Fuel cell stack design and modelling with a double-stage boost converter coupled to a single-phase inverter

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Abstract

A comprehensive proton-exchange membrane fuel cell stack model was developed and integrated with a two-stage DC/DC boost converter. It was directly coupled to a single-phase (two levels—four pulses) inverter without a transformer. The pulse-width modulation signal was used to independently regulate every converter phase. The converter was modelled using a MATLAB®/Simulink® environment and an appropriate voltage control method. The analysis features of the suggested circuit were created and, through established experiments, the simulation results were verified. A single-phase (two levels—four pulses) inverter control circuit was tested and it produced a pure sinusoidal waveform with voltage control. It matches the voltage of the network in terms of amplitude and frequency. A sinusoidal pulse-width modulation approach was performed using a single-phase (two levels—four pulses) pulse-width modulation inverter. The results demonstrated an enhancement in the standard of the output wave and tuned the dead time with a reduction of 63 µs compared with 180 µs in conventional techniques.

Graphical Abstract

Keywords: PEM fuel cell; pulse-width modulation; single-phase inverter and double-stage DC/DC boost converter

Introduction

Where power transformation occurs, the basic core of the system is the polymer electrolyte membrane (PEM) fuel cells. In every fuel cell, the resultant chemical energy from the reaction is directly transformed into electrical energy. The chemical and physical operation properties are completely dependent on the current, which is the rate of reaction, and the voltage, which is the driving force of the reaction, as investigated in [1–4]. One of the current major challenges has been solved by improving the quality of load matching between alternating-current (AC) and fuel cell stack (FCS) loads.

The inverter topology and its potential to provide a pure sinusoidal waveform in addition to managing the voltage range for AC operations are what distinguish the major method of resolving this issue. High-frequency transformers (HFTs), which are used on the direct-current-to-direct-current (DC/DC) stage, are slightly lighter than line frequency transformers (LFTs), which are built for network-side photovoltaic (PV) inverters and are therefore more difficult to install. However, they have many power stages, which makes the system more complicated and reduces its overall efficiency and dependability [5, 6]. Nowadays, obtaining the maximum power of the solar PV framework and increasing...
its output power from 24 to 100 to 312 V is challenging due to the high price of solar panels. Consequently, the 312 VDC (direct current voltage) was fully transformed into 220 VAC (AC voltage) using a single-phase inverter. The inverter power rating has been optimized to effectively run devices in the home. The most popular battery backup inverters currently in the marketplace are quasi-sine-wave or modified sine-wave inverters. Electronics powered by such inverters run the risk of being destroyed due to the presence of high harmonics [7, 8]. The synthesis of a pure sine wave has significant applications in electronics, but the bulk of sine-wave inverters on the market are very costly and have a low manufacturing capacity. The sinusoidal pulse-width modulation (SPWM) switching approach has been defined as a robust methodology employed in an original sinusoidal waveform inverter. A DC–DC converter set the solar output in VDC to a useful value and then it was transformed into VAC using pulse-width modulation (PWM) techniques in the inverter applying a two-level PWM generator [9, 10]. SPWM was created for use in electrical and electronic systems such as machine drives, renewable-energy systems and uninterrupted power supplies (UPS) [11]. Fixed peak pulses with varying switching frequencies for each interval were the hallmarks of the SPWM technique. By comparing a carrier wave (triangular) with a reference wave (sine wave), which had the required frequency, this wave was produced routinely [12–14]. A two-level PWM generator could deliver trigger signals to generate the signal needed for the PWM due to the PWM design of the module. The gate drive voltage was dominated by a two-level PWM generator that could produce an adjustable-frequency PWM wave. Although such an inverter application was from a DC source of solar PV or a fuel cell (FC) stack that had a complete control circuit in specific dead time, a two-level PWM generator produced control circuits employing either stand-alone or network-connected systems.

The control complexity of the single-phase (two levels—four pulses) inverter bridge control complexity was reduced using a two-level PWM generator, which was compatible and adaptable to change the control methods on the fly and without further hardware adjustments [15].

In [16], a significant microcontroller based on a novel control circuit was used for grid integration or as a stand-alone model, but the inverter model came from a direct supply of fuel cells that completed the control circuit with inadequate dead time. In [17], specific control algorithms were adopted with low cost in real time and without additional hardware changes, which decreased the complexity of the control circuit of the single-phase inverter bridge. In [18], the authors numerically investigated the effect of the catalyst microstructure on the performance of a 5-cm PEM fuel cell. The numerical model was validated and showed good agreement with the experimental data, thus giving confidence in the model as a design tool for future improvements of the catalyst structure. The authors in [19] proposed a hardware design for a two-stage boost converter, each stage controlled separately by a PWM signal, and modelled the inverter interfaced with a simple flexible commercial PIC microcontroller capable of generating PWM to enhance the waveform and the output voltage, and software package simulation in Proteus and PSIM to support and validate the proposed practical model.

From work carried out in the literature for a fuel cell application, the FCS power transformation based on a single-stage boost converter with an adequate inverter has been investigated. All these structures suffer from inadequate dead time.

In this research work, a PEM fuel cell (FEMFC) system with a two-stage DC/DC boost converter is simulated and validated with experimental data in order to reduce the dead time to 63 µs as opposed to the usual value of 180 µs. A two-level PWM generator that can produce PWM to boost the output voltage waveform is attached to the inverter model. Third, the effectiveness of the suggested experimental strategy is evaluated and verified using a MATLAB®/Simulink® system. The results and analyses produced using the two-level PWM generator have promptly implemented a control strategy without requiring any further hardware modifications and have minimized the difficulties associated with the gate drive of the single-phase inverter connection. Furthermore, an enhancement of the output waveform identical to the original sinusoidal waveform of the inverter reduced the dead-time control compared with corresponding studies. The model was also simulated in MATLAB®/Simulink® to evaluate and assess the outcome results and was verified experimentally using a commercial FEMFC and two-stage DC/DC boost converter.

1 Methodology

The FCS model has been developed to integrate with a two-stage boost converter, which in turn has been connected to a single-phase (two levels—four pulses) inverter without a transformer to validate the compatibility of a controlled pure sinusoidal wave for AC appliances, as depicted in Fig. 1.

Although AC uses require a high voltage level, the FCS has a modest output voltage level. Consequently, the DC/DC boost converter could not reach the improved exchange ratio in a single step, necessitating a huge input current, which increases the conduction breakage in the switching electrical network. As a result, the effectiveness of the converter decreases. The diode also has a dangerous problem of reversing recovery [19, 20]. According to Equation (1), the duty cycle is inversely related to the converter efficiency [21]:

$$\eta = \frac{1}{1 + \frac{D}{(1-D)^2} R_{real}}$$  

where $R_{real}$ represents the internal resistor of the inductor and $R_{real}$ represents the load resistance. Because the feedback loop is sophisticated for stability, the D cycle could not rise above a set peak point ($D > 0.9$), according to the formula. As a result, the transistor state changes require a specific amount of time. Therefore, the cascaded two-stage DC/DC step-up converter has been suggested to have maximum efficacy and an increased voltage ratio. Based on the boost voltage standard at every stage, the main power switch simultaneously provides a PWM signal with a different $D$ for each phase. When used, the inverter transforms its input from VDC to VAC. However, the output waveform of a perfect inverter is sinusoidal. In practice, the inverter produces a non-sinusoidal wave with harmonics. The electrical equipment that this inverter powers may be damaged by the harmonic presence [22, 23].

![Fig. 1: Proposed system configuration](https://example.com/f1.png)
number of pulses for every wave in the inverter signal [16, 23–26] determines the harmonic content. The issue of circuit triggering and power losses during switching impacts pulses and their frequency per cycle. The use of high-level switching techniques may result in significant power loss. To satisfy these requirements, the proposed model must consider elements such as the fuel percentage (hydrogen and air) fed to the fuel cell, the catalyst, DC power and output water, as shown in Fig. 1.

Therefore, this problem statement can be resolved by achieving the following goals:

- A comprehensive integrated PEMFC model is adopted to evaluate an adequate voltage profile, which is coupled with a two-stage boost converter to enhance and boost the voltage profile. This is connected to a single-phase (two levels—four pulses) inverter to match pure sine waves.
- A method is created to balance the load quality between applications running on FCS and AC networks by enhancing the effectiveness of equipment design options and completing them with a technology platform.
- A device structure for a two-stage boost converter is used; each step of the converter is controlled independently using a PWM wave to regulate the Vo profile.
- A second device design is created for a type of inverter hooked up with a two-level PWM generator that can produce PWM to improve the waveform and output voltage profile.
- A technology platform is modelled using MATLAB®/Simulink® to validate the proposed hardware design tools.
- The output current from the PEMFC after filtration is available and is easy to apply on any device using alternative current.

### 1.1 FCS modelling

Generally, a fuel cell is a galvanic cell in which the energy is converted from a chemical form into an electrical form. In addition, it can be considered as a voltage source containing a fuel substance when it oxidizes and delivers continuous electric energy.

The fuel cell arrangement mainly consists of double electrodes: an anode (−) and a cathode (+). These electrodes are separated by a very concentrated electrolyte substance, as illustrated in Fig. 2. This electrolyte is in solid or liquid form and can transfer moving ions between electrodes. Through the catalyst, which is a thin layer of leads, it maximizes the exposed surface area to facilitate ion transport and obtain the required power.

#### 1.1.1 Working principle

Fuel gas (99% hydrogen) is directed towards the negative electrode, the anode, where it undergoes the chemical oxidation process:

\[
\text{H}_2 \text{(g)} = 2\text{H}^+ + 2e^- \quad (2)
\]

The hydrogen-released electrons do not flow throughout the electrolyte. Thus, they flow throughout the outer circuit where the electrical energy is conducted and then finally move to the positive electrode, the cathode. In contrast, positive ions (H⁺) move through the electrolyte substance to the positive electrode, the cathode. On the positive electrode side, the cathode, the hydrogen atom combines with oxygen gas in the air and electrons to produce water [1, 17,27,29–33].

The concept is: Fuel + Oxidant → Product + Energy

At Anode (Oxidization)

\[
2\text{H}_2 \rightarrow 4\text{H}^+ + 4e^- \quad (3)
\]

At Cathode (Reduction)

\[
4\text{H}^+ + 4e^- + \text{O}_2 \rightarrow 2\text{H}_2\text{O} \quad (4)
\]

Overall Reaction

\[
2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{Energy} \quad (5)
\]

#### 1.1.2 FCS equivalent circuit

The basic characteristics of the fuel cell can be categorized as input chemical energy, volume and efficiency, and can be formulated, respectively, as in the following equations:

\[
\text{Input Chemical Energy} = \Delta h^\circ \times n \times X\% = \frac{\Delta h^\circ}{RT} \times P_{\text{Fuel}} \times V_{\text{Fuel}} \times X\% \quad (6)
\]

where \(V_{\text{Fuel}}\) is the fuel volume in the tank, \(P_{\text{Fuel}}\) is defined as the fuel pressure in the tank, \(\Delta h^\circ\) is the enthalpy change (Joule/mole), \(X\) is the rated percentage of hydrogen in the fuel, \(R\) is the gas constant, \(T\) is the temperature of the gas and \(n\) is the number of moles that can be calculated from the universal gas law, as follows:

\[
n = \frac{PV}{RT} \quad (7)
\]
\[ \eta = \frac{\text{Output Electrical Energy}}{\text{Input Chemical Energy}} = \frac{V_{\text{FC\_nom}} \times I_{\text{FC\_nom}} \times \text{Time}}{\frac{V_{\text{Fuel}}}{2} \times \text{PFuel} \times \text{VFuel} \times \%} \]

where \( I_{\text{FC\_nom}} \) is defined as the fuel cell nominal current.

\[ V_{\text{Fuel}} = Q_{\text{Fuel}} \times \text{Time} \]

where \( Q_{\text{Fuel}} \) is the flow rate of the fuel. The efficiency of the fuel cell can be estimated as follows:

\[ \eta = \frac{V_{\text{FC\_nom}} \times I_{\text{FC\_nom}}}{\left(\frac{Z}{2}\right) \times Q_{\text{Fuel\_lpm}} \times P_{\text{Fuel\_lpm}} \times \%} = \frac{60000 \times V_{\text{FC\_nom}} \times I_{\text{FC\_nom}}}{\left(\frac{Z}{2}\right) \times Q_{\text{Fuel\_lpm}} \times P_{\text{Fuel\_lpm}} \times \%} \]

The nominal rates of conversion (utilizations) for both hydrogen and oxygen of the number of series fuel cells (\( N \)) are presented in Equations (11) and (12):

\[ U_{\text{F\_H_2}} = \frac{60000 \times R \times T \times N \times I_{\text{FC\_nom}}}{Z \times F \times Q_{\text{Fuel\_lpm}} \times P_{\text{Fuel\_lpm}} \times \%} \]

\[ U_{\text{F\_O_2}} = \frac{60000 \times R \times T \times N \times I_{\text{FC\_nom}}}{2Z \times F \times Q_{\text{Air\_lpm}} \times P_{\text{Air\_lpm}} \times \%} \]

where \( U_{\text{F\_H_2}} \) is the utilization of hydrogen in the fuel, \( U_{\text{F\_O_2}} \) is defined as the utilization of oxygen, \( Z \) represents the number of moving electrons and \( F \) is the Faraday constant.

The number of cells in the stack is calculated as shown in Equation (13):

\[ N = \frac{Z \times F \times V_{\text{FC\_nom}} \times U_{\text{F\_H_2}}}{\eta \times \Delta I_{\text{nom}}} \]

The partial pressures for both hydrogen, oxygen and water vapour are derived in Equation (14–16), respectively:

\[ P_{\text{H_2}} = (1 - U_{\text{F\_H_2}}) \times P_{\text{Fuel}} \times \% \]

\[ P_{\text{O_2}} = (1 - U_{\text{F\_O_2}}) \times P_{\text{Air}} \times \% \]

\[ P_{\text{H_2O}} = (W + 2 \times \% \times U_{\text{F\_O_2}}) \times P_{\text{Air}} \]

The Nernst voltage \( E_n \) for the fuel cell has been developed in either Equation (17) or Equation (18): If the temperature \( T < 100 \):

\[ E_n = 1.229 - \left\{ \frac{44.43}{Z + F} \right\} + \left\{ \frac{R \times T \ln \left( \frac{P_{\text{H_2}}}{P_{\text{O_2}}} \right)}{Z + F} \right\} \]

If the temperature \( T > 100 \):

\[ E_n = 1.229 - \left\{ \frac{44.43}{Z + F} \right\} + \left\{ \frac{R \times T \ln \left( \frac{P_{\text{H_2}}}{P_{\text{O_2}}} \right)}{Z + F} \right\} \]

The steps of the converter are thought to run in a constant conducting operation.

(i) Open-circuit voltage: voltage at zero current:

\[ E_{O\_C} = K_C \times E_n \]

(ii) Exchange current (\( i_e \)): reverse saturation current, which is a very small current opposite the mainstream current \( i_{ic} \):

\[ i_e = \frac{Z \times F \times X \times (P_{\text{H_2}} + P_{\text{O_2}})}{R \times h} \times \exp \left( \frac{-\Delta G}{R \times T} \right) \]

(iii) Gibbs free energy (\( \Delta G \)): a thermodynamic energy:

\[ \Delta G \propto Z \times E_n \times F \leftrightarrow \Delta G = K_C \times Z \times E_n \times F \]

(iv) Tafel slope: the slope of the ohmic region:

\[ A = \frac{R \times T}{Z \times F \times \%} \]

where \( a \) is the exchange coefficient.

Eventually, the electric model of the stack can be as shown in Fig. 3 and derived by using Equations (23) and (24):

\[ V_{\text{FC}} = E - I_{\text{FC}} \times R_s \]

\[ E = E_{O\_C} - N \ln \left( \frac{I_{\text{FC}}}{I_D} \right) \]

where \( R_s \) is the internal resistance of the stack (ohms).

In this work, a PEMFC stack (Fuel Cells Etc, Bryan, TX, USA) has been developed, as illustrated in [33], consisting of 42 cells in series with a power capacity of 1.26 kW and a nominal voltage of 24.23 VDC.

Equations (3–24) were simulated to develop a valid premium FCS model that has been characterized by voltage–current (\( I–V \)) and current–voltage (\( I–P \)) curves, as indicated in Fig. 4.

1.2 Proposed double-stage boost converter model

Fig. 5 shows a key circuit of the suggested converter. Controllers are considered perfect controls. In addition, it is assumed that the voltage level is instantaneous and constant, and that the load is solely resistive. The steps of the converter are thought to run in a constant conducting operation.

Because the recommended boost converter contains a double stage in a cascade [5], the voltage transformation ratio can be calculated by using Equation (25):
Here, $D_1$ and $D_2$ are the duty ratios for the first and second stages, respectively. By knowing the limit of the productive electric voltage for a certain use, the $D$ cycle of both phases can be obtained.

1.2.1 Inductor design

For the converter phases, the inductor current ($I_L$) can be determined using the electric power balance formula [29, 30]:

$$I_L = \frac{V_{in}}{1 - D} \frac{1}{R}$$

(25)

Here, $D_1$ and $D_2$ are the duty ratios for the first and second stages, respectively. By knowing the limit of the productive electric voltage for a certain use, the $D$ cycle of both phases can be obtained.

1.2.1 Inductor design

For the converter phases, the inductor current ($I_L$) can be determined using the electric power balance formula [29, 30]: $P_{sys} = P_{sys}$.

Table 1: First- and second-stage parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>First stage</th>
<th>Second stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage, $V_{in}$ (V)</td>
<td>24</td>
<td>100</td>
</tr>
<tr>
<td>The output voltage, $V_o$ (V)</td>
<td>100</td>
<td>416.67</td>
</tr>
<tr>
<td>The output power, $P_s$ (W)</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>Duty ratio</td>
<td>0.76</td>
<td>0.76</td>
</tr>
<tr>
<td>Switching frequency, $f$ (kHz)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Resistance, $R$ (Ω)</td>
<td>40</td>
<td>390</td>
</tr>
<tr>
<td>Minimum inductance, $L_{min}$ (mH)</td>
<td>43.776</td>
<td>6.78</td>
</tr>
<tr>
<td>Filter capacitance, $C_{min}$ (µF)</td>
<td>19</td>
<td>1.74</td>
</tr>
<tr>
<td>Inductor current, $I_L$ (A)</td>
<td>10.42</td>
<td>2.504</td>
</tr>
</tbody>
</table>

Table 2: Fuel Cells Etc. company, 1.26-KW, 24-voltage specification model

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Nomenclature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_S$</td>
<td>Internal resistance of the stack</td>
<td>0.06187 Ω</td>
</tr>
<tr>
<td>$I_{FC}$</td>
<td>Nominal (rated) current of the stack</td>
<td>52 A</td>
</tr>
<tr>
<td>$V_{FC}$</td>
<td>Nominal (rated) voltage of the stack</td>
<td>24 V</td>
</tr>
<tr>
<td>$E_{oc}$</td>
<td>Cell open-circuit voltage</td>
<td>1 V</td>
</tr>
<tr>
<td>$E_{oc}$</td>
<td>Stack open-circuit voltage</td>
<td>42 V</td>
</tr>
<tr>
<td>$E_n$</td>
<td>Cell Nernst voltage</td>
<td>1.12 V</td>
</tr>
<tr>
<td>$K_r$</td>
<td>Voltage constant under nominal conditions</td>
<td>0.9</td>
</tr>
<tr>
<td>$A$</td>
<td>Tafel slope</td>
<td>0.045885</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of series cells in the stack</td>
<td>42 cells</td>
</tr>
<tr>
<td>$I_f$</td>
<td>Exchange current</td>
<td>0.02732 A</td>
</tr>
<tr>
<td>$V_{Fuel}$</td>
<td>Volume of fuel</td>
<td>10 m³</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of moles</td>
<td>541</td>
</tr>
<tr>
<td>$\Delta h^o$</td>
<td>Enthalpy change</td>
<td>241.830 J/mole</td>
</tr>
<tr>
<td>$P_{Fuel}$</td>
<td>Fuel pressure</td>
<td>1.5 bar</td>
</tr>
<tr>
<td>$P_{Air}$</td>
<td>Air pressure</td>
<td>1 bar</td>
</tr>
<tr>
<td>$R$</td>
<td>Gas constant</td>
<td>8.3145 (J/mole K)</td>
</tr>
<tr>
<td>$T$</td>
<td>Operating system temperature</td>
<td>338 K</td>
</tr>
<tr>
<td>$Q_{Fuel}$</td>
<td>Fuel flow rate</td>
<td>12.2 (L/min)</td>
</tr>
<tr>
<td>$Q_{Air}$</td>
<td>Air flow rate</td>
<td>2400 (L/min)</td>
</tr>
<tr>
<td>$Z$</td>
<td>Number of moving electrons</td>
<td>4</td>
</tr>
<tr>
<td>$P_{H2}$</td>
<td>Hydrogen pressure</td>
<td>1.64 × 10⁻³ bar</td>
</tr>
<tr>
<td>$P_{O2}$</td>
<td>Oxygen pressure</td>
<td>0.206 bar</td>
</tr>
<tr>
<td>$P_{H2O}$</td>
<td>Water pressure</td>
<td>96.485 A.sec/mole</td>
</tr>
<tr>
<td>$\Delta G$</td>
<td>Gibbs free energy</td>
<td>133 104.5 J/mole</td>
</tr>
<tr>
<td>$V_{1}$</td>
<td>Voltage at current of 1 A</td>
<td>35 V</td>
</tr>
<tr>
<td>$K_G$</td>
<td>Gibbs constant</td>
<td>0.61 586</td>
</tr>
<tr>
<td>$K$</td>
<td>Boltzmann constant</td>
<td>1.38 × 10⁻²⁴ J/K</td>
</tr>
<tr>
<td>$h$</td>
<td>Plank constant</td>
<td>6.626 × 10⁻³⁴ J/sec</td>
</tr>
<tr>
<td>$Q_{Air,max}$</td>
<td>Maximum flow rate</td>
<td>4800 L/min</td>
</tr>
<tr>
<td>$X$</td>
<td>Rated percentage of hydrogen in the fuel</td>
<td>99.95%</td>
</tr>
<tr>
<td>$Y$</td>
<td>Rated percentage of oxygen in the oxidant</td>
<td>21%</td>
</tr>
<tr>
<td>$W$</td>
<td>Rated percentage of water vapour in the oxidant</td>
<td>1%</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Exchange coefficient</td>
<td>0.308</td>
</tr>
</tbody>
</table>

\[
V_{in} = V_{in}\left(\frac{1}{1 - D_1}\right)\left(\frac{1}{1 - D_2}\right)
\]

(25)

\[
V_{in}I_{in} = \frac{V_S^2}{R}
\]

(26)

\[
V_{in}I_{in} = \left(\frac{V_{in}}{R}\right)^2 = \frac{V_{in}^2}{(1 - D)^2 R}
\]

(27)

\[
I_L = \frac{V_{in}}{(1 - D)^2 R}
\]

(28)
where \( R \) is the load resistance; \( V_n \) and \( I_n \) are the input voltage and current of the converter, respectively; and \( D \) is the duty cycle of the converter. The maximum and minimum values of the inductor current \( (I_{\text{max}} \text{ and } I_{\text{min}}) \) can be expressed as follows:

\[
I_{\text{max}} = I_i + \frac{V_i}{2} - \frac{V_o DT}{(1-D)R} + \frac{V_o DT}{2L}
\]  
\[
I_{\text{min}} = I_i - \frac{V_i}{2} - \frac{V_o DT}{(1-D)R} - \frac{V_o DT}{2L}
\]

where \( V_n \), \( V_o \), and \( R \) refer to the input and output voltages and the resistance of the load, respectively. The \( I_{\text{max}} > 0 \) for continuous processes therefore is:

\[
\frac{V_i}{(1-D)R} - \frac{V_o DT}{2L} ≥ 0
\]  
\[
L_{\text{min}} = \frac{D(1-D)^2 R}{2} \geq \frac{D(1-D)^2 R}{2f}
\]

where \( f \) refers to the switching frequency.

### 1.2.2 Capacitor design

The maximum fluctuation of \( V_o \) is minimized in the last step using a capacitor filter. The duty cycle \( f \) and \( R \) are dependent on the filter capacitance value. As shown in [32], Equation (33) describes the lowest value of the filter capacitance for constant operation:

\[
C_{\text{min}} = \frac{V_o DT}{R\Delta V_o} - \frac{V_o D}{R\Delta V_o}
\]  

The change in the output voltage is referred to as \( \Delta V_o \). [28]. The model parameters for the suggested two-stage boost converter are presented in Table 1 [29] based on the above calculations.

The key purpose of the boost converter is to:

- Boost the low electric voltage (15–30 VDC) of the FCS to the high-voltage DC connection (312 VDC) needed for the single-phase (two levels—four pulses) inverter to generate 220 VAC for incorporation with the utility network without using HFTs or LFTs to avert their disadvantages cited previously.
- Build a milestone control circuit for the single-phase transformer to generate a pure sine waveform VAC based on both the voltage and the frequency of the utility (220 VAC, 50 Hz).

### 1.3 Experimental set-up

To validate the Simulink® findings, an experiment was performed using a 1.26-kW, 24-V PEMFC (Fuel Cells Etc, Bryan, TX, USA) and DC/DC double-stage converter. The output of the DC/DC double-stage converter transforms into single-phase power using a two-level inverter as illustrated in Fig. 6. The way the circuit operation can be described as the two-level PWM generator’s switching pulse signals are set to the insulated-gate bipolar transistor (IGBT) switches using the IGBT driver, which is the proper trigger circuit to employ. The first- and second-stage parameters are described in Table 1. The FCS parameters in the experiment are elaborated on in Table 2. Gate signals and output voltages were measured using an oscilloscope. The hardware configuration suggested for the inverter circuit to produce a sinusoidal waveform output VAC with a frequency of 50 Hz and a peak of root mean square 220 VAC is shown in Fig. 7.

### 2 Results

The proposed configuration is examined using Simulink® and a hardware experiment to validate the integration of the fuel cell using a two-stage converter.

#### 2.1 Simulation results

Based on the preceding values of the first- and second-stage parameters, which are listed in Table 1, the suggested converter topology is validated using the Simulink® platform, as shown in Fig. 8. Fuel cell parameters are elaborated on in Table 2. The (two levels—four pulses) inverter has four fast power IGBT switches rated at 400 V. The extremely low resistance of this switch of 47 mΩ causes higher efficiency and less power dissipation. The \( V_o \) of the first and second converter stages are shown in Figs 9 and 10, respectively. A robust proportional–integral (PI) controller is applied to control the double-boost converter. Each stage is controlled by its isolated PI controller. The \( V_o \) of each stage has been determined and evaluated by comparing it with the reference value. The error is then transmitted to the PI controller to magnify the error signal in comparison with a triangle wave to produce the PWM wave. The circuit operation has been characterized as follows. The IGBT driver is an appropriate trigger circuit to be used to set the switching pulse signals from the two-level PWM generator to the IGBT switches. The PWM generator generates the SPWM signals (four cases shown in Fig. 11) and drives the IGBTs.
Each half-cycle of the sinusoidal signal should be classified into 32 variations in the PWM wave and requires 10 ms to produce a SPWM signal. So, the duty cycle can be calculated from this equation:

\[ Y_i = P_{\text{emex}} \times \sin(i \times 180/n), \]

where \( PWM = 0–255, \quad (P_{\text{emex}} = 255) \)

\( i = 0, 1, 2, \ldots, n. \)

Fig. 12 shows the simulation outcomes for the \( V_o \) for the full link single-phase (two levels—four pulses) inverter without the filter. The \( V_o \) of the inverter in actual time and its simulated output are the same, although the \( V_o \) is not entirely a sine wave-form. To get the required pure wave of the AC output waveform, an inductor-capacitor (LC) filter has been connected. The output waveform rate, which was determined through modelling and experimentation, is 50 Hz, which is the same as the utility frequency.

The distortion factor of the produced \( V_o \) of the inverter without filtration is shown in Fig. 13. The total distortion factor of the \( V_o \) of the inverter without filtration is extremely high and reaches 67.3%; according to the Institute of Electrical and Electronics Engineers (IEEE) 519–1992 requirements for utility-connected inverters [33], this total distortion factor must be <3%.

The total distortion factor of the \( V_o \) of the inverter, which is presented in Fig. 14 if the filter is installed, is 0.84%. Based on the IEEE 519–1992 rules, this number is suitable.

From the results obtained, this simulation performed on the PEMFC stack was very promising when applying the technique of the coupled inverter and, after filtration, the output pure AC signal of the sinusoidal wave was, as shown in Fig. 14, in a steady condition that is very suitable for various applications. The most essential here is the possibility of widespread use of this technique using the PEMFC in the low range of its working temperature, this will not affect the used devices and any expected noise can be overcome.

2.2 Experimental results

The way in which the circuit operation can be described is that the switching pulse signals of the two-level PWM generator are set to the IGBT switches using the IGBT driver, which is the proper trigger circuit to employ. To control the IGBTs, the PWM generator produces the SPWM signals (four examples are illustrated in Figs 15 and 16 in the online Supplementary Data). The PWM wave should be able to classify each half-cycle of the sinusoidal output into 32 different variations and should take 10 ms to produce a SPWM signal. Therefore, using the following equation, the duty cycle can be determined:

\[ Y_i = P_{\text{emex}} \times \sin(i \times 180/n), \]

where \( PWM = 0–255, \quad (P_{\text{emex}} = 255) \)

\( i = 0, 1, 2, \ldots, n. \)

The simulation results for the \( V_o \) for the full link single-phase (two levels—four pulses) inverter without the filter are displayed in Fig. 17 in the online Supplementary Data. Despite the \( V_o \) not being a pure sine wave, it is obvious that the \( V_o \) and the modelling of the inverter in real time are identical. An LC filter has been attached to obtain the necessary pure wave for the AC output waveform. The utility frequency of 50 Hz was used to calculate
the rate of the output waveform, which was established through modelling and experimentation.

3 Conclusion

This paper has managed to integrate a comprehensive resilient PEMFC stack with a convenient two-stage DC/DC boost converter, which in turn was coupled to a single-phase (two levels—four pulses) inverter to produce controlled pure sinusoidal waves suitable for various AC applications. The simulation results were obtained using MATLAB®/Simulink®. Additionally, the inverter signal was a pure sine waveform. As a result, the dead time was reduced to 63 μs as opposed to the usual value of 180 μs. Normally, a combination of a two-stage DC/DC boost converter and a PWM inverter is used to determine the optimal power of the proposed FCS. Because of the high price of FCSs, it is not only beneficial and economical in terms of energy conservation, but it has also established milestone methods for connecting to and managing AC loads.

Supplementary data

Supplementary data is available at Clean Energy online.

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Author contributions

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Conflict of interest statement

None declared.

Data Availability

Data are contained within the article and in the online Supplementary Data.

References


