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Minimising the effect of degradation of fuel cell stacks on an integrated propulsion architecture for an electrified aircraft

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***Abstract*—Proton Exchange Membrane Fuel Cells (PEMFC) are receiving interest as an electrical source of energy for aircraft propulsion electrification. However, their implementation challenges such as durability, reliability, and the dynamic behaviour of Fuel Cells (FCs) in an integrated hybrid propulsion system have not been fully explored. Currently, most commercial PEMFC stacks have maximum power close to 150kW. To achieve higher power required for aviation, these stacks can be connected in series and parallel to achieve high voltage required for propulsion. Poor design procedure of cells and stacks can cause variation between the stacks resulting in failure and fast degradation of the connected stacks. In this paper the impact of voltage and current drop of one stack, which could be caused by changes in the fuel cell's individual axillary parts, degradation of the cells within the stack, or faults in the connections and distribution is explored. Upon exploring different configurations, it is found that the arrangements of FC stacks connections could help in reducing the impact of voltage and current variations due to degradation in each stacks. The imbalance stack performance and its effects on the whole energy storage system performance is not fully explored before. It is important to conduct quantitative analysis on these issues before the PEMFC system can be implemented.**

***Index Terms*—Fuel cells, degradation, propulsion, electrified aircraft**

I. INTRODUCTION

The durability of fuel cells (e.g PEMFC) is one of the key factors which prevents them to be financially viable for commercial electrified aircraft. A service life lower than 3000 h is reported for automotive industry, where lower power (close to 150kW) FC stacks are required [1].

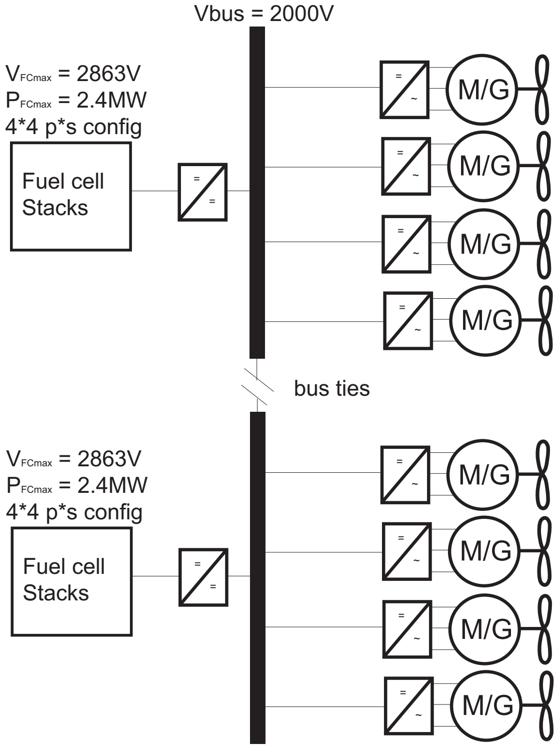


Fig. 1: An example of a propulsion system with FC stacks at high voltage. A DC/DC converter is used to maintain the bus voltage at 2000V. Eight permanent magnet synchronous machines were designed for 500kW power at rotational speed of 2000RPM.

To achieve higher system efficiencies and propulsion performance, the balance of plant in the FC system is of paramount importance. For example, performance loss can be minimized at high altitude and inclination by adjusting cathode stoichiometric ratio. Also the quality of oxygen-depleted air can be improved by controlling operating temperature and stoichiometric ratio [2]. These adjustments require real-time sensing [3] and an adaptive control, which adds complexity to the system design. Adjusting the FC system configurations for minimising the effect of failure and degradation, in addition to defining and exploring techniques for FC system prognostics can reduce system complexity and increase reliability. In the process of certifying FCs special attention needs to be made for parameters that cause starvation and FC failure, such as: poor design procedures of cells, machining with uneven mass distribution in flow fields, poor stack design, assembly with uneven flux distribution between cells, poor water management with channel block by flooding, inadequate pressure, poor heat management in cold startup with ice blocking, and misoperation with sub-stoichiometric gas feeding [4].

To consider FC driven propulsion systems, with 4MW shaft power from the electrical motors system, the propulsion power is provided only by the PEMFC stacks. The effect of degradation on efficiency and dynamic performance of the proposed electrical architecture is explored. The methods for configuring the stacks to reduce power losses and damage to the rest of nearby connected stacks are investigated. In this study the reduction of weight in comparison to a conventional propulsion system has not been investigated. A 4.8MW fuel cell stack system is chosen as an example to demonstrate the effect of voltage variations at high level distribution voltage. PEMFC is selected for this study as an example due to its technical maturity and commercial availability to be analysed for degradation and failure modes.

II. PROPULSION SYSTEM

A parallel hybrid-electric architecture was already investigated for various energy management strategies by Andrea et al [5]. In this work, a fully electrified propulsion system (Fig. 1) is considered to demonstrate the interactions between the FC stacks and the rest of the propulsion system (DC/DC converter, inverters, motors and propellers). Two DC bus at 2000V are connected with bus ties. Two identical 2.4MW energy sources are considered, only the results from one half are shown due to symmetry. Since the focus of this paper is on demonstrating the FC degradation for different configurations, the components are not sized for weight minimisation. The FC, the electrical system and the hydrogen tank weights are estimated using some typical/representative power densities and the estimated additional system weight is added to the operating empty weight of the baseline aircraft.

A. *Mission*

FC retrofit aircraft model was considered based on ATR42 [6]. The propeller behaviour was modelled using MIT's Qmil/Qprop tool [7] for propeller design and propeller performance analysis. The produced propeller maps were integrated into Hermes [8], an in-house aircraft performance and flight path analysis platform in the Centre for Propulsion Engineering at Cranfield University. The flight mission specifications for this analysis are included in Table I and the flight profile is presented in Fig. 2.

Range	300 nmi	Payload	3500 kg
Calibrated Climb Speed	160 kts	Cruise Mach	0.46
Take-off Weight	17913 kg	Cruise Altitude	19000 ft

TABLE I: Flight mission specifications

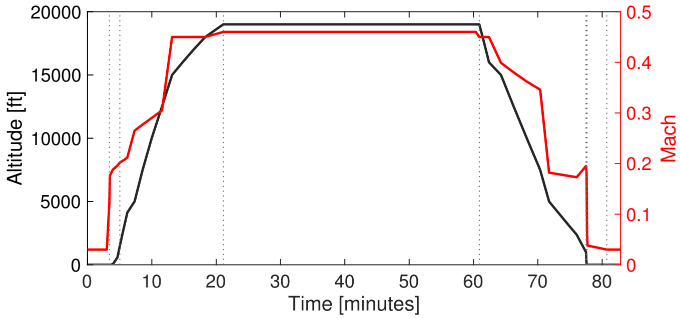


Fig. 2: Altitude and Mach variations for the duration of the flight.

III. MODELLING AND RESULTS

The electrical components such as DC/DC converters, inverters, and the electrical machines are modelled and implemented along with the FC stack model. A DC/DC buck/boost converter is modelled and the efficiency is calculated. To capture the DC/DC bidirectional converters characteristics, a converter efficiency expression is proposed. The efficiency is determined by voltage ratio between the output of the fuel cell stack V_{FC} and the bus voltage V_{bus}. Generally, the converter exhibits higher efficiency when V_{FC} is close to V_{bus}. A PI closed loop controller is adapted to maintain the bus voltage at 2000V over different power requirements. A dq model is used to capture the behaviour of the Permanent Magnet Synchronous Machine (PMSM). The rotational speed is controlled by traditional $id = 0$ strategy to minimize the d-axis current losses of the PMSM. the inverter efficiency is considered fixed at 98%. FCvelocity®-HD6 PEMFC stack operating points are chosen for this study. The FC stack modelling is presented in details in Fig. 3. Equations of key components and component specifications are presented in details in Appendix.

A. *Degradation analysis*

Depending on the configuration of the fuel cell stacks, voltage levels (for stacks in series) or current levels (for stacks in parallel) need to be maintained. If the voltage output of a FC stack on a series branch reduces due to degradation, other FC stacks need to increase their voltage level to maintain the voltage of the branch. However, if the voltage of a FC stack

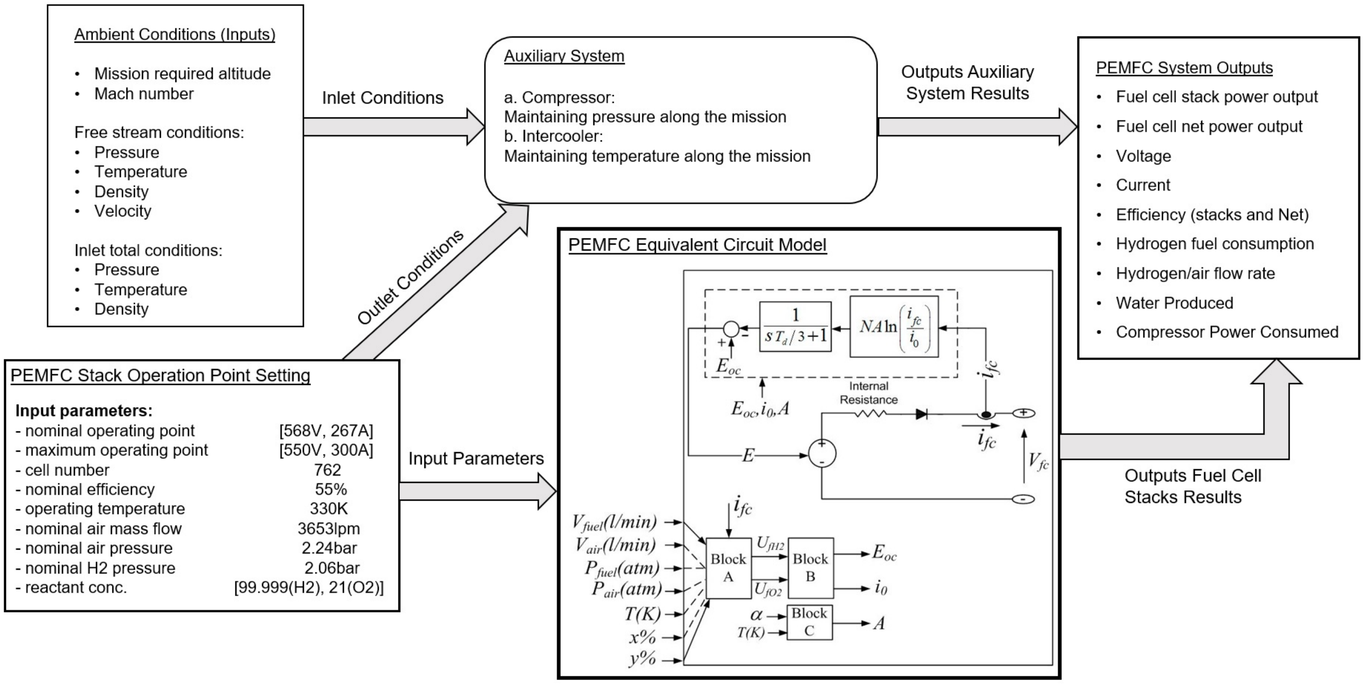


Fig. 3: The inputs and outputs to the FC system model. The FC model is adopted from existing MATLAB model published in [9].

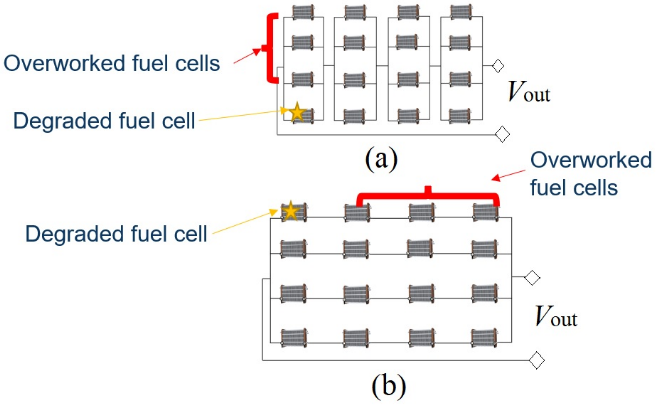
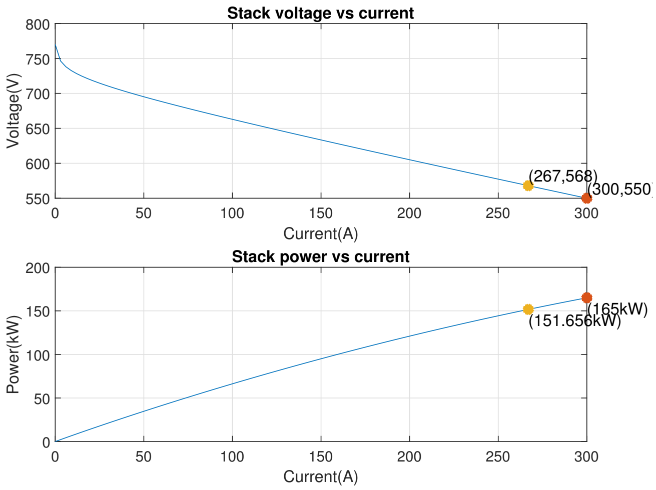


Fig. 4: (a) Parallel-Series case (b) Series-Parallel case, where the stacks are connected in series then parallel.

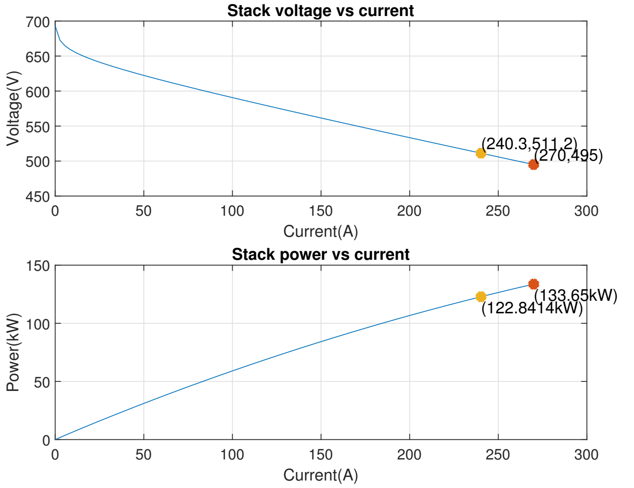
on a parallel branch reduces then the current output of the other FCs need to be increased to maintain the current. Two different configurations are shown in Fig. 4. Configurations that the FC stacks are connected in series first and then in parallel are less affected by the degradation of one FC stack on a specific branch. This is due to the fact that FC stacks are designed to be a voltage source, hence the voltage of each stack can be increased before it reaches its maximum voltage to compensate for the reduction of voltage FC stacks.

To emulate the degradation behaviour in one cell, the voltage and current of stacks are limited by 10% reduction compared to a healthy normal stack. The characteristics of a healthy and degraded stack are shown based on V-I, and P-I curve in Fig. 5. Efficiencies, power generated by FC stacks and its net power, voltage and current across one FC stack, bus current and voltage are shown in Fig. 6. FC system's net efficiency is computed, when the input power required to run the auxiliary system is deducted from the power output of the stacks. 10% voltage and current reduction for one of the stacks in the Series-Parallel and Parallel-Series cases as shown in Fig. 4 are applied and the variation in the FC efficiencies are shown in Fig. 7. Voltage and current values of the FC stacks for two proposed configurations along the flight mission are shown in Fig. 8a and 8b. Normal FC refers to a stack that is operating in a normal condition and it is not in the same branch as the degraded FC stack. Normal FC connected to the degraded FC stack refers to the overworked stack that is connected in series or parallel to the degraded stack.

There is an efficiency drop for the Parallel-Series case where the current in the stack could not reach the required value. However, in the Series-Parallel case the efficiency is only dropped slightly due to the reduction in the stack's output voltage. The Series-Parallel case is recommended as the configuration, where the system efficiency and reliability are less affected by the degradation in one FC stack.

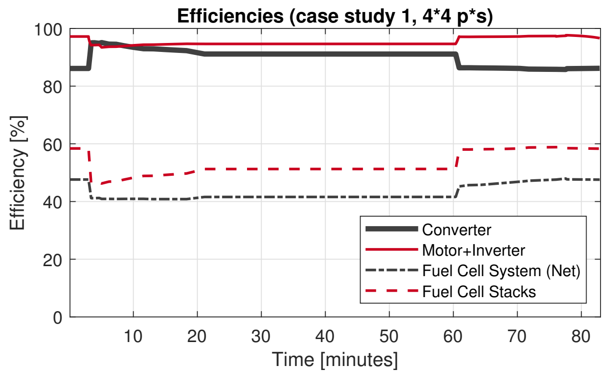


(a) Healthy FC stack outputs.

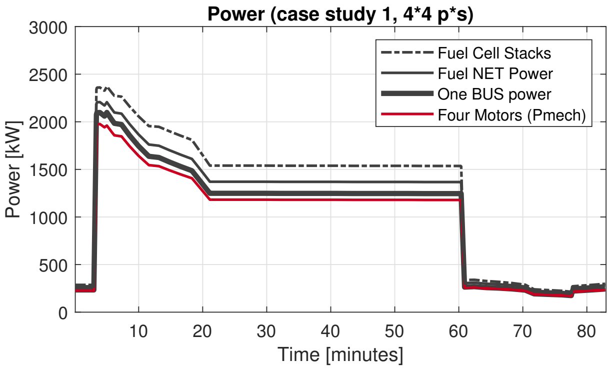


(b) FC stack with voltage and current reduction due to degradation.

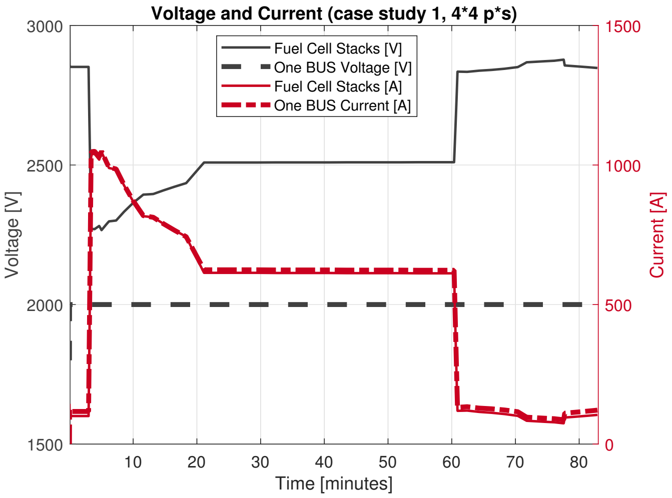
Fig. 5: Voltage-Current and Power-Current simulated results for one FC stack.



(a) Efficiencies from healthy FC stacks.

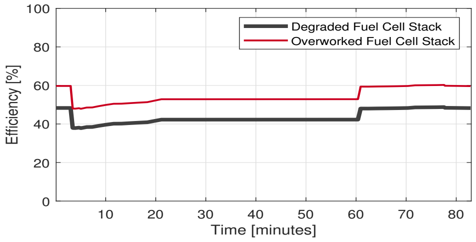


(b) Power from healthy FC stacks.

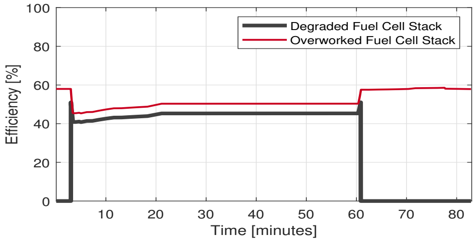


(c) Voltage and current values of healthy stacks.

Fig. 6: Efficiencies, power, and voltage values of the components of the proposed propulsion system for the duration of the flight. All FC stacks are considered healthy. FC system's net efficiency is computed, when the input power required to run the auxiliary system is deducted from the power output of the stacks.

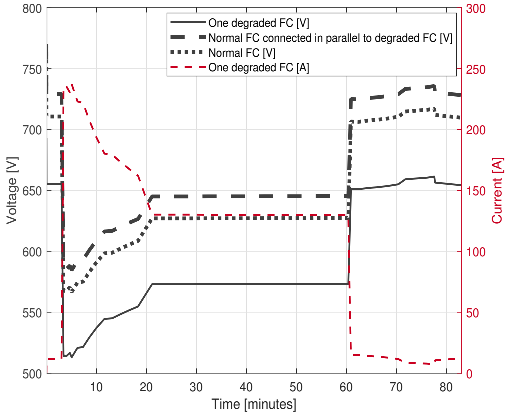


(a) Series-Parallel case

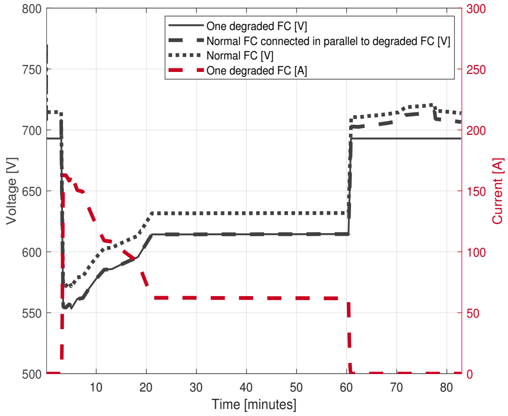


(b) Parallel-Series case

Fig. 7: Efficiencies of the FC stacks for the duration of flight for a degraded and overworked fuel cell stacks.



(a) Series-Parallel case.



(b) Parallel-Series case.

Fig. 8: Voltage and current outputs for two proposed cases

IV. CONCLUSION

In this paper, a 4 MW-scale pure PEMFC propulsion system has been developed for regional aircraft. The developed simulation framework enables system performance evaluation for various energy propulsion system configurations. In the simulation, the imbalance stack performance due to fuel cell voltage and current degradation, and its influence on the propulsion system have been evaluated. Upon exploring two proposed FC stack configurations, it is found that the fuel cell stack imbalance performance has less impact on system efficiency and reliability for Series-Parallel configuration than that for Parallel-Series.

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V. APPENDIX

A. PEMFC Equations

The PEMFC equations are adapted from [9], where the output voltage equation is expressed as:

$$V_{fc} = E_{oc} - V_{ohmic} - V_{act} \tag{1}$$

where V_{fc} is the fuel cell voltage, E_{oc} is fuel cell open-circuit voltage, V_{ohmic} and V_{act} are the ohmic and activation over-potential.

The open-circuit voltage is expressed as:

$$E_{oc} = K_c \left[1.229 + (T - 298) \frac{-44.43}{zF} + \frac{RT}{zF} \ln \Big(P_{H_2} P_{O_2}^{\frac{1}{2}} \Big) \right] \tag{2}$$

where K_c is the voltage constant at nominal condition, T is the fuel cell operating temperature, z is the moving electron number, F is the Faraday constant, R is the universal gas constant, and P_{H_2} and P_{O_2} are gas partial pressure.

The ohmic and activation over-potentials are expressed as:

$$V_{act} = \frac{1}{\tau s + 1} N A \ln \left(\frac{i_{fc}}{i_0} \right) \tag{3}$$

$$V_{ohmic} = R_{ohmic} i_{fc} \tag{4}$$

where τ is the fuel cell dynamic time constant, N is the cell number, R_{ohmic} is the stack inner resistance, and i_{fc} is the fuel cell current. The Tafel slope A and exchange current i_0 are expressed as follows:

$$i_0 = \frac{zFk(P_{H_2} + P_{O_2})}{Rh} e^{(-\triangle G/RT)} \tag{5}$$

$$A = \frac{RT}{z\alpha F} \tag{6}$$

where k is the Boltzmann's constant, h is the Planck's constant, and $\triangle G$ is the activation energy barrier.

$$\eta_{FC,stack} = \frac{P_{stack,tot}}{\dot{m}_{H_2} \triangle h_{HHV,H_2}} \tag{7}$$

$$\eta_{FC,system} = \frac{P_{stack,tot} - P_{BoP}}{\dot{m}_{H_2} \triangle h_{HHV,H_2}} \tag{8}$$

where $\eta_{FC,stack}$ and $\eta_{FC,system}$ are fuel cell stack and system efficiency, $P_{stack,tot}$ and P_{BoP} are stack and balance of plant power, $\dot{m}_{H_2}$ is the supplied hydrogen fuel flow rate, and h_{HHV,H_2} is the hydrogen higher heating value (HHV) [10].

B. Compressor Equations

Generally, compressor accounts for most balance of plant work [10]. The compressor equations are expressed as follows [11]:

$$P_{BoP} = P_C = \frac{c_{p,air} T_{C,in}}{\eta_C} \left[CPR^{\frac{\gamma - 1}{\gamma}} - 1 \right] \dot{m}_{air,C} \tag{9}$$

$$CPR = \frac{P_{C,out}}{P_{C,in}} = \left(\frac{T_{C,out}}{T_{C,in}} \right)^{\frac{\gamma}{\gamma - 1}} \tag{10}$$

where P_C is the compressor power, $c_{p,air}$ is the air specific heat capacity, $T_{C,in}$ is the inlet total temperature, η_C is the compressor adiabatic efficiency, CPR is the compressor pressure ratio, γ is the air specific heat ratio, $\dot{m}_{air,C}$ is the air mass flow rate, $P_{C,out}$ is the output total pressure, $P_{C,in}$ is the inlet total pressure, and $T_{C,out}$ is the output total temperature.

C. PMSM Equations

The PMSM equations [12] are expressed as follows:

$$\frac{\mathrm{d}i_d}{\mathrm{d}t} = \frac{1}{L_d} v_d - \frac{R_c}{L_d} i_d + \frac{L_q}{L_d} p \omega_m i_q \tag{11}$$

$$\frac{\mathrm{d}i_q}{\mathrm{d}t} = \frac{1}{L_q} v_q - \frac{R_c}{L_q} i_q - \frac{L_d}{L_q} p \omega_m i_d - \frac{\lambda p \omega_m}{L_q} \tag{12}$$

$$T_e = 1.5p[\lambda i_q + (L_d - L_q) i_d i_q] \tag{13}$$

$$\eta_{motor} = \frac{T_m \omega_m}{1.5(v_d i_d + v_q i_q)} \tag{14}$$

where i_d and i_q are motor dq currents, v_d and v_q are motor dq voltages, L_d and L_q are motor dq inductances, R_c is the motor armature resistance, p is the motor pole pair, ω_m is the motor mechanical angular velocity, λ is the magnetic flux linkage, T_e is the motor electric torque, η_{motor} is the motor efficiency, and T_m is the motor shaft mechanical torque.

D. Bidirectional DC/DC Converter Equation

The proposed converter efficiency equation is:

$$\eta_{converter} = 1 - 0.9 \left| ln \left(\frac{V_{fc}}{V_{bus}} \right) \right| \tag{15}$$

E. Component Specifications

Symbol	Description	Value
T	Fuel cell operating temperature	$330K$
N	Fuel cell stack number	762
z	Moving electron number	2
τ	Fuel cell dynamic time constant	$0.1s$
η_C	Compressor adiabatic efficiency	85% [13]

TABLE II: PEMFC system specifications

Symbol	Description	Value
V_{bus}	Bus voltage	$2000V$
$\eta_{inverter}$	Inverter efficiency	98%
L_d	D-axis inductance	$12e^{-5}H$
L_q	Q-axis inductance	$12e^{-5}H$
R_c	Motor armature resistance	0.02Ω
p	Motor pole pair	16
λ	Magnetic flux linkage	$0.1Wb$

TABLE III: Bus line, inverter, and PMSM specifications

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