of ICE power is calculated by the desired 0-40km/h, 0-100km/h and 80-120 km/h performances of the vehicle. Design requirements are given in Table.1.

Table1: Performance Requirement for Designed HEV

0-40(km/h)	$\leq 4\,\text{sec}$
0-100(km/h)	$\leq 10\,\text{sec}$
80-120(km/h)	$\leq 7\,\text{sec}$

According to the simulation results with selected electric motors, ICE power is calculated as **75kW** to achieve the performance requirements.

3 Modeling of Series-parallel Hybrid Electric Vehicle

The vehicle dynamics is modeled as a single track vehicle with its additional components such as electric motor and battery for sizing the components, designing the power split algorithm and analyzing performance of the vehicle.

3.1 Vehicle Dynamics

A single track model is used to capture the longitudinal dynamics of a hybrid electric vehicle (Fig.6). HEV dynamics is the same as the dynamics of other classical vehicles. But there are some additional components like battery and electric motor. These components only bring changes to the torque that is applied to the powertrain. A longitudinal single track model of the vehicle is usually enough for HEV controller design and performance simulation studies. Matlab/Simulink® is used in simulations and control development phase of the studies.

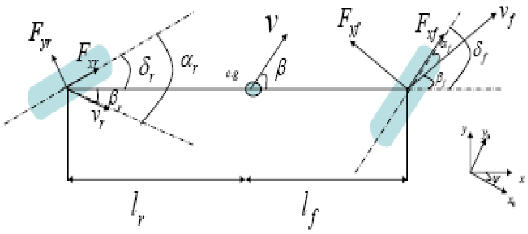

Fig. 6: Single Track Vehicle Model

3.2 Additional Components

Electric motors and internal combustion engine are modeled with their static efficiency and performance maps. Electric motor efficiency map is illustrated in Fig.7.

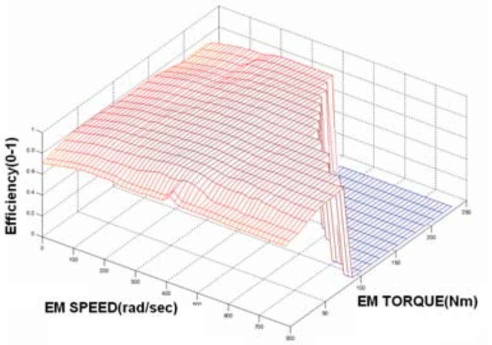

Fig.7: Electric Motor Efficiency Map

Internal combustion efficiency map is illustrated in Fig.8.

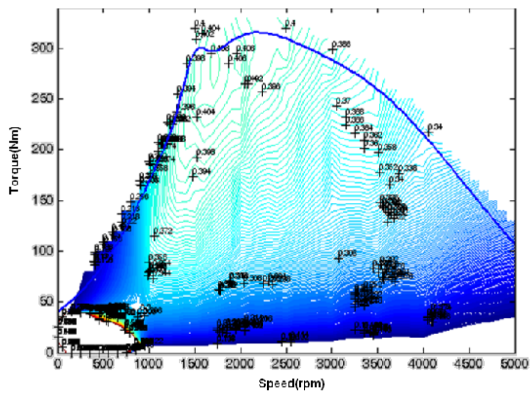

Fig.8: ICE Efficiency Map

These maps are enough for sizing and fuel minimization algorithm tests but tuning process is necessary for drivability. Suitable filters for torque command signals of electric motors and internal combustion engine are designed in implementation. Additionally, battery is modeled using its simple electrical equivalent circuit which is illustrated in Fig.9.

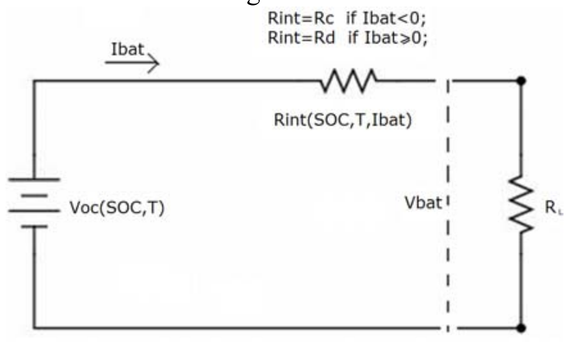

Fig.9: Battery Equivalent Circuit

Inputs and outputs of the battery model is shown in Fig. 10.

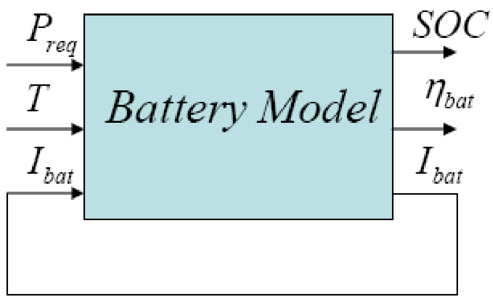

Fig.10: Battery Model Inputs and Outputs

According to the equivalent circuit of the battery, model equations are given below.

$$R_{\text{int}} = \begin{Bmatrix} R_c(SOC,T) \ if \ I_{bat} < 0 \\ R_d(SOC,T) \ if \ I_{bat} >= 0 \end{Bmatrix} \quad (2)$$

$$V_{bat} = V_{oc}(SOC,T) + I_{bat} R_{\text{int}} \quad (3)$$

$$I_{bat} = \frac{P_{req}}{V_{bat}} \quad (4)$$

$$\Delta SOC = \frac{\int_{t_0}^{t} V_{bat} I_{bat} dt}{M_{cap\_bat} 3600} \quad (5)$$

$$SOC = SOC_i + \Delta SOC \quad (6)$$

(R_{int} :Internal resistance, R_c : Charge Resistance. R_d :Discharge Resistance V_{oc} :Open Source Voltage. V_{bat} :Battery Voltage. I_{bat} :Battery Current SOC :State of Charge, M_{cap_bat} : Battery maximum energy capacity(Wh))

3.3 Model Correction

After the implementation of the hybrid vehicle which is illustrated in next section, road tests are carried out. Road test and simulation data for same input signals match each other quite well. It demonstrates the correctness of the simulator model. Simulation and experimental vehicle speed data for same pedal inputs is illustrated in Fig.11.

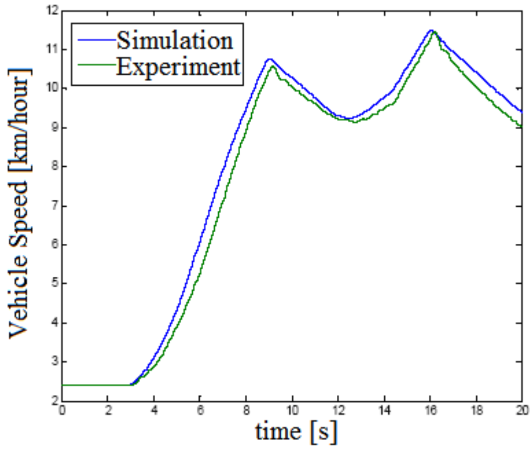

Fig.11: Simulation and Experimental Vehicle Speed Data for Same Throttle-Brake Pedal Inputs.

4 Hardware Implementation

Hardware implementation of the vehicle is divided into two main groups; electrical and mechanical integration.

4.1 Electrical Hardware

All signals that are used in the vehicle are gathered and processed via dSPACE MicroAutoBox DS-1401 rapid prototyping hardware. The HEV control strategy is modeled in Matlab/Simulink®. Automatic code generation and downloading into the power pc board is handled by the Matlab Real Time Workshop and dSPACE Real Time Interface tools.

Main controller, electric motors, battery, vehicle ECU and driver interface communicate with each other via the CAN bus. Only acceleration/brake/clutch pedal positions were monitored and driver's torque demand was given to vehicle ECU as an analog signal. Some special signals were generated for EM and battery for system start-up sequences [3]. General electrical scheme of the vehicle is illustrated in Fig.12

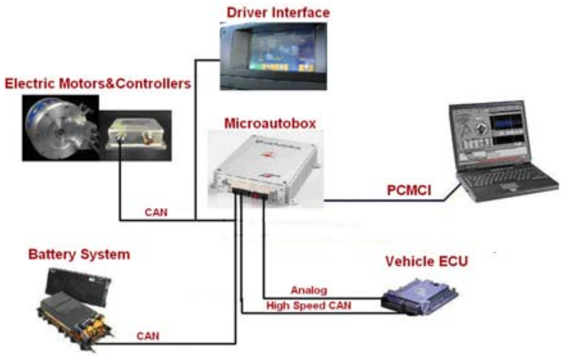

Fig.12: Electrical Scheme of the Vehicle

4.2 Mechanical Components and Integration

4.2.1 Electric Motors

The electric motors EM1 and EM2, coupled to the front and rear differential and the EM3 on the internal combustion engine are presented in Fig 13.

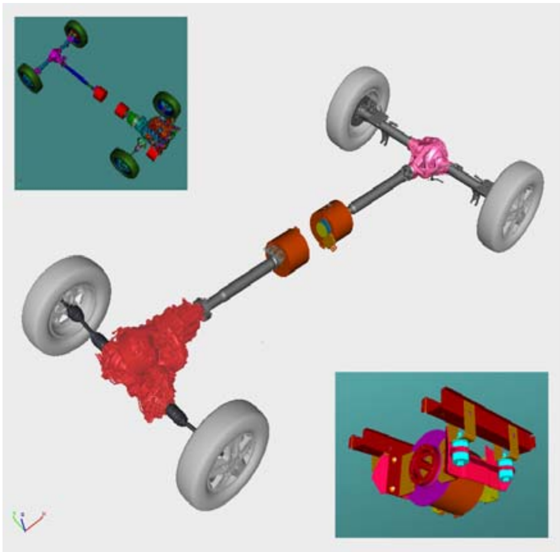

Fig.13: Electric Motor Assembly

EM1 and EM2 can be used for traction either together with ICE or independently. Since EM1 and EM2 are always connected to front and rear differentials, it is always possible to apply regenerative braking with these motors. EM3-ICE pair is used to provide charge for battery system or for other electric motors while the ICE is decoupled from the driveline with the new semi-automatic clutch control system explained below.

4.2.2 Battery System

The battery system is designed to provide the maximum power required by the traction/braking motors, EM1 and EM2. 324V 45Ah Li-Ion battery pack is designed and the system is packaged under rear cargo volume, as shown in Fig14.

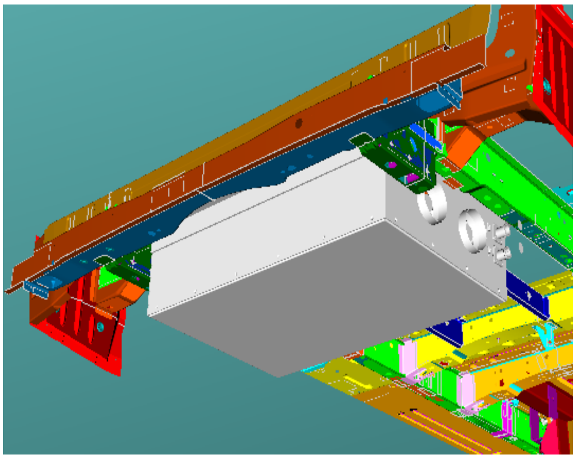

Fig. 14: Battery Assembly

4.2.3 Transmission

The designed new manual transmission, shown in Fig.15, is capable of driving the front axle by diesel and electric power. While ICE is coupled to the front input shaft with the clutch and its power is transmitted to the front differential through selected gear, the transmission has a rear input shaft directly connected to the front differential for EM1.

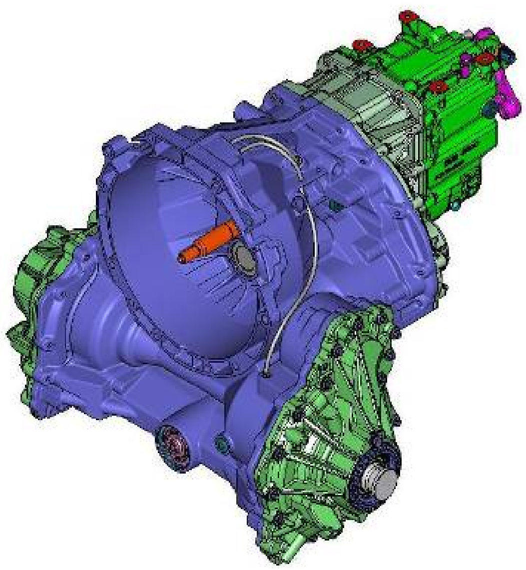

Fig. 15: New Transmission

4.2.4 Clutch Control System

The new transmission is manual hence it is not possible to make it neutral to stop the ICE during cruising. That's why the original hydraulic clutch control system is modified to keep the clutch disengaged, independent of the clutch pedal position controlled by the driver, Fig.16. With this design the clutch pedal motion can be directed to a dummy clutch with 3-way valve, while the actual clutch is controlled by a hydraulic pump – valve pair, according to the cruising strategy.

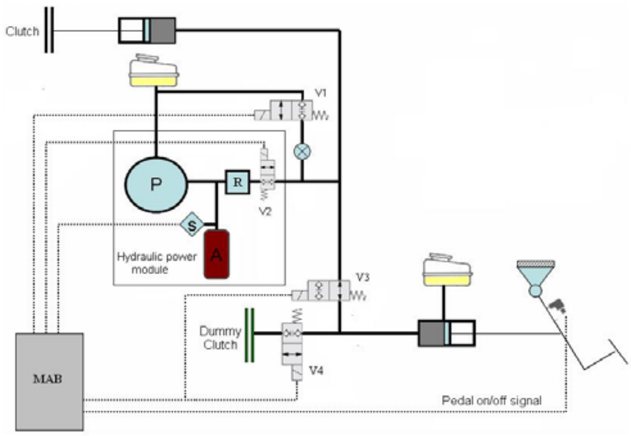

Fig. 16: Electromechanical Clutch Configuration

Vehicle is illustrated in Fig.17 after all implementation process.

Fig. 17: Hybrid Ford Transit

4.3 Driver Interface

In hybrid electric vehicles, there are more information than conventional vehicles that driver needs to follow. Data logging is also very critical in HEVs. For this reason, an LCD driver interface is designed for the vehicle.

In this design, additional button is not required to switch between screen pages with its touch screen feature. In hardware part of the monitor, Freescale's MCF5329 processor which has an LCD controller interface is selected. Additionally, this processor's CAN interface gets the data from all over the vehicles through CAN bus. Software of the design is developed with C++.

There are 4 tabbed pages on this vehicle's monitoring interface. First page gives information about power flow of the vehicle (Fig.18). It shows the power flow between ICE, EM, batteries and wheels as an animation.

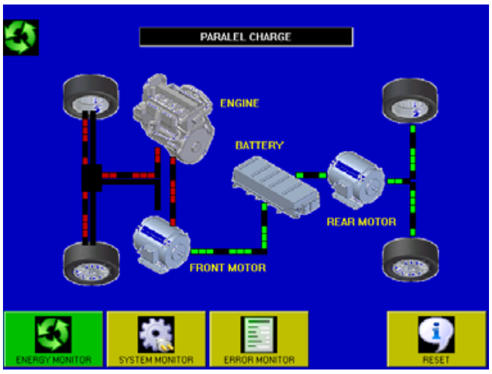

Fig. 18: Energy Flow between Components

Critical information about battery and electric motors such as voltage, current, torque, angular velocity and SOC are displayed in the second page (Fig.19).

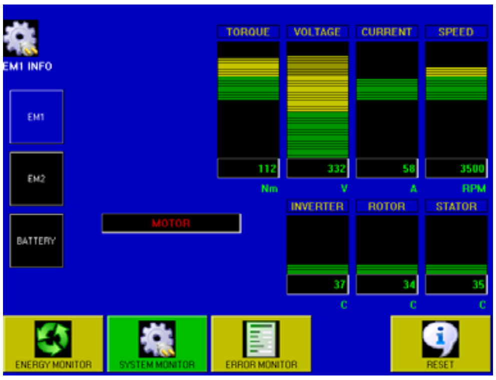

Fig. 19: Electrical System Parameters Page

Critical warning and error messages are displayed in third page (Fig.20). These messages are taken via CAN bus from EM controller, battery controller and vehicle ECU. Messages are also logged for future analysis.

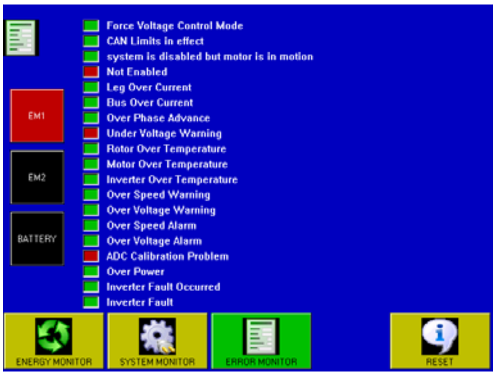

Fig.20: Electrical System Warnings and Errors Page

Final page includes service commands (Fig.21). Components errors and error logs can be erased with the help of this page.

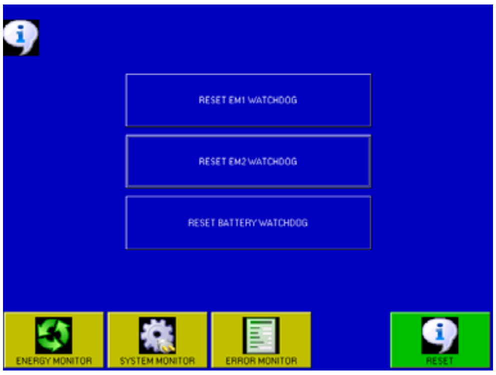

Fig. 21: Service Commands For Electrical Components

Vehicle mounted monitoring interface is shown in Fig.22.

Fig. 22: Vehicle Mounted View of the Driver Interface

5 Supervisory Control

Fuel efficiency improvement of hybrid powertrains can be done in different ways such as: load reduction, engine downsizing, running the ICE in its more efficient region and regaining brake energy. In this study, a hybrid control algorithm was developed to control the power flow of a series-parallel hybrid electric vehicle during traction and braking modes to overcome the negative impacts of the internal combustion engine such as poor fuel economy and high emission levels. In the traction mode, the torque request of the driver is defined according to the gas pedal position and distributed among the available paths to achieve the maximum overall efficiency at all times[4].

5.1 Maximizing Overall Efficiency Strategy (MOES) Algorithm

In MOES, the vehicle is considered as a system whose input is power of consumed fuel and output is the traction power. MOES differs from the other algorithms by introducing the concept of the percentage of parallel charge to regenerative braking value. The more this percentage decreases the more energy stored in the battery is used for traction.

Overall efficiency term in MOES states the efficiency value from fuel tank to wheels (Fig 23). This efficiency value η_{SYS} is calculated by using instantaneous and average efficiencies of the components which are the internal combustion engine, electric motors, battery and mechanical efficiencies of the vehicle drivelines [4].

Fig.23: System Input and Output

$$\eta_{SYS} = \frac{P_{road}}{P_{fuel}} \tag{7}$$

The algorithm has 3 main modes: battery charging, battery discharging and regenerative braking.

Depending on the battery State of Charge (SOC) value, one of the two modes of MOES charge or MOES discharge is activated. regenerative braking acts as an interrupt for the algorithm. With this algorithm the SOC value oscillates between its high limit and low limit.

In the parallel charging mode ICE produces power that is higher than the power demand from the driver. This extra power charges batteries. This electrical power will be consumed in the future to sustain the state of charge of the batteries. In this mode the overall efficiency is calculated with the extra virtual power term $P_{virtual}$ representing the obligatory future action to obtain SOC sustaining [5]. System input and output for overall efficiency calculation in Charge Mode is illustrated in Fig.24.

Fig.24: System Input and Output in Charge Mode

The overall efficiency for charge mode is expressed as ,

$$\eta_{SYS} = \frac{P_{req} + P_{virtual}}{P_{fuel\_inst}} \tag{8}$$

where P_{fuel_inst} represents instantaneous fuel consumption , P_{req} represents the power demand of the driver.

Optimal torque for the ICE and corresponding EM torques are obtained by calculating overall efficiency on grid points in the solution space. And the solutions for different driver inputs are tabulated for use in real time. Flowchart of parallel charge for tabulation is illustrated in Fig.25.

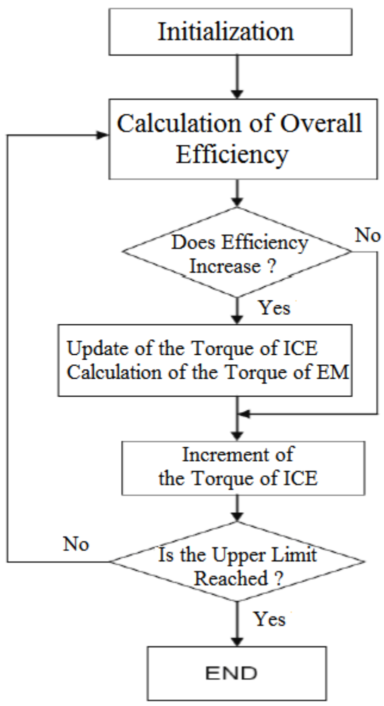

Fig.25: Flow Chart for Parallel Charge

In the assist mode, power demand of driver is provided from both electric motors and internal combustion engine. Similarly to previous mode, the overall efficiency is calculated with the extra virtual power term $P_{virtual}$ representing the obligatory future action to obtain SOC sustaining. System input and output for overall efficiency calculation in discharge (assist) mode is illustrated in Fig.26.

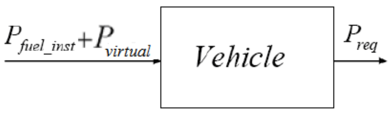

Fig.26: System Input and Output in Discharge (Assist) Mode

The overall efficiency for discharge (assist) mode is expressed as,

$$\eta_{SYS} = \frac{P_{req}}{P_{fuel\_inst} + P_{virtual}} \qquad (9)$$

The optimal solutions are tabulated with the same method as parallel charging mode. Flowchart of discharge (assist) for tabulation is illustrated in Fig.27.

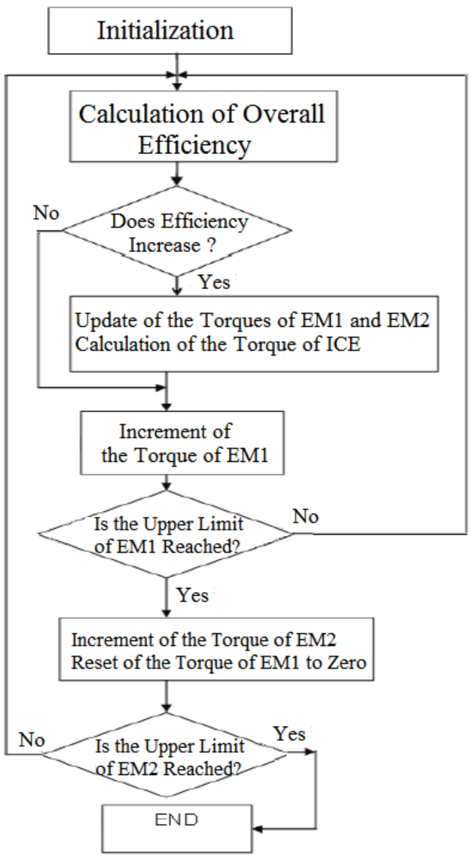

Fig.27: Flow Chart for Discharge (Assist) Mode

MOES is the key aspect of the algorithm used in the traction mode. Apart from that during the braking mode regenerative brake algorithm is activated and the energy wasted between the brake calipers and discs is recaptured and stored in the energy storage unit for later use[5]. The algorithm that runs during braking consists of a rule based controller that functions in parallel with the static brake force allotment (SBFA) maps defined for each EM. With the depression of the brake pedal, the pedal force is mechanically amplified and transmitted hydraulically through the hose that links the master cylinder to the callipers at each wheel to provide the required frictional brake torque. The brake signal is sensed via the brake pedal sensor and sent to the brake-ECU to produce proper amount of regenerative brake (RB) torque according to the operating conditions of the vehicle.

5.2 Simulation Results

ECE cycle's inner city part is used for drive cycle. A PI longitudinal speed controller is designed and used as the driver model. An automatic gear shift algorithm is also designed as part of the driver.. Simulations are performed in three different control modes to analyze the optimization results beter. Results are illustrated in Table2.

Table2: Fuel Economy Results for Three Different Modes

	Fuel Consumption(gr)	Initial SOC (%)	Finale SOC (%)	Charge Sustaining Fuel Consumption(gr)	%Fuel economy
Conventional (Only-ICE)	82.95	65	65	82.95	-
Only Regenerative Braking (Bang-Bang)	74.19	65	65.46	64	22.85
Optimization (MOES)	58.77	65	65.36	50.8	38.76

Only regenerative braking mode takes regenerative braking energy and uses this energy according to the SOC condition of the vehicle. This mode do not include an optimization routine.

According to the simulation results, total fuel economy in MOES mode is %38.76. %22.85 of the fuel economy comes from regenerative braking and %15.91 comes from optimization.

5.3 Test Results

The power management control strategy presented in the previous section was tested on road tests for different modes of operation as seen on Fig. 28, 29 and 30. In these simulations, series charge motor has not been mounted into vehicle. EM1, EM2 and ICE torque values can be seen for different operation modes.

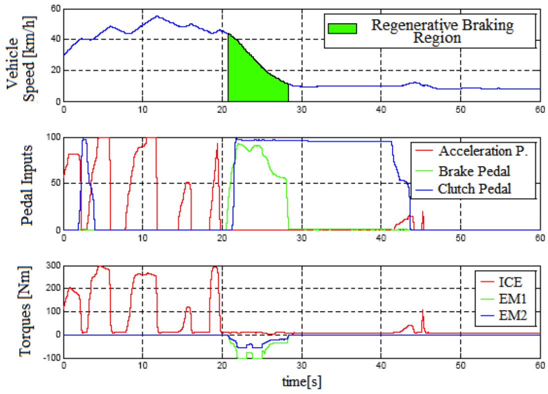

Fig.28: ICE Mode

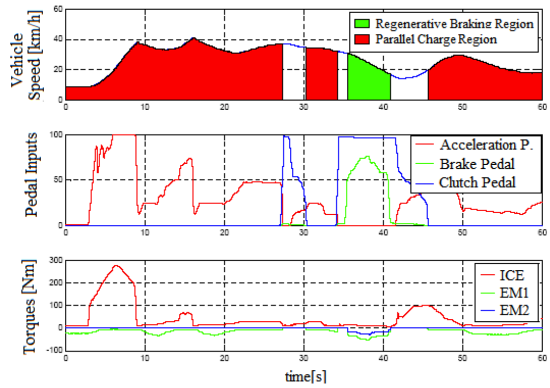

Fig.29: Parallel Charge Mode

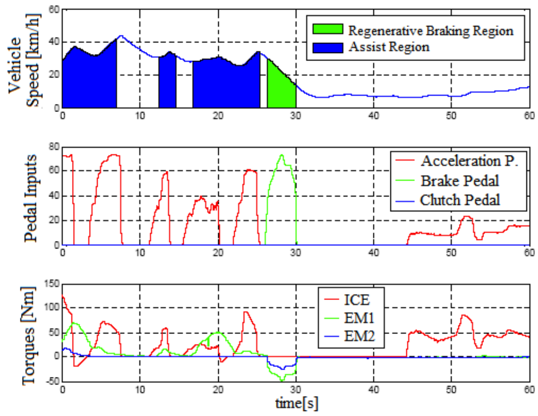

Fig.30: Assist Mode

CONCLUSIONS

In this study, the findings obtained during the overall development process of a series-parallel HEV were presented. Sizing of the components, modeling of the vehicle, hardware implementation including component integration and main control algorithm (MOES) design processes are explained briefly. Road test results of the vehicle are also illustrated. According to the road test results, designed vehicle model is corrected. Although %38.76 fuel consumption minimization is achieved with control algorithm in simulations, it is certain that real minimization value will be less than simulations due to static efficiency maps that are used in optimization and simulation.

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