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Research Article

Effect of Changes in the Parameters of a Modular Converter in Its Controllability Range in Fuel Cell Applications

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Abstract: In fuel cell systems, voltage balancing is an important consideration. The utilization of a modular construction based on a three-level boost converter was able to balance DC voltage. This paper investigates the effect of parameter variations, such as inductors and capacitors, on the converter's steady-state controllable areas. The plot of the inductor current and the voltages of the output capacitors are illustrated for different scenarios. The system simulation results were performed using MATLAB / Simulink software.

Keywords: Fuel cell modular converter, voltage balance, parameter changes, controllability.

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1. Introduction

Nowadays, the vital role of renewable energy in human life cannot be ignored. The fuel cell (FC) is a worthwhile energy-harvesting technology. It has attracted much attention in microgrid and electric hybrid vehicle applications [1, 2]. Much progress has been made in FCs, which has caused the formation of different types of FCs. Even though FCs have a great variety, they have the same operating principles and a high power density.

The polymer fuel cell (PEMFC) is popular among fuel cells [3]. Thanks to the solid electrolyte, PEMFC is shown high resistance to gas. PEMFC takes advantage of the reaction of hydrogen and oxygen to generate DC electric power. PEMFC can be set up quickly by taking advantage of low operating temperatures. These advantages cause this kind of FC in applications like vehicles and emergency systems which need high speed to be practical [3]. The advantage and disadvantages of PEMFC are enumerated in Table 1 [4-5]. Expanding the life of this type of FC is the major challenge of this technology. Although the oxygen and hydrogen inputs are connected to the FC stack in parallel, the electrical outlets are linked in series. The series connection is to boost the output voltage. Because of the series connection of cells, the whole system's lifespan depends on each cell's lifespan [6].

The phenomenon of the snowball effect is one of the significant challenges facing the FC. Fig. 1 shows the snowball effect in an FC. Chain reactions in this effect can lead to the destruction of the FC. One of the effective parameters in cell destruction is membrane drying.

Proper energy management can increase the life of any cell. One solution to prevent this is to regulate water as a product produced in the cell by regulating the FC current. A DC-DC converter can regulate current [7]. A particular unit assures water management in the fuel cell, but flow management is done with the assistance of a DC-DC converter.

DC-DC power converters are among the most important

Table 1: Advantages and disadvantages of PEMFC [4-5].

Advantages			
Good efficiency	Long life	Flexibility in use	Solid electrolyte
Non-corrosive electrolyte	Low operating temperature	Fast start-up	High power density
Consumable water producction	Simple design	Easy production	Resonable price
Disadvantages			
Sensitivity to carbon monoxide	High cost of catalysts	Limited manufacturers	Complexity of water management

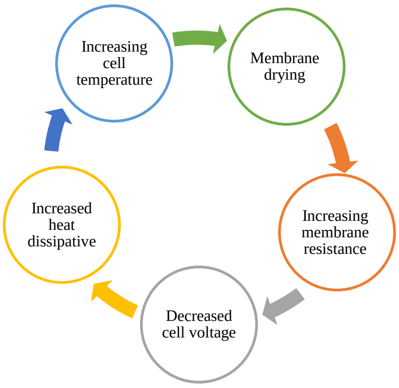


Fig. 1: Snowball effect in fuel cell.

and thought-provoking issues in hybrid systems [8]. These converters have various applications in different industries. The applications of these converters are listed in Fig. 2 [9-17].

A group of FC cells is connected in series to make an FC stack. Connecting each stack to its converter and the layout of output converters in series to DC-DC converters can effectively boost voltage [7, 18]. This structure is illustrated in Fig. 3. The possibility of controlling the output current of each cell individually in this method gives the freedom to manage and control the FC. This method can be used to solve the snowball effect.

Each FC stack operates independently according to its specific conditions. Therefore there is another new challenge. This problem occurs due to the voltage imbalance in output capacitors C1 to C4 (Fig. 3) caused by unequal stack power production. Risen stress on switches and power components and cell life reduction can be caused by voltage imbalance.

According to [18], a modular structure is suggested to solve the voltage imbalance problem in the photovoltaic system. This structure solves the problem of voltage imbalance by sharing a capacitor between two converters. Fig. 4 shows the considered structure consisting of two modules. Three capacitors are used in this circuit. The voltages of C_1 and C_2 and as well as C_2 and C_3, are equal. As a result, capacitor voltages C_1 and C_3 are equal. The equalization of the output voltages means that the voltage is balanced.

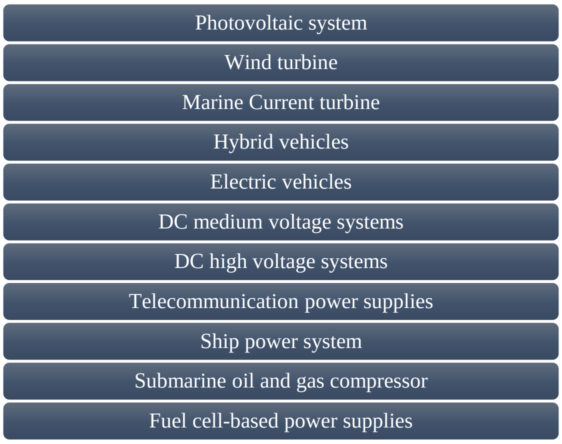


Fig. 2: DC-DC power converter applications [7-15].

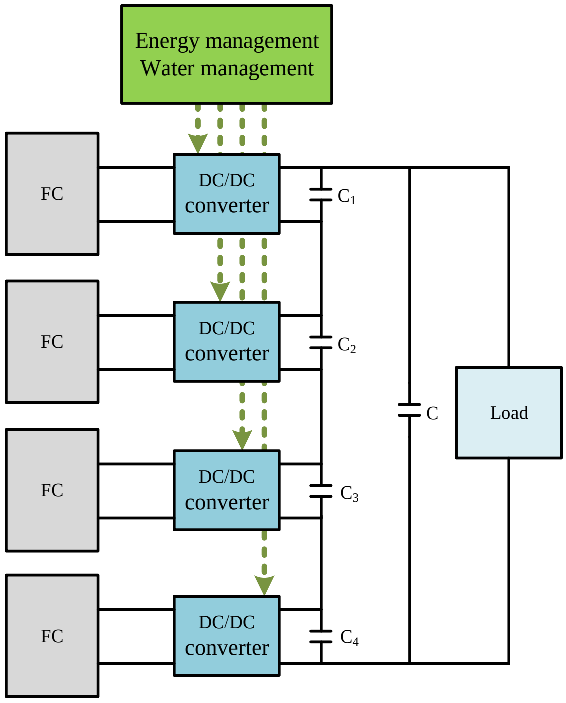


Fig. 3: Utilizing separate converters in the fuel cell.

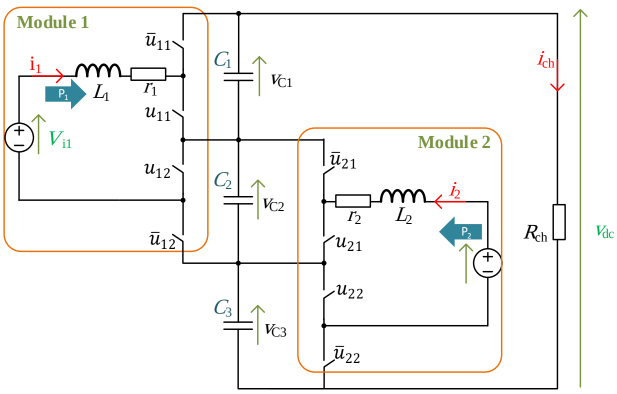


Fig. 4: Studied system: DC modular system.

Fig. 5 depicts some of the advantages of the researched structure in terms of modularity and the use of a three-level boost. The proposed system's shortcomings include a large

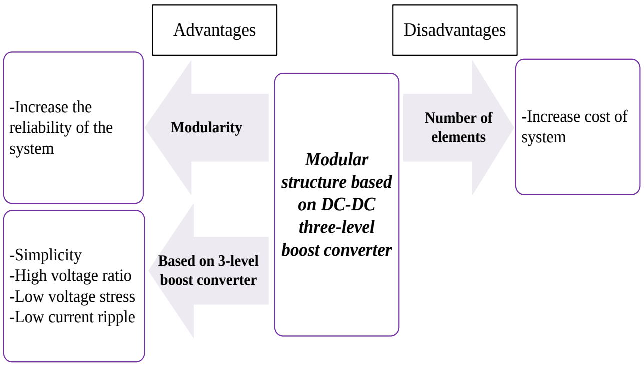


Fig. 5: Advantages and disadvantages of the studied structure.

number of switches, which raises the cost. However, despite these disadvantages, the use of this structure is justified.

The commandable areas of the considered converter in [7] are investigated. If the calculated duty cycles are between 0 and 1, the system is in the commandable areas.

The inductor and capacitor values can be planned by restricting the current ripple. Besides, they can be designed by choosing the high-frequency voltage ripple at a specific switching frequency. The inductor, capacitor, and frequency are determined using an optimization procedure that considers volume, cost, and efficiency limitations [19-20].

Because the parameters of each system will undergo possible changes in its operating point, in this paper, the change of capacitor and inductor values on the voltage balance of the system is investigated. In research [18], the capacitor and inductor values for both modules are considered equally. Moreover, in [18], the robustness of this modular converter and its sliding mode controller is investigated by changing the value of the capacitor and inductor change from 50% to 150%. Although, the effect of this change in these elements on the waveforms of inductor current or capacitor voltage and especially voltage balance is not considered. In this study, additional work was performed to further investigate and ensure that the performance of the system that we introduced in [18] does not affect by changes in capacitance and inductance, especially tracking reference currents and voltage balance.

According to Fig. 6, fuel cell systems deal with a snowball effect challenge that can damage fuel cells. To relieve this problem, separate converters might be utilized. Furthermore, boost converters are widely utilized in fuel cell systems since the output voltage is low. These converters can be coupled in series to enhance the produced voltage further. A voltage imbalance occurs in the system when a separate converter is used. Each FC may operate under different conditions and, therefore, has a different voltage at its output terminal.

The current and voltage waveform of inductors and capacitors are displayed in this paper to explore the influence of inductors and capacitor changes.

The paper structure is as follows: After reviewing the research literature in the introduction, the second part introduces the studied system. The governing equations of

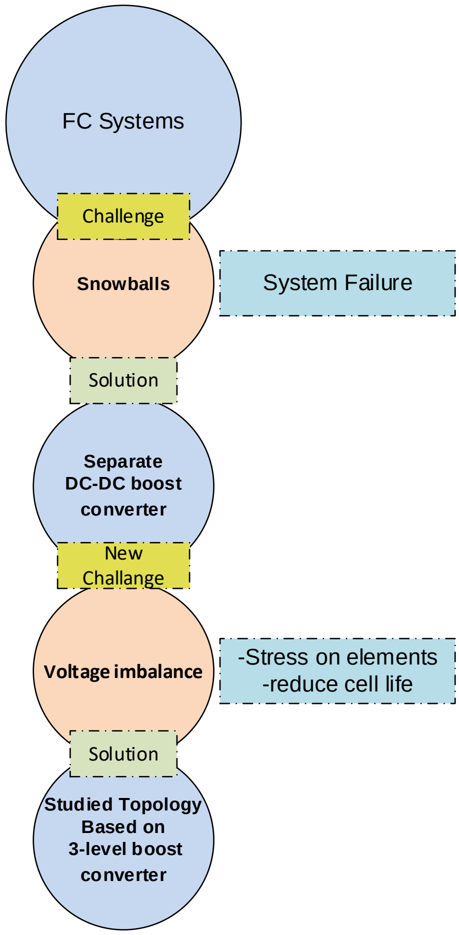


Fig. 6: Application of the studied structure in FC systems.

that system are recalled. In the third section, the results of the system simulation are shown. At the end is the conclusion.

2. Studied System

In this paper, the three-level modular converter is considered. Fig. 4 shows the studied system, which contains two modules.

An input voltage source, an inductor, and its switches are important elements that build a module.

Four switches exist in each module; two are main switches, and the others are complementary switches. The two main switches take advantage of the interleaving technique for making the command signals. In modulation, the signal phase of the first control signal shifts half the period to the second control signal.

The system incorporates five state equations shown in Table 2. The state variables are input inductors' currents and the other is capacitors' voltages.

3. Simulation of the System and Its Results

System simulation has been done with the use of MATLAB/Simulink software. A large-signal average model for the two-module system is used for simulation [18]. The simulation parameters are given in Table 3.

Table 2: System state equation.

Inductor	$L_1 \frac{di_1}{dt} = -r_1 i_1 + V_{i1} - (1-d_{11})v_{C1} - (1-d_{12})v_{C2}$
	$L_2 \frac{di_2}{dt} = -r_2 i_2 + V_{i2} - (1-d_{21})v_{C2} - (1-d_{22})v_{C3}$
Capacitor	$C_1 \frac{dv_{c1}}{dt} = (1-d_{11})i_1 - i_{ch}$
	$C_3 \frac{dv_{C3}}{dt} = (1-d_{22})i_2 - i_{ch}$
	$C_2 \frac{dv_{C2}}{dt} = (1-d_{12})i_1 + (1-d_{21})i_2 - i_{ch}$

Table 3: System parameters.

Parameter	Value
V_{i1}, V_{i2}	12 V
L_1, L_2	0.9 mH
r_1, r_2	0.06, 0.01Ω
C_1, C_2, C_3	100 µF
f_s	10 kHz
R_{ch}	8.52 Ω

Several scenarios are performed to change the values of inductors and capacitors. Table 4 is considered several cases. The simulation results for each case are presented in Figs. 10-14. In each figure, two operating points are considered for input power reference values (P_{ref}). For all figures, the power reference P_{ref} = 120 W for the upper figure (a) and P_{ref} = 500 W for the lower figure (b). As shown in Table 4, there is a normal case in which the parameters are at their nominal values. Only the capacitor or inductor is changed in other cases (Case 1, Case 2, and Case 3).

3.1. Normal Case

In this scenario, the current waveforms of the inductor and the voltage of the capacitor in a steady state are conducted without changing the parameter.

Fig. 7 shows the waveforms of the currents i_{L1} and i_{L2} and the corresponding reference currents, i_{ref1} and i_{ref2}. It can be observed that in both operating points (120 W and 500 W), inductor currents are tracking their reference current. Moreover, in those operating points, voltage balance is achieved, as V_{c1}, V_{c2} and V_{c3} are equal.

The voltage waveforms of capacitors C_1, C_2, and C_3 as a function of time are seen in Fig. 8.

3.2. First Case (Case1)

In this case, the common capacitor is changed. Figs. 9 and 10 display the voltage waveform of capacitors C_1, C_2, and C_3 as a function of time. In these two figures, the value of the common capacitor C_2 changes. In Fig. 9, by increasing the value of C_2, the ripple of its voltage decreases. In Fig. 10, voltage waveform increases rather than other capacitors. Nonetheless, the voltage balance is still achieved in increasing and decreasing values of capacitor and in both operating points (120 W and 500 W).

Table 4: Different scenarios.

Scenario	Changes		Value	Figure Number
Normal	Without change		*C_1=100 µF* *C_3=100 µF* *C_2=100 µF*	Fig. 7 Fig. 8
Case 1	Change C_2	Increase	*C_1=100 µF* *C_3=100 µF* ***C_2=200 µF***	Fig. 9
		Decrease	*C_1=100 µF* *C_3=100 µF* ***C_2 =50 µF***	Fig. 10
Case 2	Change C_1	Increase	*C_3=100 µF* *C_2=100 µF* ***C_1 =200 µF***	Fig. 11
		Decrease	*C3=100 µF* *C2=100 µF* ***C_1 =50 µF***	Fig. 12
Case 3	Change L_2	Increase	*L_1=0.9 mH* *L_2=2L_1*	Fig. 13
		Decrease	*L_1=0.9 mH* *L_2=0.5 L_1*	Fig. 14

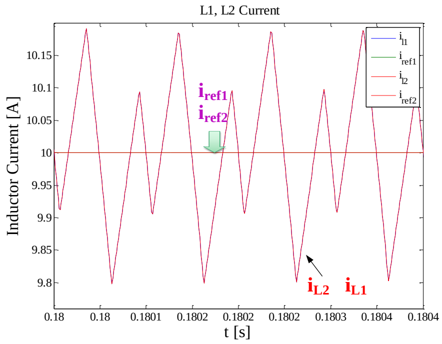
3.3. Second Case (Case 2)

In this case, the non-common capacitor is changed. Figs. 11 and 12 present the voltage waveform of capacitors C_1, C_2, and C_3 as a function of time. In these two figures, the value of capacitor C_1 changes. These figures represent that similar to Case 1, by changing the value of this capacitor, voltage balance is achieved, and changing this capacitor only changes the ripple of its voltage waveform.

3.4. Third Case (Case 3)

In this case, one of the inductors is changed. Figs. 13 and 14 illustrate the waveforms of the currents i_{L1} and i_{L2} and the corresponding reference currents, i_{ref1} and i_{ref2}. In these two figures, the value of inductor L_2 changes. In Fig. 13, the ripple of the current waveform is decreased due to the increase in the value of $L_{2.}$ In Fig. 14, L_2 is decreased, and its current waveform has larger ripples than L_1 current waveform. In both of them, tracking reference currents are done properly.

According to all the waveforms obtained from the simulation, it can be seen that changes in the value of the inductor or capacitor only change the current or voltage ripple. Changes in the parameters do not affect the voltage balance of the capacitors.



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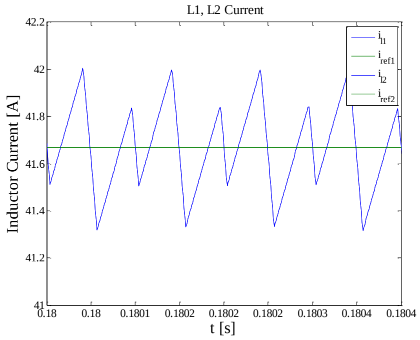
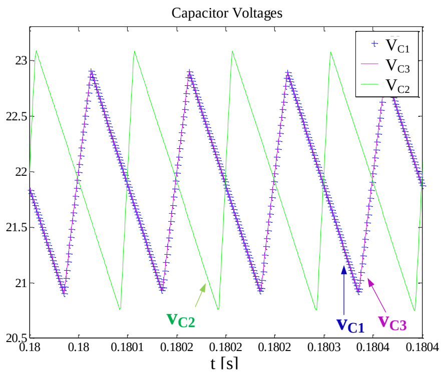


(b)

Fig. 7: Simulation waveforms: Inductor currents for L_1 and L_2 and related reference currents (normal state). Input power: (a) 120 W, (b) 500 W.



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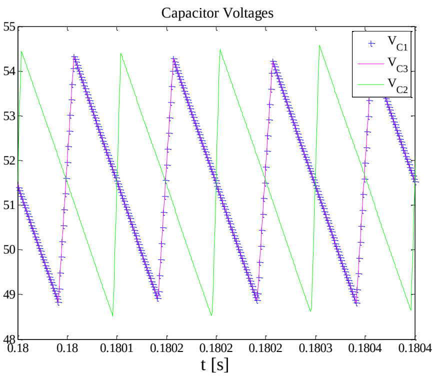

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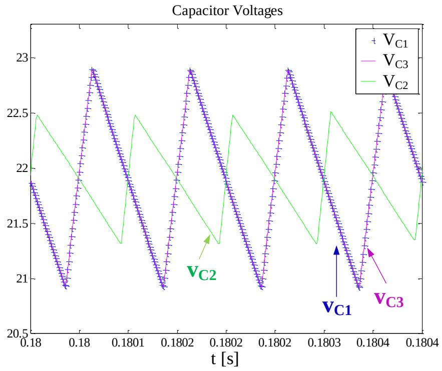
Fig. 8: Simulation waveforms: Voltage of capacitors C_1, C_2, C_3 (normal mode). Input power: (a) 120 W, (b) 500 W.



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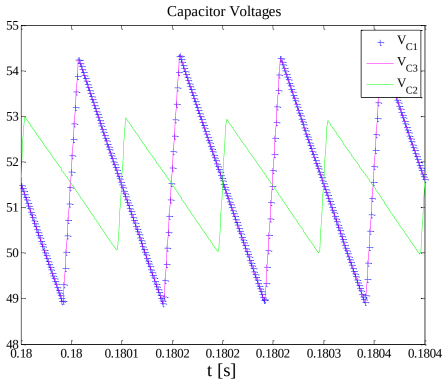
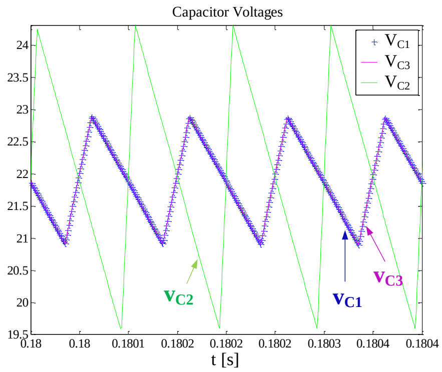


(b)

Fig. 9: Simulation waveforms: Voltage of capacitors C_1, C_2, C_3 first state (C_2 = 200 µF). Input power: (a) 120 W, (b) 500 W.



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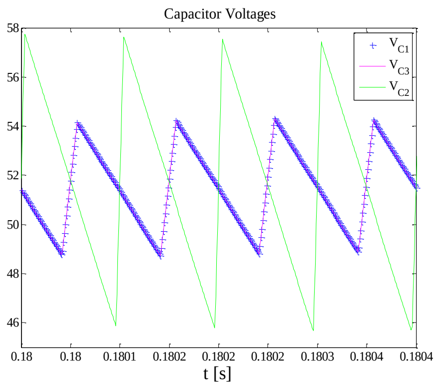
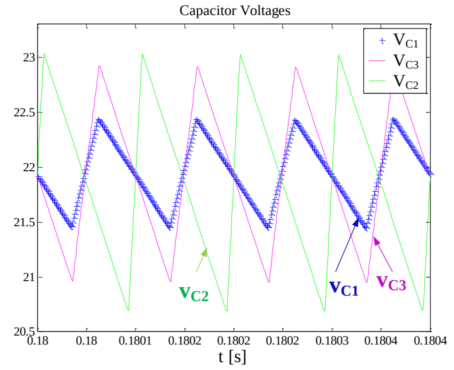


(b)

Fig. 10: Simulation waveforms: Voltage of capacitors C_1, C_2, C_3 first state (C_2 = 50 µF). Input power: (a) 120 W, (b) 500 W.



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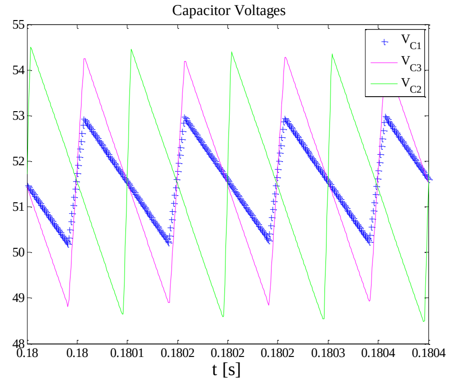

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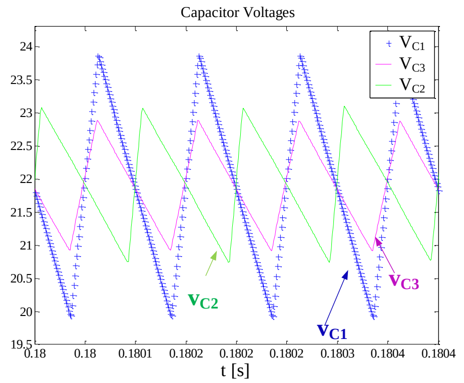
Fig. 11: Simulation waveforms: Voltage of capacitors C_1, C_2, C_3 second state (C_1 = 200 µF). Input power: (a) 120 W, (b) 500 W.



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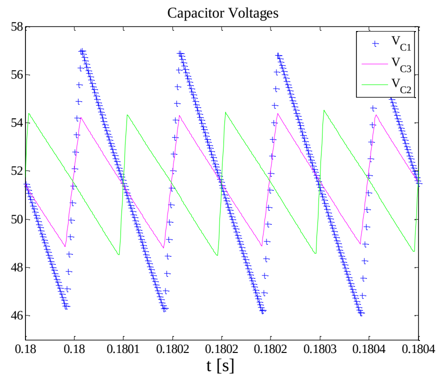
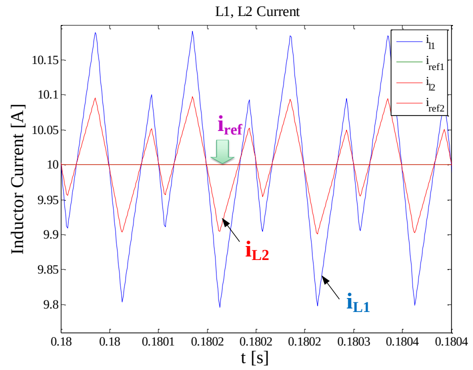


(b)

Fig. 12: Simulation waveforms: Voltage of capacitors C_1, C_2, C_3 second state (C_1 = 200 µF). Input power: (a) 120 W, (b) 500 W.



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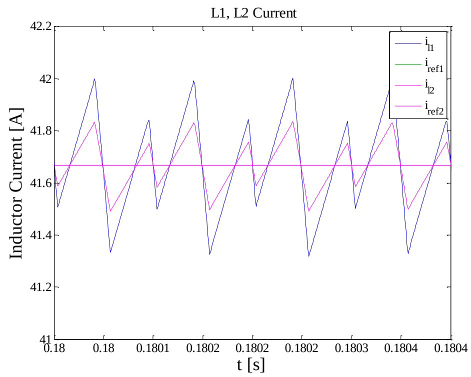
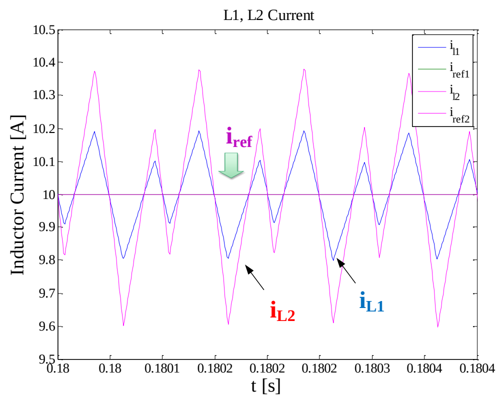


(b)

Fig. 13: Simulation waveforms: currents of L_1 and L_2 inductors and related reference currents (third case) ($L_2 = 2L_1$). Input power: (a) 120 W, (b) 500 W.



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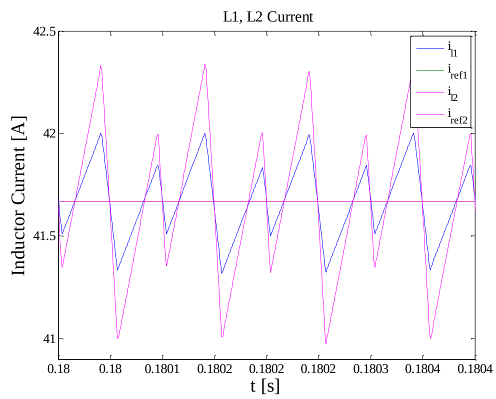

(b)

Fig. 14: Simulation waveforms: currents of L_1 and L_2 inductor and related reference currents (third case) (L_2 = 0.5L1). Input power: (a) 120 W, (b) 500 W.

4. Conclusion

In this paper, a DC modular converter is considered to balance the output voltage. This converter can be used in fuel cell applications. In several scenarios, the values of the inductors and the capacitors of the modules changed. Using MATLAB/Simulink software, the waveforms of the system are plotted. The simulation results are performed on the variation in capacitor and inductance to investigate their modification effects. It was observed that changing the values of capacitors and inductors had no effect on the capacitance-voltage balance in the steady-state regime. As a result, the inductance (L) and capacitor (C) values do not affect the controlled zones.

CRediT Authorship Contribution Statement

Mohammad Afkar: Conceptualization, Data curation, Investigation, Software, Visualization, Writing - original draft, Writing - review & editing. **Parham Karimi:** Conceptualization, Data curation, Investigation, Visualization, Writing - review & editing. **Roghayeh Gavagsaz-Ghoachani:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing - review & editing. **Matheepot Phattanasak:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - review & editing. **Serge Pierfederici:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

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BIOGRAPHY

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