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Power quality enhancement using STATCOM-Fuel Cell Energy Control

Abstract. *The escalating demand for electrical power is a direct consequence of the widespread use of electronic devices and the global population's continuous growth. This surge in demand places considerable stress on the existing energy infrastructure, prompting the need for the development of new power generation methods like fuel cells and advanced transmission systems to meet these requirements. These factors have motivated researchers to explore renewable energy sources, which have gained increasing significance as the world endeavors to diminish its dependence on non-renewable energy sources and transition toward a more sustainable energy future. Renewable energies offer a clean and dependable source of power, contributing to the reduction of greenhouse gas emissions and the response to climate change challenges. This study centers on the Static Synchronous Compensator (D-STATCOM) powered by fuel cells. The D-STATCOM not only corrects power factors but also safeguards sensitive loads against voltage fluctuations. Additionally, it is harnessed to channel surplus active power from the fuel cells to the grid or loads. To manage these multifaceted functions, the instantaneous p-q theory is employed as a control system within the D-STATCOM. The system comprises fuel cells interconnected to an inverter that supplies the D-STATCOM. The simulation results demonstrate the system's remarkable efficiency and its ability to maintain voltage control effectively.*

Streszczenie*. Rosnący popyt na energię elektryczną jest bezpośrednią konsekwencją powszechnego stosowania urządzeń elektronicznych i ciągłego wzrostu populacji na świecie. Ten wzrost popytu wywiera znaczną presję na istniejącą infrastrukturę energetyczną, co powoduje potrzebę opracowania nowych metod wytwarzania energii, takich jak ogniwa paliwowe i zaawansowane systemy przesyłowe, aby sprostać tym wymaganiom. Czynniki te zmotywowały badaczy do zbadania odnawialnych źródeł energii, które zyskały na znaczeniu, ponieważ świat stara się zmniejszyć zależność od nieodnawialnych źródeł energii i przejść na bardziej zrównoważoną przyszłość energetyczną. Energia odnawialna oferuje czyste i niezawodne źródło energii, przyczyniając się do redukcji emisji gazów cieplarnianych i odpowiedzi na wyzwania związane ze zmianą klimatu. Niniejsze badanie koncentruje się na statycznym kompensatorze synchronicznym (D-STATCOM) zasilanym przez ogniwa paliwowe. D-STATCOM nie tylko koryguje współczynniki mocy, ale także zabezpiecza wrażliwe obciążenia przed wahaniami napięcia. Ponadto jest wykorzystywany do kierowania nadwyżki mocy czynnej z ogniw paliwowych do sieci lub obciążeń. Aby zarządzać tymi wieloaspektowymi funkcjami, natychmiastowa teoria p-q jest stosowana jako system sterowania w D-STATCOM. System obejmuje ogniwa paliwowe połączone z falownikiem, który zasila D-STATCOM. Wyniki symulacji demonstrują niezwykłą wydajność systemu i jego zdolność do skutecznego utrzymywania kontroli napięcia.* (***Poprawa jakości energii elektrycznej przy użyciu STATCOM-Fuel Cell Energy Control***)

Keywords: Variable load, Reactive Power, D-STATCOM, PEMFC cells energy, Power-Factor Correction, p-q theory.
Słowa kluczowe: Obciążenie zmienne, moc bierna, D-STATCOM, energia ogniw PEMFC, korekcja współczynnika mocy, p-q

Introduction

Thanks to the rapid advancements in semiconductor switch technology; there have been significant developments in high-speed and high-power devices, including MOSFETs, MCTSs, IGBTs, IGCTs, IEGTs, and more. These switches have proven to be highly practical for current compensation, mitigation of harmonic voltages, and ensuring voltage stability. Within the realm of flexible controllers, various options have arisen, such as the Flexible AC Transmission System, active filters, Unified Power Quality Conditioner (UPQC), Distribution Static Compensator (D-STATCOM), and dynamic voltage restorer (DVR). These technologies are increasingly finding applications within the distribution network [1,2].

In the current landscape, electrical distribution systems face continual challenges posed by sudden load fluctuations [1,2]. When the equilibrium between the supply and demand for reactive power is disrupted, it leads to issues related to energy quality within the distribution network. These disruptions have adverse consequences on electrical products, subsequently impacting industrial consumers and resulting in significant financial losses. Moreover, they can cause equipment malfunctions, especially in devices reliant on sensitive electronics such as programmable logic controllers and variable speed drives [2].The primary objective of the Static Dispenser (D-STATCOM) is to shield consumers from voltage drops and overvoltage in the power lysupp. Additionally, it ensures that the power factor at the distribution point remains consistently at unity, irrespective of varying loads.

The D-STATCOM is particularly adept at delivering a swift and adaptable voltage control response at the Point of Common Coupling (PCC), which significantly enhances the electrical power quality within the distribution network. Notably, its inverter power switches operate at a high switching frequency, making Pulse Width Modulation (PWM) a feasible option for high-power applications. What sets the D-STATCOM apart is its remarkable responsiveness, capable of transitioning from fully inductive to entirely capacitive within a single cycle. This rapid adaptability renders it well-suited for scenarios with rapidly fluctuating loads [3].

This paper's analysis is centered on a system configuration featuring a direct connection between Proton Exchange Membrane (PEM) fuel cells and a D-STATCOM. This setup is employed to inject power generated by the fuel cells into the utility grid while maintaining a fixed fuel cell power output. The innovative design not only facilitates the distribution of chemical power to the grid but also operates as a D-STATCOM, effectively regulating the injection of reactive power by nonlinear loads. To mitigate the effects of voltage fluctuations, overvoltage, and enhance the overall system capacity, a simulation was conducted using a 100KW fuel cell power system connected to a three-phase power grid supplying inductive and capacitive loads. This simulation was executed within the MATLAB/SIMULINK environment.

PEM fuel cell generator modelling

In recent years, the demand for electrical energy has continued to rise. However, concerns related to pollution and global warming have prompted the development of renewable energy sources, with a specific focus on chemical energy. One noteworthy technology in this realm is the fuel cell (FC), which serves as a stationary energy conversion device. Fuel cells operate by directly converting the chemical energy of a fuel into DC electrical energy [4]. These devices typically consist of two porous electrodes, namely the anode and cathode, separated by an electrolyte layer. A visual representation of a Fuel cell, such as the Proton Exchange Membrane Fuel Cell (PEMFC), is depicted in Figure 2 [5].

The conversion of the chemical energy of the fuel takes place with the supply of hydrogen gas (H2) under specific pressure conditions. It is crucial to ascertain the concentration of hydrogen within the mixture. The fuel then disperses through the electrode until it reaches the catalytic layer of the anode, where it undergoes a reaction resulting in the formation of protons and electrons, as described in the following reaction:

(1) H2+1/2O2 $\rightarrow$ H2O+heat+electrical energy

The processes of hydrogen oxidation and oxygen reduction are kept distinct by the presence of a membrane, which serves the crucial function of conducting protons from the anode to the cathode side [4].

(2) $$H_2 \rightarrow 2H^+ + 2e^-$$ Anode

(3) $$O_2 + 4e^- \rightarrow 2O_2^-$$ Cathode

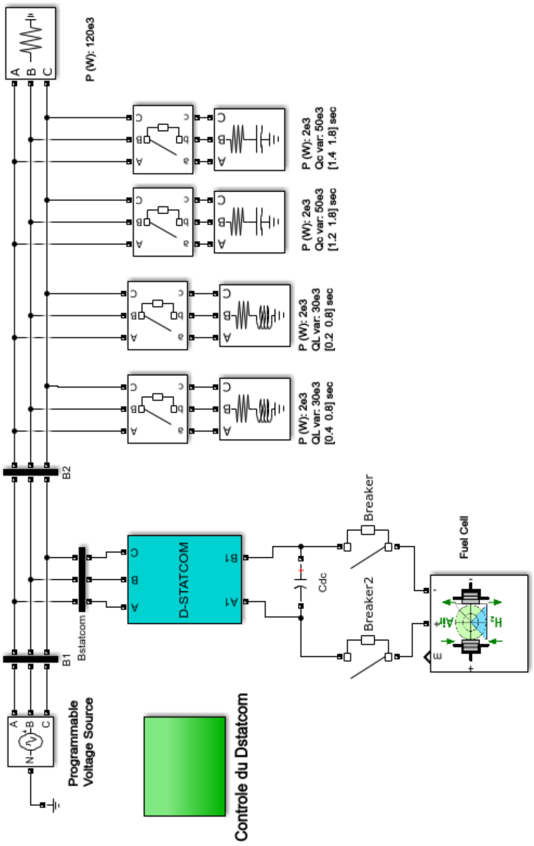

Fig.1. General structure of STATCOM with PEMFC

As protons move through the membrane and electrons traverse an electric circuit, electrical energy is generated. This electrical energy is characterized by the cell voltage, which is defined as:

(4) $$V_{FC} = E_{nernst} - V_{act} - V_{ohm} - V_{conc}$$

The cell voltage (V) is composed of several components:

1. Enernst : This term signifies the thermodynamic potential of the cell and represents the reversible voltage.
2. Vact: This component accounts for the voltage drop related to the activation of the anode and cathode.
3. Vohm: Vohm quantifies the ohmic voltage drop, which is a measure of the resistance associated with proton conduction through the solid electrolyte and electron conduction through the internal electronic resistances.
4. Vconc: reflects the voltage drop resulting from the concentration or mass transportation of the reacting gases.
5. VFC: stands for open circuit voltage.

Each of these components in equation (4) can be computed using the following equations [4].

(5) $$E_{nerst}=1{,}229+0{,}85.10^{-3}(T-298{,}15)+4{,}31.10^{-5}.T.\ln(P_{H2}.P_{O2}^{0.5})$$

PH2 and PO2 represent the partial pressures of hydrogen and oxygen, respectively, measured in atmospheres (atm). T denotes the operating temperature of the cell, expressed in Kelvin (K).

(6) $$V_{act} = -\left[\xi_1 + \xi_2 T + \xi_3 .T.\ln(Co_2) + \xi_4 .\ln(I_{stack})\right]$$

The equation shown is represented as follows:

Istack stands for the cell's operating current in amperes (A). The ξi 's correspond to parametric coefficients unique to each cell model. These coefficients have values that are determined using theoretical equations grounded in kinetics, thermodynamics, and electrochemistry [5]. Additionally, Co2 represents the concentration of oxygen in the catalytic interface of the cathode, measured in mol/cm. This concentration is determined by:

(7) $$Co_2 = \frac{Po_2}{5{,}08.10^6.e^{(-498/T)}}$$

(8) $$V_{ohmic} = I_{stack}.(R_m + R_c)$$

Rc signifies the resistance to proton transfer through the membrane, and it is typically treated as a constant value.

and: $R_m = \frac{\rho.l}{A}$ with:

ρ represents the specific resistivity of the membrane for electron flow, measured in centimeters (cm). A stand for the cell's active area in square centimeters (cm²), and l signifies the thickness of the membrane, also in centimeters (cm). This membrane serves as the electrolyte within the cell.

(9) $$V_{conc} = B.\ln\left(1 - \frac{J_n}{J_{max}}\right)$$

B, a parametric coefficient dependent on the cell and its operational condition, is represented in volts (V), while Jn denotes the actual current density of the cell in amperes per square centimeter (A/cm²). To enhance the limited conversion efficiency, it is crucial to optimize the entire conversion chain, with a particular focus on DC-DC converters. Among various DC/DC converter types, this paper specifically addresses the typical boost converter. As shown in Figure 3, the boost DC/DC converter circuit is depicted within the rectangle [6]. The feedback for output voltage regulation is also provided in Figure 4. The average output voltage is calculated as follows:

(10) $$V_{FCout} = \frac{V_{FCin}}{(1-d)}$$

The equation expresses the average output voltage, and it relies on the duty ratio denoted as "d." Because of this configuration, where ($0 \le d \prec 1$), the output voltage consistently surpasses the input voltage. This is why the circuit in Figure (3) is referred to as a boost DC/DC converter. To maintain the output voltage in line with the reference value, Pulse Width Modulation (PWM) is utilized to generate a pulse with the appropriate duty ratio. Our PEMFC generators consist of two parallels interconnected modules designed to achieve a specific operating voltage and output power. The Voltage Source Inverter (VSI) is under precise control, enabling it to inject sinusoidal current into the grid to extract energy from the PEMFC cells, irrespective of load conditions. In situations with inductive-capacitive loads, the VSI can also serve as a D-STATCOM for compensating reactive currents. For regulating the performance and efficiency of the PEMFC cells, the VSI is operated based on the principles of the p-q theory, illustrated in Figure (4). The control input involves a current error signal, which, in this specific application, represents the disparity between the actual current injected by the VSI and the desired or reference current waveform [7].

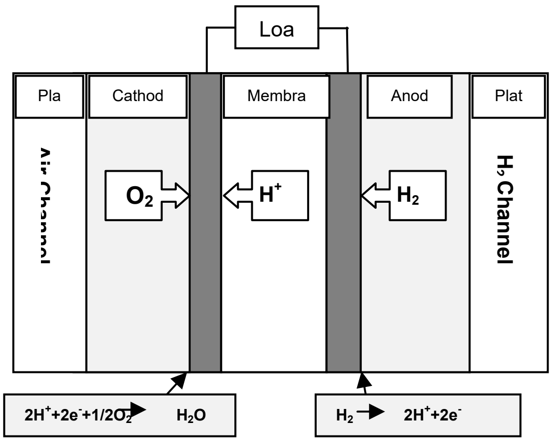

Fig.2. Basic PEMFC operation

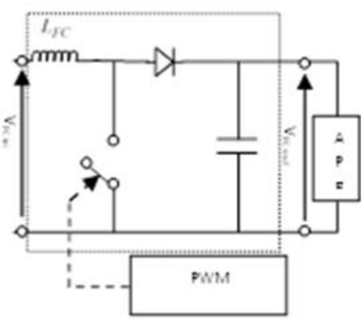

Fig. 3 Boost DC/DC converter

Reference currents generation

To determine the harmonic component of the load current, it is essential to generate a reference injected current. Subtracting this reference current from the total load current enables the calculation of the reference filter current. In this context, active and reactive power analysis in a stationary αβ frame, often referred to as p-q theory, has been employed [8]. In this framework, the load currents and source voltages are represented in the α-β frame as follows:

(11)
$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

(12)
$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

In this set of equations, ia, ib, and ic represent the load currents, while ea, eb, and ec denote the three-phase grid voltages. The instantaneous active and reactive powers in the α−β coordinates can be determined using the following expressions:

(13)
$$p_l(t) = e_\alpha(t) i_\alpha(t) + e_\beta(t) i_\beta(t)$$

(14)
$$q_l(t) = e_\beta(t) i_\alpha(t) - e_\alpha(t) i_\beta(t)$$

The instantaneous active and reactive powers can be formulated based on the equations, incorporating both the DC components and the AC components, as follows:

(15)
$$p_l = \overline{p_l} + \tilde{p}_l$$

(16)
$$q_l = \overline{q}_l + \tilde{q}_l$$

Where $\overline{p}_1$ and $\overline{q}_1$ represent the DC components attributable to the fundamental currents, whereas $\tilde{p}_1$ and $\tilde{q}_1$ denote the AC components arising from harmonic currents. In order to determine the reference currents, it is necessary to compute the instantaneous powers supplied by the source and the D-STATCOM to the load. Let (pg) and (qg) represent the real and imaginary instantaneous powers provided by the utility. On the other hand, to compensate for reactive power and harmonic current, the D-STATCOM supplies the real and imaginary instantaneous powers (pf) and (qf). The utility should supply $p_g = \overline{p}_1$ and (q_g) = 0, while the harmonic component is provided by the D-STATCOM, as well as (ql). The oscillatory part of (pl) is delivered to the nonlinear load by the D-STATCOM, ensuring that the source current maintains its sinusoidal waveform. Simultaneously, the load receives an equivalent amount of harmonic and fundamental current. In normal operation, the capacitor on the DC side of the inverter operates as follows:

(17)
$$\begin{aligned} p_g &= \overline{p_l} \\ q_g &= 0 \\ p_f &= p_l - p_g = p_l - \overline{p_l} = \tilde{p}_l \\ q_f &= q_l - q_g = q_l \end{aligned}$$

In these conditions the D-STATCOM supply only the reactive power. As a result, capacitor voltage level is constant during the steady state. When the load absorbs an exact amount of power $\overline{p_l}$ and if $p_g \prec \overline{p_l}$, the D-STATCOM supplies the rest part to regulate DC voltage level, so it is necessary to control active power balance among the grid, load and D-STATCOM and we have:

(18)
$$\overline{p_g} + \overline{p_f} = \overline{p_l}$$

So, to regulate the appropriate quantity of active power supplied by the D-STATCOM and control the power balance, the previous equations (17) need to be adjusted by introducing a gain factor (k) [3].

$$k = \frac{\overline{p_g}}{\overline{p_l}} \tag{19}$$

To recharge the capacitor to the desired VDC voltage level, the grid must provide an extra amount of active power to the D-STATCOM if the gain factor is greater than one. Conversely, when the capacitor voltage exceeds the desired level and grid power is in excess, the surplus power is provided by the D-STATCOM to the load if the gain factor is less than one. Therefore, the instantaneous reference powers for the D-STATCOM are as follows:

$$\begin{aligned} p_f^* &= \tilde{p}_l + (1-k)\overline{p_l} \\ q_f^* &= q_l \end{aligned} \tag{20}$$

In this scenario, the reference currents necessary for the D-STATCOM are determined using the following expression:

$$\begin{bmatrix} i_{f\alpha} \\ i_{f\beta} \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p_f \\ q_f \end{bmatrix} \tag{21}$$

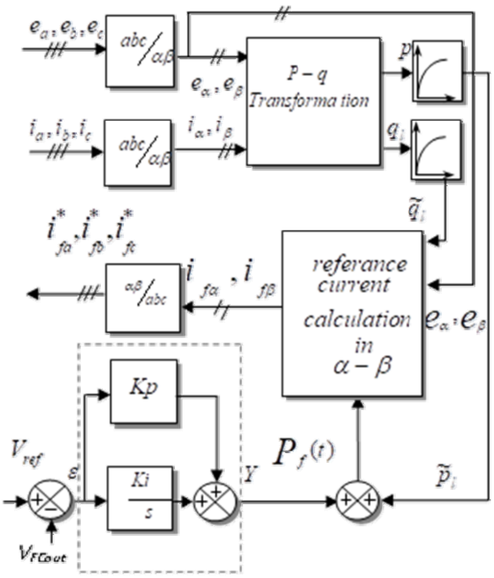

Fig. 4 Block diagram for the instantaneous active and reactive power

Simulation Results and Discussion

To validate the concepts discussed earlier, a simulation was conducted in the MATLAB/SIMULINK environment, as depicted in Figure 1. The setup comprised four PEM Fuel Cell Stacks, each rated at 625Vdc and 50kW, connected to 900Vdc DC/DC converters. These converters were interconnected in parallel with the STATCOM. Hydrogen utilization remained constant at its nominal value (Uf-H2 = 99.25%), while oxygen utilization was set at 56.67%. Each Stack consisted of 900 cells, with a Nernst voltage of approximately 1.138V. Table 1 presents the system's parameters, and the simulation included capacitive and inductive loads to represent reactive power-producing loads.

The operation unfolds as follows: Initially, an 8.8 mF fixed capacitor on the DC side of the system serves as the energy storage for the STATCOM. At t=1 second, a breaker on the PEMFC side is closed, allowing the PEMFC to supply energy to the DC side of the D-STATCOM (as shown in Figure 9). Breakers 1 and 2 are closed between t=0.4 seconds and t=0.8 seconds, connecting a heavy inductive load (60Kvar, 4kW) at the load side. The current lags the voltage by an angle of -23.40 degrees (Figure 5). This connection results in a 10% decrease in the power factor (Figure 7).

Table 1 The System parameters

Grid	values
Source Voltage Vs	220 V
Load Power PL	120kVA
Frequency fs	50 Hz
PAPF	values
Switching Frequency	12 kHz
Output Filter	1 mH
DC Link Capacitor	8.8 mF
Capacitor DC Voltage	900 V
STATCOM control	PWM + PI

Phase-a load current and voltage are presented in Figure

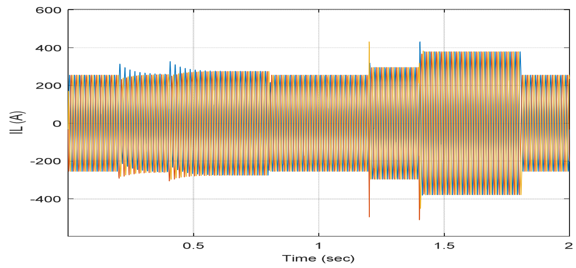

Fig. 5 load current

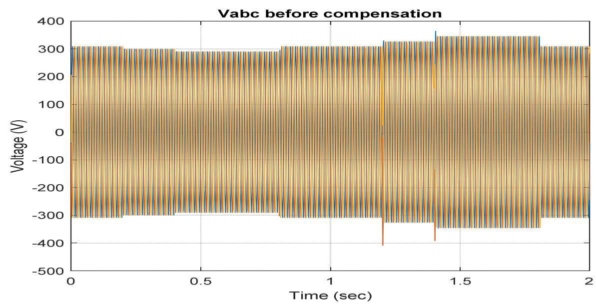

Fig. 6 source voltage before compensation

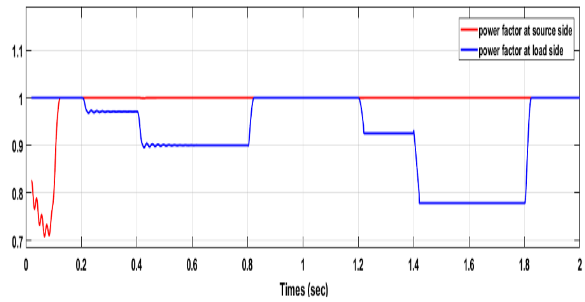

Fig. 7 The variation of power factor

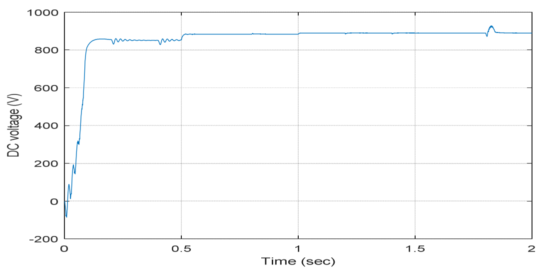

Fig. 8 DC bus voltage

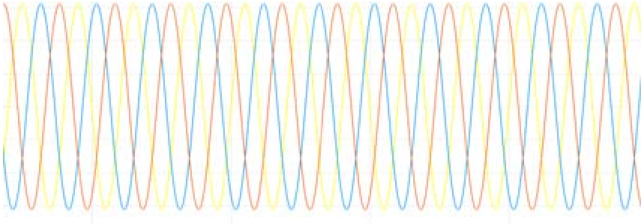

Fig.9 source voltage after compensation (with Zoom)

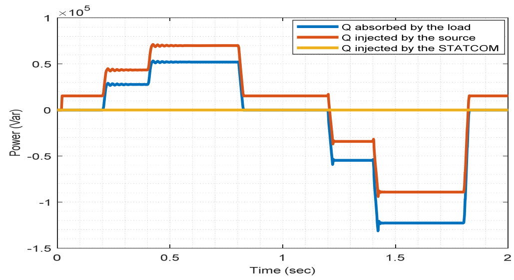

Fig. 10 The variation of reactive Power without compensation

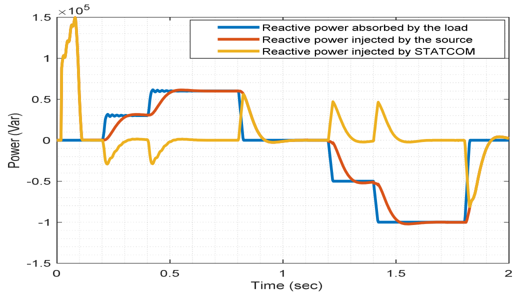

Fig.11 The variation of reactive Power after compensation

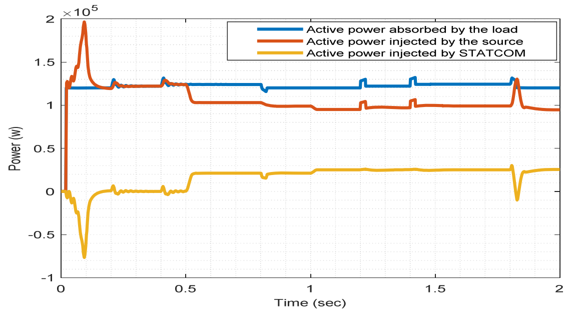

Fig. 12 The variation of active Power

6. The D-STATCOM is connected in shunt with the network via a transformer. Due to the injection of reactive current by the D-STATCOM, the power factor improves and becomes unity, as shown in Figure 7. In cases with heavy inductive loads, as seen in Figure 8, the D-STATCOM injects reactive power, thus maintaining the power factor at the reference value under inductive conditions. To replenish the capacitor value required by the VDC voltage (Figure 9), the D-STATCOM absorbs active power.

Conclusion

Issues with reactive power compensation and power quality arise in power systems when the equilibrium between the supply and demand of reactive power is disrupted. These problems lead to significant financial losses and equipment malfunctions. The effectiveness of the controller plays a crucial role in reducing losses for customers and minimizing the repair and maintenance costs associated with the distribution system. This study focuses on the utilization of fuel cells for the DC-bus voltage control of a D-STATCOM. The primary objective of the D-STATCOM is to regulate voltage and improve the power factor at the point where power is connected by injecting reactive power into the transmission line, aiming for a power factor of one. The DC-bus voltage is also managed by incorporating an appropriate direct current component. The proposed approach combines the PQ identification method with a PI controller. One of the notable advantages of this approach is its reduced sensitivity to variations in system parameters. Additionally, it exhibits an almost negligible response time. The results presented in this paper demonstrate that the PI controller offers fast dynamic response and high accuracy in tracking the DC voltage reference.

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