Voltage compensation using fuel cell fed dynamic voltage restorer

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ABSTRACT

One of the basic tasks of the dynamic voltage restorer (DVR) is to maintain voltage stability in distribution systems by correcting any deviations or disturbances in the three-phase supply. Whether they are increases or decreases. However, one of its disadvantages is its power source, as it cannot supply itself with power from the electrical grid like parallel compensators, which obtain power directly from the grid. This article presents an energy study of a dynamic voltage regulator (DVR) when operated using a power source represented by fuel cells, which are considered a clean and renewable source. On the other hand, excess energy from the regenerator or fuel cells can be output and injected into the distribution network for utilization via a parallel compensator (CP). The parallel compensator also compensates for reactive energy on the reactive load side to increase the power factor measured at the source side of the distribution system. This integrated system also uses neural networks to identify voltage disturbances and determine the voltages (modules/arguments) that must be added to the voltages in the power grid for correction. This analytical study was completed using a simulation system to confirm the effectiveness of this integrated system. The distinctive feature of this study is the integration of fuel cells and neural network-based control in the DVR system, providing a sustainable and intelligent alternative to conventional configurations, which makes it different from traditional DVRs that operate with batteries and supercapacitors. Its efficiency in compensating for voltage drops and surges is evident, and it also improves the power factor and ensures reliable operation of voltage-sensitive devices.

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1. INTRODUCTION

It is clear that electrical energy is produced from its production sources and transmitted in the form of a three-phase, sinusoidal voltage system with a well-determined frequency and phase shift. But at the user device level, they are usually operated in different ways, in particular as regards curve, amplitude, and frequency. In the past, suppliers and users changed the form of voltage or current using the electromechanical machines, but now, after the rapid development of semiconductor-based switch techniques, at low cost and volume, electromechanical machines have been replaced by static converters and electronic devices [1].

But any evolution has consequences: the excessive use of these electronic devices has led to the generalization of the use of strong inductive and non-linear loads [2]. In turn, these new loads caused the injection of harmonic currents into the electrical network, thus modifying the shape of the source voltage [3]. Inductive loads have also caused power factor reduction and voltage disturbances in electrical networks [4].

Several traditional and modern solutions have been used to correct all kinds of disturbances that can affect the source voltage [5]. Like the use of active parallel filter to inject the harmonic currents opposite to the harmonic currents existing in the network to cancel them [6], the dynamic voltage regulator (DVR) is also used in order to maintain the effective value of the voltages invariable at the level of the sensitive loads [7], and the STATCOM is used to compensate reactive power and increase power factor [8]. Recent studies confirm that artificial intelligence-based DVR control technologies, along with optimization methods, play a significant role in improving energy quality [9].

However, traditional digital devices rely on energy storage systems such as batteries or supercapacitors. These technologies have several drawbacks, including limited lifespan, charging restrictions, and energy density decline [10]. Fuel cells have been used as an alternative and sustainable solution, as they are considered a source of clean and continuous energy, making them the ideal solution for improving energy quality [11]. In addition, modern research has found that integrating fuel cells with DVRs improves power quality in modern microgrids [12]. Other researchers have relied on optimization methods and control strategies to enhance the efficiency of hydrogen fuel cells when integrated with DVR technology [13]. Other studies indicate that hybrid DVR structures combining photovoltaic cells and fuel cells contribute to reducing harmonics [14].

Advanced control methods such as PI adaptive controllers have been successfully applied to DVRs to reduce voltage drops, demonstrating the potential for using intelligent technologies to further improve performance [15]. In particular, proton exchange membrane fuel cells (PEMFCs) offer fast dynamics, high efficiency, and scalability, which are essential features for DVR applications [16]. To safeguard sensitive loads against fluctuations that may occur in the supply during voltage sags or swells, this research presents a combination of the DVR and an active compensator connected back-to-back. The two compensators are connected by a pair of common fuel cells, so that the DVR injects voltages into the network in the case of anomaly correction affecting the electrical network voltage, using the energy of the fuel cell. While the active compensator is used to clear out the excess energy in the DVR, which is not used, and the energy in the fuel cells, and this active compensator also helps to increase the power factor at the source by injecting reactive power to offset load requirements.

This combined system also used neural networks to determine the reference voltage of the DVR compensator [17], which must be injected into the network, and they were also used to determine the reference currents, which must be injected into the network to compensate for the reactive power and the discharge of excess active power in this system. This study also examines the exchange of active and reactive power flows between all the compensators and the network, in all cases: the normal state, overvoltage, and the voltage dip state. Figure 1 shows the system to be studied. The main contributions of this article can be summarized in the following points: i) A new integration between DVR and PEM fuel cell to ensure sustainable and reliable voltage compensation; ii) Development of an integrated system containing an active compensator to manage excess energy from the fuel cell and power factor; iii) Application of neural networks to extract reference voltage and current in real time; and iv) Complete simulation using MATLAB/Simulink and verification of its validity in operating conditions (normal, low voltage, and high voltage).

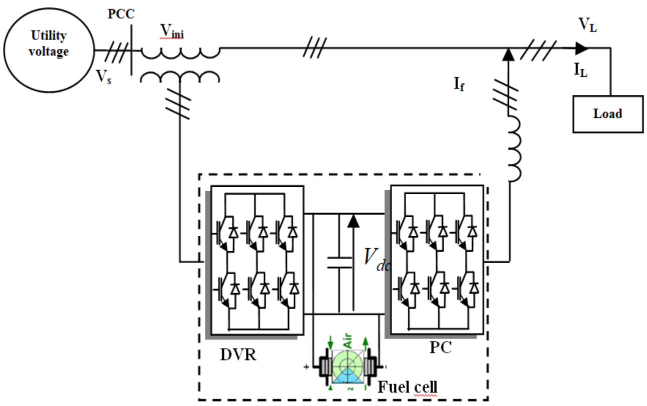

Figure 1. System circuit configuration

2. THE POWER FLOW STUDY IN THE DVR

The electrical power distributor must supply a nominal sinusoidal voltage to the consumers of this power, in particular the most sensitive. Otherwise, i.e. in the event of a fault affecting the consumer's voltage, this must be corrected, for example by using a DVR, which makes it possible to maintain the nominal voltage and this by injecting a voltage equal to the difference between the nominal voltage and the network voltage [18]. In the case of a voltage sag at the network level, the modulus of the injected voltage is the difference mentioned above and the phase shift of this injected voltage is in phase with the network voltage, while in the case of an overvoltage at the network level, the modulus of the injected voltage is the difference mentioned above and the phase shift of this injected voltage is phase shifted with respect to the network voltage.

For efficient operation of the DVR, the parallel active compensator (PC) must maintain the voltage between the terminals of the DC capacitor or the intermediate circuit [19], in order to ensure that the active power is transmitted between the two active compensators, the fuel cells, and the electrical network, as well as the parallel compensator (PC) also provides compensation for the reactive power requested by the load. The inductive load used in this system is a load with a power factor of 0.707. Figure 2 represents the equivalent model of an equivalent single-phase circuit. With: I_s,e_s: The source current and voltage source, respectively; V_s: the voltage at the point of common coupling (PCC); I_L, V_L: The load current and load voltage, respectively; V_i: the injected voltage by DVR; I_f: injected current by PC.

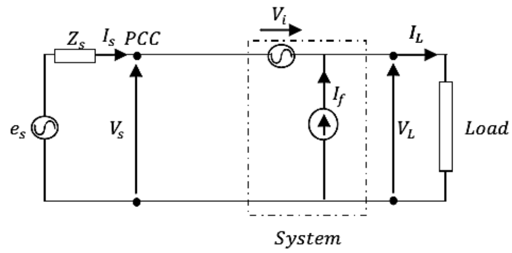

Figure 2. Equivalent circuit of the system

The load voltage v_L is taken as the reference phasor, the load power factor is $cos\ \varphi_L$, The following equations can be written as (1)-(3).

$$v_L = V_L\angle 0^0 \quad (1)$$

$$i_L = I_L\angle - \varphi_L \quad (2)$$

$$v_L = V_s(1+k)\angle 0^0 \quad (3)$$

Where k is the voltage fluctuation factor, it defined as (4).

$$k = \frac{V_L - V_S}{V_S} \quad (4)$$

The injected voltage by DVR equals:

$$v_i = v_L - v_s = kV_S\angle 0^0 \quad (5)$$

Considering that power losses are negligible in both active compensators, DVR, PC; i.e. semiconductor switches are ideal, the power balance equation can be expressed by (6)-(9).

$$P_s + P_{FC} = P_L \quad (6)$$

$$V_s . I_s + P_{FC} = V_L \cdot I_L\ cos\ \varphi_L \quad (7)$$

$$V_S . I_s + P_{FC} = V_S(1+k) \cdot I_L\ cos\ \varphi_L \quad (8)$$

$$I_s = (1+k) \cdot I_L\ cos\ \varphi_L - \frac{P_{FC}}{V_S} \quad (9)$$

The last equation shows that the source current, which represents the power of the source, is directly related to the load current and the power injected by the fuel cell.

The DVR power can be written as (10)-(12).

$$\bar{S}_i = \bar{v}_i \bar{I}_s \quad (10)$$

$$P_i = V_i \cdot I_S\ cos\ \varphi_S = kV_L \cdot I_S\ cos\ \varphi_S \quad (11)$$

$$Q_i = V_i \cdot I_S \sin \varphi_S \tag{12}$$

Since it is the active parallel compensator that keeps the power factor equal to unity at the source, then: $\varphi_S \cong 0$.

$$P_i = V_i \cdot I_S = kV_L \cdot I_S \tag{13}$$

$$Q_i \cong 0 \tag{14}$$

The PC's apparent power is (15).

$$\bar{S}_f = \bar{v}_L \bar{\imath}_f \tag{15}$$

The current supplied by the parallel compensator can be calculated by calculating the difference between the source current and the load current, and it contains the active component and the reactive component. We have:

$$i_f = i_S - i_L \tag{16}$$

$$i_f = I_S \angle 0^0 - I_L \angle - \varphi_L \tag{17}$$

$$i_f = I_S - (I_L \cdot cos\, \varphi_L - jI_L \cdot sin\, \varphi_L) \tag{18}$$

$$i_f = (I_S - I_L \cdot cos\, \varphi_L) + jI_L \cdot sin\, \varphi_L \tag{19}$$

$$P_f = V_L I_f \cdot cos\, \varphi_f \tag{20}$$

$$P_f = V_L (I_S - I_L \cdot cos\, \varphi_L) \tag{21}$$

$$Q_f = V_L I_f \cdot sin\, \varphi_f = V_L I_L \cdot sin\, \varphi_L \tag{22}$$

3. NEURAL NETWORKS FOR REFERENCE SOURCE AND VOLTAGE

Among the quality factors of the compensator is the method of determining the reference currents and voltages [20]. This work presents the use of the artificial neural network (ANN) as a system for controlling and determining the reference values of the compensator. Nowadays, researchers are interested in multilayer feedback neural networks (MLFFN), which are a set of output neurons and one or more intermediate neurons, called hidden layers. It consists of the input layer, which supervises the supply of information to the network. This information is directed to the outer layer via the hidden layers. Figure 3 illustrates this neural network structure. This correlation is performed by weight matrices W and bias vectors b. Figure 4 shows the DVR control using a neural network, converting input voltages and currents into reference currents to drive the PI controller and PWM pulses.

To make the error or difference between the image or output of the ANN function and the image of the reference function zero, the ANN uses the iterative learning method, so that the ANN network iteratively changes W and b [21]. After all the system inputs are entered into the ANN system, these inputs are weighted with the appropriate weights W, then the result is summed with bias b, the total output is made up as an antecedent of the transfer function f. We can define the activation vector "a" as:

$$a = \sum(w.x + b) \tag{23}$$

In the case of the neural network used, the transformation function used in the input layer and the hidden layer is a differentiable function, known as tan-sigmoid.

$$\tan sig(a) = \frac{2}{1+e^{-2a}} - 1 \tag{24}$$

As for the output layer, we used the linear type activation function, purelin.

$$purelin(a) = a \tag{25}$$

In order to train or guide the network towards zero error, this network must optimize these weights and these biases. This work used the LMS algorithm because this method provides a learning rule according to almost any desired network behavior.

$$\{x_1, y_1\}, \{x_2, y_2\}, \ldots \ldots \{x_n, y_n\} \quad (26)$$

If we consider that xi are the values of the inputs of the neural network, and yi are the outputs corresponding to these inputs. Immediately after obtaining these outputs, the network will compare these outputs with the corresponding target outputs Yi, in order to estimate and to evaluate these differences or errors. This evaluation depends on the average sum calculation of these differences:

$$\varepsilon = \frac{1}{n} \sum_{k-1}^{n} e\,(k)^2 \quad (27)$$

$$\varepsilon = \frac{1}{n} \sum_{k-1}^{n} (y\,(k) - y'(k))^2 \quad (28)$$

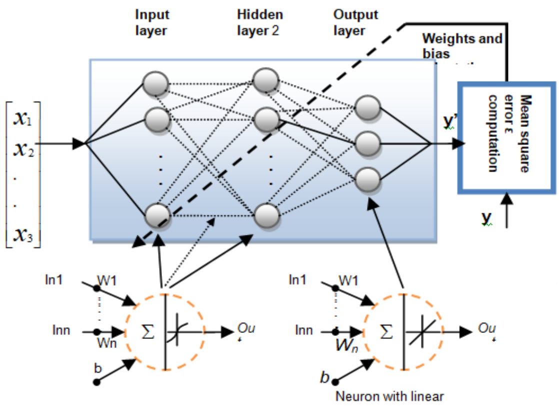

Figure 3. Neural network topology

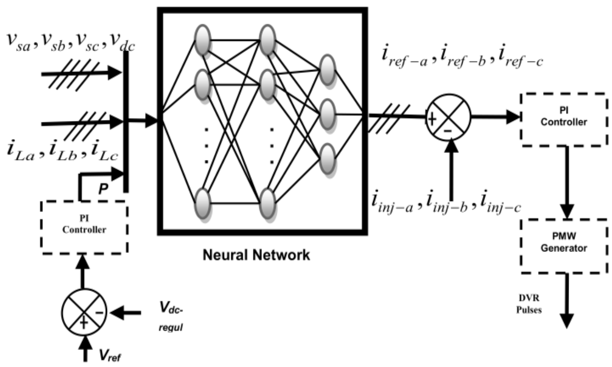

Figure 4. Simulated model of the parallel compensator controller

In order to obtain the absolute minimum value of the error, by adjusting the weights and biases of the neural network, this system used the least mean square (LMS) error algorithm method for learning [22], [23]. Initially, the neural network was used to determine the reference currents for the parallel compensator to maintain the capacitor voltage between the two compensators [24]. allowing active power to flow. For this, this work used a four-layer neural network, the input layer with 8 neurons and a hyperbolic tangent sigmoid activation function, and 2 hidden layers with 8 and 3 neurons respectively, the hyperbolic tangent sigmoid activation function and the purelin function, respectively, output layer with 3 neurons and a purelin function.

For reference voltages determination in a dynamic voltage restorer [25], this work use: four-layer neural network, the input layer with 12 neurons and a hyperbolic tangent sigmoid activation function, and two hidden layers with 12 and 3 neurons respectively, the hyperbolic tangent sigmoid activation function and the purelin function, respectively, and the output layer with 3 neurons and a purelin function. Figure 5 illustrates the simulated DVR control system based on a neural network, witch generates reference voltages from the measured three-phase source voltages to compensate disturbances via PWM control.

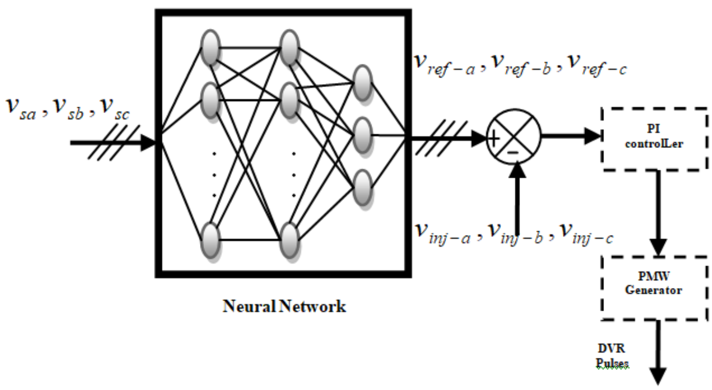

Figure 5. Simulated model of the DVR controller

4. METHOD

The developed configuration includes a balanced three-phase sinusoidal voltage source that supplies an inductive load rated at 31.5 kW and 31.5 kVA, operating at a nominal frequency of 50 Hz. This setup aims to improve overall power quality by minimizing voltage irregularities. The DVR is connected in series between the supply and the load, while its DC link is energized by two proton exchange membrane fuel cell (PEMFC) stacks. Each stack provides approximately 625 V DC at a nominal power capacity of 50 kW, ensuring sufficient energy for compensation during voltage disturbances. The two fuel cell stacks are connected in a parallel arrangement through a DC–DC converter stage rated at approximately 1500 VDC.

This configuration ensures a stable intermediate DC link voltage required for DVR functionality. The electrochemical system operates with hydrogen and oxygen utilization rates of around 99.25% and 56.67%, respectively. Each PEMFC stack comprises about 900 individual cells, with an average Nernst potential close to 1.138 volts per cell, providing the necessary energy density for dynamic voltage restoration. The DVR operates through a voltage source converter (VSC) that is governed by an intelligent control algorithm based on ANN. The ANN controller is trained to determine the reference compensation voltage, which is subsequently applied to the distribution line whenever voltage disturbances—such as sags or swells—occur. Additionally, a shunt compensator is incorporated into the system to regulate surplus energy delivered by the fuel cells while supplying reactive power to enhance the overall power factor of the network. The overall configuration of the proposed system was implemented and analyzed using the MATLAB/Simulink simulation environment. The main operating parameters were adjusted as follows: i) Three-phase supply voltage: 220 V RMS; ii) Inductive load: 31.5 kW / 31.5 kVA; iii) Total simulation duration: 2 s; iv) Numerical solver: ode23s (stiff, modified Rosenbrock); and v) Applied disturbances: a voltage sag occurring between 0.2 s and 0.4 s, followed by a swell between 0.6 s and 0.75 s. A detailed schematic representation of the complete model—including the source, DVR module, PEM fuel cell stacks, DC–DC converter stage, neural network controller, and the parallel compensator (Figure 6).

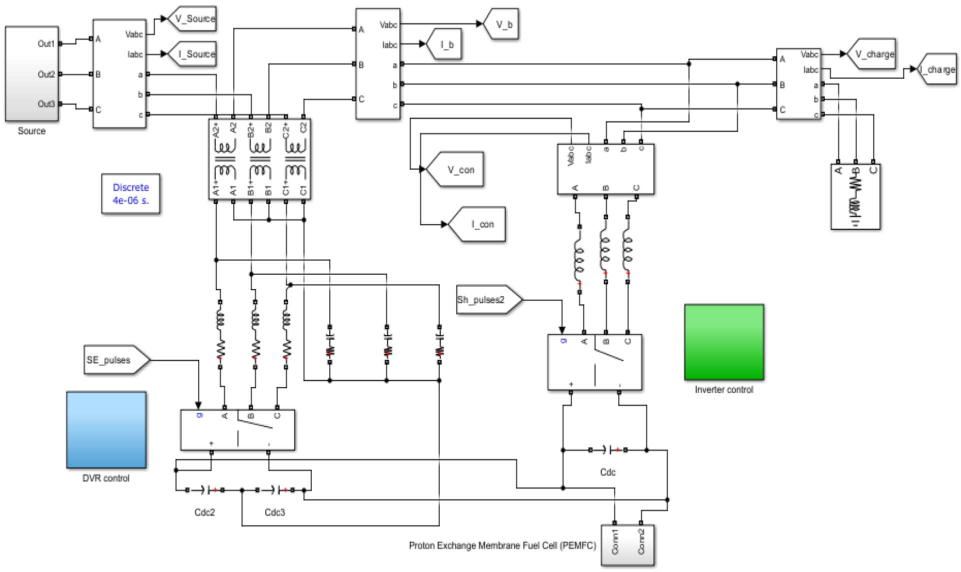

Figure 6. Proposed DVR–PEM fuel cell system modeled in Simulink

5. RESULTS AND DISCUSSION

The system to be studied contains a three-phase sinusoidal voltage source with an effective voltage of 220 volts and a frequency of 50 Hz. This source supplies an inductive load of (31.5 kW and 31.5 kVA) for each phase. This system uses a DVR in series between the source and the load to correct the imbalance that affects the voltage of the load. The DVR is powered by two fuel cells, each fuel cell is designed at a voltage of 625 Vdc and a power of 50 kW. the two cells connected in parallel with a DC/DC converter of 1500 Vdc, the two cells consume hydrogen and oxygen at constant nominal values (Uf-H2 = 99.25%) and oxygen (Uf-O2 = 56.67%), each stack has 900 cells; the voltage (nerst) of a single cell is approximately 1.138 V. Figure 6 shows the Simulink block diagram of the proposed DVR-PEM fuel cell system, including the source, DVR, fuel cell, converter, and control blocks. Figure 7 shows the characteristics of the fuel cell stack. In Figure 7(a), the stack voltage decreases as the current increases. In Figure 7(b), the stack power increases with the current until it reaches its rated value of approximately 120 kW at 230 A. These characteristics confirm the suitability of PEM fuel cells for supplying power to dynamic voltage restorers (DVRs) during voltage disturbances.

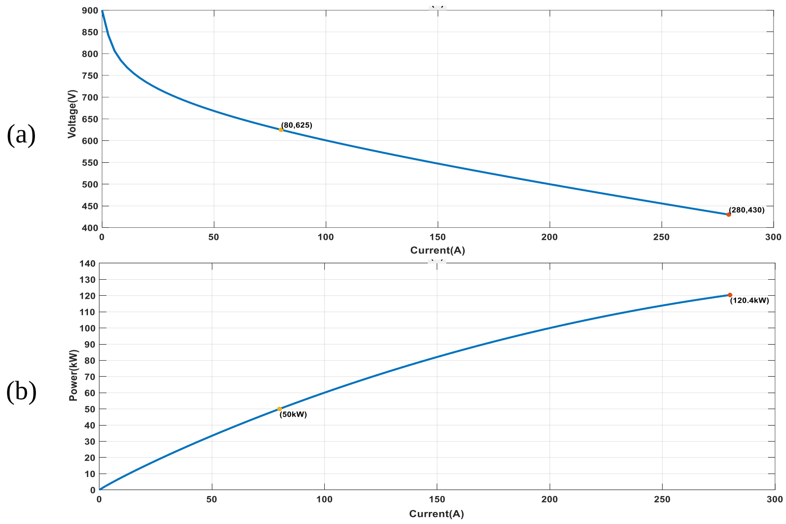

Figure 7. Fuel cell stack characteristics: (a) stack voltage vs current and (b) stack power vs current

To prove the efficiency of this system, we have created a sort of voltage imbalance, represented by a decrease in the voltage at the source by 50% compared to the nominal rms value from 0.2 seconds to 0.4 second (voltage sag), then an increase in the supply voltage at the source to 50% of the nominal rms value from time 0.6 sec to 0.75 sec (swell). As illustrated in Figure 8(a), in case the grid voltage is reduced compared to the nominal grid voltage VS > VL, and based on (4), where k < 0, the DVR intervenes to inject the voltage difference, which is in phase with the mains voltage (Figure 8(b)). DVR immediately injects the missing voltage from the fuel cell through the VSC converter. The load voltage is restored to its nominal value of 220 volts. The restoration time was approximately 0.02 seconds, highlighting the fast dynamic response of the proposed control block. Figure 8 also illustrates the performance of DVR during an overvoltage event. In this case, the network experiences a voltage swell, i.e., VS > VL, where k > 0. To compensate for this, the DVR injects a voltage equal to the difference |VS − VL| in amplitude and in phase opposition to the mains voltage. This allows the DVR to absorb the excess energy and maintain the load voltage within safe limits. Figure 8 shows in detail: Figure 8(a) the supply voltages, Figure 8(b) the DVR injected voltages, and Figure 8(c) the load voltages after compensation, which remained within ±2% of the nominal RMS value, demonstrating the robustness of the DVR–fuel cell system under overvoltage conditions.

Figure 9 illustrates the current changes during DVR operation in phase a. In Figure 9(a), it can be seen that the supply current is clearly affected by voltage disturbances. In Figure 9(b), the DVR supported by the fuel cell and the parallel compensator (PC) injects an appropriate compensating current. Finally, in Figure 9(c), the load current is shown to remain stable, confirming that the proposed system effectively maintains the load current close to its ideal form despite fluctuations in the supply voltage.

In the normal case, VS=VL, the PC plays the role of connecting devices between the fuel cell and the electrical network, by injecting alternating energy, extracted from the fuel cells (see Figure 10). As well as it also plays the role of (DSTATCOM) so it compensates for the reactive power needed by the inductive load Figure 11, so it is responsible for increasing the power factor to unity next to the source Figure 12. As long as the DVR does not perform any active or reactive power exchange with the utility grid. In case the grid voltage is reduced compared to the nominal grid voltage, (Figure 8(a)): VS>VL, and based on (4), where k < 0, DVR intervenes to inject the voltage difference, which is in phase with the mains voltage (Figure 8(b)).

The DVR intervention in case of a voltage sag is followed by the withdrawal of active energy from the PC+FC terminal to power the DVR (see Figure 10). This flow of active energy results in a decrease in the current injected by the fuel cell to the load and an increase in the current injected by the source, for the compensation of the voltage dip, and to meet the load power requirements. The DVR intervention in case of voltage swell, absorbs the active power from the electrical network, then sends it back to the network via the PC compensator (see Figure 10), the decrease in supply current (iS) means that the fuel cells and the excess power in the DVR (see Figure 10), compensate for the lack of effective power drawn by the load. This increase is done by adjusting the voltage across the capacitor terminals (see Figure 13).

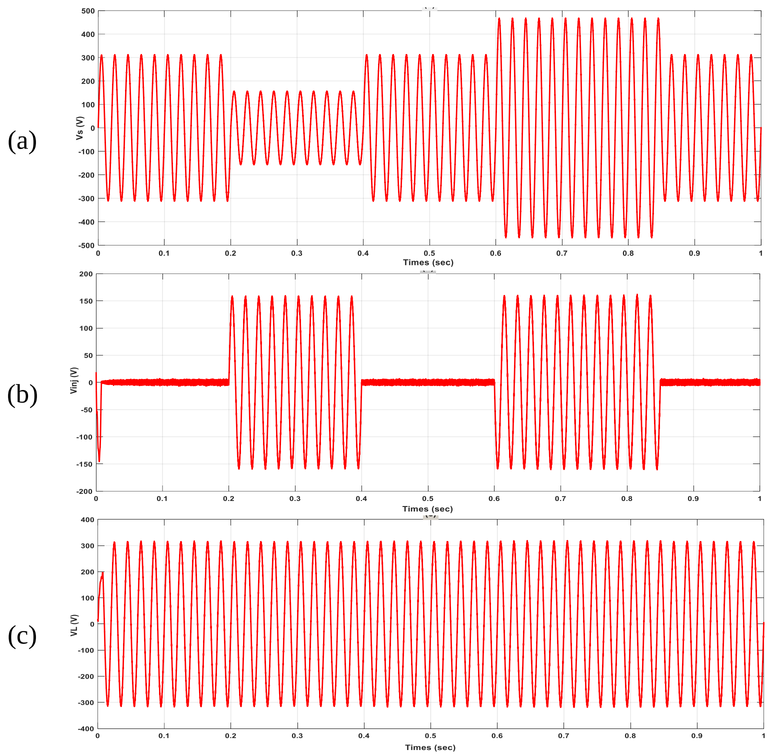

Figure 8. Voltage variations during DVR operation (phase a): (a) supply voltages, (b) the DVR injected voltages, and (c) the load voltages

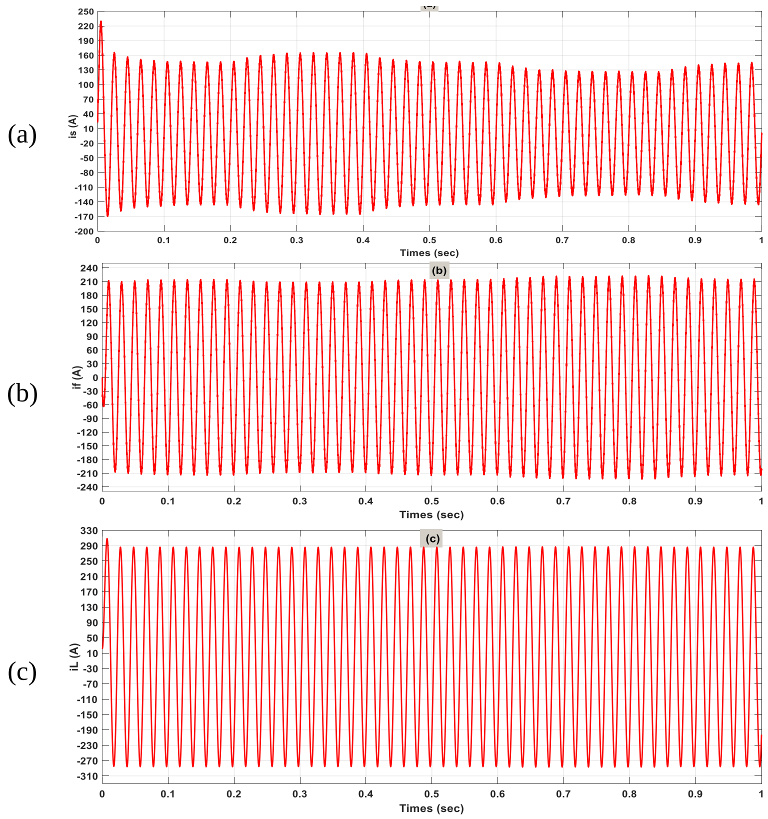

Figure 9. Current variations during DVR operation (phase a): (a) supply current, (b) the (fuel cell and PC) injected current, and (c) the load current

These results show that the proposed DVR-fuel cell system ensures rapid voltage recovery (≈0.02 seconds) and maintains the load voltage within ±2% during voltage sag and surges. Compared to traditional DVR units that rely on batteries or supercapacitors, the fuel cell-powered DVR unit provides a sustainable and continuous power supply without recharge limitations. The integration of the VSC and neural network control block further underscores the importance of this work in the field of power electronics and propulsion systems, particularly for industrial motors and microgrid applications. However, challenges remain to be addressed, such as the cost of fuel cells and startup dynamics. Future work will explore optimization techniques and hybrid energy storage integration to enhance system performance in smart grids and electric vehicle charging infrastructures.

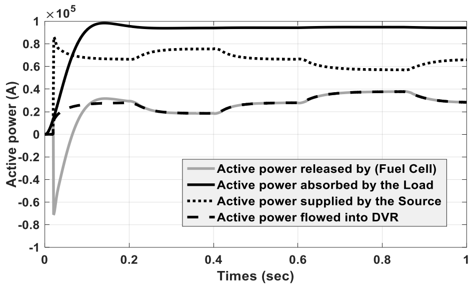

Figure 10. Active power flow between the system components

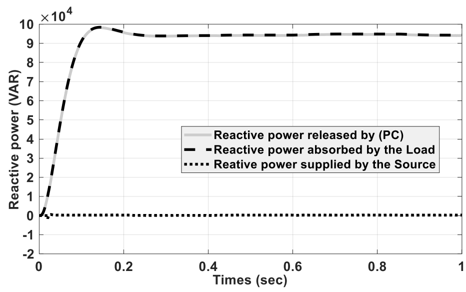

Figure 11. Reactive power flow between the system components

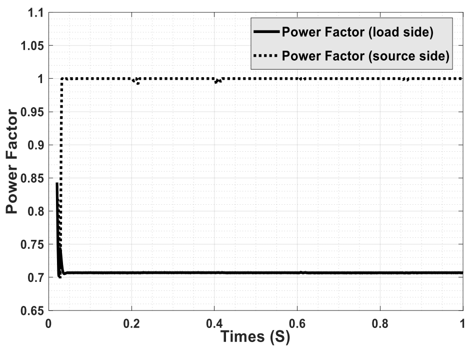

Figure 12. Power factor variations (source side)

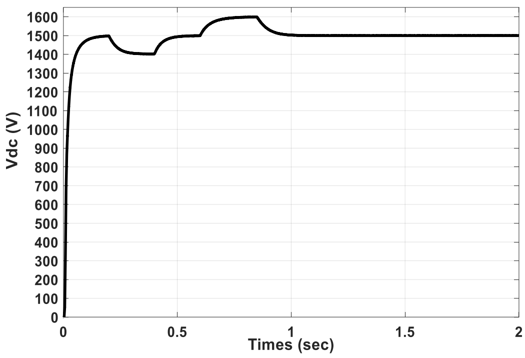

Figure 13. The average voltage across the fuel cell terminals

6. CONCLUSION

In order to use renewable energies in all electrical fields, this research presented an attempt to use fuel cells to power the dynamic voltage restorer, in the event that the latter would be exposed to voltage faults. Research has also tried to rely on neural networks to identify these faults and determine reactive currents in inductive loads to compensate for them and increase the power factor next to the power source. This research has also contributed to the study of active and reactive power flows between the DVR series compensator and the electrical network in all its operating cases to repair faults that affect the network voltage. The study of the power flows in the DVR series compensator and the parallel compensator also contributed to determining the dimensions and sizes of the components of these compensators. The results confirm that the proposed DVR fuel cell configuration is an effective and sustainable solution for improving power quality in modern electrical networks. Future studies could focus on experimentally verifying the proposed DVR-fuel cell system under real operating conditions. In addition, the integration of advanced control techniques, such as adaptive or predictive controllers, could further improve the system's performance. Extending the study to hybrid systems that combine fuel cells with other renewable energy sources, such as photovoltaics or wind power, could provide even greater flexibility and resilience for smart grid applications.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Rachid Dehini		✓				✓		✓	✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

The data and simulation models used in this study are available from the author upon reasonable request.

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