

Average Modeling of Parallel Three-Level Boost Converters for Maritime Fuel Cell Applications

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ABSTRACT - Hydrogen fuel cells are emerging as a key technology for a greener and more sustainable future. The paper explores a multi-stack hydrogen fuel cell system applied on a maritime transport (1 kV, 1 MW). The study addresses two main challenges: the high power demand of the heavy-duty transport and the efficient management of the power supplied by the sources. To meet these requirements, the proposed architecture is based on a parallel configuration of three-level boost converter. The results obtained from the average model approach are then compared to those derived from an instantaneous model incorporating pulse-width modulation. The results validate the average modeling approach, which offers significantly faster simulations and proves useful for control law design.

Mots-clés—Three level boost converter, multi-stack system, hydrogen fuel cell, average model, energy management.

1. INTRODUCTION

Hydrogen fuel cells (FCs) have emerged as a promising solution, attracting significant attention from researchers and key players in the energy transition [1]. A key focus in these efforts is the transportation sector, which accounts for over a quarter (25.8%) of the EU's total greenhouse gas emissions [2]. Nowadays, hydrogen fuel cells are increasingly recognized as a sustainable and effective approach to reduce emissions, particularly in the heavy-duty vehicle (HDV) sector, aligning with the environmental objectives set for 2050 [3].

Hydrogen-powered heavy-duty vehicles (HDVs) present significant challenges due to their substantial power requirements, which can reach several megawatts. To address this, various initiatives have been introduced or are in progress within the heavy road transport sector [3]. Although advancements in hydrogen applications for maritime transport remain limited, ongoing research is actively exploring its feasibility in this domain [4].

Various system architectures have been explored to identify the optimal topology for each application [5]. The proposed study focuses on a 1 MW maritime transport system designed with two fuel cell (FC) stacks. Each stack is

integrated with a three-level boost converter to enhance power output and facilitate efficient power management. To meet the total power demand, these subsystems—comprising the FC stack and converter—are connected in parallel.

In this paper, it is assumed that the fuel cells have different state of health, reflected in varying heat levels. To facilitate the cooling process [6], a loss balance strategy is implemented [7].

Most studies rely on the instantaneous models seeking a precise analysis, such as in [8,9]. However, the average model represents many advantages. Although it sacrifices details and precision, this approach allows to considerably reduce the computational effort, leading to shorter simulation times [10]. The aim of this paper is then to study an average model of a parallel configuration of three-level boost converters, which closely matches the instantaneous model's behavior.

The first step is to study the architecture and formulate the average model. Next, the system's behavior will be validated through comparison with the results obtained from the instantaneous model results. Once the model is validated, a realistic maritime profile will be considered and the loss balance strategy will be applied to the system.

The paper is divided into four sections. The first section highlights the parallel topology of three-level boost converters. The second section focuses on the development of the average model system. In the third section, simulation results and their analysis are presented, by comparing them to the instantaneous results. In the last section the conclusion is given.

2. SYSTEM DESCRIPTION

In this paper, a hydrogen fuel cell source is considered. Each stack is characterized by the following linear equation based on the inflection point method [11].

$$v_{FC} = E_0 - R_{FC} i \quad (1)$$

With

v_{FC} the fuel cell voltage (V),

E_0 the open-circuit voltage (V),

i the operating current (A) and

R_{FC} the equivalent resistance of the FC (Ω).

Each stack is connected to a three-level boost converter (TLBC). The use of TLBC reduces the switches' voltage stress and allows individual management of the power delivered by each source [12]. The subsystems (FC and its TLBC) are interconnected in parallel as shown in Fig. 1 which has a high level of fault tolerance.

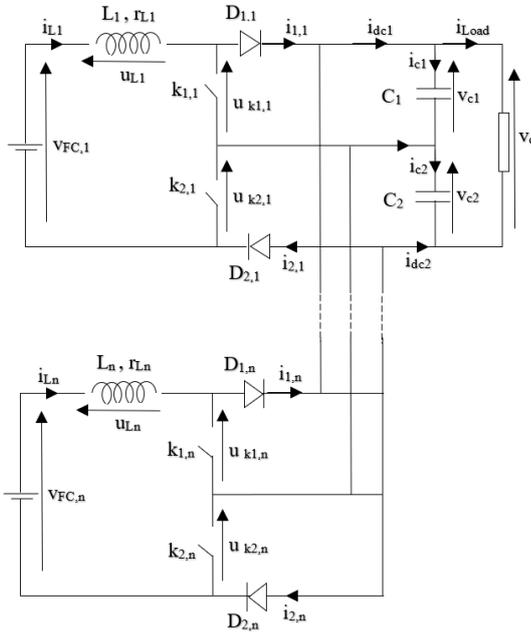


Fig. 1. System architecture.

In the paper, it is considered that the stacks have a different state of health leading to unbalanced losses in case of a uniform distribution of the fuel cell stack currents. For that, an original power management, based on a better losses distribution between fuel cell stacks, has been proposed in [7]. But to validate such energy management laws, it is necessary to simulate the system over relatively long periods of time, ranging from a few tens of minutes to a few hours. Such a simulation is too long with an instantaneous model, which takes into account the power stages and their associated modulations. It is why an average model of such interleaved three-level boost converter is proposed in this work.

3. AVERAGE MODEL

After thoroughly understanding the system, the average model is developed. For an easier analysis only one subsystem is considered. It is assumed that $k_{1,1}$ and $k_{2,1}$ are controlled switches of the first converter. The average model is defined based on four states (Fig. 3):

- State 1: Both $k_{1,1}$ and $k_{2,1}$ are ON.
- State 2: $k_{1,1}$ ON and $k_{2,1}$ OFF.
- State 3: $k_{1,1}$ OFF and $k_{2,1}$ ON.

- State 4: Both $k_{1,1}$ and $k_{2,1}$ are OFF.

During a switching period, duty cycles are defined. They are aimed to control the state of each switch.

- $(dc)_{1,1}$ defines, in average, how long the switch $k_{1,1}$ remains open during a switching period.
- $(dc)_{2,1}$ defines, in average, how long the switch $k_{2,1}$ remains open during a switching period.

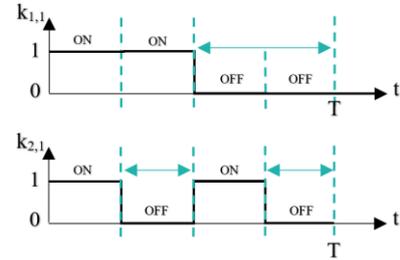


Fig. 2. The sequences.

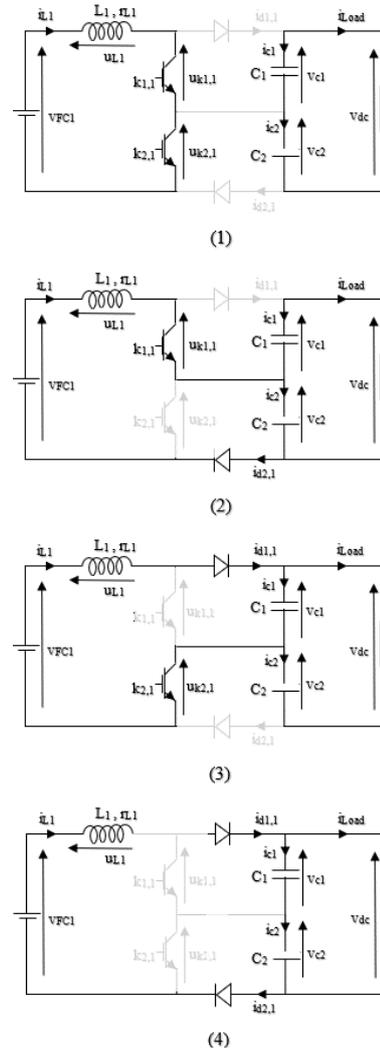


Fig. 3. The four studied phases.

A state-space representation is derived for each operating state. The equivalent system, by considering perfect switches and average model, is as follows:

$$\frac{dI_{L1}}{dt} = \frac{1}{L_1} (E_{0,1} - (R_{FC1} + r_{L1}) I_{L1} - (dc)_{1,1} V_{C1} - (dc)_{2,1} V_{C2}) \quad (1)$$

$$\frac{dV_{c1}}{dt} = \frac{1}{C_1} ((dc)_{1,1} I_{L1} - I_{Load}) \quad (2)$$

$$\frac{dV_{c2}}{dt} = \frac{1}{C_2} ((dc)_{2,1} I_{L1} - I_{Load}) \quad (3)$$

With

r_{L1} the resistance of the inductor (Ω),

I_{L1} the average input current (A),

I_{Load} the average current through the load (A),

$V_{c,1}, V_{c,2}$ the capacitors voltages (V) and

V_{dc} the output voltage (V), defined as follows:

$$V_{dc} = V_{c1} + V_{c2} \quad (4)$$

Based on the state-space equations, the matrix system (5) is obtained.

$$\begin{pmatrix} \frac{dI_{L1}}{dt} \\ \frac{dV_{c1}}{dt} \\ \frac{dV_{c2}}{dt} \end{pmatrix} = \begin{pmatrix} I_{L1} \\ V_{c1} \\ V_{c2} \end{pmatrix} = \begin{pmatrix} \frac{-(R_{FC1} + r_{L1})}{L_1} & \frac{-(dc)_{1,1}}{L_1} & \frac{-(dc)_{2,1}}{L_1} \\ \frac{(dc)_{1,1}}{C_1} & 0 & 0 \\ \frac{(dc)_{2,1}}{C_2} & 0 & 0 \end{pmatrix} \begin{pmatrix} I_{L1} \\ V_{c1} \\ V_{c2} \end{pmatrix} + \begin{pmatrix} \frac{1}{L_1} & 0 \\ 0 & \frac{-1}{C_1} \\ 0 & \frac{-1}{C_2} \end{pmatrix} \begin{pmatrix} E_{0,1} \\ I_{Load} \end{pmatrix} \quad (5)$$

$$A((dc)_{1,1}, (dc)_{2,1}) = \begin{pmatrix} \text{diag}\left(\frac{-(R_{FCi} + r_{Li})}{L_i}\right) & \frac{-(dc)_{1,1}}{L_1} & \frac{-(dc)_{2,1}}{L_1} \\ \dots & \dots & \dots \\ \frac{(dc)_{1,1}}{C_1} & \dots & \frac{(dc)_{1,n}}{C_1} & 0 & 0 \\ \frac{(dc)_{2,1}}{C_2} & \dots & \frac{(dc)_{2,n}}{C_2} & 0 & 0 \end{pmatrix} \quad (6)$$

$$X = \begin{pmatrix} I_{L1} \\ \dots \\ I_{Ln} \\ V_{c1} \\ V_{c2} \end{pmatrix}, \quad B = \begin{pmatrix} \text{diag}\left(\frac{1}{L_i}\right) & 0 \\ \dots & 0 \\ 0 & \dots & 0 & \frac{-1}{C_1} \\ 0 & \dots & 0 & \frac{-1}{C_2} \end{pmatrix}, \quad u = \begin{pmatrix} E_{0,1} \\ \dots \\ E_{0,n} \\ I_{Load} \end{pmatrix} \quad (7)$$

The model is then generalized to any number (n) of parallel TLBC. It is written as follows:

$$\dot{X} = A((dc)_{1,i}, (dc)_{2,i}) X + B u \quad (8)$$

With

\dot{X}, u an $(n+2) \times 1$ and $(n+1) \times 1$ matrixes defined in (7)

$A((dc)_{1,i}, (dc)_{2,i})$ an $(n+2) \times (n+2)$ matrix, defined in (6) with $i = \{1, \dots, n\}$ and

B an $(n+2) \times (n+1)$ matrix, defined in (7)

4. SIMULATION RESULTS

4.1. Without regulation

Once the average model is conceived, it is important to validate it. The validation is ensured by comparing both behaviors of the average model and the instantaneous model.

In the average model we only need to inject the duty cycles to the system (Fig. 4). While in the instantaneous model, the duty cycles are converted into sequences ($k_{1,i}$ and $k_{2,i}$), Fig. 2, with the use of a pulse width modulator (PWM). Each signal defines, in real time, whether the switch should be opened (0) or closed (1) (Fig. 5).

In this part the duty cycles $(dc)_{1,i}$ and $(dc)_{2,i}$ are set to 0.5. To test the dynamical response of the model a 5% perturbation is introduced at the time 0.2s.

$$\text{Perturbation: } (dc)_{1,i} = (dc)_{2,i} = (1 + 5\%) 0.5$$

In this part only two TLBC in parallel are considered for an easier analysis. In the given results (Fig. 6), it is assumed that the open-circuit voltage of each stack is 250 V. It is also considered that the stacks have different states of health: $R_{FC,2} = (1 + 5\%)R_{FC,1}$.

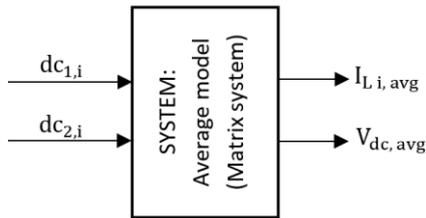


Fig. 4. The average model.

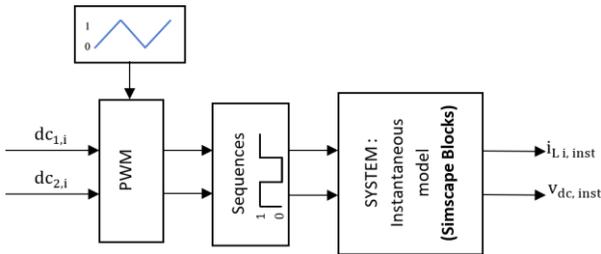


Fig. 5. The instantaneous model.

The average model and the instantaneous model results are in accordance even when a variation is considered. The differences noticed are due to the consideration of the current ripple losses in the second approach.

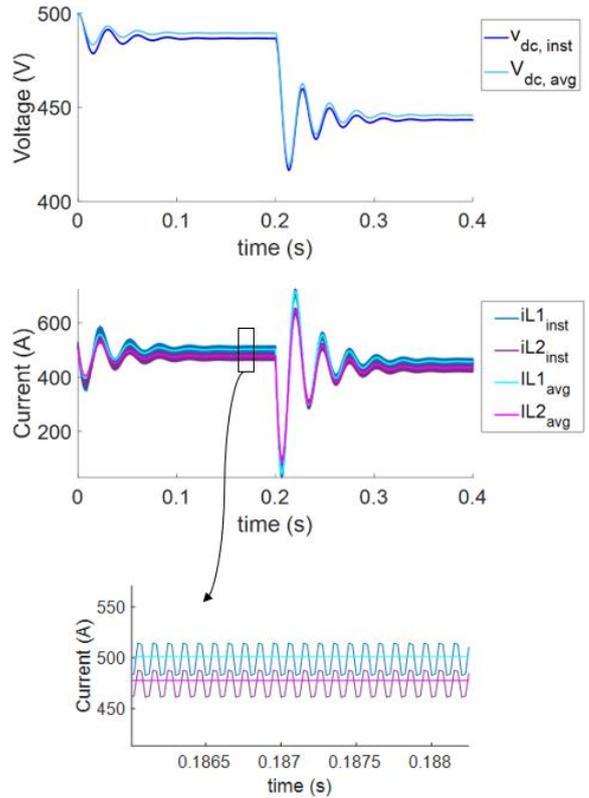


Fig. 6. The simulation results without any regulation.

4.2. With regulation

4.2.1. Voltage and current regulation

This average model is aimed to be applied to maritime applications. For a realistic study, a realistic power profile of 6h48min, given by the CEA, is considered (Fig. 7). Furthermore, the dc bus voltage (V_{dc}) reference is fixed at 1000 V.

In this part, only two TLBC in parallel are considered for an easier analysis of the system's behavior.

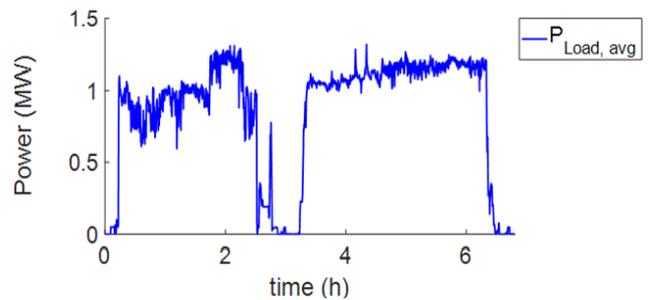


Fig. 7. The maritime profile.

To ensure power demand is met, a control system is implemented and a power management is ensured, Fig. 2. The power management is detailed in [10].

In this part, the average model system is linked to the control system to maintain the fulfillment of the maritime transport demand as shown in Fig. 8.

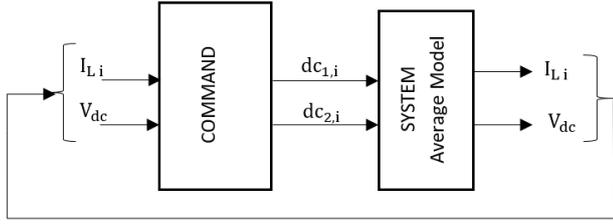


Fig. 8. The instantaneous model.

4.2.2. Voltage balance system

In this paper a three-level boost converter is used. To take advantage of this architecture it is important to ensure a voltage balance between the capacitors. This balance reduces the voltage stress on the switches.

The capacitors voltages are mainly dependent on the duty cycles that controls the switches state. If an unbalance occurs, it means that one of the switches contributes more than another in charging one of the capacitors.

Based on (2) and (3) it is clear that the state of charge of the first capacitor depends on $(dc)_{1,i}$ and the second capacitor on $(dc)_{2,i}$. In other words, to ensure the voltage balance the difference (Δdc) between both duty cycles, of the same converter, should be adjusted (Fig. 9). With Δdc proportional to $V_{c,1} - V_{c,2}$.

In this part, it is assumed that:

- $(dc)_{1,i} = (dc)_i - \Delta dc$
- $(dc)_{2,i} = (dc)_i + \Delta dc$

Which mean that:

- Case 1: If $V_{c,1} < V_{c,2}$, the charging contribution of the first capacitor should be increased, and decreased for the second, accordingly.
- Case 2: If $V_{c,1} > V_{c,2}$, the contribution in the charge of the first capacitor should be decreased and conversely for the second.

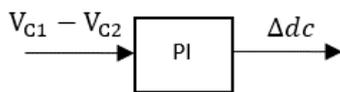


Fig. 9. The voltage balance system.

The result of the voltage balance system, Δdc , is injected to the command's outputs to apply the needed adjustments (case 1 and case 2) as shown in Fig. 10.

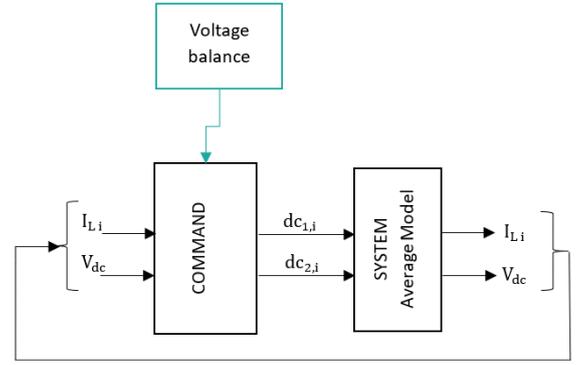


Fig. 10. The voltage balance system.

4.2.3. Results

In the following results, it is noticed that the maritime transport's demand is ensured. The output voltage is maintained at 1000 V as wanted. Despite the fluctuations due to the variable power demand (Fig. 7), the overall behavior remains stable. Furthermore, the capacitor voltages are balanced to ensure a reduced voltage stress on the switches as shown in Fig. 11.

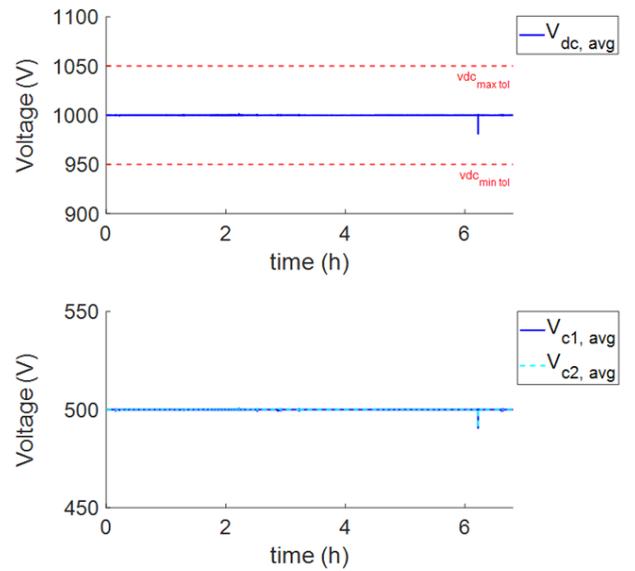


Fig. 11. The simulation results with bus regulation.

Besides, the loss balance strategy is properly implemented. The losses are maintained balanced. In other words, a uniform distribution of the considered losses is insured. Furthermore, the more the stack is deteriorated the lower is its current delivered by the sources (Fig. 12). The average model allowed to easily simulate the system's behavior over a long period of time, such as 6 hours 48 minutes.

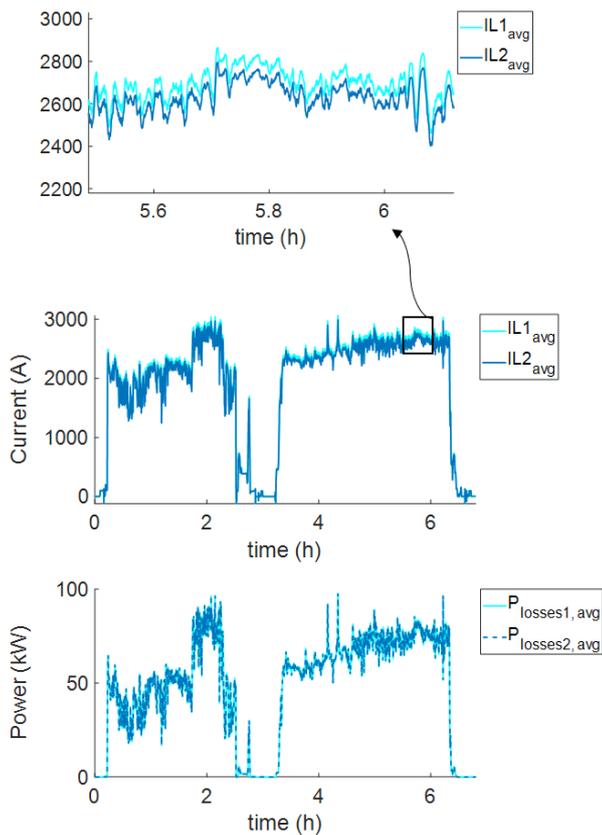


Fig. 12. The simulation results with bus regulation.

5. CONCLUSIONS

The paper studies architecture based on the parallelization of three-level boost converters. The analysis is done by adopting an average model approach. The results are then compared to the instantaneous model results.

The average model is a simplified approach compared to the instantaneous model that is considered complex but accurate. To leverage the advantages of both, it is interesting to develop an average model that approximates the overall behavior of the instantaneous model. The paper validates the model under normal conditions. Further validation is planned for faulty cases.

This study explores hydrogen fuel cell-powered heavy maritime transport. It addresses unbalanced losses in fuel cell stacks due to varying states of health. To optimize loss distribution, a power management strategy from [10] is considered. Since long-term simulations are required for validation, an average model is proposed to reduce computational complexity.

First, an analysis was conducted by imposing the duty cycles. The average model was validated by comparing its behaviour with the instantaneous model. Next, for a more realistic case study, a voltage demand was fixed at 1000 V and a real power profile was considered and simulated. This study considers only two fuel cells to simplify the analysis. As a

result, the required currents were relatively high. However, in practical applications, a larger number of stack is used.

Beside these studies, an experimental validation of the system is planned. This step will help validate the theoretical work done.

6. ACKNOWLEDGEMENT

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