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Dynamic programming-based control system development for advanced electric power drive

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ABSTRACT

An efficient method for raising the effectiveness and performance of fuel cell electric vehicles (FCEVs) is the dynamic programming controller (DPC). By using real-time data to optimize the control inputs, FCEVs can achieve higher levels of efficiency and reduce their environmental impact. The DPC algorithm works by solving an optimization problem at each time step, based on the current state of the vehicle and its environment. The optimal control inputs are then applied to the vehicle to achieve the desired performance criteria. This paper presents the study that utilized MATLAB/Simulink to design, model, and simulate DPC for a FCEV. Controlling various components of the fuel cell (FC) with the optimum power requirement is needed for increasing the performance and mileage of the FCEV. It's important to use FC energy as effectively as possible. Having supervisory control over the FCEV's energy consumption and battery charging is necessary for it to produce this output at its best. To use the hydrogen efficiently, a control strategy is designed for energy management in FCEV. The designed control strategies are implemented through simulation using Simulink in MATLAB. The results show prominent performance of dynamic programming (DP) over rule-based controllers.

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1. INTRODUCTION

The splitting of the power between the two sources is important to sustain the efficiency of operation for fuel cell (FC) and the battery such that the consumption of the hydrogen is minimized. With this the battery is kept well within the required state of charge (SOC) limit such that it should be able to drive the vehicle with the required wheel power demand. Moreover, the advanced power electronic components are allowing us to manage the switching and control of the high-power demand which is split from battery [1] and FC, thus making the control on energy within the fuel cell electric vehicle (FCEV) more efficient. Reliability is also an important component of FCEV. Assessment of reliability using two downsized FCs and its comparison with conventional designs enhances the fuel efficiency [2], and the new technologies should be reliable enough to be accepted by the market [3]. Vehicle cost and minimal fuel consumption have been modeled using a Pareto based multi objective optimization using particle swarm optimization method and the results are within the specified limits [4]. Apart from these aspects, charging infrastructure (CI) plays a vital role in the driving and maintenance of the vehicle. These entities are battery chargers, their modes types and levels [5]. Sizing of the battery pack to ascertain the energy consumption of the vehicle can be done using parametric analytical model of vehicle energy consumption (PAMVEC) where the inputs would be specific power and energy, and cell voltage and its effect on the vehicle speed, range and acceleration time [6]. To address this complexity a number of optimization methods have been used to manage the multiple power sources of a FCEV such as battery, engine, and ultra capacitor. Here dynamic programming (DP) is used to optimize the three parameters for vehicle components size and economy in fuel consumption [7]. DP is utilized for studying the strategy of power management in hybrid electric vehicle (HEV). In comparison to deterministic DP, stochastic DP gives low fuel economy because the vehicle driving cycle is directly used for optimization. Also, the deterministic DP model gives large range of battery SOC [8].

In fuel cell systems (FCS), a FC serves as the main power source and an energy storage system (ESS) helps to meet load power demands. As a result, the FCS's $P_{FC}(t)$ provides some of the load power $P_{load}(t)$, with the ESS providing the remainder, $P_{Batt}(t)$ [9], [10] as per the relationship given in (1).

$$P\_load\ (t) = P\_FC\ (t) + P\_Batt\ (t) \forall t = 1, 2, \dots, N \tag{1}$$

FCS are particularly appealing due to the additional advantages of hybridization: i) the hydrogen economy and transient reaction are improved with the utilization of a successful energy-the-board procedure to divide the power between the FCS and the ESS, ii) size reduction of the FCS, iii) cost and weight reduction of the overall system, iv) reduction of the time it takes for the FCS to warm up and reach full power, and v) potential for increased hydrogen consumption due to automotive applications [11]. Sharing of the input current as well as reduction in the ripple effect of the current is observed in a DC-DC interleaved boost converter FC under three duty cycle conductions [12]. Figure 1 displays the FCEV's block diagram and the interaction of various blocks with the controller.

The controller acts as a brain of the entire plant to keep it working in a controlled closed loop manner thereby imparting a good performance. Hence to interact with all the systems in the vehicle it needs to have very high computing power and must be able to provide the control signals by processing the input signal at any given time. In order to reduce the overhead of the main processor it is advisable to have a separate controller for systems which can work independently over a wide operating range. These systems will require action only in a certain operating range and can be coded to take the control signal from the main processor during that range only. Thus, making the overall system more robust but at the same time more complex. Hybrid dynamic systems have unpredictable behaviour and operate over wide ranges and usually need networks of sensors for the feedback operation and require a controller incorporated with different strategies to react under different conditions or to coordinate with different controller for better coherence in the overall system [13]. Figure 2 shows the energy flow with controller and its direction in the FCEV.

With the help of DP, you can create the best control strategies with a methodical approach, ensuring that you use the least amount of energy possible to get the performance you want from the system. This is especially crucial for modern electric power drives, where energy efficiency is a crucial consideration. Highly nonlinear systems, like electric power drives, are challenging to model with conventional methods. For modelling and managing nonlinear systems, DP offers an adaptable framework. Increasing performance while reducing energy consumption are two common objectives that conflict in electric power drives.

Design professionals can balance these objectives by using DP's multi-objective optimisation capability to create a control strategy that satisfies the desired performance standards. Embedded systems enable the real-time implementation of DP-based control systems. As a result, it is possible to create control systems that are both effective and efficient and that have a wide range of applications. Complex dynamic systems can be simulated using MATLAB/Simulink, a potent simulation tool. It offers a user-friendly interface for simulating DP-based control systems and is widely used in the development of control systems for cutting-edge electric power drives. Therefore, DP-based control system development is an effective method for creating the best control strategies for cutting-edge electric power drives. The creation of control systems that can be used in real-time is made possible by simulating these systems using MATLAB Simulink [14]–[16].

This paper presents the study that utilised MATLAB/Simulink to design, model, and simulate dynamic programming controller (DPC) for a FCEV. Controlling various components of the FC with the optimum power requirement is needed for increasing the performance and mileage of the FCEV. It's important to use FC energy as effectively as possible. Having supervisory control over the FCEV's energy consumption and battery charging is necessary for it to produce this output at its best. To use the hydrogen efficiently, a control strategy is designed for energy management in FCEV. The designed control strategies are implemented through simulation using Simulink in MATLAB. The results show prominent performance of DP over rule-based controllers.

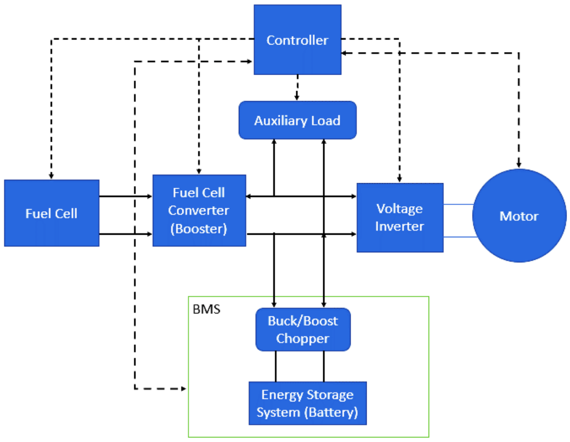

Figure1. Electric system in FCEV

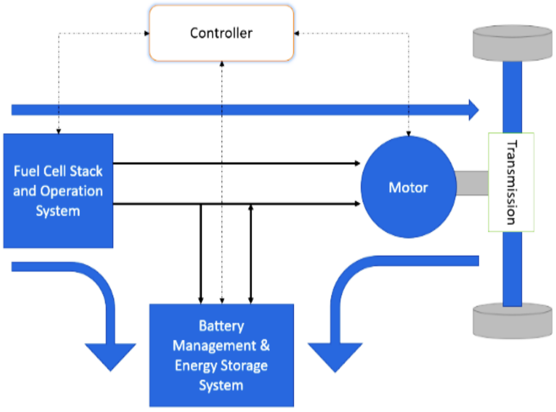

Figure 2. Energy flow with controller

2. METHOD
2.1. FCEV control strategy

For improving the automotive fuel economy, vehicles should be made to work within their feasible limits and inside the most outrageous braking points, and it fundamentally shows the improvement in vehicle performance. Use of the right power split between the energy sources i.e. battery and FC, can help one to achieve an improved fuel economy with lesser emissions. As a result, several power split control strategies have been put forth, assessed, and employed by various FCEVs. For calculation of this control strategy the vehicle controller often requires input in the form of vehicle power demand, vehicle speed, battery SOC and battery limit, and present load on the vehicle. The controller output signal includes a number of control options that specify which of the FCEV's operating modes it should operate in i) battery only, ii) FC only, iii) assist mode (battery with FC), and iv) regenerative mode (energy from braking is recovered using an electric motor). These are the 4-operating modes for any FCEV. There is a need to employ a certain kind of control strategy such that it will be able to run the vehicle optimally using these modes of operation [17], [18].

2.2. Controller

Controller uses the input signals from various subsystems like input form the driver, fuel cell output, speed of the motor, driving speed of the vehicle, battery SOC and power level. The required driving torque of the motor is provided, using the control strategy. An optimum level of motor torque and current required for driving the FC are obtained by regulating the hydrogen and oxygen/air flow to the FC. The primary goal of the controller is to implement the smooth function of various operations simultaneously such that the function of those should be in the best performance region and at the same time should be able to consume less amount of fuel for its operation. Hence a control strategy plays an important role in keeping the consumption at the bay with optimal performance. Hence it is important to develop an efficient control strategy. MATLAB Simulink environment is selected to carry out the modeling of FCS, DC-DC convertor, FC power system, and battery SOC. A proportional-integral-derivative (PID) controller is used to control the stack temperature and the controller performance was satisfactory. Moreover, the fuzzy controller reduces the amount of hydrogen used by the FC by only using the input parameters of velocity of vehicle and road gradient [19].

A FCEV typically consists of the following components: controller, FC, DC-DC converter, DC-AC converter, motor, battery pack and a transmission system. Energy from the battery and FC is used to drive the road wheel of the vehicle using the transmission system to the required power of the vehicle and is used for recovering it to power the battery while braking. A control strategy is needed to control the power split between the FC and the battery in such a way that the vehicle performance is optimized.

2.3. FCEV model

Backward and forward modelling approaches are the two modelling approaches are used for modelling electric vehicle (EV). Vehicle speed is the consequence of delivered torque as per demand of driver using forward approach whereas in backward approach, with vehicle speed in known measure, required torque is obtained using model. With V as vehicle speed, driving load power of a vehicle is dynamically modeled and expressed as per (2). Table 1 presents all the vehicle parameters pertaining to (2). Hence the total power required by the vehicle is provided by the two sources, fuel cell (FC) and the battery at any given time. Figure 3 shows the various forces acting on the vehicle [20].

$$P_{total} = V\left(Mgf_r + 0.5 * \rho_f C_d A V^2 + MgI\right) + \frac{MdVdV}{dt} \quad (2)$$

$$F_{total} = F_{inertia} + F_{aero} + F_{roll} + F_{trac} \quad (3)$$

Table 1. Vehicle parameters

Description of parameter	Nomenclature	Value
Mass of the vehicle (kg)	M	1625
Coefficient of rolling resistance	f_r	0.01
Air density (kg/m^3)	ρ_f	1.180
Frontal area of vehicle (m^2)	A	2.711
Coefficient of aerodynamic drag	C_d	0.26
Rotational inertia factor for converting inertia of rotating component to mass	ɗ	1
Grade of road	I	0

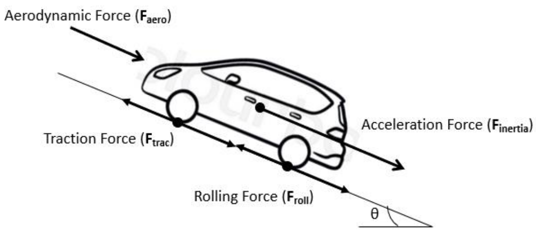

Figure 3. Forces on vehicle

2.4. Battery and battery management systems

Lithium-ion batteries, used in EV, are designed for longer life and to meet the power requirement. Major factors responsible for the degradation of the battery are the charging discharging cycle, SOC over time (SOC(t)) and battery temperature over time (Temp(t)). Hence when batteries are kept at higher SOC level its degradation is minimized. Battery management system (BMS) ensures the smooth operation of batteries. BMS controls the over and under charging, over current and voltage, and batteries temperature control as Lithium batteries require an over voltage detection system for each cell in a multi cell system to stop the over voltage from happening.

Figure 4 shows the voltage discharge of the battery with respective time. Battery works in the nominal area and is able to provide a near constant voltage. Figure 5 shows the current discharge of the battery with respect to voltage and time. Figure 4 and 5 shows the nominal current discharge of the battery over time and a constant amount of current discharge with respective to voltage and time. The battery provides a near constant voltage for a wide range till the battery is near to its complete discharge point.

If, the power $P_{chg}(t)$ and $P_{dis}(t)$ are the charge load while the battery is being charged and discharged, V_{oc} = Open circuit voltage, and Ri = Internal resistance of the battery then the discharge current and charge current of the battery can be determined by using (4) [21]–[23].

$$I_{dis} = \frac{V_{oc} - \sqrt{V_{oc}{}^2 - 4Ri\, P_{dis}(t)}}{2Ri} \;\&\; I_{chg} = \frac{V_{oc} + \sqrt{V_{oc}{}^2 + 4Ri\, P_{chg}(t)}}{2Ri} \quad (4)$$

2.5. State-of-charge (SOC) of battery

SOC is the amount of power a battery can hold and determined by dividing the total capacity by the amount of charge that can be extracted from a cell at any given time. SOC depends on many variables like battery temperature, terminal voltage, current charge and discharge rate [24], [25].

Life and operation capacity of the battery depends on SOC hence needs to be maintained in the optimal region. If the SOC falls below a certain SOC_{min}, charging will require additional power. Hence SOC is needed to be kept in the optimal operation area for extending battery life. Figure 6 shows the charging and discharging path of the battery. The depth of discharge (DOD) is the SOC's numerical compliment, such that in (5).

$$DOD = 100\% - SOC \quad (5)$$

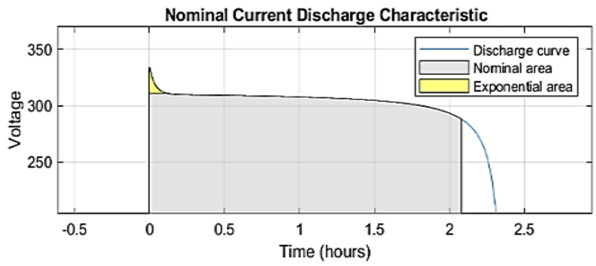

Figure 4. Nominal current discharge characteristic

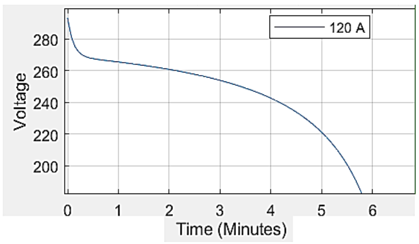

Figure 5. Current discharge w.r.t. voltage and time

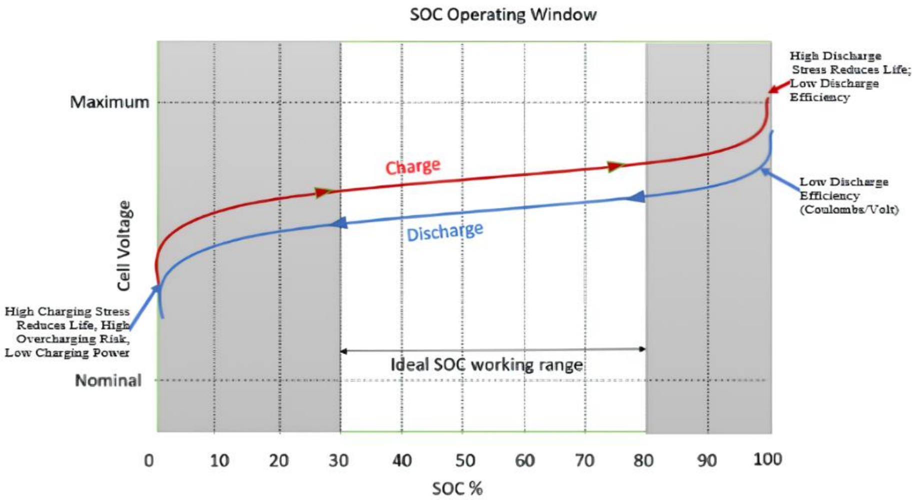

Figure 6. SOC working window

2.6. Fuel cell stack

Regulating the electric energy flow through the electric motor, batteries and electronic load circuit, we can increase the efficiency of the power source (fuel cell and battery). The fuel cell polarization curve is divided into 3 main regions namely activation region, Ohmic region and mass transportation region as shown in Figure 7. The slowness of the chemical reactions that occur at the electrode surfaces is what causes the activation region. Ohmic region is resistive losses due to the fuel cell stack's internal resistance, and mass transport region is the mass transport losses brought on by a shift in the reactant concentration [26]. Idea for effective implementation of the combine strategy is when the SOC of the battery falls below a certain level, fuel cell will start charging the battery as well as drive the load of the vehicle whenever required. The fuel cell will stop charging the battery once the SOC reaches the maximum set limit of the battery. Also, during this process certain conditions are also implemented to keep the SOC within a range as well keeping the fuel consumption of the fuel cell as minimum as possible. The fuel cell efficiency, used in the model, varies between 0.45 and 0.55. Hence the fuel cell should be operated within the Ohmic region, but some time when the load is high, we some time need to use the mass transport region for some extent, but once we see the fuel cell in mass transport region, we need to take the extra power from the battery and then put the fuel cell back to Ohmic region. Figure 8 shows the voltage vs current plot and power vs current plot of the fuel cell used in the current model. Hence, in our case we are operating the fuel cell in the high efficiency region, such that when the power required by the vehicle is high and the battery is below the SOC_{min} or battery is not able to drive the load and needs extra power. So, for the remaining time when the load can be driven by the battery, and by keeping the FC in standby mode.

SOC_{min} and SOC_{max} are used to start the charging or discharging limits of the battery. Control strategy can be described as: i) If SOC is below the SOC_{min}, fuel cell will start operating in the ohmic region and will start producing extra power required for charging of the battery as well as for driving the load of the vehicle; ii) SOC is greater than SOC_{max}, fuel cell will stop working and the vehicle entirely will be driven by the battery as per the dynamic programming optimization method; and iii) When the load on the vehicle is more and the battery alone will not be able to drive the load of the vehicle, the fuel cell will assist the battery to overcome the force by providing the extra needed power.

These rules can be used for making the control strategies using various parameters as a decision-making variable to optimize the control strategies further. Hence the control logic of the controller can be formulated as shown in Table 2.

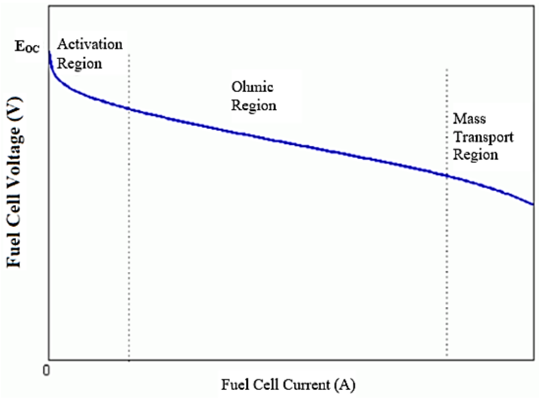

Figure 7. Fuel cell polarization curve

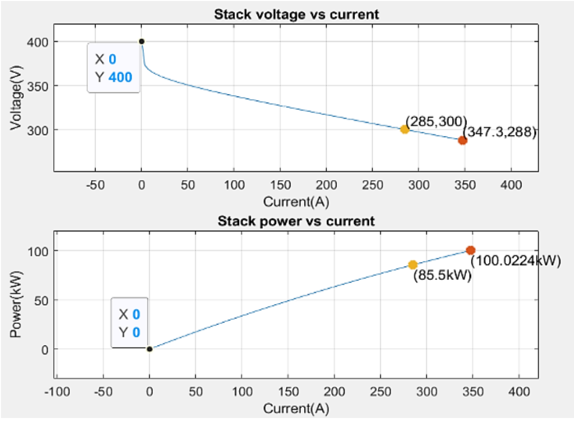

Figure 8. Fuel cell stack voltage vs current plot and stack power vs current plot

Table 2. Control logic for new strategy

Load \ SOC	High ($SOC_{max} \geq 0.9$)	Medium ($SOC_{min} > 0.55$ and $SOC_{max} < 0.9$)	Low ($SOC_{min} \leq 0.55$)
High	Pbat = Discharging; Pfc = ON	Pbat = Discharging; Pfc = ON	Pbat = Discharging; Pfc = ON
Medium	Pbat = Discharging; Pfc = OFF	Pbat = Discharging; Pfc = OFF	Pbat = Charging; Pfc = ON
Small	Pbat = Discharging; Pfc = OFF	Pbat = Discharging; Pfc = OFF	Pbat = Charging; Pfc = ON

2.7. Regions of SOC operation

SOC of a battery as shown in Figure 9 is divided in three main regions as follows: i) Charge depleting region: It is the region where the battery is used for running the vehicle. Meaning the enter power required for the vehicle is being provided by the battery; ii) Charge sustaining region: It is the region where the controller will not allow the SOC to fall below the lower set limit such that when the SOC% is started going down below the lower limit it will start the engine/Fuel cell to recharge the battery; and iii) Charging region: Charging region, it is the part when the load on the vehicle is not much at that point of time the battery will start recharging. Hence the SOC will start increasing to the SOCmax region. Once the charging is done the controller will start using the battery for its operation and stopping the fuel cell for recharging.

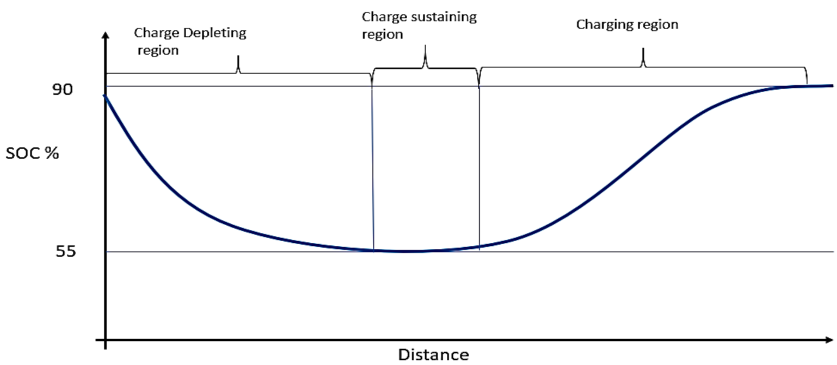

Figure 9. SOC operational regions

2.8. Motor and its characteristics

Motor is used to drive the vehicle using the gear transmission mechanism. Using the speed torque characteristic, the motor is operated in the efficient region where the energy consumption is optimum and performance is high [27]. Motor is running up to 7000 rpm and a torque range of -70 Nm to 40 Nm. From

Figure 10, the motor is running between 2500 rpm to 4400 rpm producing torque 20 Nm to -20 Nm with respect to the urban dynamometer driving schedule (UDDS) drive cycle. Hence the motor is running at high speed for maximum times. Figure 11 shows the speed, torque and efficiency plot of the motor. The efficiency of the motor is high at high speed but the torque is low, but at low speed the efficiency is less and torque produced is high. Hence, we need to keep the motor running in the high-speed region for most of the operation when it is required to deliver the required amount of torque. For low torque operation we need to keep the motor for very small or little amount of time and only when it is required.

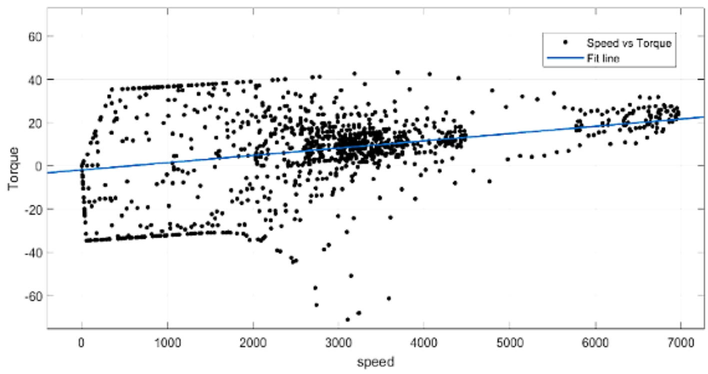

Figure 10. Speed torque characteristic of motor used with UDDS drive cycle

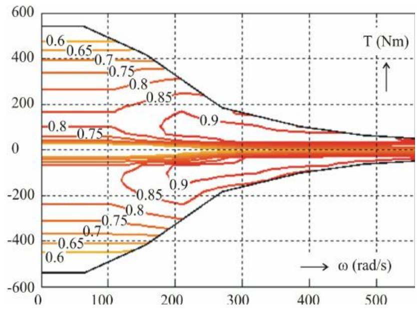

Figure 11. Motor Speed, torque and efficiency plot

2.9. System block diagram

Figure 12 is the block diagram of the FCEV. It consists of three main blocks, energy management block, fuel cell electric subsystem and fuel cell vehicle dynamics. Figure 13 shows the DPC block which is designed to act as a power management block to control power flow through the system. It has six input variables and gives out three outputs which are to be connected to the battery and fuel cell and motor for generating torque to drive the vehicle. The controller will take input from various systems represented in the vehicle model, process it, simulate the output in accordance with the dynamic controlling algorithm, and then produce the output with the necessary torque for the motor and fuel cell current for the device to function.

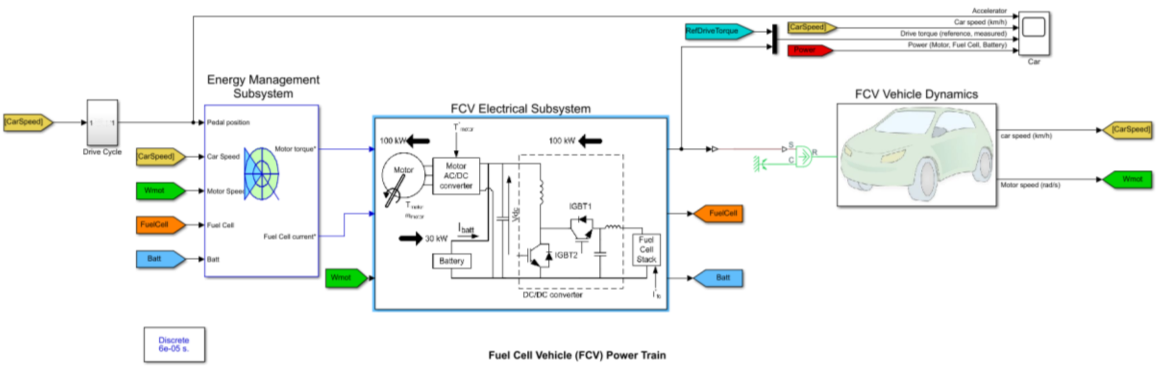

Figure 12. FCEV block diagram

2.10. Power demand

FCEV have two sources (FC and battery) for meeting the power demand of the vehicle. Working of both these sources in the efficient area is the need for efficient use of power thus reducing fuel consumption. By calculating the forces from in (2) the power required by the vehicle can be ascertained. Hence to overcome the demand power of the vehicle, the battery and FC should deliver that much power for the vehicle to move at a desired driving cycle speed as shown in Figure 14.

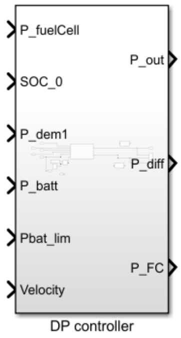

Figure 13. DP controller block

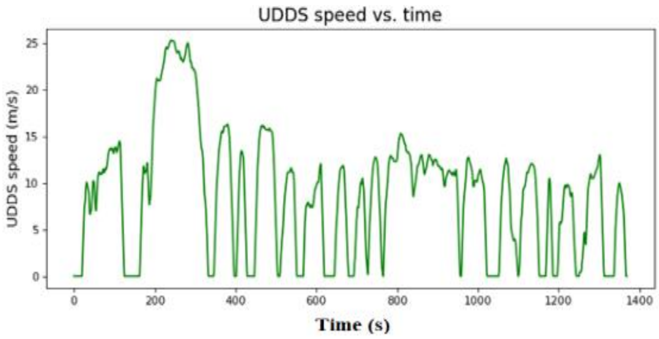

Figure 14. UDDS cycle

2.11. Dynamic programming

Goal programming optimization technique algorithms are used to optimize the problem. In order to find the best control sequences in the time domain and lower the overall cost of the control process, DP is a technique used to make control decisions step-by-step. The objective of this work is to reduce the FCEV's fuel consumption using the DP while following a specific driving cycle. For FCEV, discrete time system is described as (6):

$$X_{t+1} = f(X_t, u_t) \tag{6}$$

Hence the equations for system are designed as (7) and (8).

$$SOC(t+1) = f\big(SOC(t), I_{bat}(t)\big) \tag{7}$$

$$SOC(t+1) = f\big(SOC(t), I_{bat}(t)\big) \tag{8}$$

$$SOC(t+1) = SOC(t) - \alpha * \frac{I_{bat}(t)}{Q_{max}}$$

Where, $I_{bat}(t)$ represents the battery's current flow, Q_{max} is the battery's capacity for charge; the charge losses are taken into account using α correction factor; $SOC(t)$ is the state variable SOC of the battery at time t, $SOC(t+1)$ is SOC at time t+1. Fuel consumption depends on $I_{bat}(t)$ and is a control variable of the system.

DP finds out the optimal decisions $SOC(t)$ and $I_{bat}(t)$ at each step, as a control variable and helps minimize the fuel consumption for the overall driving cycle. Using forward DP to solve cost function minimization problems. Recursive is (9):

$$J^*\big(SOC(t+1)\big) = \min[F\big(SOC(t), I_{bat}(t)\big) + J^*\big(SOC(t)\big)], \text{ for } 1 \le t \le N-1, \text{ and } J^*\big(SOC(0)\big) = 0, \tag{9}$$

Where, F is the fuel consumption for current state or instantaneous cost. $SOC(0)$ is the initial state, or the initial SOC value. The $J^*\big(SOC(t)\big)$ is the minimal fuel consumption from the initial state to state $SOC(t)$ at t^{th} step. After the optimization process, the optimal state sequences and the control sequences are determined. The problem is formally defined as finding the control law u_k, k = 1N that minimizes the cost [28].

$$\sum_k^{N-1} m_f(u_k, k) \tag{10}$$

Subjected to constraints:

$0 \le P_{FC}(t) \le P_{FCmax} \forall$ t = 0, 1, …, N-1
$P_{Motor\_min} \le P_{Motor}(t) \le P_{Motor\_max} \forall$ t = 0, 1, …, N-1
$P_{batt\_min} \le P_{batt}(t) \le P_{batt\_max} \forall$ t = 0, 1, …, N-1
$SOC_{min} \le SOC(t) \le SOC_{max} \forall$ t = 0, 1, …, N-1

where, P_{FC} is the FC power, P_{Motor} is the power required by the motor to operate at particular speed, pbatt battery power, SOC is the state of charge of the battery.

Figure 15 shows how the optimum paths are estimated and then chosen according to the control variable to draw the optimum path till the SOC_{final} is reached. The controller will calculate the current SOC, speed of the vehicle, torque required and current battery power to estimate the optimal power that must be provided by the battery such that all the constraints shown in (9) and (10) are satisfied.

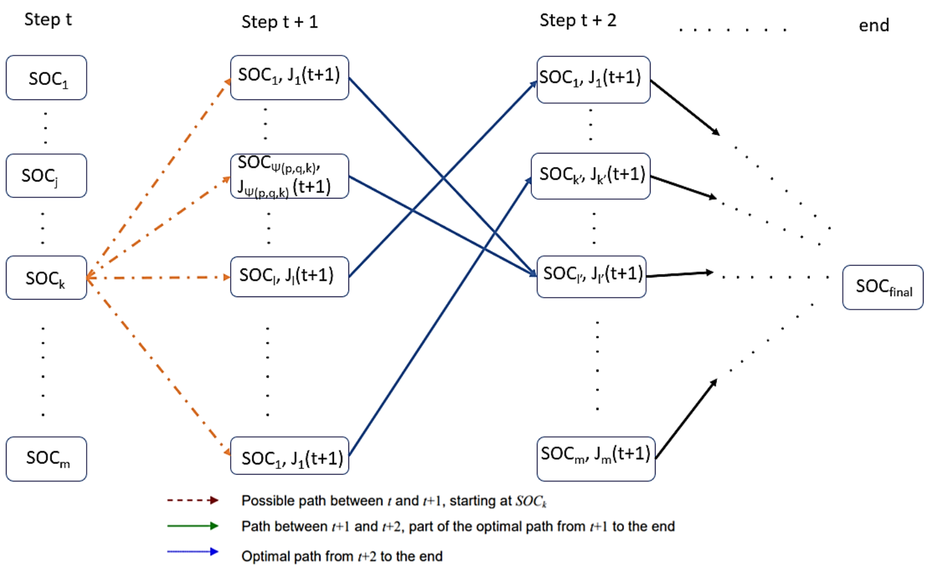

Figure 15. Global optimization with backward recursion method

3. RESULTS AND DISCUSSION

Figure 16 and Figure 17 shows the output of the rule-based and dynamic programming model respectively. SOC is important parameter which is used for control strategy development and its variation with respect to time is shown below. Power required by the vehicle is provide by the Fuel cell and the battery which is being controlled by the controller in optimum way. Controller manages the current required for the flow control of hydrogen.

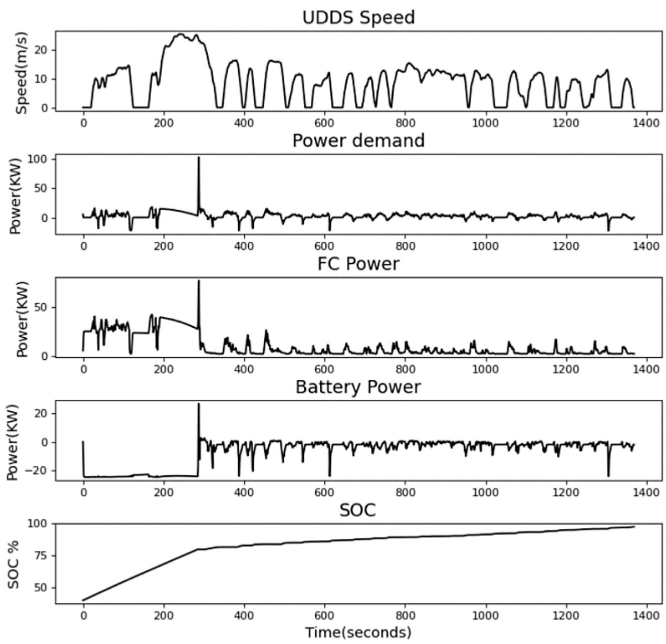

Figure 16. Power output for UDDS cycle with rule-based model

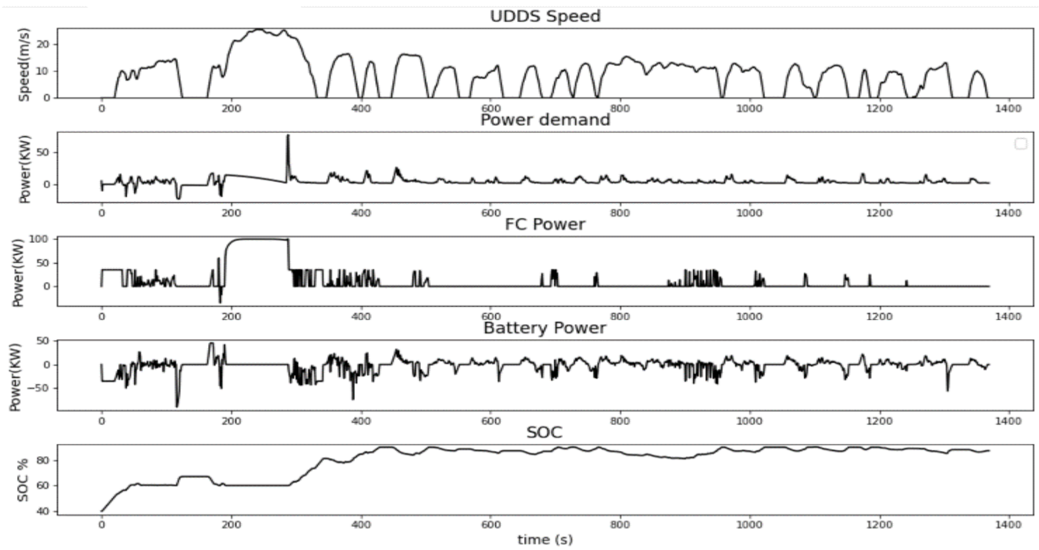

Figure 17. Power output for UDDS cycle with DP model

Figure 18 shows comparative result of the flow rate current required by the hydrogen flow rate. It is observed that the current required in DP model is less as compared to that in rule-based model. We are able to reduce the current required for controlling the hydrogen tank by 22.36% (shown in Figure 19) hence the consumption of the fuel is reduced without affecting the vehicle performance. The SOC path followed by the DP shows that the battery is charged to SOC_{max}. Figure 19 shows the comparison of fuel consumption between rule-based and dynamic models and is observed that the fuel consumption in DP model is less compared to rule-based model.

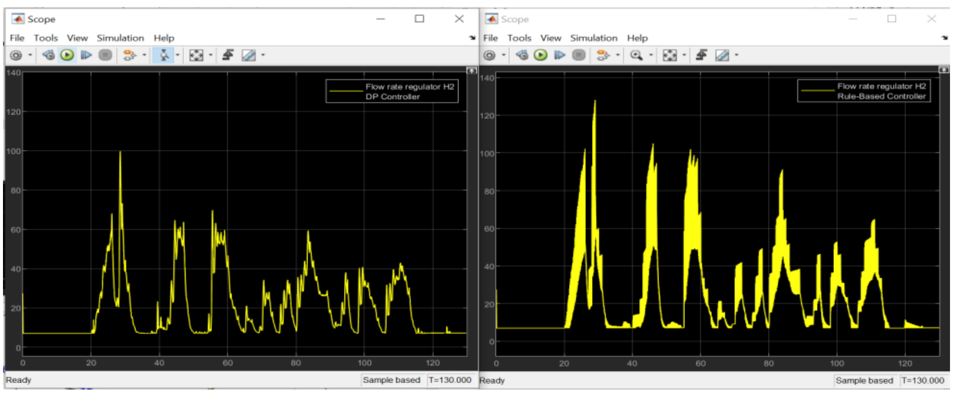

Figure 18. Sample data current required for between hydrogen tank flow rate regulator

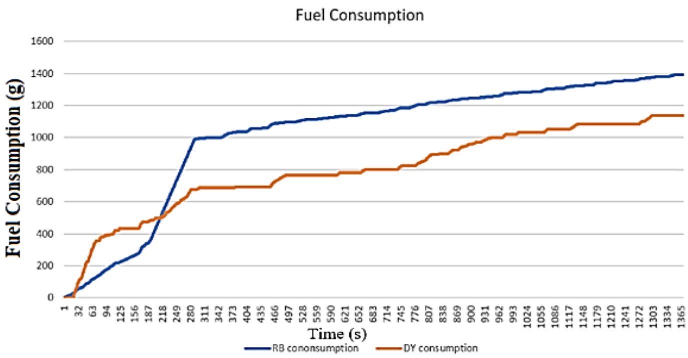

Figure 19. Fuel consumption comparison rule-based and dynamic programming model

4. CONCLUSIONS

By enabling the motor to continue operating in its high-efficiency region, DP boosts efficiency of the motor. In order to meet the target of least amount of fuel usage/consumption, the DP algorithm offers the best solution to the problem of managing the energy in EVs. It also serves as a standard to evaluate the lowest possible fuel economy. DP saves more fuel than the Rule-based controller. DP allows for a quick solution to maximize fuel efficiency by applying guidelines such as operating the motor in the ideal region where the motor's efficiency is high and maintaining the battery's SOC in a region where performance and life span are at their peak.

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