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Improved operational state control strategy for performance enhancement of fuel cell/ battery/supercapacitor hybrid electric vehicle

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Abstract— ***This paper presents an improvement in the operational state control strategy (OSCS) for the fuel cell/battery/supercapacitor hybrid electric vehicle. The main objective of this paper is to present the detailed comparative study between the OSCS and the improved OSCS for the performance enhancement of hybrid energy sources (HESs) mainly in terms of stress on the fuel cell, battery state of charge (SOC), and the dynamics of the individual sources. The low pass filter is added in the OSCS for the desired improvement. The simulation is carried out in MATLAB/Simulink environment for the high dynamic arbitrary and standard ECE-15 driving cycles. The results indicate that the improved OSCS ensures the fuel cell to operate at nearly constant power with reduced stress, improvement in the SOC level of battery and better dynamics of the individual energy sources.***

Keywords— Operational state control strategy (OSCS), hybrid energy sources (HESs), battery state of charge (SOC), driving cycle, electric vehicle.

INTRODUCTION

The ever increasing population and vehicular transportation has led to the increase in the depletion of fossil fuels, rigorous emissions of the harmful gases, therefore resulting in increasing amount of global warming. Subsequently, there is urgent need to explore alternative energy sources for the propulsion purposes [1]. From the studies it is known that the electric vehicles are the most effective source in reducing the greenhouse gas emission. Thus they are vital for reducing huge amount carbonisation in the transportation sector. In this regard both automakers and government are paying more and more attention on the development of electric, hybrid and fuel cell vehicles [2, 3]. The fuel cell especially the Proton Exchange Membrane Fuel Cell (PEMFC) is the most appropriate alternative energy source for the vehicular transportation because of its high energy density, low operating temperature, quit operation and ability to rapidly adjust the changes in the power demand [4]. However, fuel cell cannot be operated alone especially during high peak demands in the vehicle. It is so because the fuel cell has poor dynamics, low power density. Thus the energy storage devices such as battery and supercapacitor are used along with the fuel cell to power the vehicle [5]. The battery has the advantage of high energy density (less than fuel cell) but poor power density while the supercapacitor has high power density but poor energy density. Thus both the devices are complementary to each other [5, 6]. Hence battery is used to power the load when the transients are present for longer duration of time. The supercapacitor is used when the large peak power in short duration is required. In addition to this both battery and supercapacitor absorbs the power during deceleration (or braking) [4,7]. Thus this hybrid combination requires the suitable energy management strategy to share the load demand among the energy sources on-board the vehicle [1,8-10].

The operational state control strategy (OSCS) used in this paper has same control operation as [11, 12, 13] with modified operating states. However this existing strategy indicates that the fuel cell delivers the transient load due to which the stress on the fuel cell increases and also causes more battery usage. Moreover, the dynamics of the fuel cell, battery, supercapacitor are not respected with full utilization of their individual capabilities. To overcome these drawbacks the low pass filter is added to the OSCS. The concept of the frequency splitting has been studied by various authors [8, 14-17]. However this paper focuses on the comparative analysis of OSCS and improved OSCS for performance enhancement of hybrid energy sources (HESs) namely fuel cell, battery, supercapacitor. This low pass filter acts as frequency splitter which divides the load demand in such a way that the fuel cell provides almost constant power with reduced stress on the fuel cell, minimum use of battery and also the dynamics of the fuel cell, battery and supercapacitor is respected in better way. Thus the performance of the HESs is improved. The comparative analysis is carried out for the high dynamic arbitrary and the standard ECE-15 driving cycles in the MATLAB/Simulink environment.

DESCRIPTION AND MODELING OF HYBRID FUEL CELL/BATTERY/SUPERCAPACITOR POWER SYSTEM

A. System Description

Fig.1 shows the hybrid system that consists of fuel cell, battery and supercapacitor for an electric vehicle. The fuel cell is connected through the boost type dc-dc converter to raise the fuel cell voltage equal to the dc bus. This converter is unidirectional in nature that means energy flows only in one direction. The battery is connected through the buck-boost type dc-dc converter and the supercapacitor is connected directly to the dc bus. The buck-boost type dc-dc converter is bidirectional (flow of energy in both directions) in nature and thus allows the battery to discharge during the high load demands and charge during the regenerative braking.

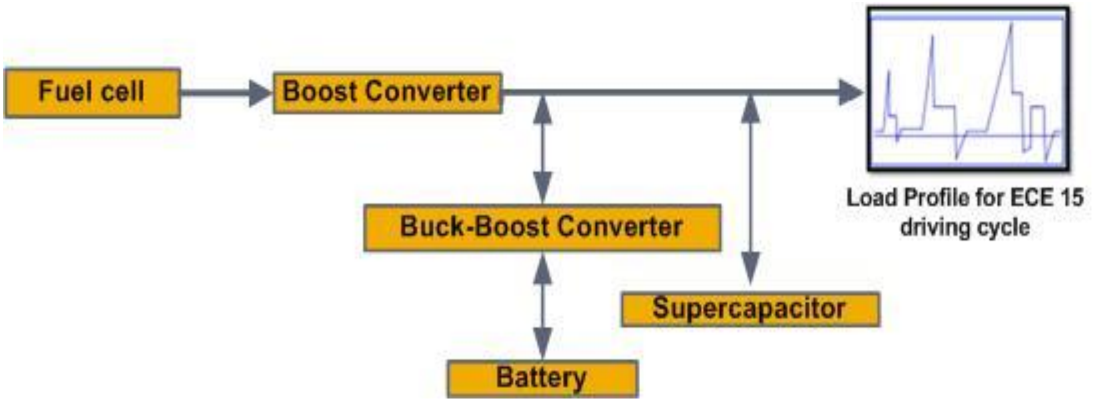

Fig. 1 The hybrid fuel cell/ battery/supercapacitor configuration.

All these three sources supply power to the ac load (motor) through the inverter. The amount of power shared by each source is determined by the reference signal send to the converters which are generated by energy management strategy. Hence the load demand supplied is the summation fuel cell, battery and supercapacitor power. The system under consideration consists of 12.5KW, 30-60V of fuel cell having 65 cells in the series, 48V, 48Ah Li ion battery and 291.6V, 12.5F supercapacitor (having six 48.6V in series). The following section describes the modeling of fuel cell, battery and supercapacitor.

B. Modeling of Fuel Cell

A detailed generic model of fuel cell stack is available in MATLAB/Simulink environment [18, 19].This model is based on the certain assumptions and some limitations [18]. The open circuit of fuel cell (E_{OC}) is given by:

$$E_{OC} = N \times E_{Nernst} \tag{1}$$

where N is the number of cells in the stack, E_{Nernst} is internal voltage of fuel cell or Nernst potential which is expressed as:

$$E_{Nernst} = E_0 + \frac{RT}{nF} \ln\left(\frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}}\right) \tag{2}$$

where E_0 is the reference potential, P_{H_2}, P_{O_2} and P_{H_2O} are the partial pressures of hydrogen, oxygen and steam, respectively. The R denotes the gas constant, T is operating temperature (kelvin) and n is number of participating electrons, F is faraday constant.

The fuel cell output voltage (V_{FC}) is the function of open circuit voltage (E_{OC}), activation voltage $(V_{act(cell)})$, ohmic voltage drop $(V_{ohm(cell)})$ and concentration voltage $(V_{conc(cell)})$ which is expressed as:

$$V_{FC} = N \times V_{cell} == N(E_{OC(cell)} - V_{act(cell)} - V_{ohm(cell)} - V_{conc(cell)}) \tag{3}$$

where V_{cell} is the individual cell voltage, $V_{act} = NA\ln\left(\frac{i_{fc}}{i_0}\right)$, $V_{ohm} = i_{fc} r_{fcin}$, A is the tafel slope, i_{fc} is the output current, i_0 is the exchange current (A), r_{fcin} is the internal resistance. However in this study the concentration voltage is neglected as it affects the system efficiency. Hence the fuel cell output voltage is expressed as:

$$V_{FC} = N(E_{OC} - NA\ln\left(\tfrac{i_{fc}}{i_0}\right) - i_{fc} r_{fcin}) \tag{4}$$

C. Modeling of Battery

The battery is modeled in MATLAB/Simulink which describes the dynamic characteristics of Li-ion battery [19, 20].

The discharging equation (i*>0) is given by:

$$V_{Batt} = E_0 - K \cdot \left(Q/_{Q-it} \right) \cdot i^* - K \cdot \left(Q/_{Q-it} \right) \cdot it + A \cdot \exp\left(-B \cdot it\right) \tag{5}$$

Similarly battery charging Equation (i*<0) is expressed as:

$$V_{Batt} = E_0 - K \cdot \left(Q/_{it+0.1Q} \right) \cdot i^* - K \cdot \left(Q/_{Q-it} \right) \cdot it + A \cdot \exp\left(-B \cdot it\right) \tag{6}$$

where V_{Batt} is nonlinear voltage (volts), E_0 is constant voltage (volts), i^* is filtered battery current (ampere), i is the battery current (amperes), it is available battery charge (ampere-hours), A is the exponential region amplitude (volts), B is the exponential region time constant inverse (Ah^{-1}), $K \cdot \left(Q/_{Q-it} \right) \cdot i^*$ is the polarization voltage, $K \cdot \left(Q/_{Q-it} \right)$ is the polarization resistance (in ohms) and K is the polarization constant (in $A.h^{-1}$).

D. Modeling of Supercapacitor

The generic model of supercapacitor is studied using MATLAB/Simulink Software. This model is based on the Stern model which combines both the Helmholtz and Gouy-Chapman model [15]. The voltage across supercapacitor is given by:

$$V_{SC} = \frac{N_s Q_T d}{N_p N_e \varepsilon \varepsilon_0 A_i} + \frac{2 N_e N_s RT}{F} \sinh^{-1}\left(\frac{Q_T}{N_e^2 A_i \sqrt{8RT\varepsilon\varepsilon_0 c}} \right) \tag{7}$$

where N_s is the number of cells in series, N_p is the number of cells in parallel, Q_T is the total electric charge, N_e is the number of electrode layers, ε and ε_0 are the permittivity values (in farads per meter) of the electrolyte material and free space, A_i is the interfacial area between electrodes and electrolyte (in square meters), d is the Helmholtz layer length (or molecular radius) (in meters), R is the ideal gas constant, F is the faraday constant, T is the operating temperature, c is the molar concentration (in $mol \cdot m^{-3}$).

ENERGY MANAGEMENT STRATEGIES

Operational State Control Strategy

Operational State Control Strategy (OSCS) is the type of deterministic rule based strategy whose main goal is to determine various operating states of the system [13]. These states are user defined and the accuracy of this depends on the knowledge of the designer. In this type of control strategy, the load power (P_L) and the battery SOC are used as the input variables to determine the operating levels and fuel cell reference power (P_{fcref}). The strategy mentioned below is the modified form of those mentioned in [11, 12]. There are three operating levels based on the battery SOC *i*.e. High, Normal and Low and the eleven operating states based on both the battery SOC and the load power (P_L) (as shown in Table 1). This type of control is easy to implement and allows real time operation of the system.

TABLE I
OPERATING STATES OF OPERATIONAL STATE CONTROL STRATEGY

Battery SOC levels	State	Load power	Fuel cell reference power (P_{fcref})
High (*SOC > 90%*)	1	$P_L < P_{fcmin}$	P_{fcmin}
	2	$P_{fcmin} \leq P_L < P_{fcmax}$	P_L
	3	$P_L \geq P_{fcmax}$	P_{fcmax}
Normal (*60%≤SOC≤ 85%*)	4	$P_L < P_{fcmin}$	P_{fcmin}
	5	$P_{fcmin} \leq P_L < P_{fcopt}$	P_{fcopt}
	6	$P_{fcopt} \leq P_L < P_{fcmax}$	P_L
	7	$P_L \geq P_{fcmax}$	P_{fcmax}
Low (*SOC ≤ 60%*)	8	$P_L < P_{fcmin}$	$P_L + P_{battchar}$
	9	$P_{fcmin} \leq P_L < P_{fcopt}$	$max(P_L + P_{battchar}, P_{fcopt})$
	10	$P_{fcopt} \leq P_L < P_{fcmax}$	$P_L + P_{battchar}$
	11	$P_L \geq P_{fcmax}$	P_{fcmax}

The two important features of operational state control strategy (OSCS) are operating limits of the components of the hybrid system and chattering phenomenon. The chattering phenomenon is avoided through the hysteresis control [5]. The operational limits of the components mainly consists of minimum, optimum, and maximum fuel cell power values (P_{fcmin}, P_{fcopt}, P_{fcmax}), the maximum battery charging power and maximum battery power values ($P_{battchar}$, $P_{battmax}$) and the minimum and maximum battery SOC (SOC_{min}, SOC_{max}). The limits are set on the battery operation so that it can provide the transient power for the longer duration maintaining its SOC level and can absorb the braking power. Similarly the fuel cell power is limited to avoid the fluctuations and to maintain the system efficiency [12].

The existing control strategy (as shown in Fig.2) provides the fuel cell reference power which is divided by the fuel cell voltage to determine the fuel cell reference current. Then the maximum and minimum limit is set on the fuel cell reference current that the fuel cell can generate. The difference between the required load power and fuel cell power is used to charge/discharge the battery and supercapacitor. The priority of charging and discharging is given to the supercapacitor. The voltage of supercapacitor (dc-bus voltage) is controlled through the battery converters by voltage regulator.

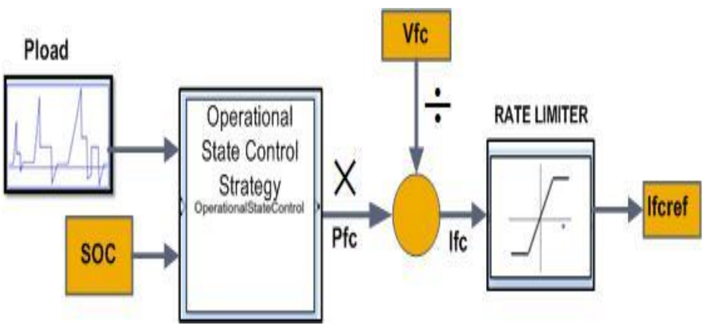

Fig. 2 Operational state control strategy.

Fig. 2 shows that since the load demand is directly used as an input to the above mentioned operational state control strategy, so the fuel cell is subjected to the transient load due to which the stress on the fuel cell increases. The battery usage is also high in this strategy and thus affects the battery useful lifespan. Moreover the dynamics of the fuel cell, battery and supercapacitor is also not fully respected.

Hence the frequency spitting strategy is used along with the operational state control strategy to rectify the above mentioned drawbacks.

Improved Operational State Control Strategy

The frequency splitting is used to separate the load demand into low frequency component and high frequency component. The low frequency component is applied to the fuel cell and the high frequency component is applied to the battery and supercapacitor. Thus fuel cell operates at nearly constant power. In this work, low pass filter is used for the frequency splitting as shown in Fig. 3. This reduces the stress on the fuel cell and thus improves the lifetime of fuel cell; ensure minimum use of battery, and respect the dynamics of the energy sources. However the frequency splitting cannot be used as an independent control strategy because it can reduce the stress on the fuel cell but cannot limit the fuel cell power [21].

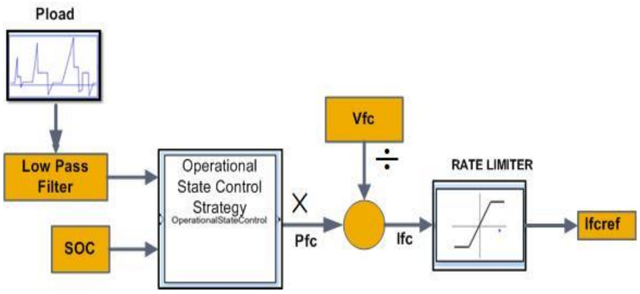

Fig. 3 Improved operational state control strategy.

Thus the proposed strategy is the combination of both the frequency splitting and OSCS as shown in Fig. 3. This strategy combines the merits of both the strategy and compensates each other's drawback**.**

RESULTS

The comparison between the existing and the proposed energy management strategy is evaluated by the simulation in MATLAB/Simulink. To ensure the robustness of the proposed strategy, the analysis is done for both high dynamic arbitrary and standard ECE-15 driving cycles. Both the strategies are compared in terms of fuel cell power, battery SOC and dynamics of the energy sources. Hence the results are presented into two sub-sections; Section A present analysis for high dynamic arbitrary driving cycle and Section B for standard ECE-15 driving cycle.

A. Section A:Result Analysis for high dynamic arbitrary driving cycle

Fig. 4 shows the power profile of the high dynamic arbitrary driving cycle. Thus both the existing and proposed energy management strategy is verified for the arbitrary driving cycle in MATLAB/Simulink environment for the 350 seconds duration.

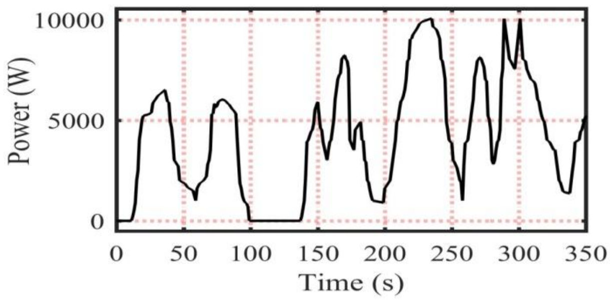

Fig. 4 Load profile for high dynamic arbitrary driving cycle.

Fig. 5 shows that the improved operational state control strategy (OSCS) allows the fuel cell to operate at reduced power as compared to the existing OSCS, since the transient load is now handled by the battery and supercapacitor. Thus the stress on the fuel cell is reduced and hence the lifetime of the fuel cell is improved.

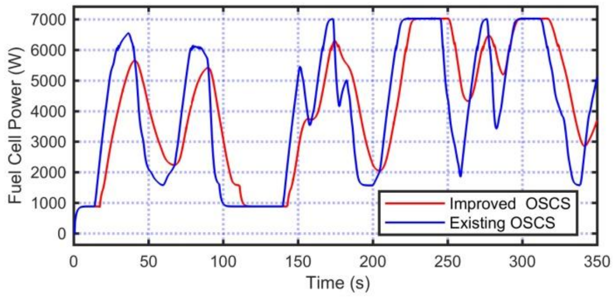

Fig. 5 Comparison of fuel cell power between two strategies for the high dynamic arbitrary driving cycle.

The SOC of the battery is improved in the proposed strategy as compared to the existing strategy (as shown in Fig. 6). This is so because the improved OSCS allows full utilization of capacity of energy sources due to which the high frequency component of load demand is shared by the supercapacitor. Hence use of the battery is less which enhances its lifetime.

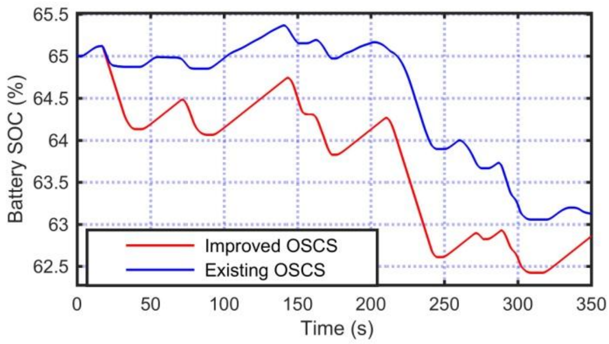

Fig. 6 Comparison of battery SOC between two strategies for the high dynamic arbitrary driving cycle.

Fig. 7 and Fig. 8 show the sharing of load power between the fuel cell, battery and supercapacitor for existing and proposed OSCS respectively. The proposed strategy respects the dynamics of the energy sources in better way compared to existing control strategy i.e. the fuel cell operates at nearly constant power, battery having high energy density but poor power density operates when the transients are present for the longer duration and the supercapacitor operates when the large transients for short duration is present because of its high power density. However the existing energy management strategy also follows the dynamics of the energy sources but with lesser degree, which ultimately reduce the overall efficiency of the system.

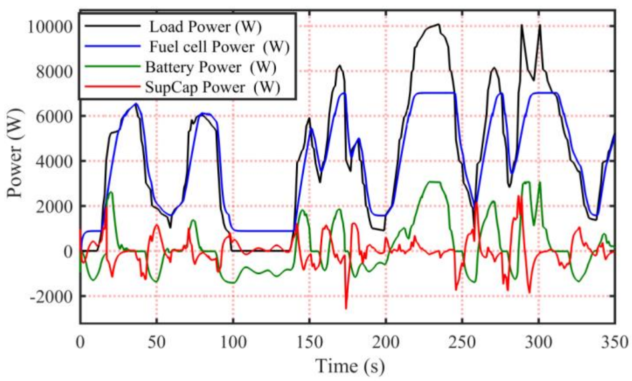

Fig. 7 Load power sharing for the existing OSCS (dynamics is not respected).

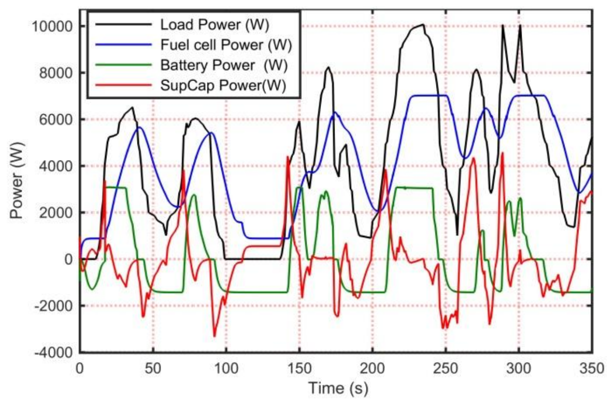

Fig. 8 Load Power sharing for the improved OSCS (dynamics is respected).

B. Section A:Result Analysis using ECE-15 driving cycle

ECE-15 is the European driving cycles which indicates the urban driving. This driving cycle covers the distance of 995 meters for 195 seconds with an average speed of 18.4 km/h. The speed profile of ECE 15 is shown in Fig. 9. The simulation results for the fuel cell power, battery SOC and the dynamics of the energy sources is obtained and compared for both the existing and improved OSCS.

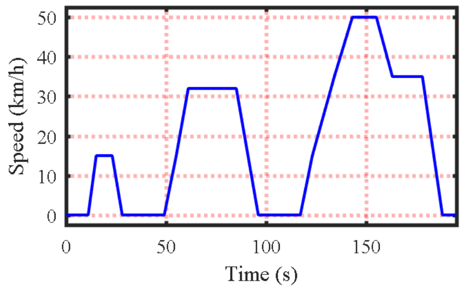

Fig. 9 Speed profile ECE 15 driving cycle.

Fig. 10 illustrates the reduced and more stable fuel cell power is obtained from the improved OSCS in comparison to existing one. Thus reduced stress on the fuel cell. In addition to this there is significant improvement in the SOC of the battery as shown in Fig. 11. Thus lifetime of the battery is improved. The Fig. 12 and Fig. 13 show the load power sharing between fuel cell, battery and supercapacitor for the existing and improved OSCS which indicate that the dynamics of fuel cell, battery, supercapacitor is followed in better way in improved OSCS.

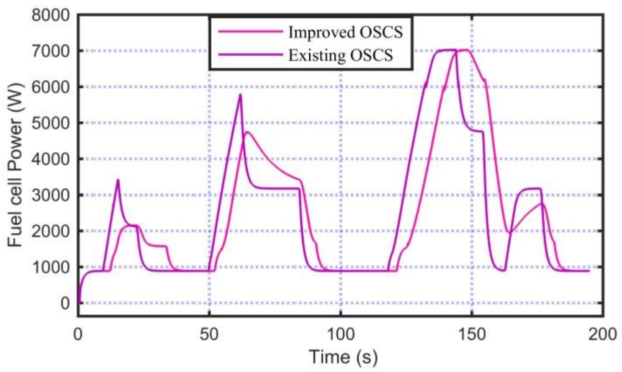

Fig. 10: Comparative results for fuel cell power between two strategies along the ECE-15 driving cycle

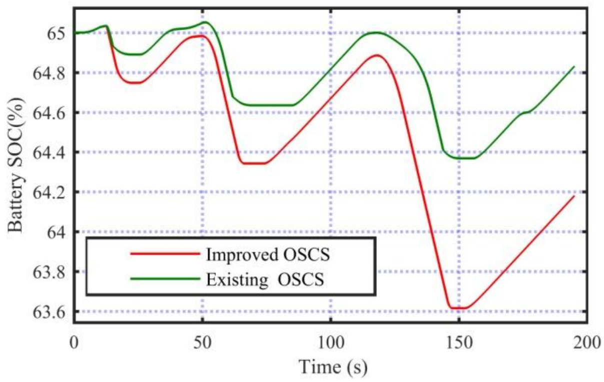

Fig. 11: Comparison of battery SOC between two strategies for the ECE-15 driving cycle.

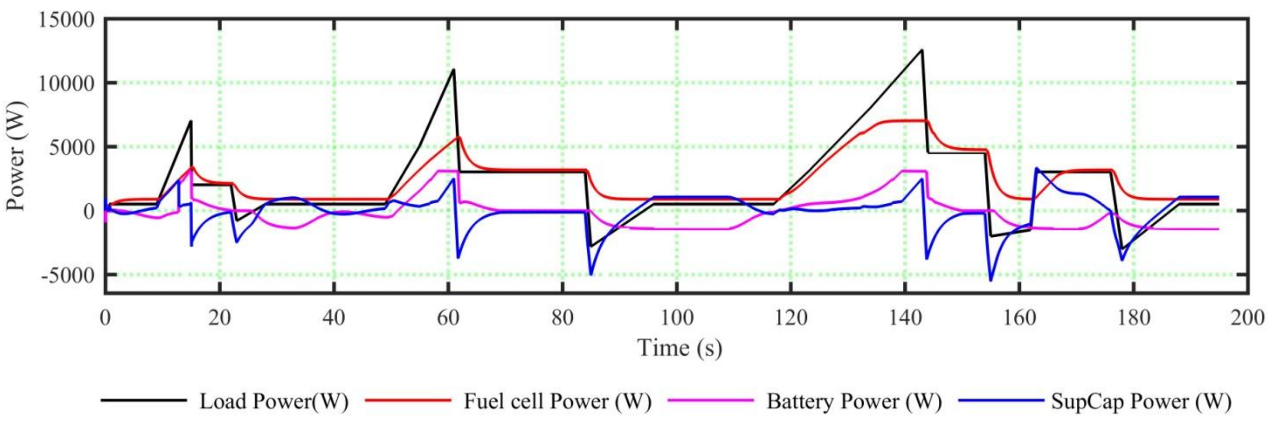

Fig. 12 Load power sharing for the existing OSCS (dynamics is not respected)

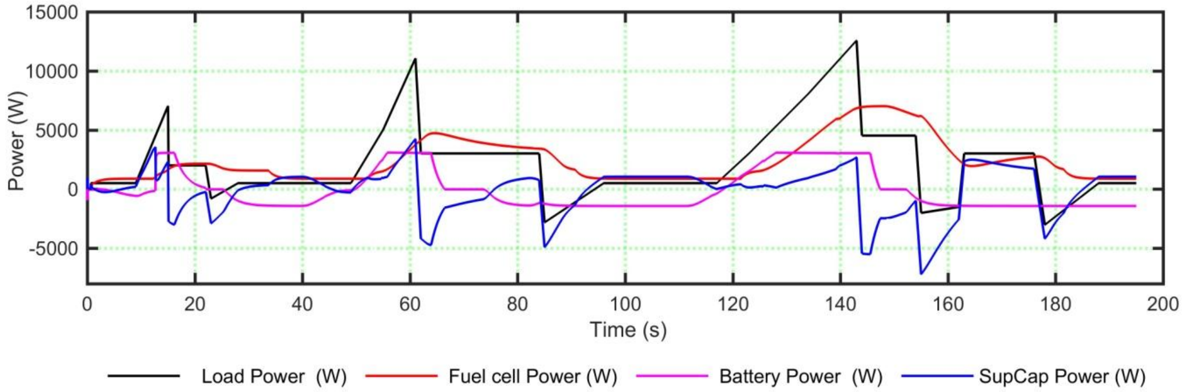

Fig. 13 Load power sharing for the improved OSCS (dynamics is respected).

CONCLUSIONS

In this paper, the detailed comparative analysis of existing and improved operational state strategy (OSCS) is carried out for the high dynamic arbitrary and the standard ECE-15 driving cycles using MATLAB/Simulink Software. Even though the existing operational state strategy has certain restriction on the fuel power, battery power and its SOC so that both sources operate with maximum capacity yet the application of transient load directly to the fuel cell results in the increased stress on the fuel cell. Moreover it does not respect the dynamics of the energy sources in appropriate way and consume more battery power which affects the battery life cycle.

The low pass filter added in the improved operational state control strategy acts as a frequency splitter which splits the load power into low frequency component and high frequency component. Thus fuel cell is subjected to the low frequency component and the battery and supercapacitor handles the high frequency component of the load demand. Hence, the fuel cell operates at almost constant power and thus the stress on the fuel cell due to the transient load is reduced. Eventually, the fuel cell lifetime is improved. The lesser use of battery causes improved SOC level which in turn also improves the battery cycle life. Lastly, the load sharing by the fuel cell, battery, supercapacitor is studied for both the driving cycles. This indicates that the improved operational state strategy respects the dynamics of the HESs i.e. fuel cell, battery and supercapacitor.

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