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MODELING AND SIMULATION OF A SUSTAINABLE EXTENDED RANGE ENHANCED ELECTRIC VEHICLE

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Abstract. *The global demand for energy and the environmental impact study of fossil fuel consumption has gained worldwide attention due to its importance and is a topic of ongoing discussion among researchers and policymakers. Proposing an alternative and environmentally friendly energy source is therefore of utmost relevance in promoting sustainable mobility. This project proposes the development of a solution for a connection and charging control system for electric vehicle range extenders using sustainable hydrogen generation and the use of fuel cells. The system to be studied includes a 5kW PEMFC, powered by a sustainable aluminum-based hydrogen generator delivering 70A at 72V, and commonly, electric vehicle high voltage systems are designed above 300V and up to 900V, requiring a system that can accommodate charge transfer between the fuel cell and the electric vehicle. The innovation of this project lies in the absence of a "off the shelf" ready to use solution available on the market and the need for control over different requests and specific operating conditions. For the study, a demonstrator electric vehicle with a range extender system is under construction, where experimental data such as power, voltage and current will be collected to assist in the development of a Matlab Simulink model for simulating operation and determining control parameters. The model includes a closed-loop PID controller driving a boost-type DCDC converter to increase the voltage from 72V to 350V. Its sizing must cover the operating range of both the fuel cell (60V to 110V) and the vehicle (280V to 400V) simultaneously. Preliminary results of this model show a good level of conversion and stability for an output voltage range around 350V using a PI type controller, with convergence to the reference output voltage in less than 5s.*

Key words: *Sustainable mobility, connection system, load control, Simulink model, electric vehicle.*

1. INTRODUCTION

The global demand to transition from fossil fuels to renewable and low-impact energy sources has been increasing over time, driven by UN policies such as the Sustainable Development Goals (SDGs) 2030, which aim to reduce non-renewable energy consumption and promote sustainable change (Lúcia, 2013). The current market is already witnessing the introduction of new technologies and products that seek to bring about transformative change, as exemplified by the automotive sector's efforts to replace fossil fuels with all-electric, CO2-free systems (Ruojinga, 2023).

However, the growing use of electric vehicles has brought challenges related to the availability of charging points and the still limited batteries range, necessitating the development of new solutions.

One way to increase autonomy and reduce anxiety about the need for recharging is to adopt a range extension system, which may consist of an external traction battery, production of electrical energy through a high-efficient internal combustion engine or even a fuel cell.

These complementary systems (range extenders) that incorporate fuel cell devices to power batteries expand new possibilities to improve and enable the use of electric vehicles (Júnior, 2019).

The connection system under study in this article aims to integrate and make the fuel cell compatible with the electric vehicle, being capable of managing the input voltage variation (coming from the fuel cell) with the high voltage bus of the vehicle's traction battery, which must be constant and stable to ensure efficient and safe load transfer.

The objective of this article is to study, simulate and propose a solution for transferring electrical energy from a PEMFC to a traction battery of an electric vehicle. For this, a MatLab Simulink model was used to determine the system topology, components and study of the controller's PI parameters using the Ziegler Nichols methodology.

The simplified scheme of the proposed system can be seen in Figure 1.

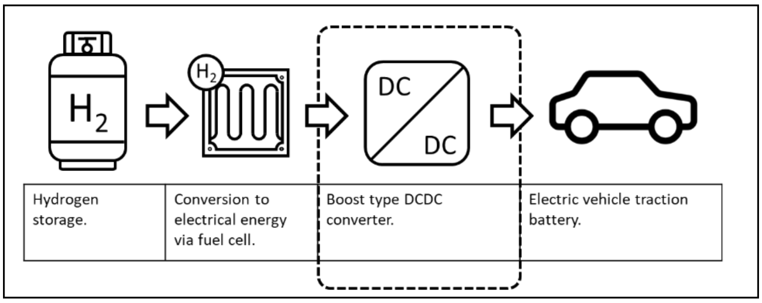

Figure 1. Simplified system diagram.

2. MATERIALS AND METHODS

2.1 Fuel Cell

Fuel cells are electrochemical devices that convert chemical energy into electrical energy, capable of providing large amounts of energy quickly, safely and cleanly. The most common and commercially available fuel cell systems involve proton exchange membrane fuel cells (PEMFCs), which operate using only hydrogen and oxygen gases. These fuel cells operate at low temperatures and their reaction products consist only of water and released energy, making the device extremely clean (Atyabi, 2019).

The fuel cell used to study this article is the Horizon FCS-C5000 and has a polarization curve between 115V (in open circuit) and 60V (shutdown voltage), which depends on the flow of hydrogen and charge, with 72V being its nominal operation point, delivering 70A of current in full load. Its characteristics are summarized in Table 1 and the polarization curve is in Figure 2.

Table 1. Characteristics of the Horizon FCS-C5000 fuel cell.

Parameter	Value
Type of fuel cell	PEM
Number of cells	120 cells
Rated Power	5000W
Performance	72V @ 70A
Reactants	hydrogen and Air
Efficiency of stack	40% @ 72V
Low voltage shut down	60V

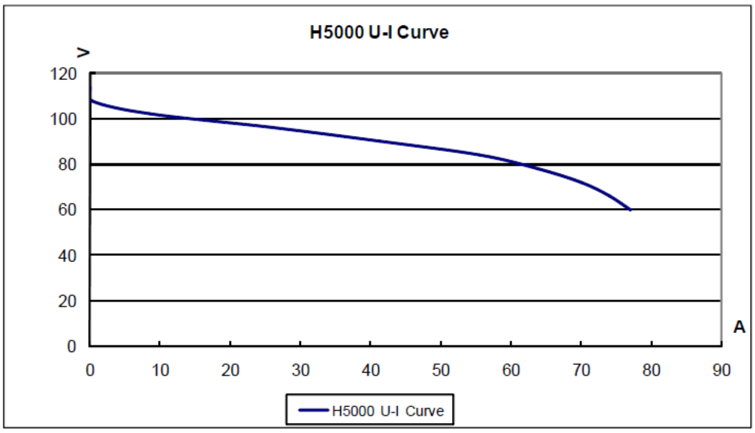

Figure 2. Voltage vs current polarization curve.

2.2 Electric vehicle

Vehicles with electric powertrains are designed for zero-emission mobility and have advantages that include zero emissions, high energy efficiency, lower operating costs, quiet performance, reduced dependence on oil, tax incentives, simplified maintenance, convenient recharging at home, advanced technology, and smooth driving due to its instant high torque.

Electric vehicles commonly available on the market have a high voltage battery for traction and these systems have operating voltage characteristics commonly above 300V and can reach up to 900V.

High voltage systems are used to increase power transmission efficiency, reducing power losses and allowing for lighter, more compact components. This results in more energy-efficient vehicles with greater range.

The vehicle used for the study is the Renault Zoe, which has a 400V high voltage system with a 100% charged battery. Its characteristics are summarized in Table 2.

Table 2. Features traction battery electric vehicle Renault Zoe.

Parameter	**Value**
Chemistry	Lithium - Ion NCM 712
Energy	52.2kWh
Voltage range	400V
Nominal voltage	350V
Cell type	LG E78
Number of cells	192 / 12 modules
Configuration	96s2p
Cell capacity	78.0Ah
HV battery mass	332kg

2.3 Boost type DCDC converter

A boost type DCDC converter is an electronic device that converts an input direct voltage to a higher output direct voltage. It is designed to raise the input voltage, usually from a power source such as a battery or fuel cell, to an output voltage greater than the input. This is achieved through a switching process that controls the delivery of power to the output based on the duty cycle, seen in Figure 3. In a DCDC boost converter, the duty cycle is a crucial parameter that determines how the converter operates. It’s a ratio that represents the amount of time the switch transistor is on compared to the total switching period.

The Figure 3 below shows the dependence of the output voltage on the duty cycle of a typical DCDC boost converter, where the circuit responds proportionally until 80% of duty cycle. The duty cycle zone from 80% to 99% must be avoided in order to exclude risks of control instability.

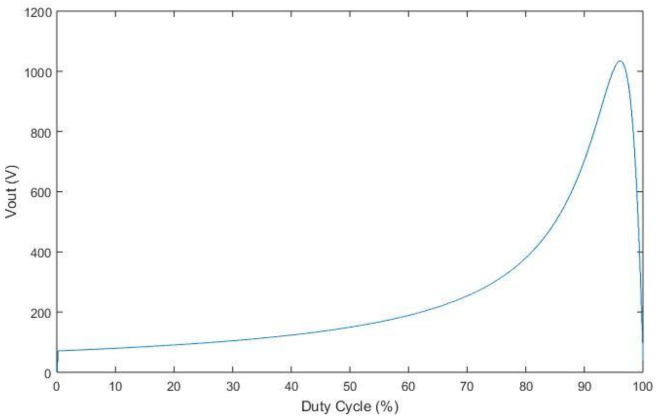

Figure 3. Output voltage response depending on duty cycle switching, considering 72V input voltage.

In this article, the modeled system has the DCDC converter as a central component as it is capable of guaranteeing constant adequate voltage at the output according to the needs of the electric vehicle, regardless of the voltage supplied by the fuel cell, which in turn depends and can vary depending on the hydrogen supply.

Other functionalities required in the real demonstrator concept are the ability to control the current and manage the activations and shutdowns of the range extender to avoid specific and restrictive conditions of use of the electric vehicle such as regenerative braking phases and battery states of charge (SOC) above of 90%.

In this case, the DCDC converter is essential to make the fuel cell output voltage compatible with the electric vehicle's high voltage bus and during dynamic conditions. Through the DCDC converter we are able to control the output voltage at 350V, for the correct transfer of energy to the traction battery, acting on the switching, regardless of the input voltage.

2.4 MatLab Simulink mathematical model

To mathematically simulate the control system, the MatLab Simulink software was used, which allows modeling, simulating and analyzing dynamic systems. Its main interface consists of a graphical block diagram tool and customizable block libraries. It is used as a graphical environment for creating models of complex physical systems and controllers. The simulated model can be seen in Figure 4.

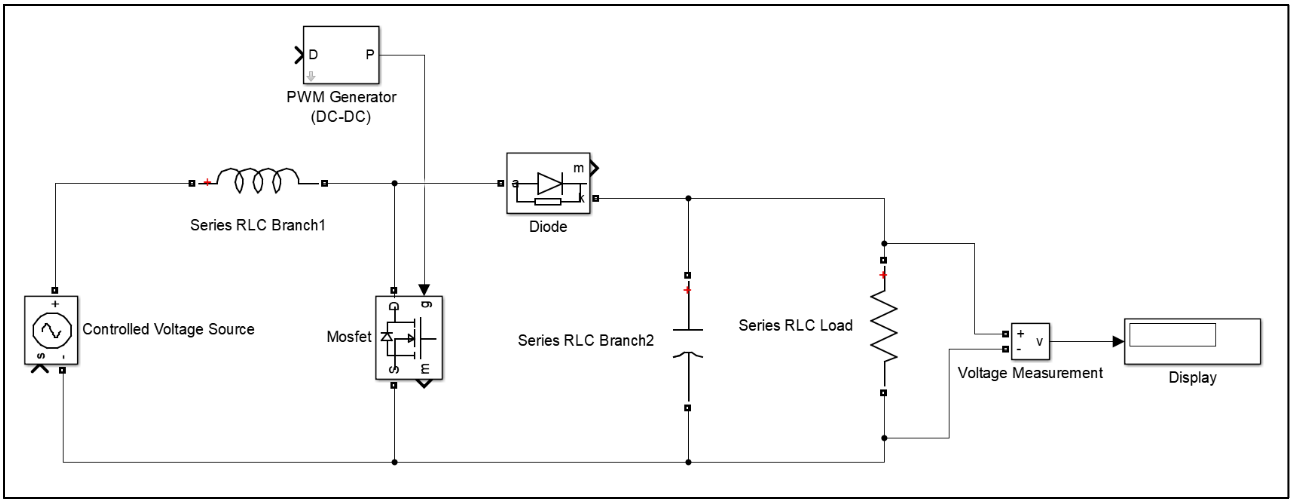

Figure 4. MatLab Simulink model of the boost DCDC converter.

Figure 4 shows that the simplified modelled circuit comprises the basic elements of a DCDC boost converter, such as an inductor, switching transistor (driven by the PWM generator), diode, capacitor, and resistive load. For the development of PID control with constant output, the circuit is treated as a black box where the output is compared to a reference value of 350V, and the controlling action is performed in the transistor switching cycle.

2.5 PID controller

In order to control the closed-loop and self-adaptive system, a PID system was added to check the voltage output and pilot convergence to the reference value of 350V acting on the switching value, as can be seen in Figure 5. To obtain the best parameters of the PID controller, the Ziegler Nichols Method methodology was used.

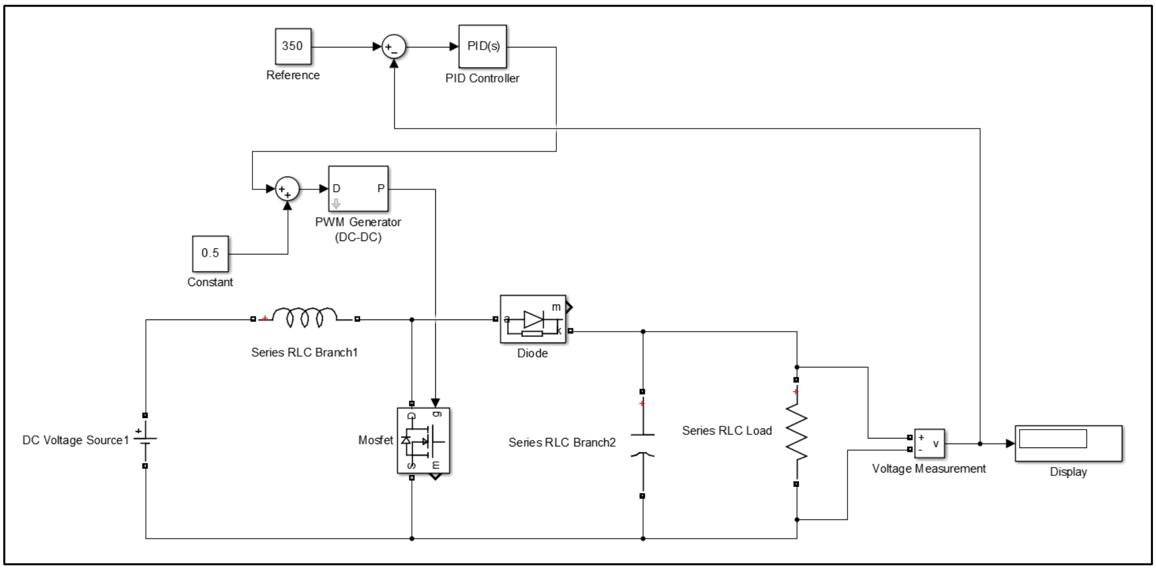

Figure 5. MatLab Simulink model of the DCDC boost converter with PID control.

2.6 Ziegler Nichols Method

The original objective that led to the creation of the Ziegler-Nichols method was to develop a technique for determining the control parameters of a PID (Proportional, Integral and Derivative) control system. The method was proposed by engineers John G. Ziegler and Nathaniel B. Nichols in 1942 and aims to tune the PID controller coefficients to obtain a stable and fast response from the controlled system. This method is based on the analysis of specific process characteristics in open-loop and closed-loop systems. Based on these characteristics, the parameters Kp , Ti and Td are determined using simple mathematical expressions. These parameters are used in the PID controller tuning process. According to Ziegler and Nichols' proposal for PID controller tuning, it is based on empirical data from dynamic systems. Therefore, detailed knowledge of the mathematical model of the system to be controlled is not necessary to tune the PID controller, which is key in our application.

In the Ziegler-Nichols model, K is the proportional controller gain constant (Kp), L is the time it takes for the process output value to reach 63% of its final response (Ti) and T is the time it takes for the system returns to 63% of the output value after a disturbance (Td).

Thus, a straight line was drawn on the open-loop system output graph, as seen in Figure 6. Although not precise, the values considered are: K=284.5, L=0.008 and T=(0.062-L) = 0.054.

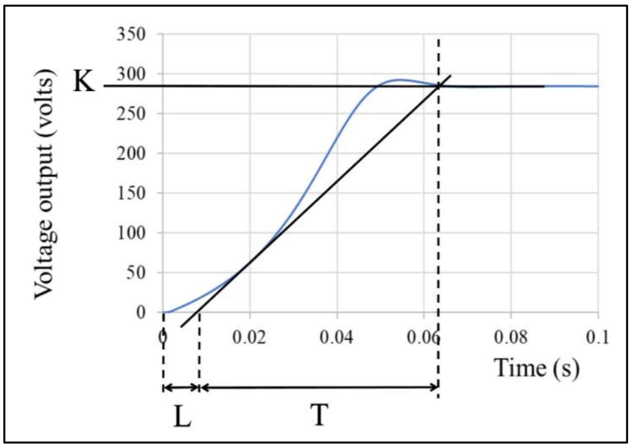

Figure 6. Output voltage with values for Ziegler Nichols.

2.7 Fuel Cell Voltage Model

Theoretical and experimental data obtained from tests carried out at FC demonstrate a curve of battery output voltage over time as a function of hydrogen supply that can be seen in Figure 7. This profile was used to shortly demonstrate the fuel cell voltage behavior in where we have an initial phase of open circuit, which means 110V, gradually load raise, steady full load condition and shut down phase.

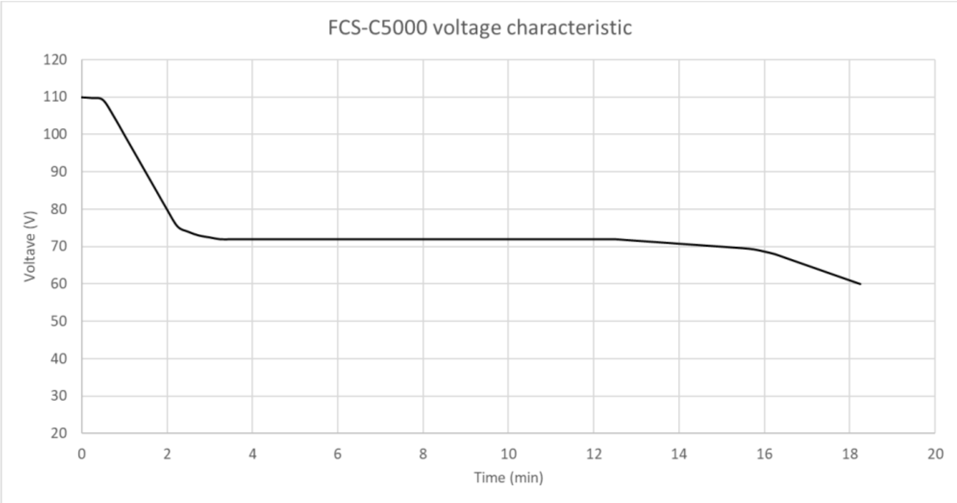

Figure 7. Converter output voltage.

3. RESULTS AND DISCUSSIONS

All simulations were done using the fuel cell voltage delivery characteristic curve as input to the DCDC converter as shown and 350V as a reference.

The methodology for obtaining the PID control parameters was using the Ziegler-Nichols methodology. This can be seen in Table 4.

Table 4. PID control system parameters

Parameter	**Value**
Kp	$\frac{1,2\times T}{L\times K}=0,0073$
Ki	$2\times L=0,2018$
Kd	$\frac{L}{2}=0,0007$

Initially the fuel cell is biased at 110V, its open circuit value. There is also a gradual load application curve making the voltage reach its nominal value for 5kW which lasts around 3s. The Figure 8 show the dynamic behavior of the duty cycle depending on the initial conditions during the first second and converging to value at 80% during the steady input 72V zone.

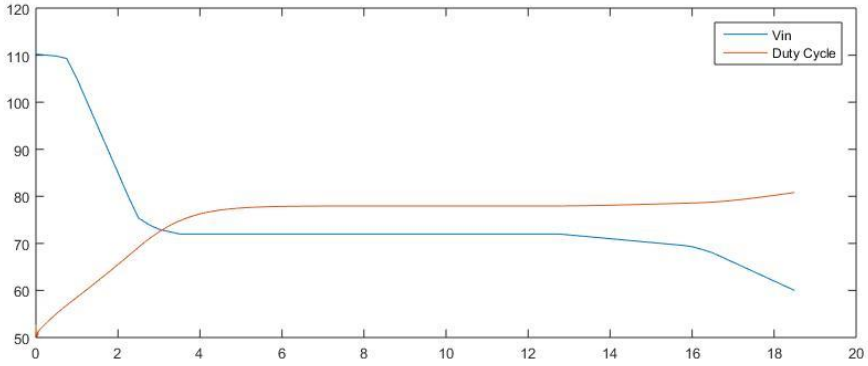

Figure 8. Result of duty cycle voltage control and switching application.

Through figure 9 we can verify that the MatLab Simulink mathematical model proposed for voltage control correctly suits the need and the PID closed loop control is efficient to seek the 350V reference condition.

Our objective was to achieve convergence in a time of less than 5s and with the PID controller correctly parameterized using the Ziegler Nichols methodology we observed that this objective was achieved.

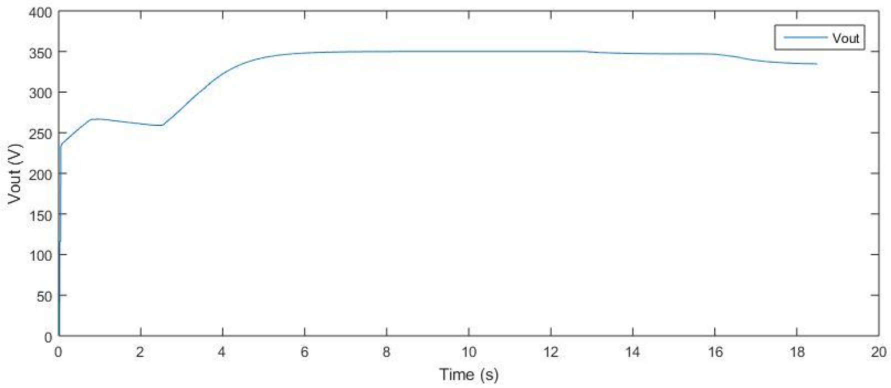

Figure 9. Output voltage with values for Ziegler Nichols.

4. CONCLUSIONS

In recent times, there has been a substantial surge in energy consumption. The ongoing economic expansion in many countries is driving a commensurate increase in energy demand. The scientific community has long been committed to seeking alternative, renewable, and environmentally friendly energy sources and diversifying the energy supply. The current global context makes this pursuit more pressing than ever.

Numerous innovative energy sources have emerged, with hydrogen production from diverse raw materials standing out as a particularly promising alternative to conventional fuels and other renewable energy sources and can be combined to enhance electric vehicles supporting energy production throughout range extenders.

The aim of this article was to construct a mathematical model that characterizes the control of a hydrogen-based range extender. The model proposed aligned closely with the experimental data, offering an effective means of transmitting power to an electric vehicle as a concept. Creating and enhancing mathematical models for this purpose is essential in order to render the suggested technology practical and achievable, thereby enhancing the overall system's performance and curbing energy costs.

The next steps of this work will involve other variables involved in the process, to make the model even more refined and able to predict and converge faster.

These results will be used to calibrate the demonstrator and check the model accuracy.

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