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Effect of Fuel Cells on Voltage Sag Mitigation in Power Grids Using Advanced Equilibrium Optimizer and Particle Swarm Optimization

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Abstract— Integration of Proton Exchange Membrane Fuel Cell (PEMFC) with electrical power grid (EPG) can improve the power quality (PQ) of EPG by injecting the required power. However, this makes the PQ issue more complicated due to the negative impact of voltage sag on EPG. Unfortunately, the classical P-I controllers fail in eliminating the voltage sag. In this context, this paper, attempts to mitigate the voltage sag in an interconnected PEMFC-EPG system by utilizing advanced equilibrium optimizer (AEO) and particle swarm optimization (PSO) controllers, and their efficiency is demonstrated by comparison with conventional P-I controllers. To achieve this goal, the AEO-PEMFC and PSO-PEMFC are employed in the EPG line with different fault scenarios. The obtained results unveil that both AEO-PEMFC and PSO-PEMFC provide the needed boost of voltage in the single line-to-ground faults (SLGF) scenario by 100.00%. For double line-to-ground faults (DLGF) scenario, a voltage boost of 99.56% and 98.39% is achieved while a voltage boost of 98.50% and 97.45% for the three line-to-ground faults (TLGF) scenario is obtained by the AEO-PEMFC and PSO-PEMFC, respectively.

Keywords— Proton exchange membrane fuel cell; Electrical power grid; Voltage sag; Advanced equilibrium optimizer; Particle swarm optimization; Proportional integral control.

1. INTRODUCTION

Nowadays, the electrical power grid (EPG) is getting complicated due to the disconnection of renewable energy sources (RES), in practical fuel cells (FC) [1]. There is no doubt that the FC can offer a clear advantage to improve the power quality (PQ) on EPG by injecting the required power. In this context, solving the PQ issue also became more complicated due to the negative impact of voltage sag on EPG [2]. The FC-EPG integration is accomplished via inter-power feeders, which are essential for power transfer between various control areas. In addition to that, the implementation of PEMFC-EPG interconnection provides clean and reliable source that can be applied in the generated unit, transformation network, and distributed systems. The Proton exchange membrane fuel cell (PEMFC) can be deemed an uttermost resource that has significant advantages of using on EPG including zero emission of power, high robust reliability, and high efficacy, scalability, low operational costs.

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The goal of advanced equilibrium optimizer (AEO) and particle swarm optimization (PSO) are to increase the productivity of the PEMFC-EPG interconnection. In this regard, an overly developed AEO and PSO are essential for the settlement of the parameter estimation issue of PEMFC-EPG models. To obtain the maximum reliability and high PQ of the EPG, the time and magnitude voltages are essentially monitored and regulated as well. The adapted AEO and SPO for figuring out this issue is demonstrated in the following sections. To further elaborate the contributions, flexible simulation parameters for PEMFC-EPG interconnection strategies are applied due to different fault scenarios.

A recent study [3] has indicated that the grid-integrated PEMFC system serves the purpose of sharing available power while also reducing current harmonics at power grid-scale currents. In this direction, current harmonics affected by nonlinear loads are decreased drastically to values under 5% THD, as described by IEEE-519 requirements. In addition to that, a more comprehensive description can be found in [4] which deals with double Q reinforcement learning to achieve the near-optimal average cost of the fuel cell. Importantly, the results provide evidence for the mitigation of voltage sag. It was the primary purpose of the work in [5] to reduce the voltage sag effect by interfacing a PEM with the distribution network and applying a DSTATCOM technology within proportional integral (P-I) control. Moreover, in another study, suggested controller is initialized based on Equilibrium Optimization and verified its superiority by comparison with a classical PI optimized base. Findings indicate that the fuzzy PI controller can decrease the peak-to-peak deviation in the frequency by 30–59% under wind disturbance, compared to a classical PI optimized base [6]. Therefore, previous research demonstrated an improved equilibrium optimizer (IEO) for determining the optimal location and effective size of distributed generation units (DGUs) in the electrical distribution networks in order to reduce the total power loss on distribution branches, investment cost, operation, and maintenance cost. In a good obtained solution, limits of voltage, current, and harmonic flows are also seriously considered, exactly satisfying predetermined ranges [7].

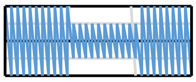
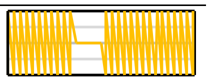
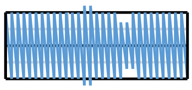
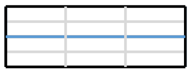
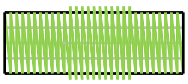
PEMFC has made significant contributions to EPG due to its technical advantages, low maintenance requirements, and low operating costs. PEMFC can be widely utilized and incorporated into the EPG. When compared to internal combustion engines, PEMFC provides two significant benefits: greater performance and zero air pollution. However, despite these advantages, PEMFC suffers from some limitations caused by its slow transient feedback, which must be taken into consideration to avoid premature aging. Regrettably, one of the most critical complications with the EPG procedure is PQ, particularly voltage sag. In this direction, voltage sag causes a significant decrease in the overall EPG performance. One of the most main complaints that have drawn the attention of numerous scientists is voltage sag, which could also cause major harm to EPG and machinery, customer requirements, and engineering products. In addition to that, this article represents a major contribution to improving the PQ issue at PEMFC-EPG interconnection using the advance equilibrium optimizer (AEO) and particle swarm optimization (PSO), and P-I controller during a single line-to-ground fault (S-LGF) Scenario, double line-to-ground fault (D-LGF) Scenario, three line-to-ground faults (T-LGF) Scenario. According to this manuscript, the modeling burden has been reduced, resulting in more rapid system efficiency of PEMFC to incorporate voltage into the EPG. It is obvious that the AEO, PSO and P-I controller increase outpaced growth in productivity of EPG with less computational burden, less complicated scheme and highly beneficial optimized feedback in several circumstances. The AEO, PSO, and P-I controller of PEMFC-EPG capability is validated for operating environments using simulation modeling.

In the following sections, the authors addressed the next parts of the manuscript. Section 2 discusses the power quality issues. Section 3 shows the control strategies of PMEFC-EPG interconnection including advanced equilibrium optimizer (AEO), particle swarm optimization (PSO), and proportional-integral (P-I) control. Section 4 shows the model of PMEFC-EPG interconnection. Section 5 addresses the result and discussion. Section 6 contains the conclusions.

2. POWER QUALITY ISSUES

In this regard, this manuscript addresses the links between the issue of Power Quality (PQ) and the power devices of customers (PSC), which has attracted particular attention in the EPG utilities, industrial, end-users, and researchers [8] with increased competition and decreased government subsidies especially in third-world countries. Thus, the electric power utility can't be developed, innovative, dynamic as a consequence of increasing blackouts, and less efficiency of these utilities. For this reason, the notion of PQ and PSC have turned out to be crucial for utilities, governments, and end-user. Among various PQ issues, the voltage sag is one of the most serious issues compared to other issues such as harmonics, voltage swell, interruption, notch, flicker, and transients. Unless these underlying deficiencies of PQ issues are rectified, the distribution system can never be efficient. Table 1 shows PQ issues and waveform.

Table 1. PQ issues and their waveforms [1, 8].

PQ issues	Description	Waveform
Voltage Sag	The IEEE defines voltage sag as an event in which the root mean square value of voltage drops rapidly between 10% and 90% of the rated value and the duration lasts from 0.5 cycles to 1 min.	
Short interruptions	Total interruption of electrical supply for the duration from a few milliseconds to one or two seconds.	
Voltage spike	Very fast changing of the voltage rate for durations from several microseconds to a few milliseconds. Even in low voltage, these variations may reach thousands of volts.	
Long interruptions	Total interruption of electrical supply for period greater than one to two seconds.	
Voltage Swell	Momentary rise of the voltage, at the power frequency, outside the common tolerances, with a period of more than one cycle and usually less than a few seconds.	

3. CONTROL STRATEGIES OF PMEFC-EPG INTERCONNECTION

In this section, the operating principles of control strategies of PEMFC-EPG are utilized to eliminate the voltage sag issue. The advanced equilibrium optimizer (AEO), particle swarm optimization (PSO), and proportional-integral (P-I) control were used to determine the scope of the manuscript.

3.1. Advance Equilibrium Optimizer

Advance Equilibrium Optimizer (AEO) is well known as a physics-based meta-heuristic algorithm. AEO utilizes the underlying processes in order to predict and simulate behavior on a control volume. As a result, it determines the amount of chunk that moves out, takes in, and produces in a control volume over a moment using a chunk mass equation and attempts to determine the state that will contribute to the volume's equilibrium. Fig. 1. illustrates the flowchart of the AEO-PMEFC-EPG. Moreover, AEO can utilize a bunch of particles to model the vector of mass on volume. In this regard, AEO behavior is characterized such as the other meta-heuristic algorithms begin with the optimization algorithm by dispersing the particles within the optimal power flow problem's search space.

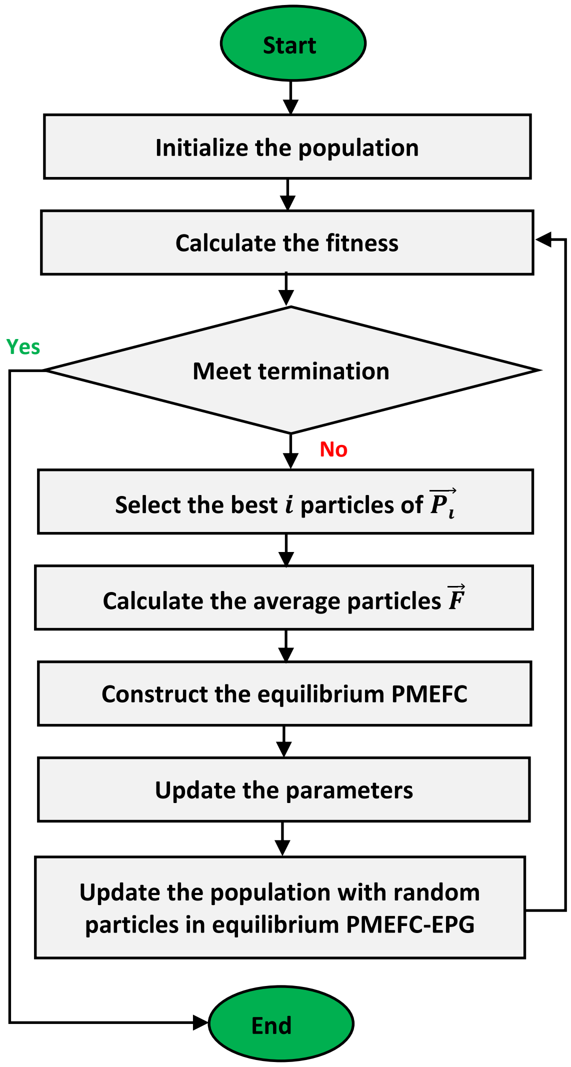


Fig. 1. Flowchart of the AEO-PMEFC-EPG.

This manuscript demonstrates the mathematical model of AEO using Eq. (1):

$$\vec{P_i} = \overrightarrow{H_{min}} + (\overrightarrow{H_{max}} - \overrightarrow{H_{min}}) * \vec{r}, i = 0, 1 \ldots, N \quad (1)$$

where $\vec{P_i}$ refers to the level vector of i^{th} particle, $\overrightarrow{H_{max}}$ and $\overrightarrow{H_{min}}$ represents the constraints of the issue, $\vec{r}$ demonstrates a vector produced randomly. The term N illustrates the scale of the population (particles). The balance between the EO's exploration and production abilities is expressed as in Eq. (2):

$$\vec{F} = e^{-\vec{\lambda}(t-t_0)} \tag{2}$$

The aforementioned term ($\vec{F}$) achieves a balance between the EO's exploration and production abilities, with this factor initially trying to find a solution with a massive scale factor that declines with iterations. $\vec{\lambda}$ is a variable with values ranging from 0 to 1.

$$t = \left(1 - \frac{it}{t_{maxIter}}\right)^{\left(a_2 * \frac{it}{t_{maxIter}}\right)} \tag{3}$$

where t is reduced by the rise of the it iteration using Eq. (3); It is well known as the current iteration. The maximum iterations can be presented as $t_{maxIter}$. Last but not least, a_2 illustrates constant rule rate lasting the exploitation ability. The production volume in AEO is clarified to strengthen the potential of exploration and exploitation, as well as to avoid becoming stuck in a local optimum. The mass balance estimation is defined as the following equation:

$$Q(C_e - C) + G = V\frac{d_c}{d_t} \tag{4}$$

where Q describes the flow rate, the term of C_e presents the concentration in the equilibrium position, C is the heart of concentration, and the term G refers to inner mass generation level. $V\frac{d_c}{d_t}$ shows the mass change level, and V relates to the control volume.

3.2. Particle Swarm Optimization

In this subsection, Particle Swarm Optimization (PSO) made a determined effort to improve PQ at the power grid. In this context, the PSO is specifically aimed to optimize iteratively issues such as set, population, and candidate solutions. Thus, each particle step is determined as the top global location with the swarm coupled with its individual superior position based on its fitness value. These effects are particularly noticeable in process of finding the original problem's optimal solutions. Regular insights, improvements, and learning can be implemented in PSO in each iteration (the velocity and the position). Fig. 2 illustrates the flowchart of the PSO-PMEFC-EPG.

For better understanding, through each iteration of the algorithm, the velocity of each particle i in the swarm is adjusted using Eq. (5) [7].

$$\overrightarrow{V_{t+1}^{i}} = \vec{V}_t^i + \varphi_1\, R_1{}_t^i\, (\vec{p}_t^i - \vec{x}_t^i) + \varphi_2\, R_2{}_t^i\, (\vec{g}_t^i - \vec{x}_t^i) \tag{5}$$

where φ_1 and φ_2 are actual acceleration coefficient vectors referred to as cognitive and social weights, that also manage how much each particle's velocity and trajectory should be influenced by the particle's global and individual strongest position. Thus, fine-tuning PSO parameters is particularly important in multimodal concerns, where major applications of the search process are showing promising domains. In this context, both R_1 and R_2 demonstrate d-dimensional random variables with uniform probability that are employed to keep the swarm population diverse. To sum up, $\vec{p}_t^i$ and $\vec{g}_t^i$ present the individual most optimal setting of particle i at iteration t, and the prevailing overall optimized position of the swarm.

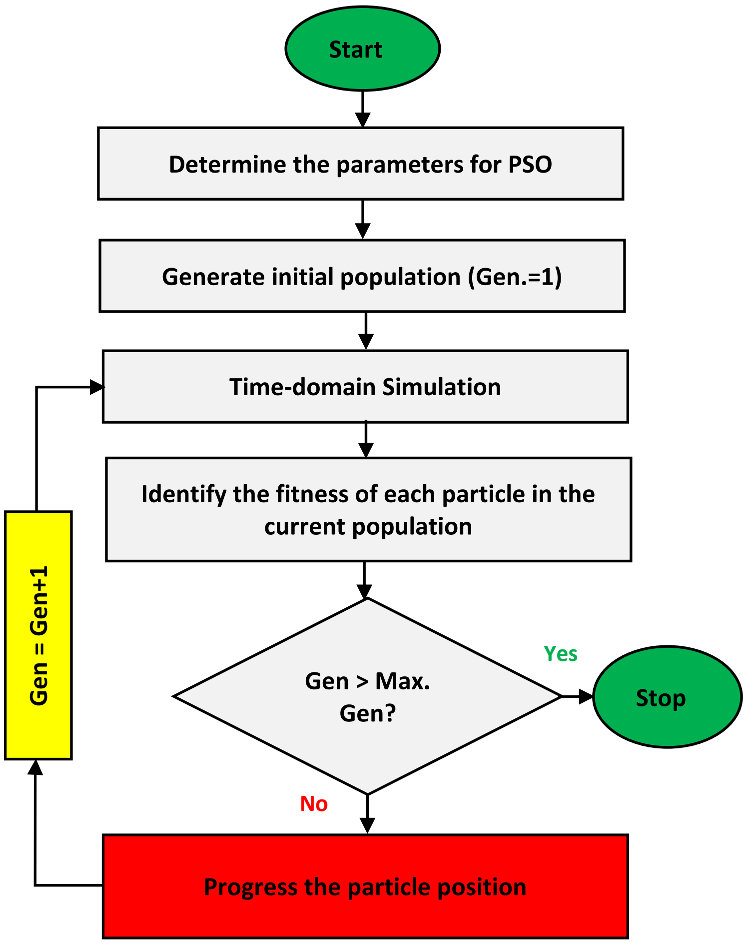


Fig. 2. Flowchart of the PSO-PMEFC-EPG.

3.3. Proportional Integral Control

The Proportional Integral (P-I) control is the desired control mechanism for PEMFC-EPG interconnection due to improvements in accuracy and power consumption. In addition, the P-I controller is a considerate of linear-controller, as it determines the control error concerning the adjusting value and output of a process and then constructs the controller output value using the linear product of the error's proportion and integration. In the case of P-I controllers, the control signal is calculated from the input signal at the time (t) as expressed in Eq. (6). Moreover, the P-I controller's transfer function is as described in Eq. (7):

$$u\ (t) = K_p\ e(t) + K_i \int_0^t e\ (t)\ dt + u_0 \tag{6}$$

$$G_c\ (s) = \frac{U\ (s)}{E\ (s)} = K_P + \frac{K_i}{s} \tag{7}$$

where $u\ (t)$ presents the controller yield, u_0 refers to the controller's primary yield, K_P shows the proportion parameter of the system, K_i is well-known as the integral parameter of the system, and $e\ (t)$ presents the error at a defined time (t).

4. MODEL OF PEMFC-EPG INTEGRATION

The PMEFC is widely regarded as the innovator of green electricity. The primary aspiration of this paper is to establish PMEFC output that is suitable for the electrical power grid (EPG) in order to eliminate voltage sag [8]. Notwithstanding, assessing the effectiveness of PMEFC outlet power is a highly complicated and challenging condition because the constituents of the measurement vary significantly among other renewable energy technologies. Fig. 3 illustrates the configuration of the PEMFC-EPG interconnection within the advance equilibrium optimizer (AEO), in which several elements including DC-AC converters, filters, and transformers can be amalgamated to integrate with the PG [9].

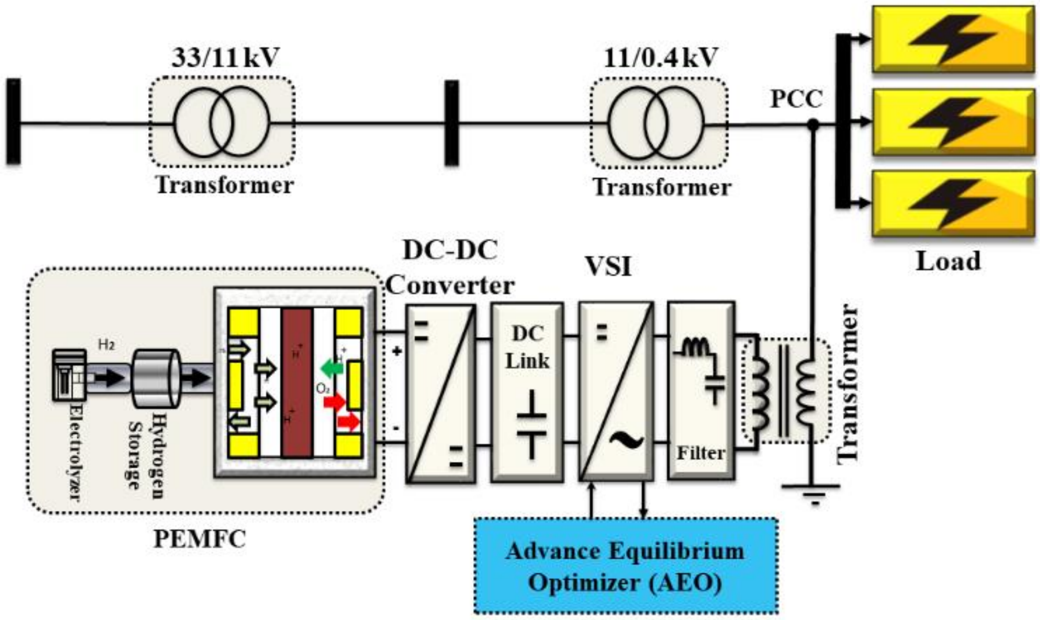


Fig. 3. Configuration of the PEMFC-EPG interconnection within the AEO.

While Fig. 4 describes the configuration of the PEMFC-EPG interconnection within Particle Swarm Optimization (PSO), Fig. 5 presents the configuration of the PEMFC-EPG interconnection within proportional-integral (P-I) control.

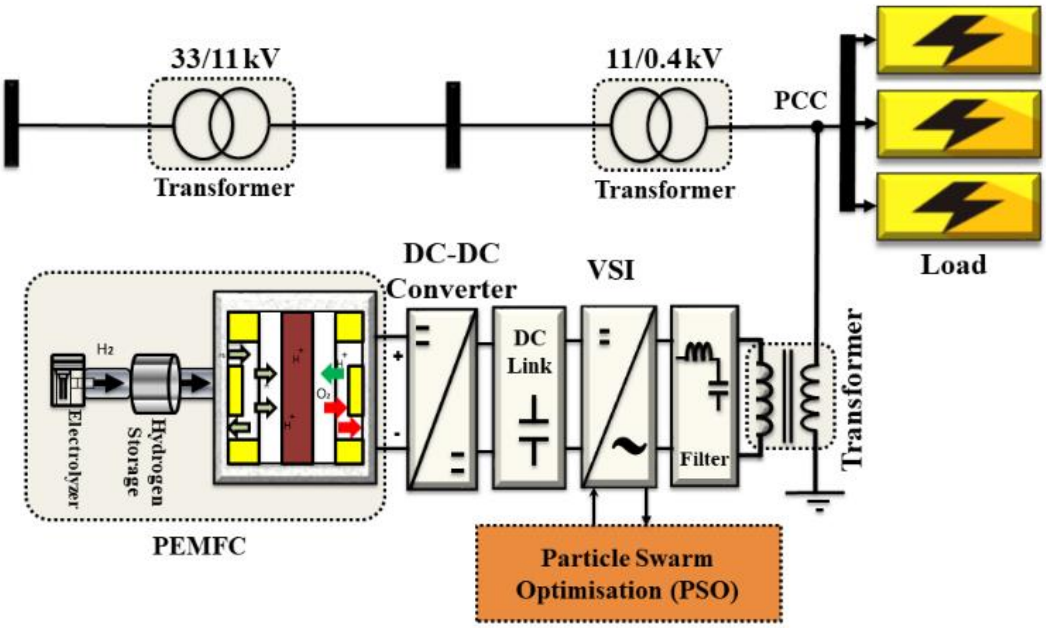


Fig. 4. Configuration of the PEMFC-EPG interconnection within PSO.

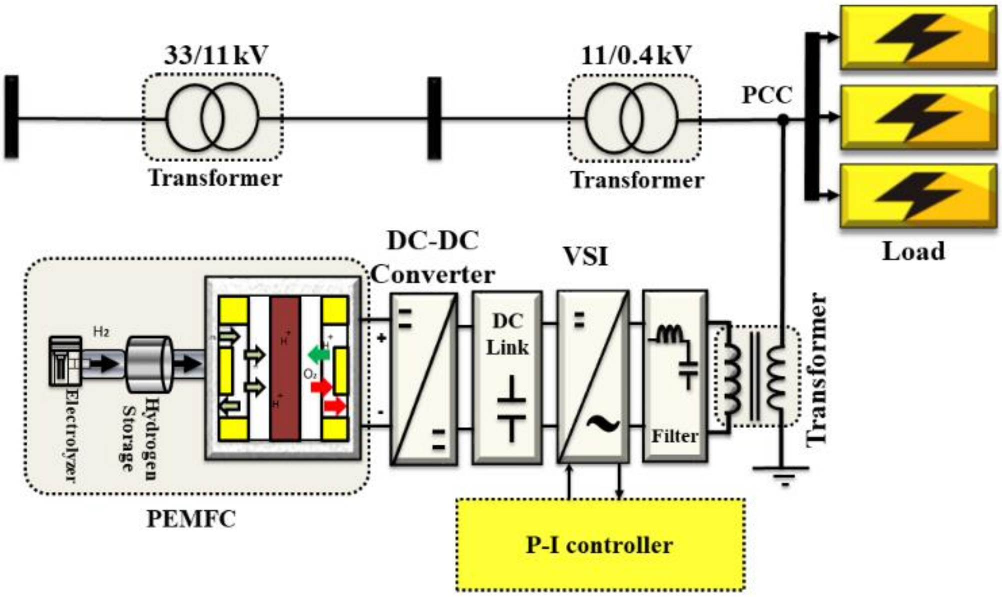


Fig. 5. Configuration of the PEMFC-EPG interconnection within the P-I controller.

In the field of energy storage systems (ESS), the Fuel Cell (FC) has been considered one of the potential solutions to the future energy crisis in the power grid due to the ability to guarantee adequate energy supplies based on load demand [10]. FCs offer excellent facilities for the power grid [11, 12]. Fig. 6 demonstrates the PEMFCs power technology.

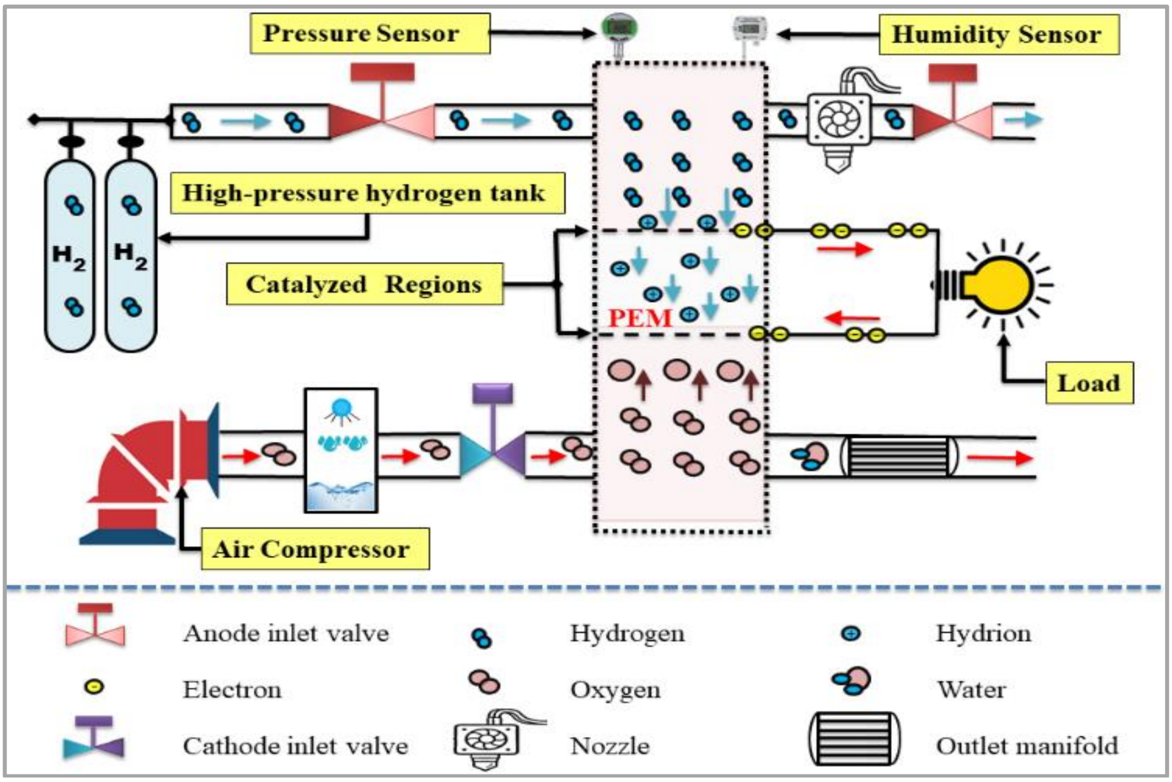


Fig. 6. The PEMFCs power technology [6].

In order to increase PMEFC productivity and corrosion resistance, affordable bipolar plates have evolved. By optimizing the operating parameters of the PEMFC for dynamic performance, the durability of the membrane can be enhanced [13]. The EPG-interconnection with PEMFC has received special attention from academics. To implement the systems, a deeper understanding and detailed analysis are necessary [14]. Detailed estimates are necessary for normal and abnormal EPG operations. In this direction, the EPG-interconnection with FC can be operated effectively using advanced power electronics converters. By using the integrated power converter, most of the power can be extracted from the supply and put into the grid. It requires a DC-DC converter to boost it for various applications [15]. EPG applications require DC voltage (V_{dc}) to be converted to AC voltage (V_{ac}) by a PG side converter. In this context, EPG integrated PEMFC technology is increasingly being installed due to advances in power electronics. In PEMFC-EPG mode, VSI functions as a voltage source rather than a current source. This achieves efficient EPG-interconnection through the control of inverter voltage using AEO and PSO. However, the PEMFC current supplied to the EPG can have phases with the grid fundamental voltage based on the standard of EPG-interconnection [16].

The maximum power of the PEMFC is calculated by subtracting the voltage acquired as a result of a reaction between chemicals from the power dissipation along its path, as shown in Eq. (8).

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{Electricity+Heat} \tag{8}$$

An improvement of almost 90% in efficiency has been observed for PEMFC energy at 250.0 °C. Rated power gains can conceivably be noticed with a full-load design and utilization of boost converters. The voltage level and predictor in PEMFC-EPG power applications are changeable and have a heavy reliance on process parameters. As a result, DC/DC converter topologies are widely used to keep a stable voltage that meets the requirement of the EPG Feeder. Due to the parameter variations of the PEMFC-EPG and load characteristics, a more robust power converter design is required. In the PG aspect, these implementations are rapidly evolving. Even though, bidirectional power flow is supported by the DC-DC converter. Fig. 7 illustrates the category of inverter topologies utilized in FC-EPG interconnection.

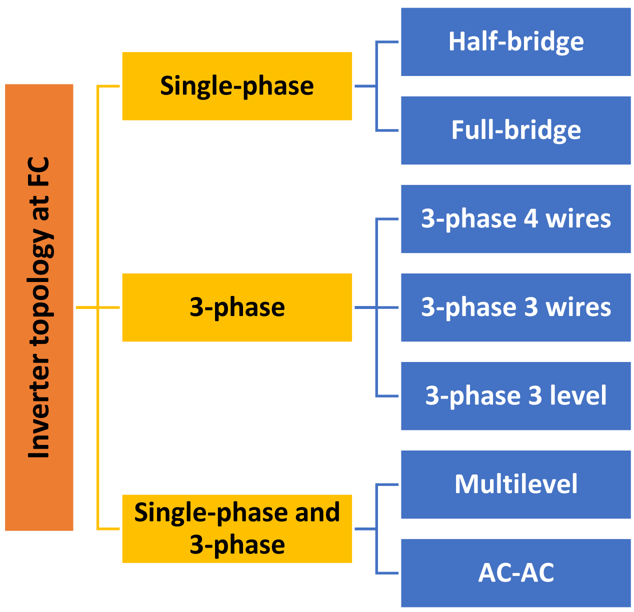


Fig. 7. The categories of inverter topologies utilized in PEMFC-EPG interconnection.

DC-AC converter topology is a well-known voltage source inverter (VSI) that converts the topology of the DC to AC voltage to provide energy within the PEMFC-EPG interconnection. In this way, these converters control active and reactive power between the PEMFCs-EPG interconnection.

5. RESULTS AND DISCUSSION

The PEMFC-EPG parameters that can be seen in Table 2 indicate implementation parameters in MATLAB/Simulink software. PEMFC simulation models are used to mitigate the voltage sag issue at EPG. In addition, the result of using AEO, PSO, and P-I control across 33/11 kV EPG is improving the PQ issue.

Table 2. Simulation parameters of PEMFC-EPG.

Parameter	Unit	Ratings
Voltage source	kV	11/0.4
Voltage line	V	230
Rated power of PEMFC	kW	19.5
Rated current of PEMFC	A	265
Rated voltage of PEMFC	V	19.5
Model coefficients ξ_1	V	0.96
Model coefficients ξ_2	V/°C	-0.0030
Model coefficients ξ_3	V$cm^3/(mol°C)$	-6.9 x 10^{-5}
Model coefficients ξ_4	V/(A°C)	1.6 x 10^{-4}
Contact resistances R_c	Ω	0.0003
Line-impedance	H, Ω	0.006, 0.002
Load-resistance	Ω	201.2
Load-inductance	H	20.1999

Furthermore, the effectiveness of involving and without the installation of PEMFC-EPG is achieved using MATLAB/Simulink environment. In this regard, Fig. 8 depicts the electrical properties of the PEMFC throughout operating conditions. In accordance with the waveforms, the PEMFC voltage and current are approximately 75.0 V and 265.0 A, respectively. The energy delivered to EPG by PEMFC corresponds to the peak power of 19.5.0 kW.

The optimization approach illustrates that EPG voltage sag appears for 2 s. It begins at second 2 and ends at second 4. Without PEMFC, the voltage sag has reached 58.70% due to the single line-to-ground fault (SLGF) scenario. Fig. 8 depicts the injection voltage produced by PEMFC-EPG in the event of a SLGF scenario.

On contrary, AEO-PEMFC and PSO-PEMFC are employed in the EPG line, and values of injection voltage are achieved at 100 % in the SLGF scenario. Thus, AEO-PEMFC and PSO-PEMFC have both achieved great results. Meanwhile, the P-I controller interfaced with PEMFC is employed in the EPG line, and values of injection voltage are achieved at 94.75 % in the SLGF scenario. Fig. 9 demonstrates the injection voltage by PEMFC-EPG due to the double line-to-ground fault (DLGF) scenario.

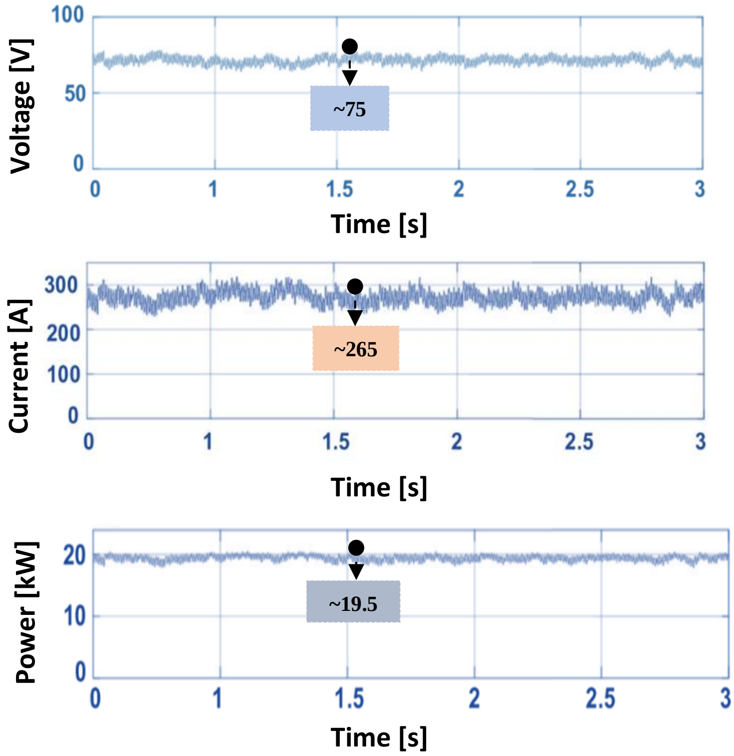


Fig. 8. The electrical waveforms at PEMFC outflow.

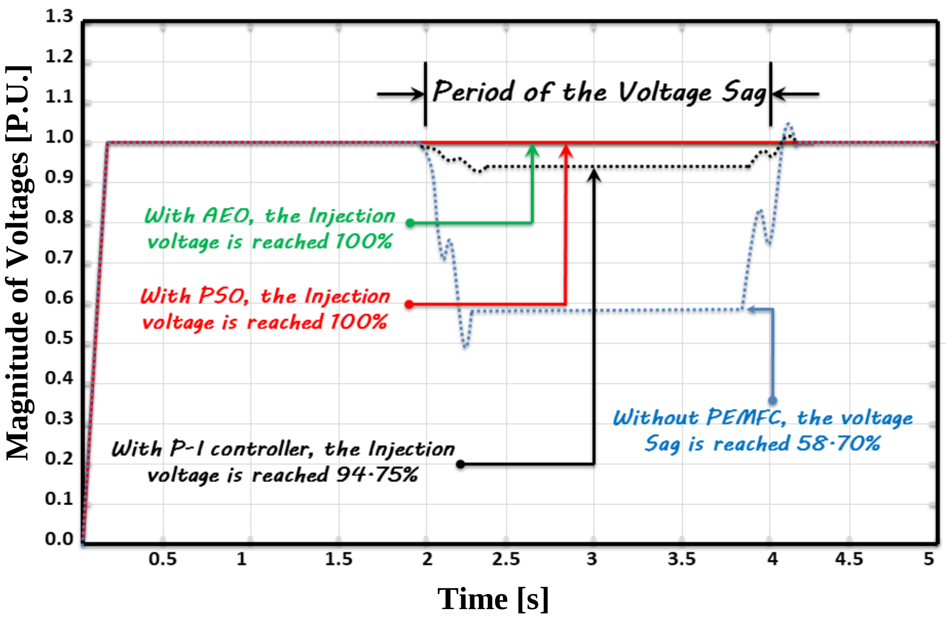


Fig. 9. Injection voltage by PEMFC-EPG due to SLGF scenario.

Due to DLGF scenario, the AEO and PSO approaches investigate that EPG voltage sag appears for 2 s. Without PEMFC, the voltage drop has reached 53.40 %. On the other hand, AEO-PEMFC is employed in the EPG line and values of boost voltage are achieved at 99.56% in the DLGF scenario. In this context, the PSO-PEMFC is employed in the EPG line and values of boost voltage achieved 98.39 % at the DLGF scenario. Moreover, the P-I controller interfaced with PEMFC is employed in the EPG line and values of boost voltage achieved 71.75 % at the DLGF scenario. Fig. 10 demonstrates the injection voltage by PEMFC-EPG due to DLGF scenarios.

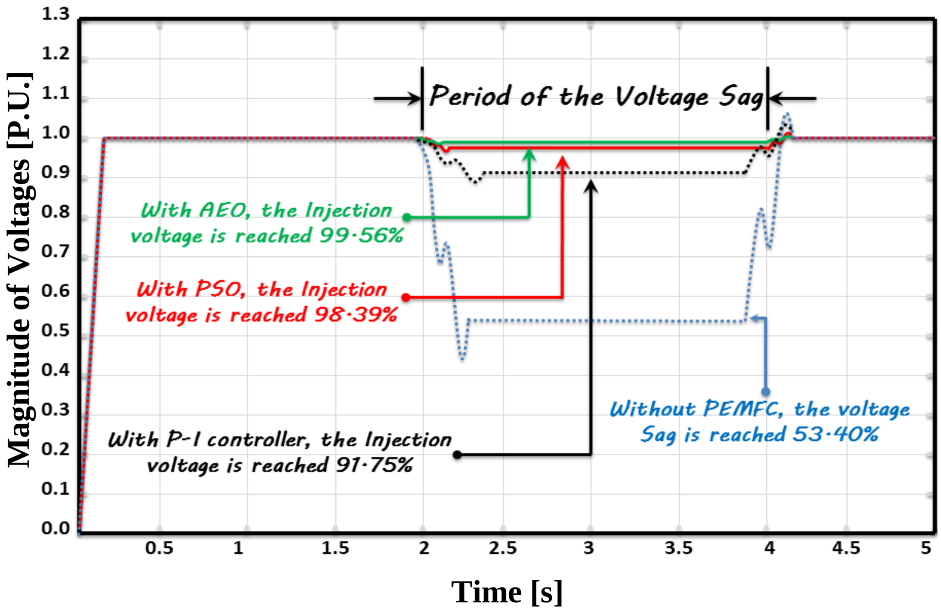


Fig. 10. Injection voltage by PEMFC-EPG due to the DLGF scenario.

Due to the TLGF scenario, the AEO and PSO approaches investigate that EPG voltage sag appears for 2 s. Without PEMFC, the voltage drop has reached 50 %. On the other hand, AEO-PEMFC is employed in the EPG line and values of boost voltage achieved 98.50 %. In this context, the PSO-PEMFC is employed in the EPG line and the amount of boost voltage achieved 97.45 % at the TLGF scenario. Moreover, the P-I controller interfaced with PEMFC is employed in the EPG line and values of boost voltage achieved 89.50 % at the TLGF scenario. Fig. 11 demonstrates the injection voltage by PEMFC-EPG due to TLGF scenarios.

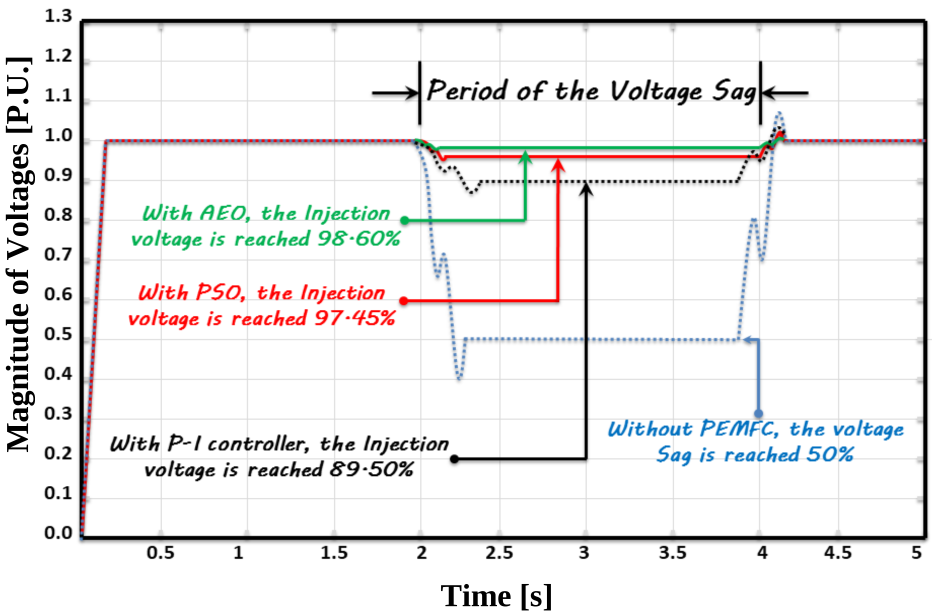


Fig. 11. The injection voltage by PEMFC-EPG is due to the TLGF.

6. CONCLUSIONS

The main conclusion that can be drawn is that the benefits of PEMFC-EPG interconnection have developed by utilizing the advanced equilibrium optimizer (AEO), particle swarm optimization (PSO), and P-I controller to eliminate voltage sag. However, there are significant challenges associated with enabling and securing the EPGs' operational control, with the problem of optimization selection of droop coefficients taking the lead. Besides that, the mathematical models of AEO, PSO, P-I controller, and modeling effect of PEMF-EPG interconnection have also been considered. In this context, the obtained results of the input parameters for PEMFC-EPG interconnection demonstrate high performance to mitigate the voltage sag. AEO-PEMFC and PSO-PEMFC are employed in the EPG line and values of boost voltage are achieved at 100% in the SLGF scenario. The AEO-PEMFC and PSO-PEMFC are utilized in the EPG line and the amount of boost voltage obtained is 99.56% and 98.39% in the DLGF scenario. The AEO-PEMFC and PSO-PEMFC are operated in the EPG line and values of boost voltage gained 98.50% and 97.45% due to the TLGF scenario, respectively. Future research should further develop and confirm these initial findings by utilizing optimal placement sizing of wind turbine Generators, superconducting magnetic energy storages, solar photovoltaics, and other hybrid energy storage system in the EPG.

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