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Research Article

Power Flow Management for the Fuel Cell Hybrid Electrical Vehicle Based on State Logic Controller Algorithm implemented in FPGA Environment

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Abstract

A power flow management based on State Logic Control (SLC) for the hydrogen fuel cell hybrid electric vehicle (FCEV) is proposed in this paper. To improve the dynamic response of the fuel cell generator and reduce the fuel consumption the developed hybrid system has been integrated with the battery and ultracapacitor energy storage resources. SLC has been designed to satisfy the performance of vehicle in terms of fuel consumption, battery state-of-charge (SOC), fuel cell output voltage fluctuations, FC stack efficiency, overall system efficiency, and DC link voltage regulation. Cascade controller has been utilized to control the power conditioning unit of the FCEV, regulate the DC link voltage and manage the battery and ultracapacitor SOC. The proposed energy management system in combination with the converters' controller is capable of tracking the preferred fuel cell power and retains the DC link voltage nearby its nominal level. This can be done by providing propulsion power and recovering braking energy. The model of vehicle dynamic load is developed by the ADVISOR software, while the MATLAB & Simulink are used to prove the efficacy of the proposed power management system. Processor-In-the-Loop (PIL) approach has been used to validate the source code algorithm of the developed energy management scheme. To do that, Xilinx ISE 14.6 is used as a project aid to interface with FPGA card for synthesis and implementation the validation approach.

Keywords: *SLC, FPGA Environment etc.*

1. Introduction

The internal consumption engines (ICEs) which uses the gasoline fuel as the primary input source are used in most of the transportation services to drive the vehicle. But the ICE has many disadvantages such as low energy efficiency, environment and human life problems which led to global warming and air pollution due to the high emission of CO_2 gases (A. Panday *et al*, 2016).

In contrast, the Fuel Cell (FC) vehicles have the potential to address all the problems surrounding the ICE vehicle, while offering the consumer no significant sacrifice in performance or driving range. The FC vehicles, uses hydrogen as a fuel while the exhaust is water only so it does not cause any pollution. Regrettably, the FC generator has some disadvantages such as the slow dynamic response, high hydrogen cost and it cannot accept the regenerative braking power for the vehicle. To overcome these drawbacks the FC generator should be hybridized with an energy storage resources such as the ultracapacitors and the batteries. The ultracapacitor (UC) has a very fast dynamic response to respond to the sudden load changes of the vehicle. To reduce the high hydrogen cost the Battery (BAT) can be used to assist the FC to supply the load demand. Hence, the FC will operate with a high efficiency, which consequently lead to reducing the size of the FC stack, thus the FC cost will also reduce. Also, the UC and the BAT can successfully overcome the problem of the regenerative power, produced by braking state. Thus, in the case of sudden braking the power will return back to charge the UC and when it fills, the remaining power will be stored in the BAT (O. Ahmed, 2011; L. Wang, 2009).

In seek of high efficiency FC operation, the FC should be provided only the steady-state load power. Hence, the output power of the FC should be controlled. In addition to that, the power flow between the BAT, UC, and the load its require to manage optimally during the charging and discharging periods. Accordingly, Energy Management System (EMS) is required. To actively do that, power electronics converters are required to interface the power sources with the load in combination to the central controller system for each converter. The EMS with the controllers should not manage only the power flow between the FCEV sources but it must control the SOC

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for the BAT and UC and maintain the DC link voltage (O. Ahmed, 2011).

Several papers have covered different EMS schemes to improve the performance of the FCEV. To manage the power flow between FC, BAT and UC and to meet the required power of the load in the hybrid EV, a fuzzy logic controller is presented in (M. C. Kisacikoglu *et al*, 2007). In (J. Wong *et al*, 2011), a six control loops are applied to regulate the DC bus voltage, control the current flow and maintain the SOC of the energy storage resources within the acceptable limits. For optimal load sharing between the FC, BAT, and the load, ant-colony is proposed in (A. P. Pourhashemi *et al*, 2013). A genetic-fuzzy control strategy is employed in (M. Bostanian *et al*, 2013) to tune the rules of the fuzzy logic controller and manage the power flow between the IC engine and the BAT. The main purpose of this scheme is to reduce the CO_2 emission and the fuel cost. Other EMS schemes used PSO algorithm to minimize total energy cost from vehicle utilization. An example of this kind of topology is presented in (Z. Chen *et al*, 2015), where a rule-based strategy containing three operation states is achieved, and then the PSO algorithm is implemented on four threshold values in the EMS strategy.

In this work the FC power is controlled by the SLC method and the BAT charging/discharging is controlled by using a PI controller. This is lead to reduce the complexity of the EMS scheme than the other topologies and can be implemented easily. The PIL approach has been used to validate the source code algorithm of the developed EMS on Spartan-3A 3400A FPGA, where the calculated readings of the power conditioning unit and power sources are employed as inputs to the embedded algorithm, while the outputs of the EMS algorithm executed on the actual processor are feedback into the simulation model in Matlab/Simulink environment.

Proposed Hybrid Management System Description and Methodology

The main objective of the developed EMS in this work is to increase the BAT lifecycles through increasing the UC charge/discharge cycles and increasing efficiency. Also, EMS has been designed so that provides the load power demand with a less hydrogen consumption. Fig.1 shows the developed hybrid plug-in FCEV configuration in combination with controller and EMS that based on the Semi-active connection topology.

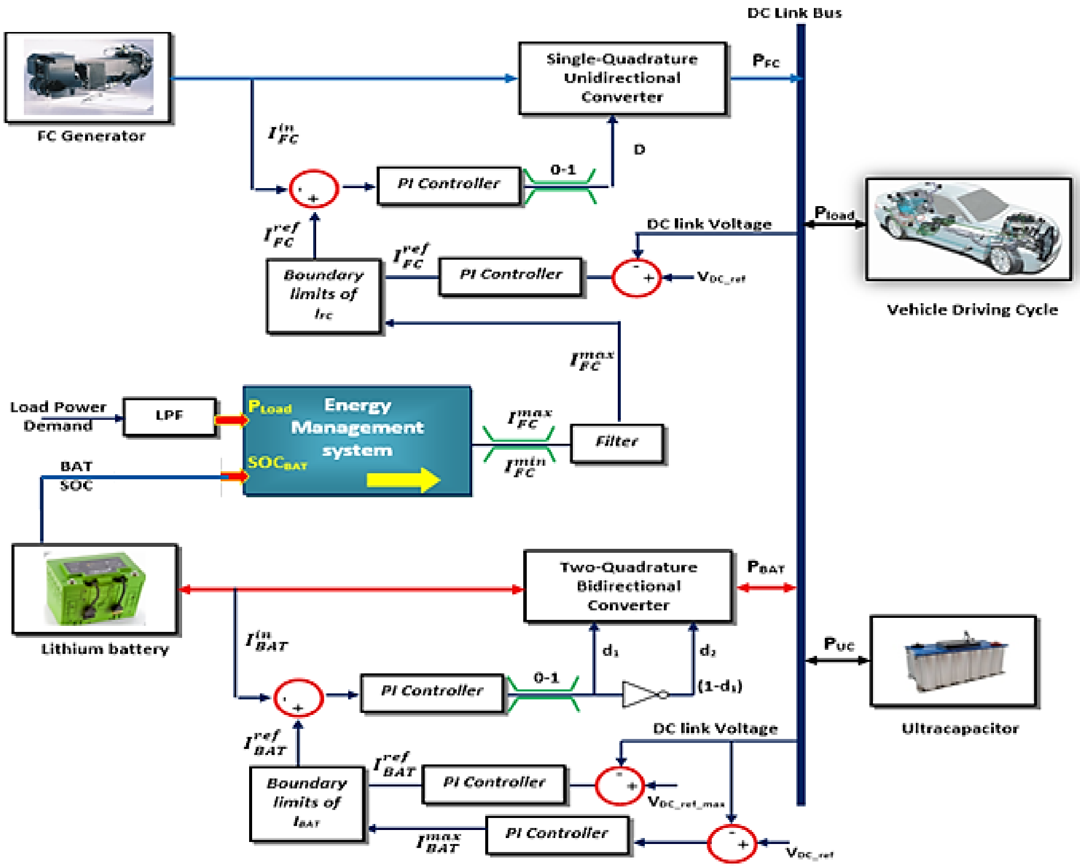


Fig.1 The developed hybrid FCEV system

To control the FC output power, the FC is connected to the load through a single-quadrature boost converter which is also used to boost up the FC voltage to the required DC link voltage, which is set to 300 volts. The BAT is connected to a two-quadrature DC-DC converter to manage the power flow between the DC link, load and the BAT using cascade control structure. Also, this converter steps up the BAT voltage to the required DC link voltage and control the BAT's SOC. The UC directly connected to the DC link to regulate the DC link voltage and response to the load changes in a very short time. A SLC techniques are used to control the output power of the FC with respect to the load power demand by given the current control signal to the FC's converter. A cascade control structure with a fast-inner current control loop and an outer voltage control loop for the FC and BAT converters have been developed, as shown in Fig.2. The DC link voltage is regulated by the outer loop via the FC and BAT currents which is tightly controlled by a faster inner loop. It obvious that the FC reference current i_{FC}^{ref} is produced from the outer voltage loop of the FC converter controller. This is done after a DC voltage reference V_{Dc_ref} is subtracting from the actual DC link voltage. The i_{FC}^{ref} is passed to the inner current control loop if its value not exceed the FC current i_{FC}^{*} produced by the EMS. The EMS determine the minimum and maximum values of the i_{FC}^{*} in a way to ensure the FC generator not respond to the negative power and the maximum positive power requirements. The i_{FC}^{*} is depending on the EMS rules (which will be explain later) based on the load power demand and the state of the BAT. The i_{FC}^{ref}, after passing the boundary limit block, is subtracted from the real output FC current then the error signal is treated by the FC PI compensator to control the duty cycle (D) of the FC converter, which is limited between (0-1).

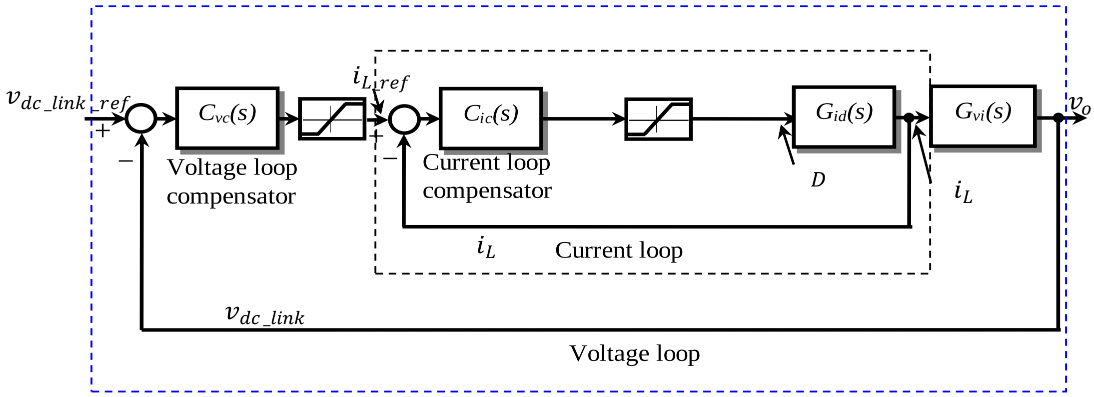


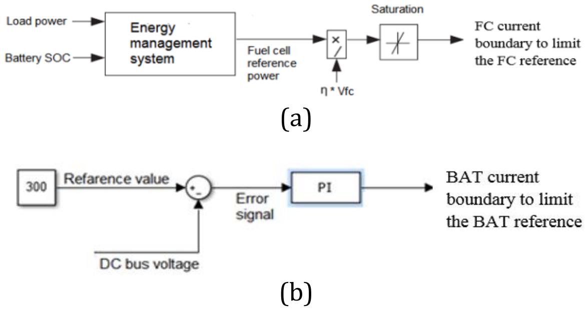
Fig.2 Block diagram of the cascade controller system

A LPF is connected via the power load demand to ensure a smooth response for the FC and permits to the UC to respond to the load transients. A second LPF with a higher cut-off frequency has been used with the BAT to achieve a decoupling between the FC control loop and the BAT control loop to remove the interaction between them. The output current of the BAT is compared with the requested BAT reference current i_{BAT}^{ref} which is generated by the voltage loop controller of the BAT's converter, and then the produced error signal is treated via the inner current loop controller to control the two power switching devices of the BAT's converter. The i_{BAT}^{ref} is passing if its values verifying the maximum charging and discharging of the selected BAT. This has been achieved by the PI controller which is generating the i_{BAT}^{max} based on the difference between the DC link voltage and the DC bus nominal voltage.

The proposed system has been designed so that the UC use more often than BAT since it is more efficient and has a longer lifetime than the BAT. Therefore, no direct controller has been designed for the UC storage. In the acceleration periods, the DC link voltage is reducing less than the limit voltage determine by the BAT converter controller system. Hence, if the acceleration of the vehicle changes rapidly with high transit load power requirement, the UC will be responded directly. On other hand, for the load demands that have variations less than the high transit load demands and higher than the FC power response, the PI controller of the BAT converter produces suitable duty cycles so as boost the DC link voltage to its reference value. Besides, during the braking periods, the DC link voltage increases and provides the capability of transferring the available braking energy to UC. The developed controller architecture with the EMS scheme ensures that the current of the FC and BAT not exceeding their rating current. In addition, the FC and BAT converters keeping the DC link voltage in a desired level and offers the ability to deliver the desired power value from the power sources.

Control System Model for the Power Conditioning unit

In this section, the individual controller systems for the single and two quadrature converters will be described and defined to select the proper controller design parameters. As mentioned earlier, the developed EMS that used in this work is determine the FC current boundary i_{FC}^{*} which is fed to the FC single-quadrature converter to control the output current of the FC so that the FC is respond only for the steady-state load power, as modelled in Fig.3a. To control the charge and the discharge periods of the BAT a PI controller is used, the output of which is fed to the two-quadrature converter of the BAT, as shown in in Fig.3b.



(a)

(b)

Fig.3 Controllers that used to determine the (a): FC current boundary and (b): BAT current boundary

In the single and two quadrature converters, the parameters that should be controlled to maintain the DC link voltage and limit the input current are the output voltage and input current. The transfer function of the boost or buck converters can be found in the different contexts (R. W. Erickson *et al*, 2004; B. Dokic *et al*, 2015).

Its known that the boost converter under voltage loop controller has a right-half plane zero (RHPZ). Therefore, to improve the converters stability and eliminate or for reduction in the RHPZ effect, a cascade controller is preferable. This controller system will permit the FC to intuitive management of the power flows within the FCEV system. With a cascade control structure the FC and BAT output currents are controlled to follow the reference currents from the outer voltage control loop, within a given tolerance band, in order to charge and discharge the BAT/UC and keep a regulated output DC-link voltage. This system is expected to keep the DC-link voltage at the desired value even under fast loop variation. It can be seen in Fig.2 that the control to output voltage transfer function ($G_{vd}(s)$) of the converter are separated into two transfer functions with the cascade controller system, which are the current-to-output voltage transfer function ($G_{iv}(s)$) and control-to-input current transfer function ($G_{id}(s)$). The PI controller equations for the inner current loop and the outer voltage loop are given by:

$$C_{vi}(s) = K_{pv} + \frac{K_{iv}}{s} \quad (1)$$

$$C_{id}(s) = K_{pc} + \frac{K_{ic}}{s} \quad (2)$$

where C_{vi} and C_{id} are the PI compensators transfer function for the voltage and current loops respectively. The parameters the PI compensators denied as K_{pv}, K_{iv}, are the parameters of the voltage loop compensator and K_{pc}, K_{ic} are the parameters of the current loop compensator.

Description of the Developed EMS Schemes

As mentioned earlier, the EMS in the FCEV is necessary to increase fuel economy, sturdiness, and performance, while minimizing cost. The EMS with the cascade controller can manage the power flow between the FCEV power sources and maintain the SOC for the BAT and UC with keeping the DC link voltage at acceptable level. SLC is considered and designed in this study to achieve the above requirements. The SLC controller consisting of 13 rules of (if-else) statements, based on these rules, SLC controls the output power of the FC and satisfy all the operating conditions of the FCEV. To satisfy the optimum power flow between the input resources and the load in addition to avoid the effect of the sharp and instantaneous changes in the load power on the FC and BAT life time, the state logic controller rules are divided into three modes as given below:

Mode1: In this mode, the SOC of the BAT is lower than minimum SOC (SOC_{min} =60%,). Five rules have been applied in this mode.

1. If the load power is more than the maximum then the FC will give a maximum power $P_{fc\ max}$, the additional power will be supplied by the BAT and UC.
2. If the load power between the maximum and the optimal FC power $P_{fc\ opt}$ the fuel cell will deliver the load power.
3. If the load power between the optimal value and the minimum value $P_{fc\ min}$, the FC will supply the optimal power. The difference between the $P_{fc\ opt}$ and the load power will charge the BAT.
4. If the load power is lower than the $P_{fc\ min}$ but greater than zero, the FC will supply the load power and charging the BAT.
5. If the load power is negative (breaking mode), the FC will supply the BAT charging power only.

Mode 2: In this mode, the SOC of the BAT is between SOC_{nom1} (85%) and SOC_{nom2} (60.1%). Four rules have been achieved in this mode.

1. If the load power is more than the $P_{fc\ max}$ then the FC will give a maximum power, the additional power will be supplied by the BAT and the UC.
2. If the load power between the $P_{fc\ max}$ and the $P_{fc\ opt}$ the FC will give the load power.
3. If the load power between the $P_{fc\ opt}$ and zero, the FC will supply optimal power. The difference between the $P_{fc\ opt}$ and the load power will charge the BAT.
4. If the load power is negative, the FC will supply $P_{fc\ min}$.

Mode 3: In this mode, the SOC of the BAT is greater than the $P_{fc\ max}$. Also, four rules have been achieved in this mode.

1. If the load power is more than the peak FC power, then the FC will deliver the load with a maximum power. The additional power will be supplied by the BAT and the UC

2. If the load power between the $P_{fc\ max}$ and the $P_{fc\ opt}$, the FC will provide the load power.
3. If the load power between the $P_{fc\ opt}$ and zero, the FC will supply minimum power. The additional power will be supplied by the BAT.
4. In the breaking mode, the FC will not supply any power.

Designed of the Developed System Parameters

To evaluate the performance of the developed EMS that based on SLC scheme and the performance of the FCEV, the system has been assessed by Urban-Dynamometer-Driving-Schedule (UDDS) driving cycle. Table I shows the main drive cycle parameters of UDDS acquired from ADVISOR software.

Table I Summary of data for the 23.3min UDDS driving cycle

Parameters	Values
Time	1396 sec
Distance	7.45 miles
Maximum speed	56.7 mph
Average speed	19.58 mph
Maximum acceleration	4.84 ft/s^2
Maximum deceleration	-4.84 ft/s^2
Average acceleration	1.66 ft/s^2
Average deceleration	-1.9 ft/s^2
Idle time	259 sec
Number of stops	17

According to the load power profiles of the UDDS driving cycle shown in Fig.8a, the power demand can be provided during a period equal to 23.3min. The UDDS load characteristics can be derived: Average power = 7kW, Overshoot peak power for 10sec = 11kW, and Peak continuous power =8kW for 23.3min. For different applications, many various designs of FC, BAT and UC can be achieved. By considering the nominal power ratings for FC, BAT and UC as illustrated above, the sizing of the developed plug-in FCEV system components is realized. To be the results of the system performance close to the reality, a detailed model for the FC, BAT and UC has been developed by extracting the practical technical specifications of these resources and included them in the Simulink model. For the sizing methodology, Hydrogenics 12.5kW HyPM-HD12 PEMFC (HyPM-HD12 PEMFC Datasheet), Valence Technology U-Charge U1-12XP lithium-ion BAT (U-Charge U1-12XP Lithium-ion Battery Datasheet) and Maxwell Boostcap®BCAP1200 UC (Maxwell Boostcap®BCAP1200 UC Datasheet) are used for the developed plug-in FCEV. Table II show the parameters of the FC, BAT, and UC respectively.

Table 2 Technical specifications of the used FC, UC and BAT

HyPMHD12 PEMFC		U1-12XP LI-ion BAT		Boostcap®BCAP1200 UC	
Voltage @ 0 A and 1 A [V_0 (V), V_1 (V)]	[52.5, 52.46]	**Nominal Voltage**	48 **V**	**Rated Capacitance**	10F
Nominal operating point [I_{nom} (A), V_{nom} (V)]	[250, 41.15]	**Rated Capacity**	40 **Ah**	**Equivalent Series Resistance DC**	0.0696**Ω**
Maximum operating point [I_{end} (A), Vend (V)]	[320, 39.2]	**Maximum Capacity**	40 **Ah**	**Rated Voltage**	300 **V**
Number of cells	**65**	**Fully Charged Voltage**	55.88 **V**	**Maximum Voltage**	324 **V**
Nominal stack efficiency (%)	**50**	**Nominal Discharge Current**	17.4 **A**	**Number of Series Capacitor**	120
Operating temperature (Celcius)	**45**	**Internal Resistance**	0.012 **Ω**	**Number of Parallel Capacitor**	1
Nominal Air flow rate (lpm)	**732**	**Capacity (Ah) @ Nominal Voltage**	36.17	**Operating Temperature**	25 **^{o}C**
Nominal supply pressure [Fuel (bar), Air (bar)]	[1.16, 1]	**Exponential Zone**	[52.3 **V**, 1.96 **Ah**]		
Nominal composition (%) [H_2, O_2, H_2O (Air)]	[99.95, 21, 1]	**Battery Voltage response time**	30 **sec**		
Fuel cell voltage response time (sec)	**1**				
Peak O2 utilization (%)	**60**				
Voltage undershoot (V) @ Peak O_2 utilization	**2**				
Peak O2 utilization (%)	**60**				
Voltage undershoot (V) @ Peak O_2 utilization	**2**				

Table 3 PI Parameters of FC converter controller

	Voltage Loop		Current Loop	
Boost Converter	K_{pv}	K_{iv}	K_{pc}	K_{ic}
	10.6839	285.9535	0.0668×10^{-3}	22.3467×10^{-3}

Table 4 PI Parameters of BAT converter controller

	Voltage Loop		Current Loop	
Buck Converter	K_{pv}	K_{iv}	K_{pc}	K_{ic}
	1042.8	34863	10.5991	2836.8
	Voltage Loop		Current Loop	
Boost Converter	K_{pv}	K_{iv}	K_{pc}	K_{ic}
	1042.8	34863	0.0668	22.3467

The efficiency of the FC converter is assumed to be 88%, then for an average load power equal to 7kW, the FC can be provided about 7.95kW. Thus, as shown in [11], the rated output power of this module can completely be satisfied the reference power signal of UDDS power load demand.

For the developed plug-in FCEV system, a BAT is modeled in Simulink with four cells connected in series. The nominal voltage for each series string is 12.6V. Thus, 48V can be obtained so that should not exceed the stable dynamic range of the converter duty cycle. Furthermore, the nominal capacity of U-Charge U1-12XP is 40Ah. This is means that this BAT pack system can provide a total energy content of 1920Wh. Hence, the battery system must can supply 4.937kW which is easily meets the designed requirements for the proposed system.

The Maxwell, 1200F, 2.7V/cell Boostcap®BCAP1200 UC unit is selected in this study. The 120 cells connected in series (n cells) is considered to obtain the required 300V DC link voltage of the FCEV system. The selected UC unit must be capable of supplying the peak power demand which is 11kW for 10sec as mentioned earlier, where the maximum energy density of the UC unit is 5,800W/kg as shown in [13]. Therefore, the UC unit design must have a minimum rating of 101.85Wh for a typical depth-of-discharge is 30%. For a DC output voltage equal to 300V, the corresponding energy in joule equal to 450kJ. Thus, this UC unit can be provided about 125Wh. Hence, the required power demand can be effortlessly providing by the selected UC unit.

The single and two quadrature FC and BAT converters have been modeled using average-switch model to simplify the system operation. The model included cascade control system with two-PI controllers, where their parameters are obtained as shown in Table VII and Table VIII for the FC and BAT converters respectively. The current loop has been designed to be faster than the voltage loop with the bandwidth frequency equal to 472.72rad/sec compared with 47.27rad/sec for the voltage-loop controller. The design of PI parameters considered the input inductance and output capacitance values of the FC and BAT converters. For the FC converter L_{boost} is selected equal to 100μH and C_{boost} is selected equal to 800μF, while for the BAT converter $L_{buck\text{-}boost}$ is selected equal to 10mH and $C_{buck\text{-}boost}$ is designated equals to C_{boost}.

Validation and Analysis

The developed EMS and the converters controller has been verified using detailed simulation results using Simulink and ADVISOR software, then the validation of the EMS is achieved by executing the EMS scheme in a synchronous fashion with the physical models of the FC, BAT, UC, and their converters in addition to the EV load model using PIL environment. Xilinx ISE 14.6 Simulator is employed to generate the SLC algorithm. As shown in Fig.4, the SLC source code has been written as VHDL code, which is created in Xilinx ISE, then introduced to the System Generator via "Black Box" block, and then simulated via MATLAB/Simulink accompanied with Xilinx system generator.

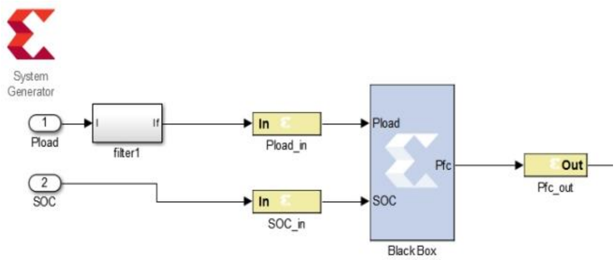


Fig.4 EMS subsystem shows the generated black box block

Fig.5 Connection between the host and target board

Fig.6 The simulation developed EMS scheme behavior

Fig.4 EMS subsystem shows the generated black box block FPGA card type Spartan-3A DSP 3400A used to implement the developed EMS scheme, where the connection between the FPGA and PC is shown in Fig.5.

The simulation behavioral of developed EMS scheme which includes two inputs and one output of the Black Box is shown in Fig.6.

As shown in Fig.7, the Xilinx system generator compiles the developed EMS algorithm and produces the hardware or PIL co-simulation (hwcosim). The hwcosim is implemented in the FPGA system. By using Xilinx system generator, the data transferred and received between the host (PC), which is included the physical model of the FCEV system and the target (FPGA), which is included the EMS algorithms. Once the Matlab/Simulink begun, the algorithm afterward is downloaded to the FPGA in order to configure it. Afterword, the configuration of the device is achieved, the integration between the FPGA and hardware co-simulation will be re-established, which is represented the starting of the PIL co-simulation of the FCEV system.

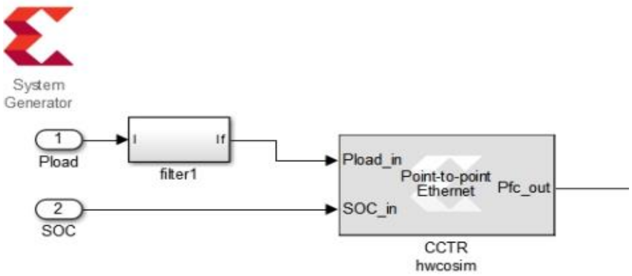
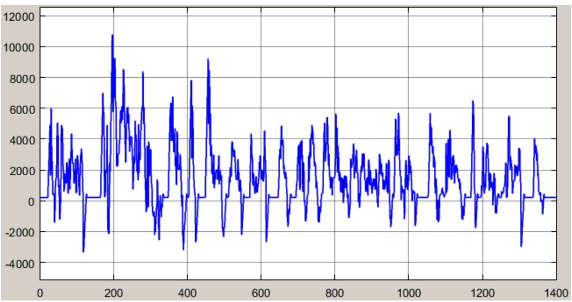


Fig.7 Compilation of the developed SLC algorithm using Xilinx system generator

To start the evaluation, Fig.8a-d show the changes of FC output power, BAT output power, and UC output power respectively under the UDDC driving cycle for a short period of 23.3min of the drive cycle as shown in Fig.8a.



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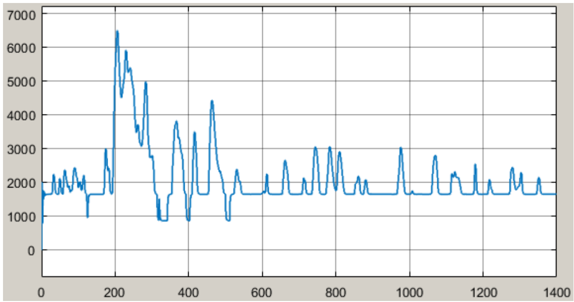

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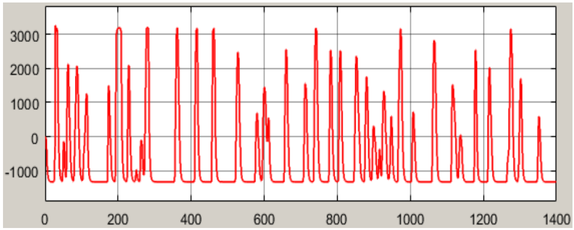

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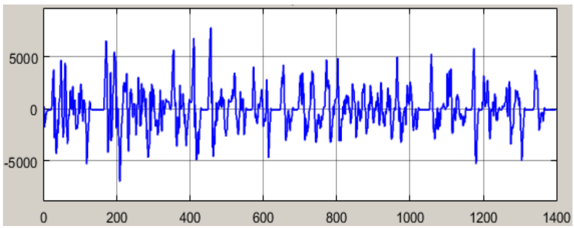
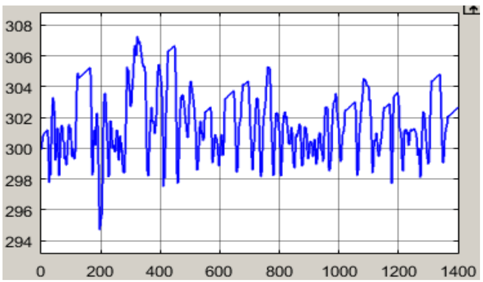


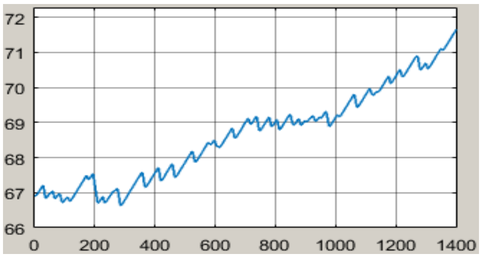
(d)

Fig.8 Power distribution for the power train of the: (a) UDDS driving cycle(b) FC power, (c) BAT power, and (d) UC power

It is obvious from Fig. 8b that the FC system provide the steady-state load power without facing the sudden variations. The BAT is responded to the medium frequency component of the load power and help the FC to supply the power to the load. When the BAT SOC reaches to its minimum value (60%), the FC deliver the power to the load and the surplus power of the FC tries to recharge the BAT. The BAT charge and discharge power is shown in Fig.8c. The positive signify the transmitted power to the load to help the FC generator to deliver the base power and to respond to the low variations portion of the load demand. Whereas the negative power of Fig.8c signify the power captured by the BAT either from the FC or from UC. As mentioned before, since the battery is not responding to the sudden load changes this helps the BAT to operate in a safe operation, which consequently increase the lifetime of the battery. As expected the UC is supply the high frequency components of the load power (sudden load changes), as shown in Fig.8d. From Fig.8, it can be seen that at the highest power demand (at the time instant 195sec), which is about 10680W (see Fig.8a), the peak power delivered by the FC system is only 3200W (see Fig.8b) in respect to 7480W (see Fig.8d and e) delivered by the BAT and UC energy storages. Fig.8c shows the UC discharging and charging output power change based on the sudden load power demand. Hence, the UC effectively delivers the fluctuations and the peak load power demand, which accordingly help in improving the operation of the developed FCEV.



(a)



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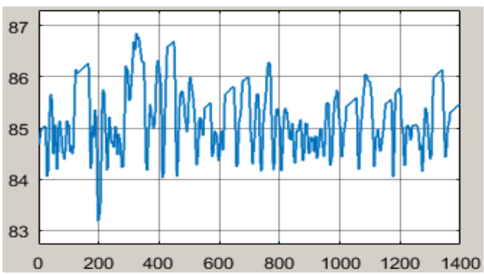
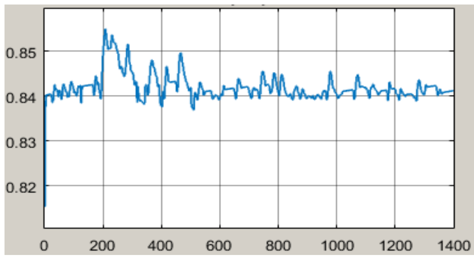


(c)

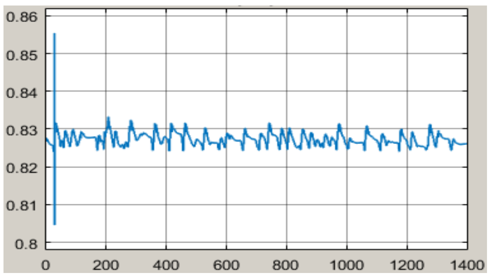
Fig.9 The variations of (a) DC link voltage (b) BAT state-of-charge (c) UC state-of-charge of the FCEV

The DC link voltage variation due to the changes in the load power demand shown in Fig.9a and the changes in the SOC of the BAT and UC in respect to the load demand are shown in Fig.9b and c, respectively. It can be seen in Fig.9a that the voltage of DC link not exceeded the designed DC bus voltage level, which is set between 290 to 325V. In this case the DC link voltage changes between 294.7 and 307.255V. Once the DC link voltage exceeding the reference voltage (300V), these results in the BAT converter to operate in the buck mode and recharge the BAT. The DC link voltage kept in the acceptable level by proper changes in the duty cycle of the FC and BAT converters as shown in Fig.10.

It's obvious from Fig.9b and c that the developed EMS algorithm describes to maintain designed SOC values of BAT and UC, which is set between 60% and 90%. In this case, it can be seen from Fig.9b the SOC of BAT varies between 66.6% and 71.66%, while the SOC of UC varies between 83.2% and 86.85%, as shown in Fig.9c. The developed EMS algorithm try to ensure that the BAT and UC continuously have sufficient charge for the accelerating times of FCEV, whereas adjusting the energy flow between the resources and the load with the aim of reducing the H_2 consumption. Hence, it can be concluded that the BAT and UC successfully deliver the required load power demand and reduce the fuel economy that is consequently increasing the efficiency.



(a)



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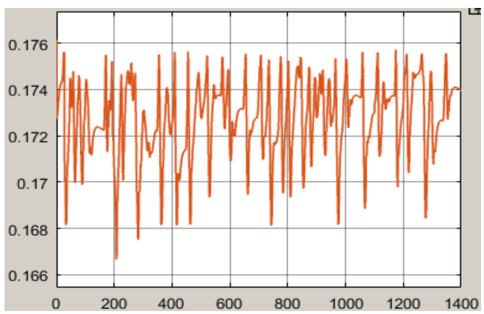
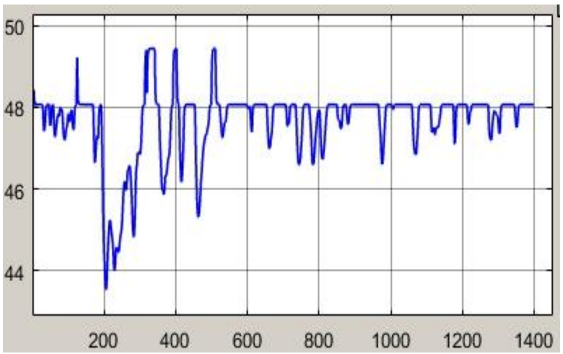


(c)

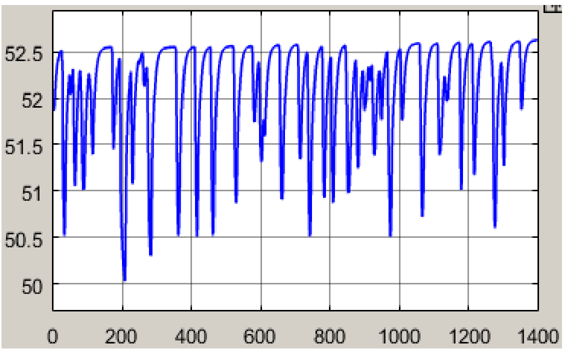
Fig.10 The variations of the duty cycle due to changes in the load power demand (a) D of FC boost converter switch (b) D of BAT boost converter switch and (c) D of BAT buck converter switch

From Fig.10, it's obvious that the duty cycle not reaching to the unacceptable value, which is >90%, even at high load power demand, where the duty cycle for the FC converter's switch changes between 0.84 and 0.855 while for the BAT converter's switches changes between 0.825 and 0.835 for the boost switch and between 0.167 and 0.176 for the buck switch.

It's clear from Fig.11a that the FC voltage changes in the acceptable limits between 43.56V and 49.44V under the full range of UDDS cycle, where the FC voltage range for each cell changes between 0.67V and 0.76V. The maximum variations in the FC voltage occurred in the duration between 195-350sec. This is the period of high power demand by the vehicle based on the UDDS cycle. Even though, the FC still operating in the Ohmic region. The FC variations reduced due to the optimum operating of the EMS controller, which is cannot be occurred without using the energy storage sources. Hence, the combination of the FC vehicle with the energy storages and EMS controller which consequently increases the FCEV efficiency, while large variation intervals in the FC voltage results significantly in reducing the FC system efficiency.



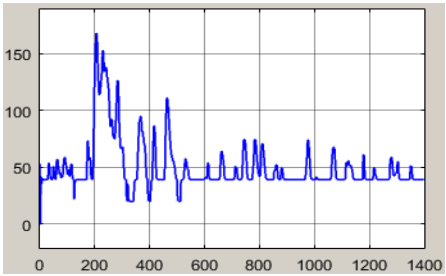
(a)



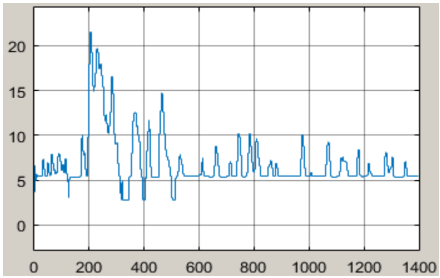
(b)

Fig.11 Illustrate a) The variations of the FC and b) BAT input voltage under UDDS power demand

Fig.11b shows the variations in the BAT voltage under different UDDS cycle power demand. It is clear that BAT voltage is changing with very narrow between 50V to 52.5V without causing overcharge for the battery. Moreover, the frequency changes of the BAT voltage is lower than the UC voltage variations shown in Fig.9a and higher than FC voltage variations shown in Fig.11 which is lead to increase the lifetime of the battery. The FC input and output currents, BAT input and output current under various load power demands are shown in Fig.12 (a, b, c, and d) respectively. These results show that the FC and BAT not exceeding their output rating currents at the peak load demand, where the maximum current ratings of FC and BAT is 250A and 80A respectively.



(a)



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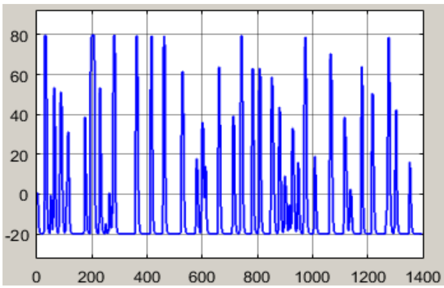

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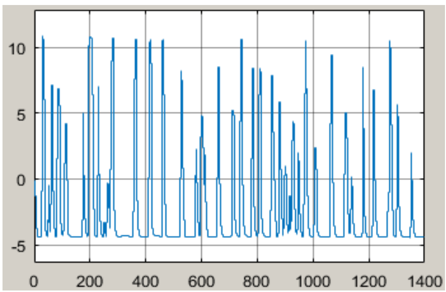


(d)

Fig.12 The variations of the FC and BAT currents in ampere (a) FC input current, (b) FC output current (c) BAT input current and (d) BAT output current, under UDDS power demand

Fig.13 shows the hydrogen flow amount in lpm acquired to meet the different UDDS load variations. It is worth to mention here that an integrated the FCEV with the energy storages such as BAT and UC is not only improving the FC response and increasing the FC and BAT lifecycles, but also contributes in reducing the FC system size. This is depending on the amount of H_2 consumption. From Fig.13 at the maximum load, the H_2 consumption is found equal to 76.96 lpm. Finally, the FC stack efficiency and the overall system efficiency have been calculated and plotted as shown in Fig.14a and b. The overall system efficiency calculated by dividing the summation of FC, BAT, and UC input power to the load power demand. The average FC stack efficiency is about 58%, while the average overall system efficiency is equal to 71.6%.

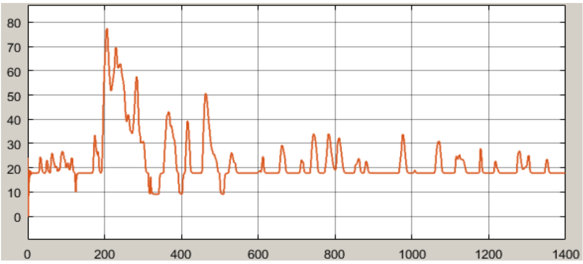
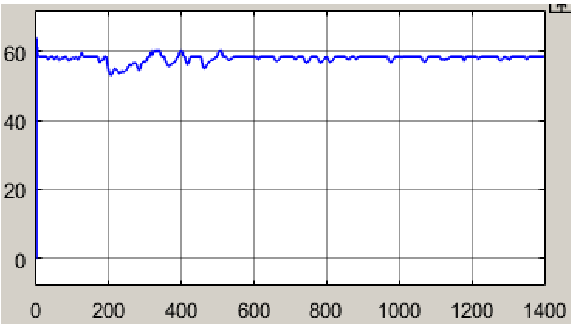
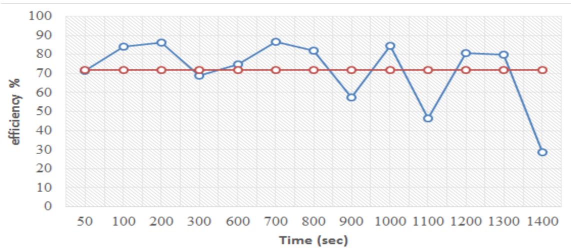


Fig.13 The amount of hydrogen flow in lpm under UDDS power demand



(a)



(b)

Fig.14 Efficiency of (a) FC stack and (b) overall system under UDDS power demands

Conclusion

The aim of this research was to develop an EMS scheme to reduce the fuel of the FCEV powertrain and increase the system's efficiency that based on the combination of FC, BAT, and UC. The main concluding that can be extracted from this work can be summarized as follows:

1. The FC plug-in electric vehicle was intended taken into the consideration the power load requirements of the vehicle under UDDS driving cycle. It depended on fuel cell, batteries and ultracapacitors, together with related DC-DC converters.
2. To represent the acceleration and grade test procedures which are used to analyze the dynamic property of hybrid vehicles and to get the electrical load power profile, ADVISOR software provided by the National Renewable Energy Laboratory has been used. Using this software, the UDDS driving cycle has been extracted, which is then used as a load on the FCEV to evaluate the performance of the developed EMS scheme under.
3. The base power of the vehicle can be satisfied by the FC and BAT, while the UC responding to the fast load power demand, such as fast acceleration and regenerative braking periods. The BAT and UC together can also take in the energy produced by the regenerative braking of the vehicular system.
4. An energy management system is proposed for the load power sharing to ensure that the three power sources are operating at high efficiency with their mechanism performance.
5. Computer software such as Matlab/Simulink can accurately simulate the performance of the FCEV system under the developed algorithm for the EMS scheme. However, to validate the developed EMS, processor-in-the -loop approach is used. In this technique, the algorithm of the EMS scheme executes on the actual embedded processor in the real time, while the other components of the FCEV are operating in simulation time. FPGA card type Spartan-3A DSP 3400A used to implement the developed EMS scheme. The validation results shown an excellent match with the simulation results.

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