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Research Article

Fuzzy Logic Based Control of a Fuel Cell/Battery/Ultra-capacitor Hybrid Power System via a Multi-Phase Multi-Input Converter

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ABSTRACT

Fuel-cell (FC) based electric vehicles (EVs) are promising to reduce the carbon footprint due to the transportation sector. FCs are environmentally friendly systems that generate electricity from hydrogen and oxygen. Unfortunately, FCs solely fail to meet the high power density requirements of EVs. Therefore, this paper presents a FC/battery/ultra-capacitor (UC) hybrid power system (HPS) for electric vehicle applications. In this work, the power conversion is realized employing a single dc-dc converter which is a multi-phase multi-input converter to offer a compact and efficient HPS. After analyzing the converter, a fuzzy-logic-based energy management strategy (EMS) is developed to limit the rate of change of FC and battery power levels and regulate the voltage of UC. Finally, the offered EMS has been evaluated thanks to simulation models of the converter and sources.

Keywords: *Fuel-cell electric vehicles, Battery, Ultra-capacitor, Multi-phase multi-input converter*

Çok-Fazlı Çok-Girişli Bir Dönüştürücü ile Yakıt Hücresi/Batarya/Ultra-kapasitör Hibrit Güç Sisteminin Bulanık Mantık Temelli Yönetimi

ÖZ

Yakıt Hücresi (YH) temelli elektrikli araçlar (EA'lar) ulaşım sektöründen kaynaklanan karbon ayak izini düşürmek için gelecek vadetmektedir. YH'leri hidrojen ve oksijenden elektrik üreten çevre dostu sistemlerdir. Maalesef, YH'leri elektrikli araçların yüksek güç yoğunluğu gereksinimlerine tek başlarına cevap verme konusunda yetersiz kalmaktadır. Bu yüzden, bu makale elektrikli araç uygulamaları için bir YH/batarya/ultra-kapasitör (UK) hibrit güç sistemi (HGS) sunmaktadır. Bu çalışmada, güç dönüşümü kompakt ve verimli bir HGS oluşturmak için çok-fazlı ve çok-girişli bir adet dc-dc dönüştürücü aracılığıyla gerçekleştirilmektedir. Dönüştürücünün analizinden sonra, YH ve bataryanın güç değişim hızlarını sınırlamak ve UK gerilimini ayarlamak için bir bulanık mantık temelli enerji yönetim stratejisi (EYS) geliştirilmektedir. En sonunda, geliştirilen EYS, dönüştürücünün ve kaynakların benzetim modelleri yardımıyla değerlendirilmektedir.

Anahtar Kelimeler: *Yakıt hücreli elektrikli araç, Batarya, Ultra-kapasitör, Çok-fazlı çok girişli dönüştürücü*

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I. INTRODUCTION

Fuel cell hybrid electric vehicles (FCHEVs) offer a variety of benefits, including long driving range, high efficient energy/power ratio, and so forth [1,2]. A FCHEV comprises hybrid power systems (HPSs) including a fuel cell (FC) and energy storage systems (ESSs) to improve the durability of the FC, maximize energy density and save fuel [2]. In the FCHEVs, there are two prevalent architectures: FC/ultra-capacitor (UC) and FC/battery/UC. In [3], it is showed that the FC/battery/UC system is superior to the FC/UC system when considering many parameters such as system size, fuel consumption, and system lifespan. Source energies in FC/battery/UC HPSs are regulated via proper power electronics structures. In the first structure, certain sources are linked to the dc bus directly while other sources through bidirectional or unidirectional dc-dc converters [4]. Even if semi-active systems are functional and easy of handling, they do not permit to adjust the voltage of the dc bus and source energies freely. Furthermore, some studies as in [5] suggest using separate converters for each source to solve semi-active design difficulties at the cost of extra cost and complexity. The other structure takes the advantages of multi-input converters (MICs). When comparing the other structures, utilizing MICs in HPS allows building more compact and efficient HPSs [6]. Power electronics converters can be constructed as having single-phase or multi-phase. The multi-phase converters (MPCs) have parallel legs which ideally split the power equally to realize the power conversion. It is addressed in [7, 8] that although MPCs may increase the complexity and cost, they do not only enable efficient conversion but also help to reduce filter requirements, inductor sizes, electromagnetic interference problems, and hot spots on the printed circuit boards. Thus, there can be found several structures in the literature combining the advantages of two-input MICs and MPCs as in [9, 10]; on the other hand, it can be asserted that three-input case requires more research effort.

In addition to the power electronics structures, the energy management strategies (EMSs) are another key factor that affects the performance of the FCHEVs. Researchers have studied many EMSs based on numerous approaches, such as optimization methods [11], wavelet transformation (WT) [12], adaptive control [13], and fuzzy logic controller (FL) [14]. Among these approaches, the FLC-based ones come to the forefront thanks to their simple implementations; moreover, they do not require mathematical models or prior knowledge of the applied systems.

In [15], a FC/battery/UC HPS is structured via a single-phase MIC; therefore, this system may suffer from the aforementioned issues associated with the single-phase converters. Moreover, the proposed system in [15] is supervised an energy management strategy (EMS) which is essentially a frequency decoupling method consisted of two low-pass-filters (LPFs) and a polynomial. Although the mentioned EMS successes to smooth FC and battery power profiles and regulate UC voltage, it does not offer flexibility in terms of managing source energies. Thus, this paper proposes a FLC-based EMS for a FCHEV in which a FC/battery/UC HPS is built by a three-input multi-phase MIC (MPMIC).

II. ANALYSIS OF THE MPMIC

The proposed three-input MPMIC is given in Fig.1. As can be seen, the each input is connected to a pair of a switch-diode-inductor group while these groups are connected to a switch pair. Therefore, the proposed structure is a two-phase MIC consisted of 8 switches, 6 diodes, 6 separate inductors, and a capacitor. Since FC and battery inputs are unidirectional, 2 diodes are attached to these inputs. The proposed system has three operation modes. In Mode-1, the output is powered through all input sources. In this mode, the input switches (S_{1A}, S_{1B}, S_{2A}, S_{2B}, S_{3A}, S_{3B}) and the low-side output switch S_4 are controlled via pulse-width-modulation (PWM). The duty cycles of $S_{1A,B}$, $S_{2A,B}$, $S_{3A,B}$, and S_4 are denoted by d_1, d_2,d_3, d_4, respectively. Please note that there are 180° between gate signals of input switches for interleaving operation and the switching frequency of the output switch is twice of one of input switches for obtaining the same effective switching frequency. Furthermore, UC is charged by FC and battery in Mode-2 in which the charging energy is transferred through L_{3A}, L_{3B} and the body diodes of S_{3A} and S_{3B}. Finally, UC is charged by the regenerative energy flowing from the output in Mode-3. In this mode, only S_5 is controlled with PWM; therefore the converter operates like a traditional buck converter in this case. Here, the duty cycle of S_5 is d_5.

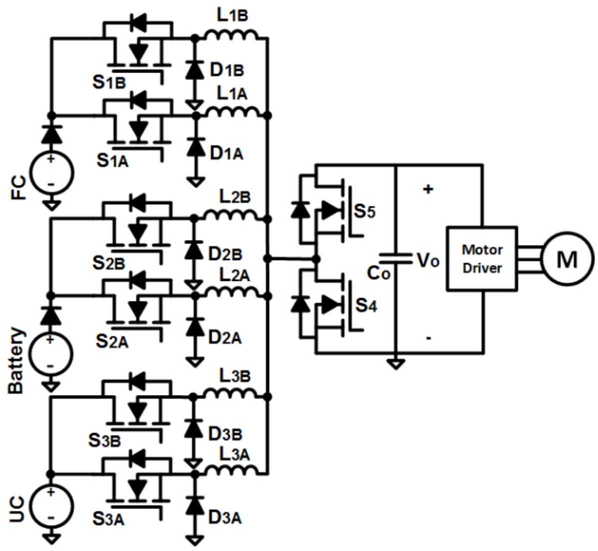

Figure 1. *The proposed FC/battery/UC hybrid power system via the MPMIC.*

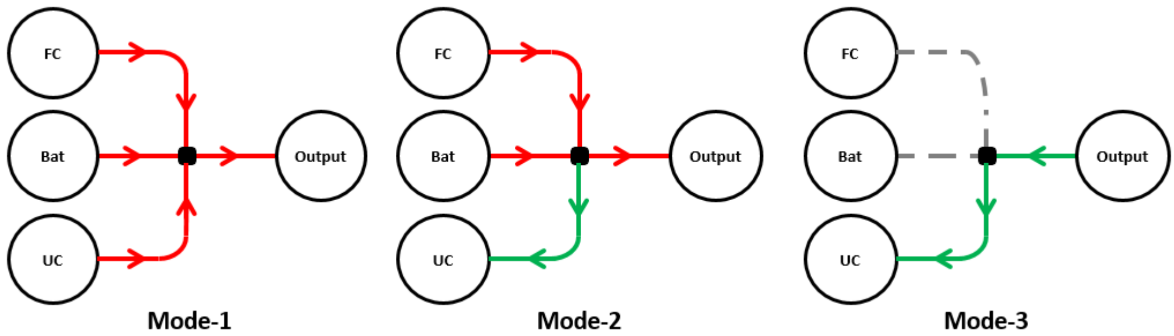

Figure 2. *The operation modes.*

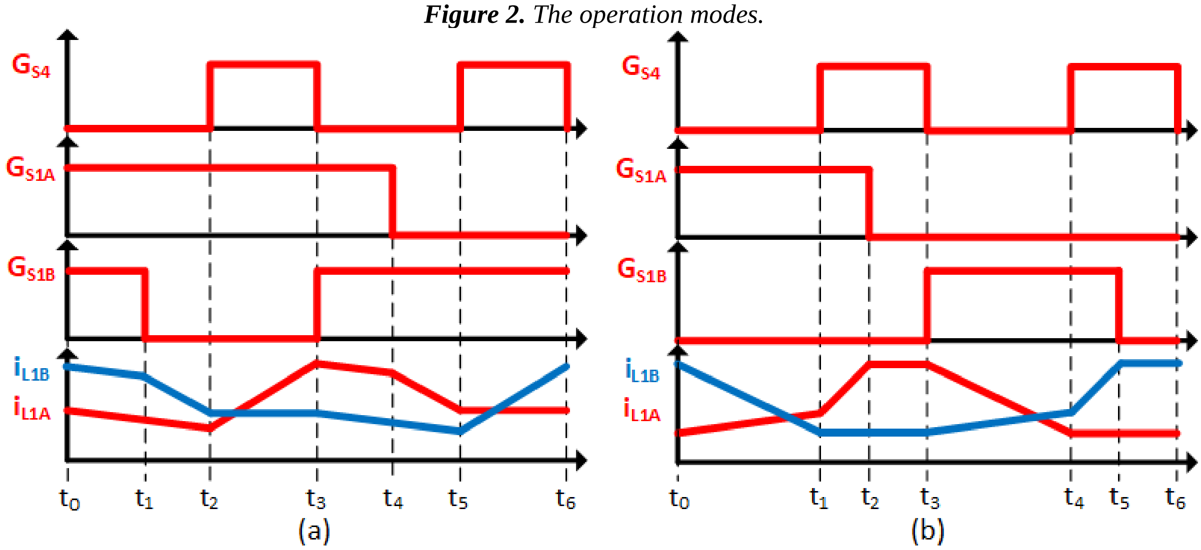

Figure 3. *Typical waveforms for Mode-1 a) boost mode, b) buck mode.*

A. ANALYSIS OF MODE-1

In this mode, FC, battery and UC discharge to feed the output. The proposed converter has the ability to operate in buck and boost modes according to the determined duty cycles. Since each input energy is controlled independently, the converter can be considered three separate converters connected in parallel to a common output. Therefore, the analysis can be realized for a single input then it can be extended for three-input. Accordingly, typical waveforms for the boost mode can be seen in Fig. 3 (a) where there are 6 different stages to examine.

Stage 1 [t_0-t_1]: In this mode, S_{1A} and S_{1B} are on while S_4 is off. Moreover, D_{1A} and D_{1B} are off while the body diode of S_5 is on. Therefore, both L_{1A} and L_{1B} currents decrease since their voltages are equal to v_{FC}-v_o.

Stage 2 [t_1-t_2]: Turning off S_{1B} starts this period. D_{1B} starts to conduct therefore the voltage on L_{1B} becomes -v_o. As a result, L_{1B} current slope becomes more negative.

Stage 3 [t_2-t_3]: In this period, S_4 is turned on while S_{1A} and S_{1B} keep their previous states. L_{1A} starts to be charged by the input source while L_{1B} experiences the freewheeling mode. Therefore, the voltage of L_{1A} is equal to v_{FC} while the voltage of L_{1B} is equal to zero.

Stage 4 [t_3-t_4]: This mode is equivalent to Stage-1.

Stage 5 [t_4-t_5]: This mode is initiated by turning off S_{1A} while S_{1B} is on and S_4 is off. D_{1A} conducts; therefore the voltage of L_{1A} becomes equal to -v_o. As a result, the slope of L_{1A} current becomes more negative.

Stage 6 [t_5-t_6]: In the final stage, S_{1A} is off, S_{1B} in on and S_4 is on. Therefore, the current of L_{1A} is in freewheeling mode thus its voltage is zero. Moreover, L_{1B} starts to be charged by the FC. L_{1B} voltage is equal to v_1.

By considering other inputs and applying volt-second-balance (VSB) principle to L_{1A} and L_{1B} voltages, the following equation can be written:

$$V_o(1-d_4) = \mathrm{V}_{FC}d_1 = \mathrm{V}_{bat}d_2 = \mathrm{V}_{UC}d_3 \tag{1}$$

Additionally, the output capacitor C_o current is equal to negative output current (I_o) when S_4 is on while it is equal to the difference between the sum of inductor voltages and output current. Therefore, based on amp-second-balance (ASB) principle, the relationship between average inductor currents (I_{L1}, I_{L2}, I_{L3}) and the output current can be obtained as in (2).

$$I_o = 2(I_{L1} + I_{L2} + I_{L3})(1-d_4) \tag{2}$$

Additionally, typical waveforms for the buck mode are given Fig. 3 (b). By analyzing six stages in this mode, one can derive the same equations with the ones given in (1) and (2). From (1), it can be seen that the converter operates in boost mode when 1-d_4 is lower than the duty cycle of input switches, otherwise it operates in buck mode.

B. ANALYSIS OF MODE-2

In this case, UC is charged by FC and battery thus L_{3A} and L_{3B} carry the UC charging current. By comparing this case and Case-1, the relationship between voltages in this case can be written as in (3).

$$V_o(1-d_4) = \mathrm{V}_{FC}d_1 = \mathrm{V}_{bat}d_2 = \mathrm{V}_{UC} \tag{3}$$

Moreover, the current equation in this stage is same with the one given in (2). Please note that I_{L3} is negative here.

C. ANALYSIS OF MODE-3

As declared, UC is charged by the regenerative braking energy in this mode by controlling S_5. The studied converter operates as a traditional buck converter; therefore the well-known voltage and current equations in (4) and (5) can be written for this mode.

$$V_o d_5 = V_{UC} \tag{4}$$

$$I_o = 2I_{L3} d_5 \tag{5}$$

III. FLC BASED EMS

The details of FLC based EMS is illustrated in Fig.4. As can be seen, first of all, a FLC produces a reference power (P_{ref}) according to levels of output power (P_o) and SOC of UC ($SOUC_{UC}$). Then, the reference of FC power ($P_{FC\text{-}ref}$) is determined by filtering P_{ref} through a low-pass filter (LPF) whose time constant is 5s. Then, the reference of battery power is obtained by filtering the difference between P_{ref} and $P_{FC\text{-}ref}$ through another LPF whose time constant is 2s. By this way, it is aimed to smooth FC and battery power levels. Fig.4 also shows the developed control strategy. In Mode-1 and Mode-2, d_1 and d_2 are determined by two separate proportional-integral (PI) controllers so as to regulate FC and battery power levels according to designated references by the proposed EMS. In Mode-1, another PI controller adjusts d_3 for the output voltage regulation to discharge UC accordingly. Moreover, d_4 is obtained based on the following equation which basically sets d_4 to the possible lowest value for maximizing the efficiency [15].

$$d_{4-opt} = 1 - \frac{min\,(v_{FC}, v_{bat}, v_{UC})}{v_{out}}\beta \tag{6}$$

In (6), β is the adjustment coefficient which is introduced to consider the voltage drops due to inductor resistances.

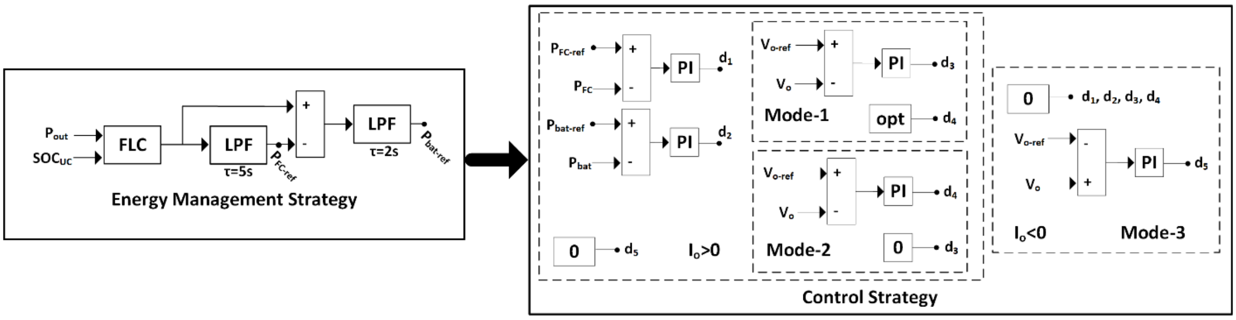

Figure 4 *The FLC based EMS and the control strategy.*

In Mode-2, another PI controller designates d_4 for transferring excessive energy to UC thus realizing output voltage regulation. Moreover, d_5 is controlled in Mode-3 for charging UC through regenerative braking energy. In this mode, a positive feedback of the output voltage is utilized for the voltage regulation.

The design procedure of FLC is conducted in Matlab by using Fuzzy toolbox. In Fig.5, the details of developed FLC is demonstrated. As seen, there are two input membership functions: SOC_{UC} and P_o. For SOC_{UC}, three input membership functions are designed: low (L), medium (M), high (H). Besides, 6 input membership functions are designed for P_o: regenerative (R), very low (VL), low (L), medium (M), high (H), very high (VH). The output membership function, P_{ref}, has 6 output membership functions, namely, idle (I), very low (VL), low (L), medium (M), high (H), very high (VH). Fig.5 also shows the determined rule base. Finally, the decision surface is formed as in Fig. 7 based on the membership functions and rule base. According to this figure, the maximum P_{ref} is 2500W which is equal to the maximum allowable power provided by FC and battery. Moreover, when SOC_{UC} increases, P_{ref} decreases, and vice versa, for regulating SOC_{UC}.

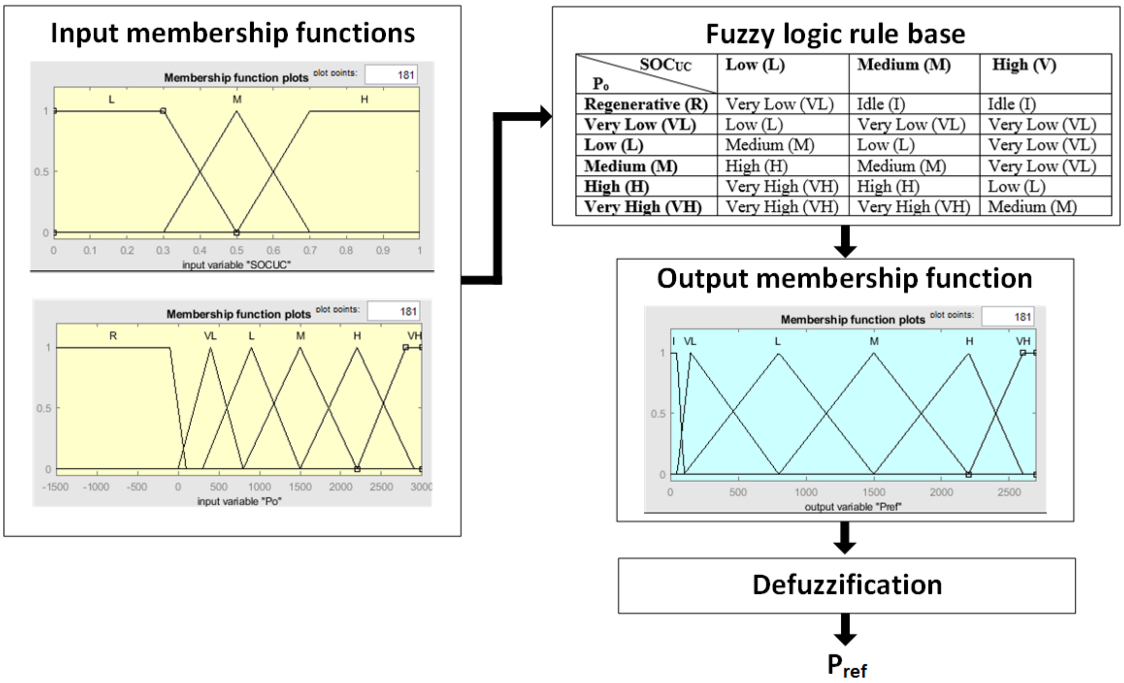

Figure 5. *Details of fuzzy logic controller.*

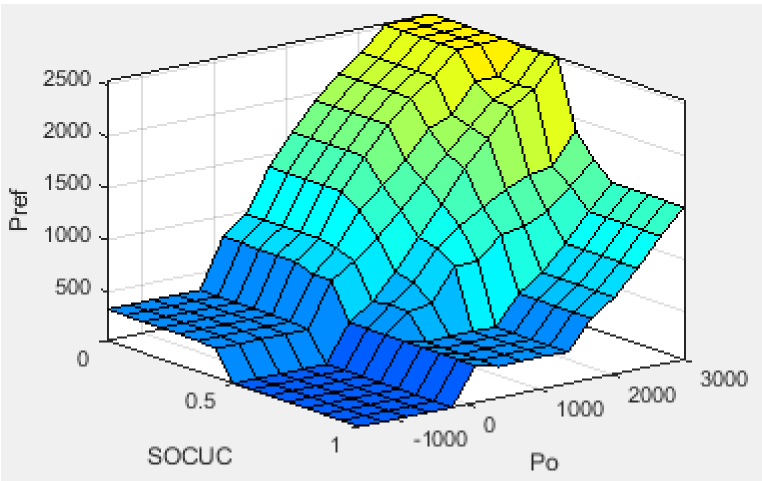

Figure 6. *Decision surface of fuzzy logic controller.*

IV. TEST AND RESULTS

Table 1. *System parameters.*

Element	Power	Voltage range	Max. current	Other parameters
FC	1.2kW	20-36V	60A	Nexa 1200, PEM FC
Battery	1kW	16-32V	60A	8x9, 3.7V, 3Ah Li-ion
UC	2kW	0-32V	90A	2x BMOD0500 P016 500F
Output	3kW	48V±4.8V	62.5A	-

In order to test the proposed EMS, a non-linear average model of the converter is built in Matlab/Simulink based on the parameters given in Table 1. For this task, the equations derived in Section II is modified. By assuming perfect current sharing between phases and considering the inductor internal resistances which are assumed to be equal, (7) and (8) are written for Mode-1.

$$
\begin{aligned}
I_{FC} &= 2I_{L1} = \frac{1}{L_1}\int (V_o - V_{FC}d_1 - 2I_{L1}R_{L1})dt \\
I_{bat} &= 2I_{L2} = \frac{1}{L_2}\int (V_o - V_{bat}d_2 - 2I_{L2}R_{L2})dt \\
I_{UC} &= 2I_{L3} = \frac{1}{L_3}\int (V_o - V_{UC}d_3 - 2I_{L3}R_{L3})dt \\
V_o &= \frac{1}{C_o}\int ([I_{FC} + I_{bat} + I_{UC}][1 - d_4] - I_o)dt
\end{aligned} \tag{7}
$$

For Mode-2, only the equation related to I_{UC} changes as given in (8) while others are same with the ones for Mode-1.

$$
I_{UC} = 2I_{L3} = \frac{1}{L_3}\int (V_o - V_{FC} - 2I_{L3}R_{L3})dt \tag{8}
$$

Similarly, the relationships given in (9) can be written for Mode-3.

$$
\begin{aligned}
I_{FC} &= 2I_{L1} = 0 \\
I_{bat} &= 2I_{L2} = 0 \\
I_{UC} &= 2I_{L3} = \frac{1}{L_3}\int (V_o d_5 - V_{UC} - 2I_{L3}R_{L3})dt \\
V_o &= \frac{1}{C_o}\int (I_{UC}\, d_5 - I_o)dt
\end{aligned} \tag{9}
$$

In the model, FC, battery and UC models are created as in [15]; moreover, a scaled power profile obtained according to Urban Dynamometer Driving Schedule (UDDS) is utilized. Two cases are considered in the simulation. In the first case, initial SOC_{UC} is 0.55, while it is 0.75 in the second case. By this way, it is aimed to evaluate the performance of the proposed EMS in terms of SOC_{UC} regulation. Figs. 7-9 show the simulation results.

In Fig.7, the output power and resultant source power variations are shown. As seen, the maximum output power is about 3kW while the maximum regenerative power is about 1kW according to scaled UDDS power profile. Moreover, one can observe that UC power profile exhibits sudden changes while FC and battery power profiles are smoothed as intended. When comparing the results retrieved for the considered two cases, it can be observed that FC and battery inject more power at the beginning of the simulation when the initial SOC_{UC} is set to 0.55 as an indication of charging of UC.

In Fig.8, the voltage levels of the output, FC and battery along with SOC_{UC} variations are given. First of all, it is clear that the output voltage regulation is realized in two cases. Furthermore, the voltage drops due to the internal resistances of the FC and battery can be observed. The battery final voltage is slightly lower when the initial SOCUC is 0.55 since it transfers more power to charge UC in this case. When it comes to SOC_{UC} variations, it can be clearly seen that the developed EMS in coordination with the proposed MPMIC achieves SOC_{UC} regulation for the studied cases.

The variations for d_4 and its optimum values determined according to (6) are demonstrated in Fig.9. At the beginning of the simulation, the optimum d_4 takes smaller values when the initial SOC_{UC} is 0.75 because of the higher UC voltages. After a while, the optimum d_4 values in two cases coincide with each other by validating the achieved SOC_{UC} regulation.

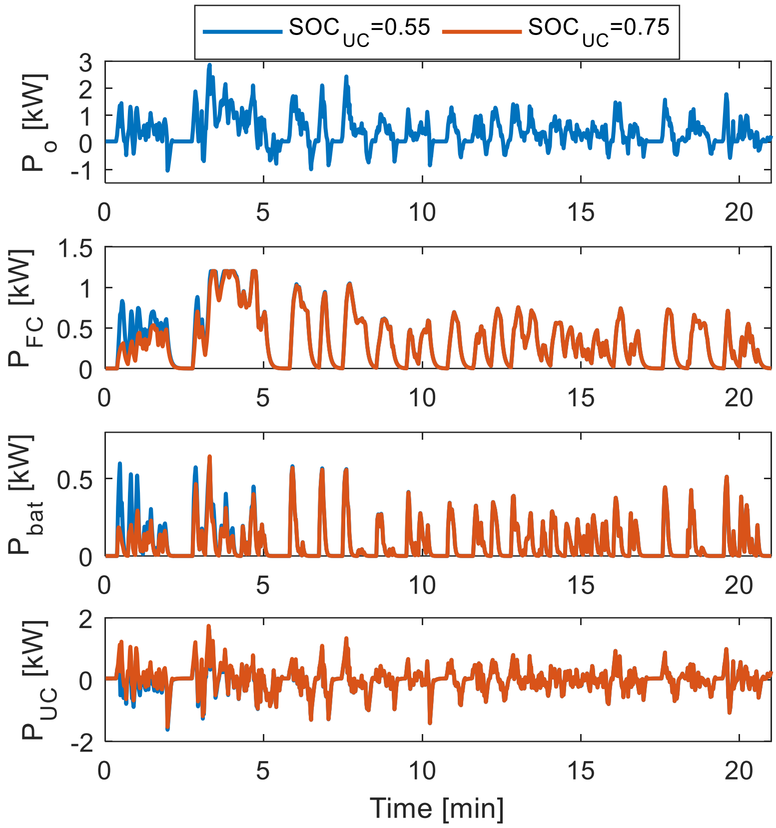

Figure 7. *Simulation results: power variations.*

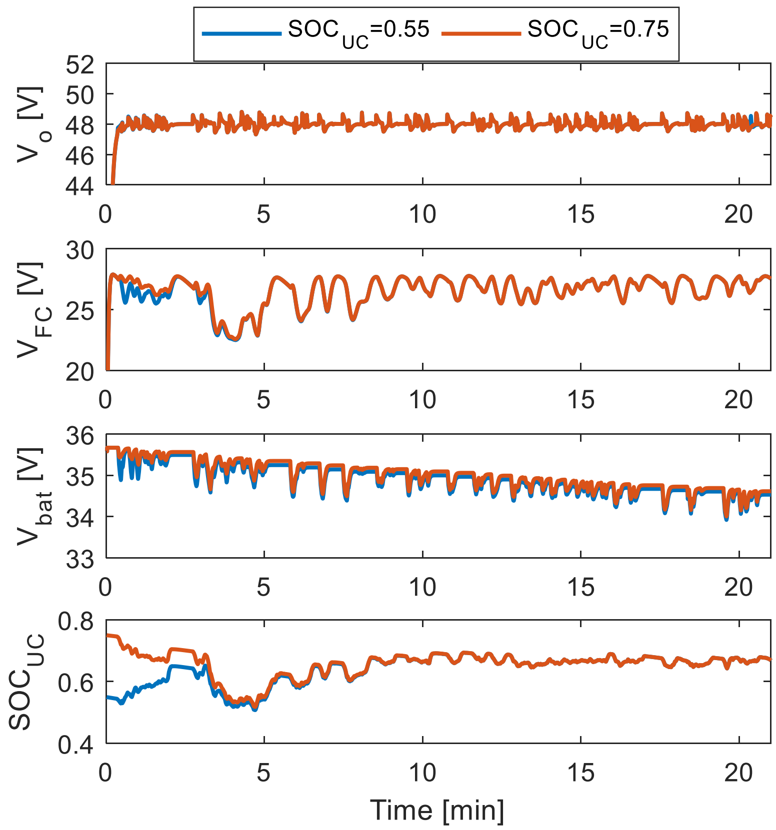

Figure 8. *Simulation results: voltage and SOC_{UC} variations.*

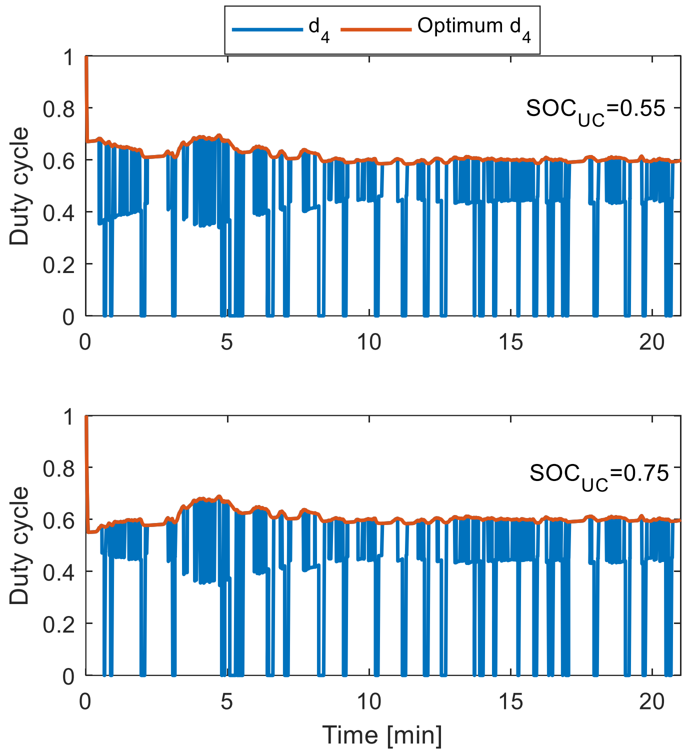

Figure 9. *Simulation results: d_4 and its optimum value variations.*

Finally, the frequency distribution of power profiles in the case of 0.55 initial SOC_{UC} are shown in Fig.10. From this figure, one can easily observe that FC power profile does not include high frequency components. Additionally, although the battery power profile includes slightly higher frequency components in comparison with the one of FC as dictated by the selected time constants of LPFs, its DC component is dominant. Moreover, unlike others, UC power profile involves high frequency components. Therefore, it is validated that UC fulfils the duty of keeping FC and battery safe from the transient power variations.

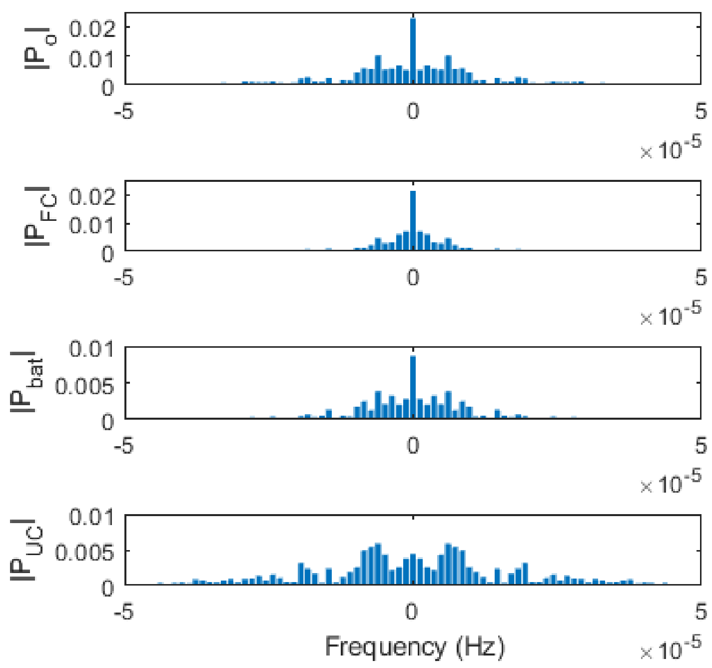

Figure 10. *Simulation results: frequency distributions of power variations.*

V. CONCLUSION

In this work, a FC/battery/UC HPS has been created through a MPMIC for a FCHEV application. Moreover, a FLC based EMS has been designed not only to smooth FC and battery power profiles but also to regulate SOC of UC. First of all, the analysis of the MPMIC has been presented. Then, the details of the developed EMS including the design procedure of membership functions of FLC and LPFs have been given. Finally, test results obtained from the simulation model of the system, consisting of the non-linear average model of MPMIC, models of the sources and FLC based EMS, have been discussed. It has been observed that the proposed converter successfully creates such a HPS. Moreover, it has been explored that the developed EMS achieves FC and battery power profile smoothing as well SOC regulation of UC.

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