Chapter 4

Power management for EV Powered by Dual Battery System

4.1 Introduction

The use of clean energy in the transportation industry has gained substantial attention in the last two decades with the increase in fuel price and harmful gases emitted by burning fossil fuels in conventional vehicles. EVs emit no greenhouse gas, and hence they are a potential alternative to the internal combustion engine (ICEs) automobiles. However, the automobile industry had been limited to EVs with short range because of small battery capacity, long charging time, and lack of charging infrastructure. Nowadays, the advent of Li-ion batteries has reinforced the automobile sector to develop long-range EVs. Brands such as Mercedes Benz, Nissan, Tesla, Toyota, and others are developing EVs with the single sizeable Li-ion battery which leads to an oversizing of the battery and high initial cost. However, in [14] author suggested the concept of EV having two different size battery sources. Small size battery pack is fixed, and big size battery pack can be swape according to requirement. For short range, fixed small size battery is used which will reduce the mass of the EV and improve the energy consumption per unit distance. For more extended range, small size battery with swappable large size battery pack is utilized to power the drive train in the EV. The author has analyzed and evaluated the performance of proposed EV concept in comparison with single larger pack EVs and proved that there is a significant improvement in energy consumption (up to 17 %), and economic benefits are achievable by distributing the cost of the large battery pack over the lifetime of the vehicle. Benefits of using different size batteries encourage further studies in the development of power management systems for the dual battery-powered EVs. The core concerns of power management systems are to effectively provide energy from each battery source to match the power demanded and stored energy in the battery sources during regenerative braking. In this chapter, requested power computation for a given driving cycle has been performed with detail modeling of dual battery power EVs is presented in Section 4.2. In the literature, various power management strategies have been developed for hybrid EVs. On the basis of thorough analysis about different power management strategies, it could be concluded that rule-based power management approach has been commercially adopted due to its east implementation and high computational efficiency. However, as any optimization is not involved, the optimal solution cannot be obtained. Optimization-based approaches overcome inherent drawbacks of rule-based approach through the implementation of optimization control procedure. Optimization-based approaches demand high computation power for real-time application. Practically, the hybrid power management strategy should be utilized which would not only have the optimal solution but also readily applicable to real-time control. In this chapter advanced and simple control rule-based meta-heuristic optimization power management strategies are developed to achieve optimal power distribution between dual battery sources while keeping the operation of battery in the defined safety region. The transition between the vehicle's operation modes has determined with the helps predefined rules based on the current operating condition. Whereas, the power-sharing between the two batteries determined by utilizing optimization based techniques. Problem formulation and architecture of the power management system for dual battery powered EV are presented in Section 4.3. Discussion on outcomes of the power management system is present in Section 4.4. The main conclusion and summary of the chapter has been given in Section 4.5.

4.2 Test bed system modeling

A small dimension EV based on Toyota S model 85D is considered as test-bed to investigate the power management strategies developed for the dual battery-powered EVs. The architecture of the power management system for dual battery powered EV is presented in Figure 4.1. In this test-bed modeling, the main components are two batteries for power supply, two bidirectional DC-DC converters for controlling each battery source, one power management system, propulsion motor drive and drivetrain of the EV. The calculation of power demanded from energy sources is evaluated using detail modeling of vehicle drivetrain in the present section.

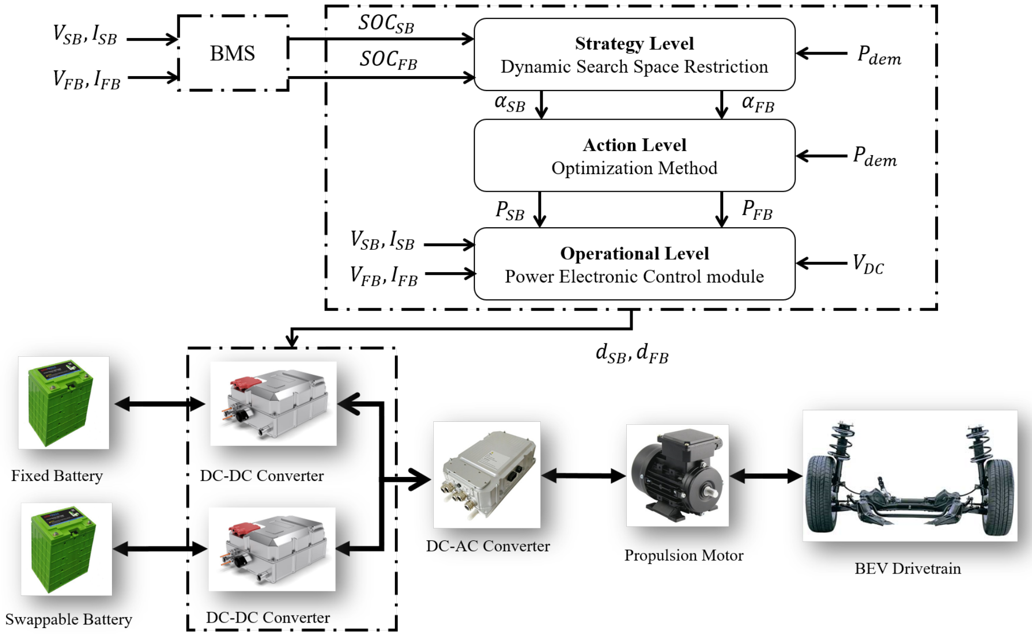


FIGURE 4.1: Architecture of the power management system for a dual battery powered EV platform

4.2.1 Drivetrain modeling

The EV dynamics work on the fundamental principle of physics, i.e., Newton's second law of motion. Newton's second law of motion states that the acceleration of an object produced by a net force is directly proportional to the magnitude of the net force. The first step in EV modeling to determine the value of resultant tactive effort applied by drivetrain to overcome the resistive forces which try to retard the motion of the EV. The tractive force (F_{te}) produces enough momentum in the contact area between the tires and the road surface to drive the EV in the forward direction. The resistive forces that are influencing the movement of the EV along a slope shown in Figure 4.2. The resistive forces can be classified as follow: rolling resistance force (F_{rr}), aerodynamic drag force (F_{ad}), hill climbing force (F_{he}), linear acceleration force (F_{la}) and rotational acceleration force (F_{wa}).

Rolling Resistance Force (F_{rr})

The rolling resistance forces are the friction forces that arise when the tires of the EV rolls on the surface of the road. It is directly proportional to the weight of the EV hence its is approximately constant and does not depends on upon the speed of the EV. The equation for rolling resistance force can express as :

$$F_{rr} = \mu_{rr} g M_{ev} \tag{4.1}$$

Here M_{ev} represents the mass of EV which include curb and cargo weight $[kg]$; g represents standard gravity constant [9.81 m/s^2]; μ_{rr} refers to rolling resistance coefficient of the tires. The value of μ_{rr} depends upon the type of tires and pressure exerted on the tires.

Aerodynamic Drag Force (F_{ad})

The aerodynamic drag forces are the friction forces that arise due to motion of EV through the air. It defined as the function of air density, shape, the frontal area of the EV and air passages. The equation for the aerodynamic drag force can be expressed as:

$$F_{ad} = \frac{1}{2} \times \rho_{air} \times A_{front} \times C_{drag} \times (\nu_{ev})^2 \tag{4.2}$$

Here A_{front} represents the cross-sectional area of the EV $[m^2]$; ν_{ev} is the speed of EV $[m/s]$; C_{drag} is a constant called the aerodynamic drag coefficient; ρ_{air} refers the density of the air $[kg/m^3]$ and air density depends on the variations od temperature, humidity and attitude. This thesis considers the value of air density to be 1.225 kg/m^3 which has been reported in the literature.

Hill Climbing Force (F_{hc})

The hill climbing force arises when EV drives upon slope. This force includes EV weight component acting along the direction of the slope. The equation for the hill climbing force can be expressed as:

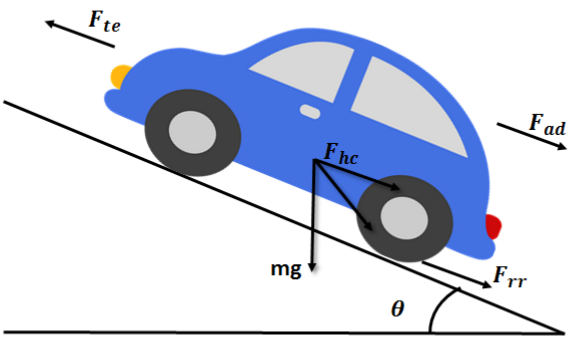


FIGURE 4.2: The resistive forces applied on a EV moving along a slope

$$F_{hc} = g \times sin(\alpha_{gra}) \times M_{ev} \tag{4.3}$$

Here α_{gra} refers the gradient of the road and all the other variables are same as defined in Section 4.2.

Linear Acceleration Force (F_{la})

According to Newton's second law, if the vehicle velocity is changing, then it will generate a force in addition to the forces illustrated in Figure 4.2. This additional force will cause the linear acceleration of the vehicle. The equation for the linear acceleration force can be expressed as:

$$F_{la} = M_{ev} \times \frac{d\nu_{ev}}{dt} \tag{4.4}$$

Rotational Acceleration Force ($F_{\omega a}$)

In addition to linear acceleration in the EV, rotational acceleration is also required to considered. Rotational acceleration force is applied for the faster angular rotation of the wheels. The equation for the rotational acceleration force can be expressed as:

$$F_{\omega a} = J \frac{G^2}{r_{wh}^2 \eta_g} \frac{d\nu_{ev}}{dt} \tag{4.5}$$

Here G refers the gear ratio of transmission system; r_{wh} refers the radius of wheel [m]; η_g is efficiency of gear system and J refers propulsion motor rotor inertia.

Tractive Effort (F_{te})

The Vehicle propulsion system must generate a tractive force (F_{te}) to overcome rolling resistance force, aerodynamic drag force, hill climbing force, linear acceleration force and rational acceleration force to accelerate the vehicle. The total tractive effort is the sum of all these forces:

$$F_{te} = F_{rr} + F_{ad} + F_{hc} + F_{la} + F_{\omega a} \tag{4.6}$$

When EV slows down then linear acceleration force and rotational acceleration force will consider as negative, and when the vehicle is coming down a slope, then hill climbing force will be considered as negative.

To accelerate the vehicle the required traction torque (τ_{te}) $[Nm]$ at wheels and angular speed (ω_{wh}) $[rpm]$ of the wheels can be intuitively computed as follow:

$$\tau_{te} = F_{te} \times r_{wh} \tag{4.7}$$

$$\omega_{wh} = \frac{60 \times \nu_{ev}}{2\pi r_{wh}} \tag{4.8}$$

If desired speed values are defined, then the torque values can be compute using vehicle dimensions and parameters data as listed in Appendix A.

Traction power P_{te} $[W]$

To estimate the total power requirement by drivetrain can be calculated by using the traction torque and angular speed (obtained from drive cycle)

$$P_{te} = F_{te} \times \nu_{ev} \tag{4.9}$$

A gear-box is placed in between the propulsion motor and the wheels to reduce the shaft torque ω_s $[rpm]$ and to amplify the shaft torque τ_{st} $[Nm]$. The gear ratio is fixed during the operation; thus, shaft torque, shaft angular velocity, and power P_m $[W]$ of the propulsion motor can be expressed as:

$$\tau_{sh} = \begin{cases} \frac{\tau_{te}}{\eta_g \times G} & if\ P_{te} \geq 0 \\ \frac{\tau_{te} \times \eta_g}{G} & if\ P_{te} < 0 \end{cases} \tag{4.10}$$

$$\omega_{sh} = \omega_{wh} \times G \tag{4.11}$$

$$P_m = \frac{\pi}{30} \times \tau_{sh} \times \omega_{sh} \tag{4.12}$$

Here G represents transmission ratio of gear-box.

The electrical power demanded from sources can be computed from drivetrain mechanical power with taking into consideration the efficiencies of the propulsion motor (η_m), the inverter (η_{VFD}), and the dc/dc converter (η_{con}). The requested power from energy sources can be expressed as:

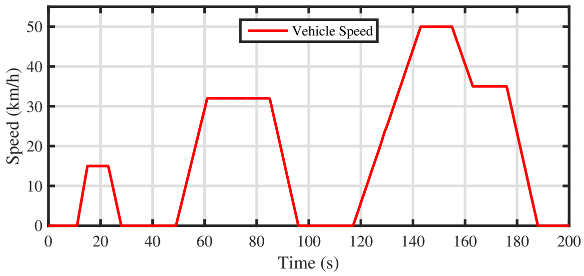
$$P_{dem}(t) = \frac{P_m(t)}{\eta_m(t).\eta_{VFD}(t).\eta_{con}(t)} \tag{4.13}$$

4.2.2 Driving cycle

Power demanded by a drivetrain or power requested from the source as a function of time for ECE 15 urban driving cycles can be calculated using equation (4.9) and (4.13) respectively. The detailed specification about vehicle body, transmission units, dynamic and aerodynamics vehicle characteristics are given in Appendix A. In this work ECE 15 driving cycle speed profile $\nu_{ev}(t),\ t\ \epsilon\ [0, T_{dc}]$ with specified vehicle data are utilized to determine the power demanded P_{dem} by the considered EV. Vehicle speed profile and total power demanded from battery sources are shown in Figure 4.3. Detail parameters of ECE 15 driving cycles are given in Table 4.1.

TABLE 4.1: Driving cycles main parameters

Driving Cycle	Standing [%]	Driving [%]	Acceleration Speed [km/h]	Maximum Speed [km/h]	Total Distance [km]	Time [min]
ECE 15 [0 195]	23.08	76.92	18.4	50.07	5.968	19.5



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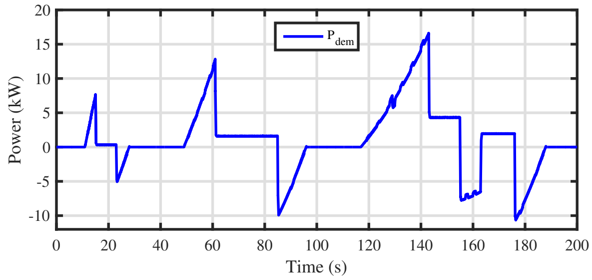


(b)

FIGURE 4.3: The speed and power demand for EV for ECE 15

4.3 Power management system architecture

The primary objective of the power management system is to minimize the difference between power demanded and power supplied by the batteries while keeping the operation of batteries in a defined safety region and without degradation of their lifespan. The power management problem includes the real-time optimal power-sharing between two batteries promoting to the maximization of usage of batteries capacity while maintaining SOC of batteries at adequate levels. Another objective of power management problem is regulating the DC link voltage at desired values. These two problems can not be decoupled entirely and should be jointly tackled. To solve these problem power management system is proposed for the dual battery powered EVs. The hierarchy structure of the subsystems of integrated rule-based metaheuristic optimization power management approach is presented in Figure 4.1. The proposed power management system architecture consists of three management levels: strategic level, action planning level, and operation level. Initially, in strategic level the search space is recursively constraints based on a set of rules. These set of rules are developed on the basis of power demanded by EVs and present value of SOC in the batteries. Action layer is formulated to address real-time power-sharing optimization problems using metaheuristic techniques. The differential evolution metaheuristic is used to define an optimized power share without prior knowledge of power demand. In the operational level, strategies for development of duty cycle for DC-DC converters are presented. The reference power signal values for the controllers are obtained by optimizing the power management problem in action planning level. Before discussing the operation of each level in detail, problem formation for the power management system is done in the next subsection.

4.3.1 Problem formulation

Batteries are the primary sources of power in proposed EV concept hence the overall objective of power management system is to know how to optimally split the required power between batteries in such a way that it leads to the maximization of usage of batteries capacity while maintaining SOC of batteries at adequate levels. The instantaneous power demanded by drivetrain is a linear combination of the instantaneously available power acquired from both the batteries. In the proposed power management system the equation for the fundamental power balancing equation can be expressed as:

$$P_{dem}(t) = \sum_{j \, \epsilon \, SB,FB} P_j(t) \tag{4.14}$$

Here $P_{dem}(t)$ refers to the power demanded by the drivetrain of the EV and $P_j(t)$ refers to the power supplied from each of the battery where j is the specified battery.

The optimal quantity of the power supplied by each of the battery source for the given demanded power by drivetrain can be obtained by identifying optimal solution for equation (4.14). To limit the instantaneous power retrieves or supplied from each battery, a set of constraints is defined based upon the specification and characteristics of each battery. The set of constraints can be defined as:

$$P_j^{min} \leq P_j(t) \leq P_j^{max} with\ j\ \epsilon\ SB, FB \tag{4.15}$$

The power $P_j(t)$ of each battery can be represented in terms of a power assignment factor $\alpha_j(t)$

$$P_j(t) = \alpha_j(t).P_i^{max};\ \alpha_j(t)\ \epsilon\ [LB_j, HB_j] \tag{4.16}$$

Here, $\alpha_j(t)$ power assignment factors are control variable in the power management optimization problem which applies constraints on the power supplied by the batteries. $\alpha_j(t)$ varies between the lower and upper bound for the power sharing by the batteries. $\alpha_j\ \epsilon\ [-1, 0]$ means that the battery j will absorb power and $\alpha_j\ \epsilon\ [0, 1]$ means that the battery j will supply power.

Objective function

The fundamental objective of the power management system is to optimally share the power demanded by the drivetrain of the EV. This objective can obtain by minimizing the difference between power demanded and power provided by each the battery source at each instant of time subjected to the constraints which establish the operation range defined by the practical limits of each battery. Mathematically it can be expressed as:

$$\begin{aligned} minimize \quad & |P_{dem}(t) - [\alpha_{SB}(t)P_{SB}(t) + \alpha_{FB}(t)P_{FB}(t)]| && (4.17) \\ subject\ to: \quad & \alpha_j\ \epsilon\ [LB_j, UB_j] \\ & P_j^{min} \leq P_j(t) \leq P_j^{max} \\ & SOC_j^{min} \leq SOC_j(t) \leq SOC_j^{max}\ with\ j\ \epsilon\ SB, FB && (4.18) \end{aligned}$$

For an online implementation of the power management problem, the constraints set α_j must redefine in each iteration depending upon P_{dem} and current SOC of each battery. These set of constraints will restrict the search space to obtain the optimal solution for the power management optimization problem. Then, optimization techniques are used to achieve optimal power-sharing by each battery to define the reference power signal values for controlling of DC-DC converters. Thereby, the power management problem has been subdivided into three levels, and each level is throughly discussed in next sections.

4.3.2 Strategy Level

The strategy level is related to restrict the search space by defining some sets of rules which are determined mainly by experience and expert knowledge. These sets of rules are designed to restrict the solution search space according to demanded power and the SOC values for the batteries at every instant of time by mapping of SOC into search space. The search space is restricted to help the optimization technique to determine a battery solution quickly by narrowing down the search space to the regions of interests. The solution search space is restricted by imposing lower and upper bound to power assignment factor $\alpha_j(t)$.

Displacement of the vehicle can be divided into the following phases: standing phase, an acceleration phase (light or high) and a deceleration phase. The sets of rules implemented with if-then operation rules as a function of demanded power P_{dem} and SOC_j using thresholds values defined by a fine-tuning process with complete knowledge of the characteristics and efficiency of the batteries are shown in Algorithm 8.

Algorithm 8 Set of rules for search space restriction scheme

Rule 1 : Standing

if $P_{dem} = 0$ **then** $\alpha_{SB}\ \epsilon\ [0,0],\ \alpha_{FB}\ \epsilon\ [0,0] \Rightarrow$ **CASE A**

if $P_{dem} = 0 \cap SOC_{SB} > \tau^{min}_{SOC_{SB}} \cap SOC_{FB} < \tau^{min}_{SOC_{FB}}$ **then** $\alpha_{SB}\ \epsilon\ [0,1],\ \alpha_{FB}\ \epsilon\ [-1,0] \Rightarrow$ **CASE B**

if $P_{dem} = 0 \cap SOC_{SB} < \tau^{min}_{SOC_{SB}} \cap SOC_{FB} > \tau^{min}_{SOC_{FB}}$ **then** $\alpha_{SB}\ \epsilon\ [-1,0],\ \alpha_{FB}\ \epsilon\ [0,1] \Rightarrow$ **CASE C**

Rule 2: Light Acceleration

if $P_{dem} > 0$ **then** $\alpha_{SB}\ \epsilon\ [0,1],\ \alpha_{FB}\ \epsilon\ [0,1] \Rightarrow$ **CASE D**

if $P_{dem} > 0 \cap SOC_{SB} > \tau^{min}_{SOC_{SB}} \cap SOC_{FB} < \tau^{min}_{SOC_{FB}}$ **then** $\alpha_{SB}\ \epsilon\ [0,1],\ \alpha_{FB}\ \epsilon\ [-1,0] \Rightarrow$ **CASE E**

if $P_{dem} > 0 \cap SOC_{SB} < \tau^{min}_{SOC_{SB}} \cap SOC_{FB} > \tau^{min}_{SOC_{FB}}$ **then** $\alpha_{SB}\ \epsilon\ [-1,0],\ \alpha_{FB}\ \epsilon\ [0,1] \Rightarrow$ **CASE F**

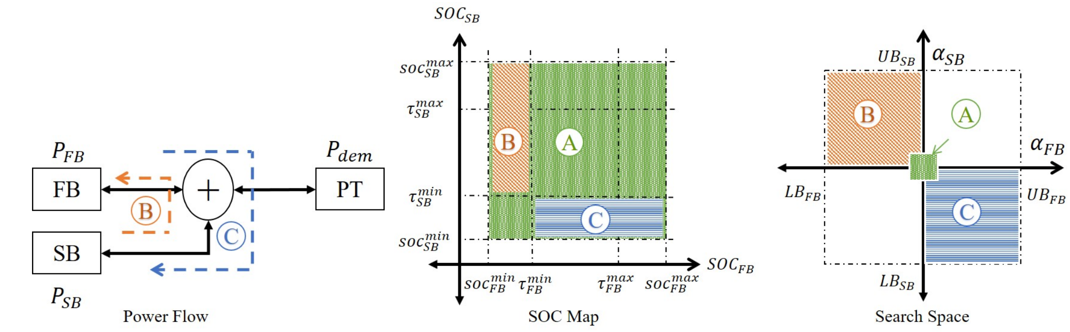
Rule 3: Deceleration or Braking

if $P_{dem} < 0$ **then** $\alpha_{SB}\ \epsilon\ [-1,0],\ \alpha_{FB}\ \epsilon\ [-1,0] \Rightarrow$ **CASE G**

if $P_{dem} < 0 \cap SOC_{FB} < \tau^{min}_{SOC_{FB}}$ **then** $\alpha_{SB}\ \epsilon\ [0,1],\ \alpha_{FB}\ \epsilon\ [-1,0] \Rightarrow$ **CASE H**

if $P_{dem} < 0 \cap SOC_{SB} < \tau^{min}_{SOC_{SB}}$ **then** $\alpha_{SB}\ \epsilon\ [-1,0],\ \alpha_{FB}\ \epsilon\ [0,1] \Rightarrow$ **CASE I**

To understand the underlying rationale for the each given set of rules based on expert knowledge corresponding power flow, SOC map and constrained search space are shown



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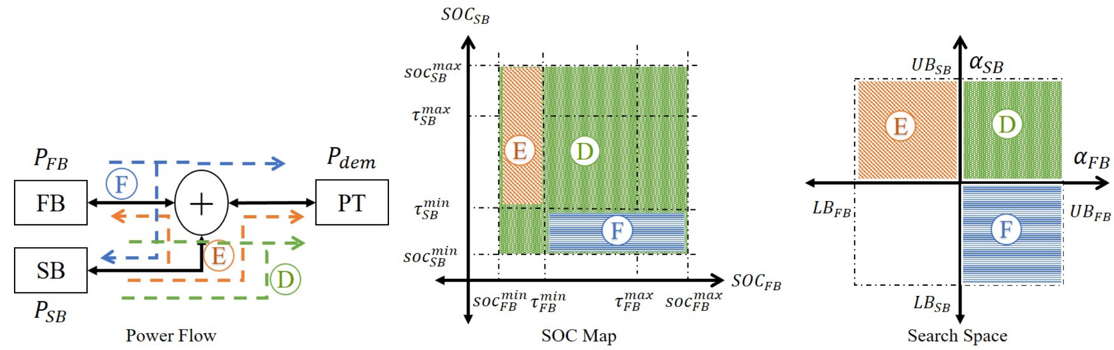

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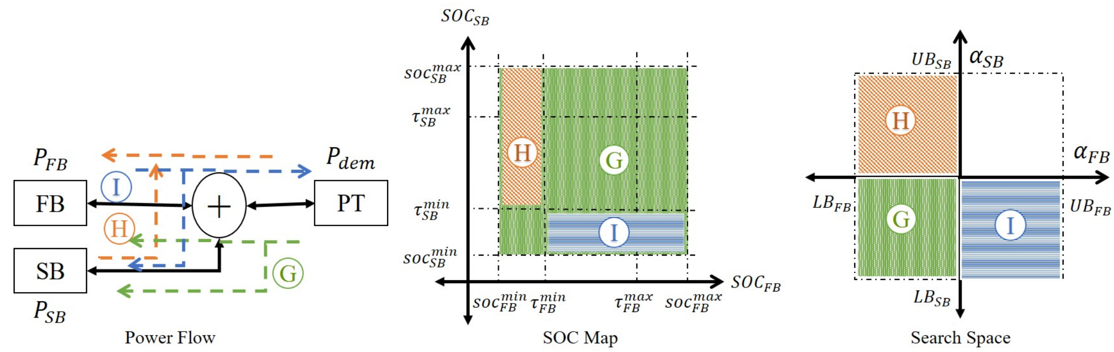


(c)

FIGURE 4.4: Rules for strategy planning level

in Figure 4.4. Figure 4.4(a) presented power flow direction, SOC map and constrained search space corresponding to rule 1 for the standing mode of EV. According to rule 1, three cases (A,B,C) are considered depending upon P_{dem} and SOC values of batteries. Case A states that when there is no power demand $P_{dem} = 0$, and both the batteries have high SOC value, then the search space will be reduced to $\alpha_j \epsilon [0, 0]$. Hence, nothing will happen if both the batteries are well charged, and there is no power required by the drivetrain. Whereas for the same power demand if the SOC value for the fixed battery

SOC_{FB} is below the threshold value $\tau^{min}_{SOC_{FB}}$ while swappable battery is still have enough energy i.e. ($SOC_{SB} \geq \tau^{min}_{SOC_{SB}}$) then the search space is defined to $\alpha_{SB}\ \epsilon\ [0,1]$ and $\alpha_{FB}\ \epsilon\ [-1,0]$ (see Case B). This means the swappable battery will charge the fixed battery to enable future acceleration requiring power peak to be supplied by the fixed battery. Inversely, when the fixed battery have high SOC value SOC_{FB} then the search space is restricted to $\alpha_{SB}\ \epsilon\ [-1,0]$ and $\alpha_{FB}\ \epsilon\ [0,1]$. Hence, the fixed battery will discharge to the swappable battery for leveling the SOC values so that it could charge during braking model of operation of the EV. Figure 4.4(b) presented power flow direction, SOC map and constrained search space corresponding to rule 2 for the light acceleration mode of EV. According to rule 2, three cases (D, E, F) are considered depending upon P_{dem} and SOC values of batteries. Case D states that when there is power demand $P_{dem} > 0$, then the search space will be reduced to $\alpha_j\ \epsilon\ [0,1]$. Hence, both batteries will be utilized to supply the demanded power. Whereas for the same power demand if the SOC value for the fixed battery SOC_{FB} is below the threshold value $\tau^{min}_{SOC_{FB}}$ while swappable battery is still have enough energy i.e. ($SOC_{SB} \geq \tau^{min}_{SOC_{SB}}$) then the search space is defined to $\alpha_{SB}\ \epsilon\ [0,1]$ and $\alpha_{FB}\ \epsilon\ [-1,0]$ (see Case E). This means the swappable battery will supply the demanded power by charging the fixed battery to enable future acceleration requiring power peak to be supplied by the fixed battery. Inversely, when the fixed battery have high SOC value SOC_{FB} then the search space is restricted to $\alpha_{SB}\ \epsilon\ [-1,0]$ and $\alpha_{FB}\ \epsilon\ [0,1]$. Hence, the fixed battery will supply the demanded power by charging the swappable battery. Figure 4.4(c) presented power flow direction, SOC map and constrained search space corresponding to rule 3 for the declaration or braking mode of EV. According to rule 3, three cases (G, H, I) are considered depending upon P_{dem} and SOC values of batteries. Case E states that when there is regenerative power $P_{dem} < 0$ due to braking, then the search space will be reduced to $\alpha_j\ \epsilon\ [-1,0]$. Hence, both batteries will are utilized to store the power generated from braking. Whereas for the same generated power if the SOC value for the fixed battery SOC_{FB} is below the threshold value $\tau^{min}_{SOC_{FB}}$ then the search space is defined to $\alpha_{SB}\ \epsilon\ [0,1]$ and $\alpha_{FB}\ \epsilon\ [-1,0]$ (see Case E). This means the fixed battery will be charged from regenerative braking and swappable battery. Inversely, when the swappable battery is below the threshold value SOC_{SB} then the search space is restricted to $\alpha_{SB}\ \epsilon\ [-1,0]$ and $\alpha_{FB}\ \epsilon\ [0,1]$. Hence, the swappable battery will be charged from regenerative power.

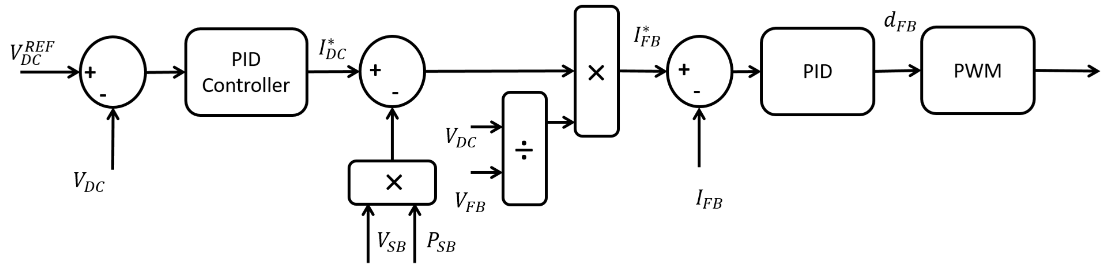
4.3.3 Action Planning Level

The primary objective of action planning level of global power management system is to feed the power request of EV with available energy continuously.

This level can be implemented by using optimization techniques having objective function defines as the online power-sharing between both the batteries under the strict guidelines developed by the power management system in strategy level. The aim of the action planning level is to supply the demanded power without any interruption and reduced degradation of batteries lifespan. Action planning level produces a set of the decisions within the operation region constrained by strategy level depending upon power demanded and SOC values of batteries. Therefore, action planning level determines the references power signals to control the converters operations in the operational level of the power management system. In this research work, the DE optimization approach has been implemented to obtain the optimal solution for the formulated problem. Pseudo-code for implementation of DE optimization technique is presented in Algorithm 4 of Chapter 2. The objective function for power sharing is defined using equation (4.17). The initial solution considered for implementation of optimization is $\alpha_{SB}(t) = \alpha_{FB}(t) = 0$. Depending on the demanded power and SOC of each battery the power management systems reduce the search space for optimization technique. The process of reducing search space will increase the speed of optimization techniques. When the solution is converged to the optimal solution optimization techniques will stop and provides reference power signals of operational level.

4.3.4 Operation Level

The operational level of power management system deals with dynamics and operations of power electronics converters used in the dual battery powered EV. Power flow of each battery sources is controlled by the individual bi-directional DC-DC converter for each of them. The function of converters is to step up the input voltage and control the power flow from each battery. The proposed control management for each DC-DC converters is shown in Figure 4.5. The reference signals for controlling the converters are the set points for the DC-link voltage and the swappable battery pack current. The controller for the fixed battery is composed by a double loop controller with the combination of current and voltage controllers, and for swappable battery, only current controller is used. The double loop controller having a voltage controller as the outer loop will maintain constant DC link voltage depending upon nature of the loads, i.e., voltage fed drive for the electric motor. Hence, voltage controller regulates the DC link voltage (V_{DC}) to a constant voltage reference value (V_{DC}^{REF}). Current controllers in both the controlling blocks control the current flow in the battery by means of proportional integral controllers which develop pulses for triggering of the gates with duty-cycles (d_{SB}) and (d_{FB}) for swappable and fixed battery respectively.



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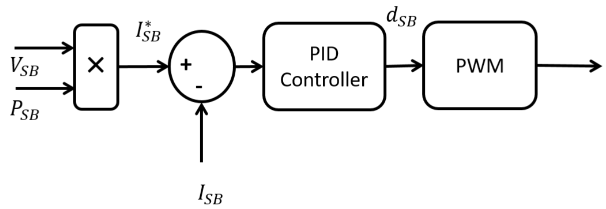


(b)

FIGURE 4.5: Controlling strategies for DC-DC converter (a) Fixed battery (b) Swappable battery

4.4 Results and Discussion

Dual battery powered EV testbed system based on the specification of Tesla Model S with the Power management system has been implemented in MATLAB/Simulink as shown in Figure 4.6. Simulink model contains three main blocks: one block for power management systems, one for electrical components and one for mechanical components of considered EV. The detail specification for vehicle model and both the batteries are given in Appendix A. The reference load for simulated EV is defined by an ECE 15 driving cycle. Proposed dual battery power management algorithm is validated by obtaining simulation outcomes for the ECE 15 driving cycle with different initial SOC values of the batteries. Three different initial values of SOCs considered for testing and validation purpose are

- **Case I:** When SOC of both battery are same
- **Case II:** When $SOC_{SB} > \tau_{SOC_{SB}}^{min}$ and $SOC_{FB} < \tau_{SOC_{FB}}^{min}$

- **Case III:** When $SOC_{SB} < \tau^{min}_{SOC_{SB}}$ and $SOC_{FB} > \tau^{min}_{SOC_{FB}}$

The SOC threshold values were set as: $\tau^{max}_{SOC_{FB}} = 0.85$; $\tau^{min}_{SOC_{FB}} = 0.35; \tau^{max}_{SOC_{SB}} = 0.85$; $\tau^{min}_{SOC_{SB}} = 0.35$. Power management for dual battery powered EV is performed with unknown demanded power until the end of the cycle. In all simulations, the DE algorithm was parameterized with N_{cycles}=30. The control parameters of DE optimization techniques have been tuned after extensive experimentation. For tuning purpose, present SOC of each battery is considered. Figures 4.7 , 4.8 and 4.9 represents the results for ECE 15 cycle with different initial SOC values. These figures present the results for powers sharing, SOCs evaluation, strategy level cases histogram, and power assignment factors.

Case I: When SOC of both battery are same

The ECE 15 driving cycle power-sharing decompositions between dual battery sources when the initial SOCs values are equal i.e. $SOC_{SB} = SOC_{FB} = 60\%$ is presented in Figure 4.7 (a). Simulation of ECE 15 driving cycle begins with $P_{dem} = 0$, and as both the batteries are above the specified minimum threshold, then strategy level defines these conditions as CASE A. Accordingly, the DE optimization techniques restricted the search space where the solutions correspond to no power flow through the drivetrain. This aspect is clear in the first part of the power-sharing graph. Hence when there is no demand power and both the batteries SOC are above the specified minimum threshold, there will be no change in SOC values also. The next EV operations are acceleration; now the strategy level defines search space for DE optimization techniques referring to CASE D. Power demanded by drivetrain is supplied by both the battery sources as above are having sufficient SOCs. When there is power demanded and both batteries are having sufficient SOCs then power is supplied by both of them with the same discharging rates. The objective of using both battery source for supply demanded power is to avoid the burden on single battery source because if the single battery is used to supply the power, it will discharge at the high current rate compared with when both the batteries are used. The low discharging rate will increase the battery lifespan. It is clear from Figure 4.7 (b) that both the batteries sources are discharging with approximately same discharge rate hence one single battery is overburdened. After acceleration, EV will operate in deceleration mode for the given driving cycle. During deceleration, the strategy level restricts search space for DE optimization techniques referring to CASE G. During regenerative braking, both batteries are charged at same rate. The previously defined case will repeat in the next displacement for given driving cycles since the battery SOC will remain above the threshold. The

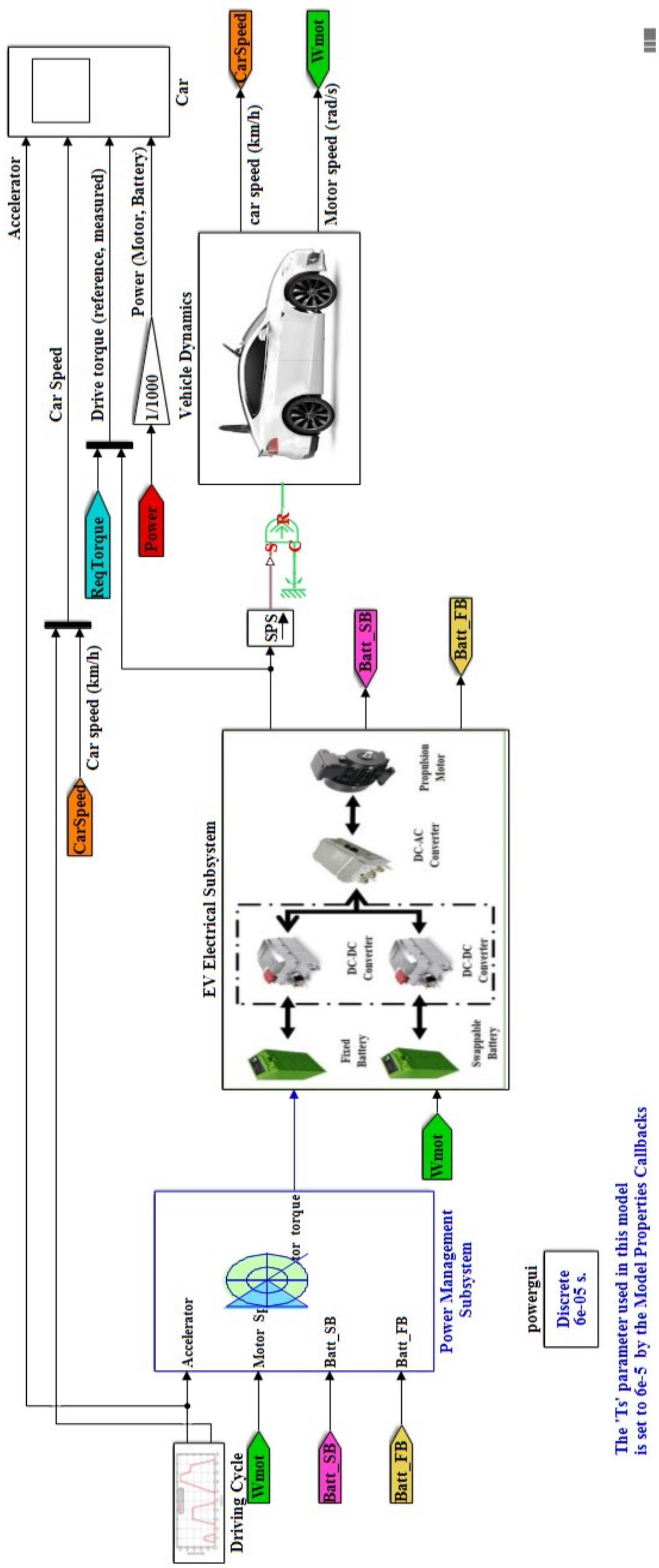


Figure 4.6: Dual battery powered EV in MATLAB/Simulink

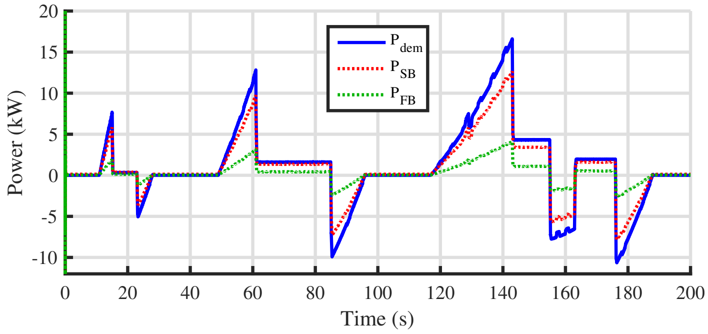
variation of operation cases depending on power demanded by the drive train and SOCs values of each source are shown in Figure 4.7 (c). The graphical representation of the power assignment factor depending on restricted search space computed by the power management system is presented in 4.7(d).

Case II: When $\mathbf{SOC_{SB}} > \tau^{\mathbf{min}}_{\mathbf{SOC_{SB}}}$ and $\mathbf{SOC_{FB}} < \tau^{\mathbf{min}}_{\mathbf{SOC_{FB}}}$

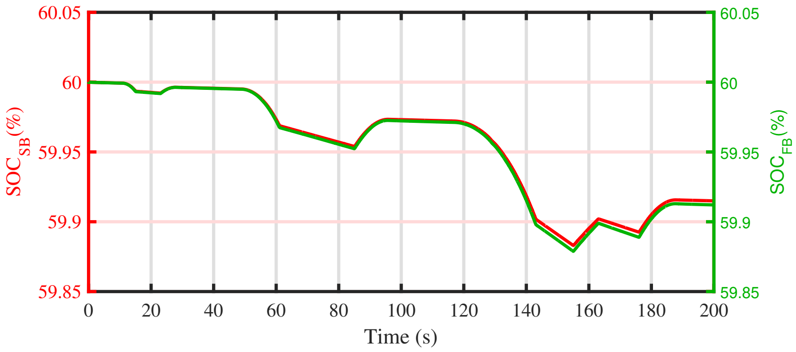
The ECE 15 driving cycle power-sharing decompositions between dual battery sources when the initial SOCs values for sizeable swappable battery is higher than minimum threshold value, i.e., $SOC_{SB} = 80\%$ and initial SOC values for fixed small battery is less than minimum threshold value, i.e., $SOC_{FB} = 30\%$ is presented in Figure 4.8 (a). At the beginning of the ECE 15 driving cycle, the assumption that the fixed battery SOC will be below minimum threshold leads the strategy level to guide the DE optimization technique differently from the previous cases simulations. For this case, strategy level reduces the search space for implementation of DE optimization to the region designated as CASE B in Figure 4.4. At standing mode, when there is no power demand swappable battery will charge the fixed battery pack so that both of them can be utilized when power demanded by EV to maintain the low discharging rate. Whereas in Case I for the standing condition of the EV strategy level define CASE A depending on the SOC condition of the batteries. The DE optimization technique decides to charge fixed battery using swappable battery such that SOC_{SB} reduces and allows storing of the power in the next regenerative braking mode. In the cruising phases strategy level reduces the search space to the region defined by CASE E in Figure 4.4 where as for Case I it was CASE D in the simulation for the same time interval. The DE optimization technique decides to supply demanded power using swappable battery because it is having sufficient SOCs to maintain the power flow. In the regenerative braking compared to last Case I strategy level to restrict the search space to the region defined by CASE H. In this mode, fixed battery is charged using regenerative braking power because its SOC level is less than the minimum threshold value. For the ECE 15 driving cycle in the given time interval same cases will repeat for all next standing, acceleration and regenerative braking mode. The variation of operation cases depending on power demanded by the drive train and SOCs values of each source are shown in Figure 4.8 (c). The graphical representation of the power assignment factor depending on restricted search space computed by the power management system is presented in 4.8(d).

Case III: When $\mathbf{SOC_{SB}} < \tau^{\mathbf{min}}_{\mathbf{SOC_{SB}}}$ and $\mathbf{SOC_{FB}} > \tau^{\mathbf{min}}_{\mathbf{SOC_{FB}}}$

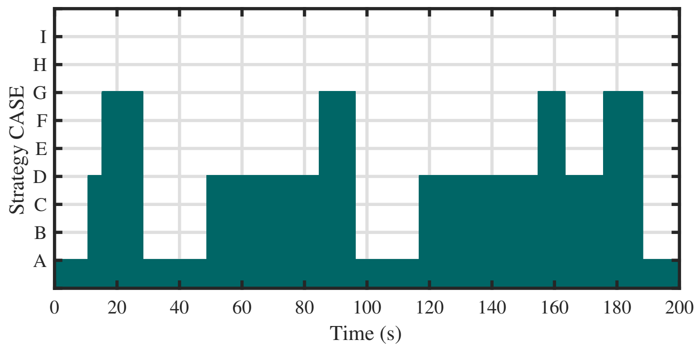
In this case, the ECE 15 driving cycle power-sharing decompositions between dual battery sources is different with the last section. In this section, the initial SOCs values for swappable battery is lower than minimum threshold value, i.e., $SOC_{SB} = 30\%$ and initial SOC values for fixed small battery is higher than minimum threshold value, i.e., $SOC_{FB} = 80\%$. Simulation results for powers sharing, SOCs evaluation, strategy level cases histogram, and power assignment factors for this CASE are presented in Figure 4.9. In this case, for standing mode strategy level restrict the search space to the region designated as CASE C in Figure 4.4. Since the SOC of swappable battery is less then the minimum threshold value, it will get charge from small battery to supply the demanded power in acceleration mode with low discharging rate. Otherwise full power demand by drivetrain will be supplied by small battery at high discharging rate. Discharging with high current rate will decrease the life of the battery. Other reason is for reducing fixed battery SOC level is to allowing storing of the excess power in the regenerative braking mode. In the cruising phases, strategy level reduces the search space to the region defined by CASE F in Figure 4.4 bases of which the DE optimization technique decides to supply demanded power using fixed battery because of higher SOCs level to maintain the power flow. In the regenerative braking strategy level restrict the search space to the region defined by CASE I. In this mode, swappable battery is charged using regenerative braking power because its SOC level is less than the minimum threshold value. For the ECE 15 driving cycle in the given time interval same cases will repeat for all next standing, acceleration and regenerative braking mode. The variation of operation cases depending on power demanded by the drive train and SOCs values of each source are shown in Figure 4.9 (c). The graphical representation of the power assignment factor depending on restricted search space computed by the power management system is presented in 4.9 (d).



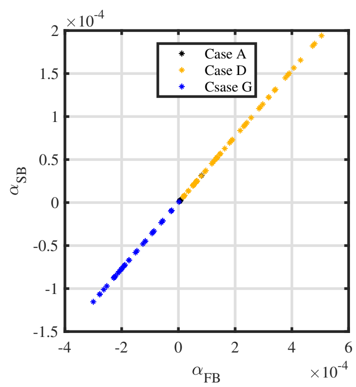
(a)



(b)

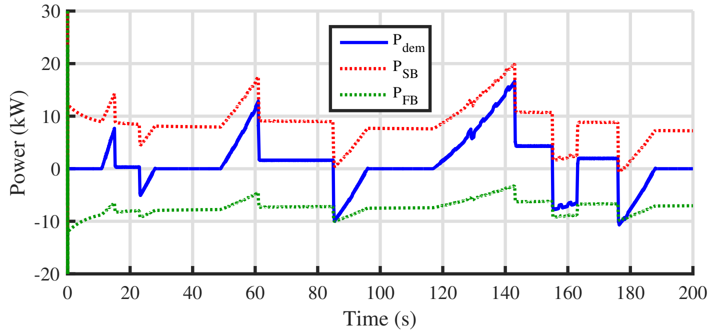


(c)

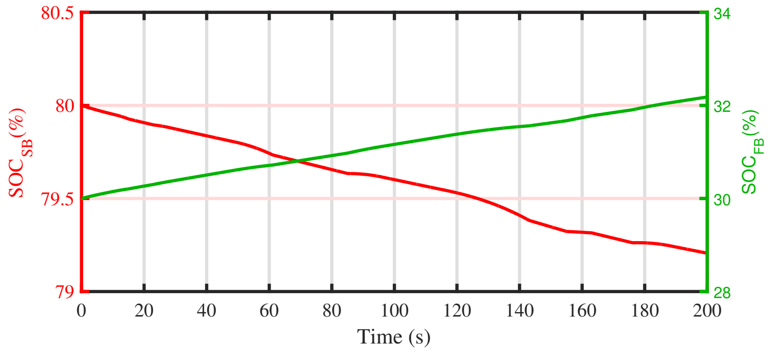


(d)

FIGURE 4.7: ECE 15 driving cycles results for initial SOC values $SOC_{SB} = 60\%$ and $SOC_{FB} = 60\%$



(a)



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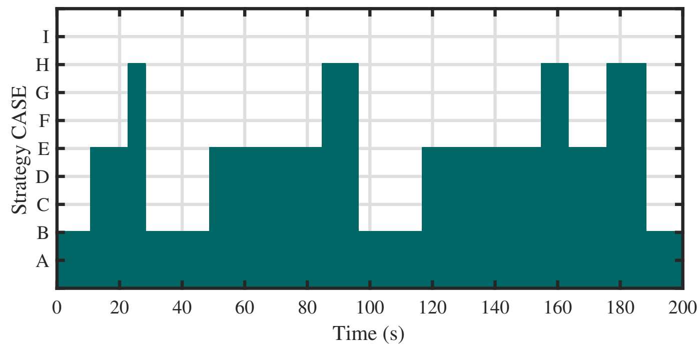

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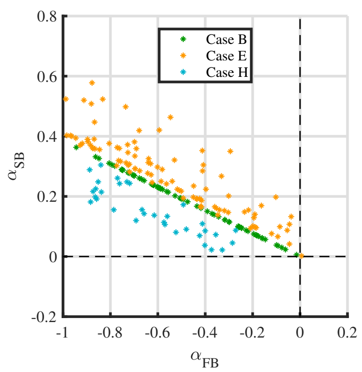

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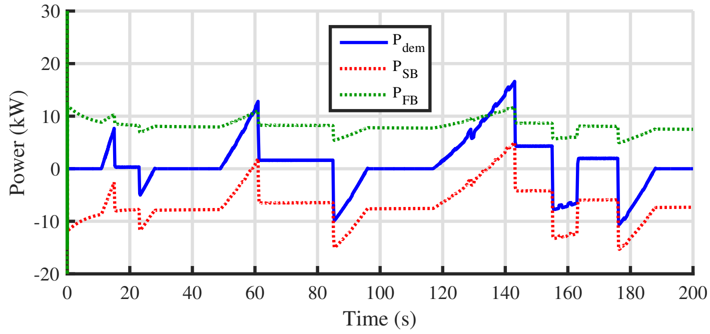
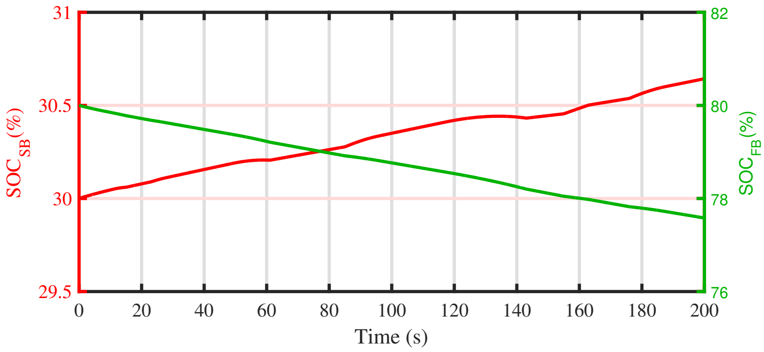
FIGURE 4.8: ECE 15 driving cycles results for initial SOC values $SOC_{SB} = 80\%$ and $SOC_{FB} = 30\%$



(a)



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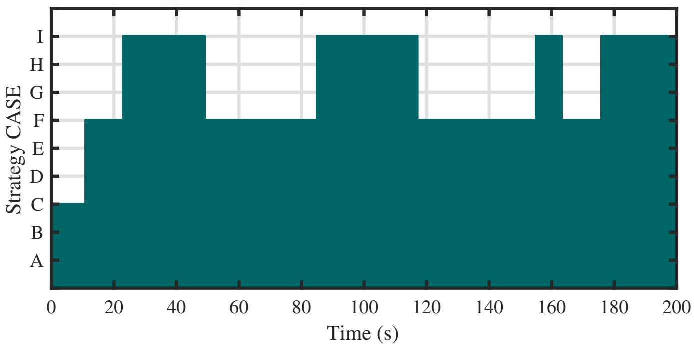

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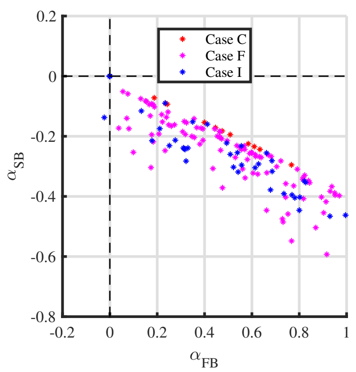

(d)

FIGURE 4.9: ECE 15 driving cycles results for initial SOC values $SOC_{SB} = 30\%$ and $SOC_{FB} = 80\%$

4.5 Chapter Summary

This chapter proposes a rule-based heuristic optimization power management system for optimally sharing demanded power between the batteries in the dual battery powered EVs. In this approach, three level power management scheme has been formulated based on strategy, action planning and operational levels. Firstly, strategy level restricted the search space using a sets of rules and in action level this search space is utilized to identify the reference power signals for controlling bidirectional converters used for given power sources. In operational level, DC-DC converters are used to control the power supply from each batteries depending on the demanded power. Validation of proposed power management system tested for normalized ECE 15 driving cycle depending on different initial SOC conditions. The simulation results prove the effectiveness of the proposed power management system with allowing to fulfill the demanded power requirement among the both the batteries. The power management system avoid the burden on single battery for long distance, it share load among both the batteries with equal charging and discharging rates. Low charging rate and discharge rate compared to single battery will increase the life of batteries. Development of effective power management system help in increasing range of batteries for extended range and increase the probability of using dual battery powered EVs. Since Dual battery powered EVs have less weight for short range which will also increase their battery life and long range covered compared to single large size battery.