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REVIEW ARTICLE **OPEN ACCESS**

A review: compatibility of fuel cells as promising technology for DC-microgrids

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Abstract. Due to a well-established infrastructure developed over the years, fossil fuel-based energy remains the predominant global energy source. Nevertheless, with heightened global attention towards addressing climate change concerns, there has been an increased focus on green energy technologies across various sectors. The advancement of distributed renewable power generation technologies such as solar photovoltaics (PV), wind, wave, tidal, etc., has contributed to a growing independence of power consumers from centralized grids, leading to a pronounced shift towards distributed microgrids. Notably, numerous electrical devices operate on DC power, aligning with the DC power output of many distributed renewable sources. Consequently, the concept of DC microgrids is gaining traction. Amid this context, fuel cells have resurged in prominence on a global scale, alongside the development of hydrogen economies. Given fuel cells DC-based nature, they are well-suited to explore new frontiers within DC microgrids. However, the seamless integration of fuel cells into DC microgrids requires effective power electronic interfacing. Thus, a comprehensive examination of the integration of fuel cells into DC microgrids becomes imperative. This article aims to address this gap by offering an extensive review of fuel cell technologies, the landscape of DC microgrids, and the prevailing context of control architectures. Notably, this review article fills an existing void in the literature by consolidating the key elements into a unified discussion.

Keywords: DC microgrids / fuel cells / hydrogen

1 Introduction

Global warming, which has been led by the increase of average atmospheric temperature, has been driving swift changes to climate systems. These changes are happening due to the emission of heat-trapping greenhouse gases (GHGs) [1]. The electricity industry is a substantial contributor for the world's carbon emissions. In 2022, more than 40% of global energy related CO_2 emissions are from the burning of fossil fuels for the electricity generation [2]. With the high level of carbon emission in electrical power generation, the electricity industry is under heavy regulations to reduce its carbon footprint [3]. Global level agreements such as the Paris Agreement [4], Kyoto Protocol [5], and Kigali Amendment[6] make sure that carbon generation is well under control levels. To align with the carbon emission reduction targets, globally, the power generation is rapidly moving toward renewable energy-based power generation. In recent years, many state-of-the-art technologies have been developed to accommodate more renewable-based energy sources such as solar, wind, tidal and biomass for power generation. As a result, the percentage of renewable energy in power generation is rapidly growing. In 2021 renewable electricity generation has expanded by more than 8%, which is the fastest year-on-year growth since 1970 s [7].

Many of renewable energy technologies, produce power in DC domain. Therefore, when these renewable energy sources (RES) are integrated to the conventional AC power systems, inverters are essential part of it. Also, considering the demand side, most of the new appliances built upon power electronic circuits such as computers, variable speed drives and LED lights are based on DC power systems. So, intermediate power conversions from DC-AC and again AC-DC are required for powering these devices with the distributed RES which causes substantial energy losses in the conversion processes [8]. As the applications of DC

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Table 1. Comparison between fuel cells and batteries.

Property	Battery	Fuel Cell
Power flow	Bidirectional	Unidirectional
Transient response	Fast (milliseconds to seconds) [13]	Slow (Minutes) [13]
Energy density	Low (~200 W/kg) [14]	High (~35 000 W/kg) [14]
Investment cost	Low (~$ 151 per kWh) [15]	High ($ 1000–1500 per kW) [16]
Relative maintenance cost	Depends on the battery type (high for a lead-acid battery)	Low

energy sources and DC loads are used rapidly in power systems, DC based power networks gain more popularity due to the higher efficiency of power transmission between RES and loads. Furthermore, controlling is easier in DC systems than the AC systems due to the absence of synchronization and other frequency-based concerns. Therefore, DC microgrid concept has gained popularity in the power networks to maximize the utilization of RES in power networks and to reduce the impact of power conversion losses in the consumer appliances.

Due to the intermittent nature of the RES, they cannot be used alone to obtain the variations in demand. Therefore, to achieve the balance between supply and demand, a power system with RES may utilize energy storage systems. Among these, batteries have been widely deployed for short-term and long-term energy storage. Nevertheless, the high initial and maintenance costs associated with batteries limit their use in microgrids [9]. As a result, there is a growing demand for alternatives to battery storage systems in microgrids.

Hydrogen energy has been emerged as a major source of future energy in the world due to its distinctive advantages such as higher energy density, low maintenance requirements, no production of toxic materials and ability to use as a long-term energy storage. Applications of hydrogen energy are expanding due to the rapid technological advancements related to production, storage, and distribution of hydrogen [10].

Fuel cells are being used for electricity generation using hydrogen as fuel. Water and heat are produced as byproducts in the process. Characteristics of these fuel cells deviate from the batteries due to the slower time response, unidirectional power flow and the ability of supplying electrical energy as long as fuel is available [11]. A comparison between batteries and fuel cells is given in Table 1. Fuel cells have been deployed in many industrial applications such as electrical vehicles (EVs) and microgrids. However, fuel cells require external support to maintain the stability of the system where it is deployed due to their poor transient response.

2 DC microgrids

As shown in Figure 1, DC microgrid is a power distribution system which consists of one or more interconnected DC power sources which then supply to DC loads or DC to DC converters or AC loads via nverters [12].

DC microgrids create an easy and economical platform to deliver DC power to DC loads from DC power sources. Typical advantages of DC microgrids can be summarised as below:

- Simple and economical solution to intergrade DC driven loads and sources.
- Higher energy efficiency as power conversions are lesser. All equipment can be connected to DC bus via single power conversion.
- Controlling is easy due to the absence of frequency related issues such as synchronization, harmonic issues, and reactive power compensation etc.

As a result, the DC microgrid concept is already effectively deployed in data centers, telecom stations, DC-powered homes, Renewable energy parks, zero-emission buildings, railways and hybrid energy storage systems etc. [17]. Sweden and Japan had recently energized DC microgrids with a capacity of 5 MW to supply power to their data centres which are operating at 380 V and 400 V voltages respectively [18]. Furthermore, New Zealand has a DC-powered data centre with a capacity of 14 MW at Auckland which is operating at 220 V [19].

Due to the rapid growth of DC microgrids, standards are required to maintain the power quality and the compatibility in DC microgrids. However, still there are very few standards available for DC microgrids and various voltage levels are used in DC microgrids based on the applications. Table 2 represents a summary of DC voltage levels used in various applications [20].

IEEE Standard for DC Microgrids for Rural and Remote Electricity Access Applications is the commonly followed standard for DC microgrids [21]. According to the standard, 48 V is the standard nominal voltage to be used in DC microgrids. However, it allows to fluctuate the voltage from 36 V to 58 V during operation. The acceptable transient fluctuation limitations are categorized as in Table 3.

In terms of DC power quality, ripple voltage is a key performance indicator. Table 4 represents the minimum ripple voltage levels which are required to be maintain in DC microgrids according to the IEEE standard.

DC voltage is the most critical parameter in DC microgrids which directly influence to the power quality. Continuous monitoring and controlling are required to maintain the DC voltage at a constant value. Supply demand change is a main culprit for the variations of the DC link voltage. There are many controlling techniques

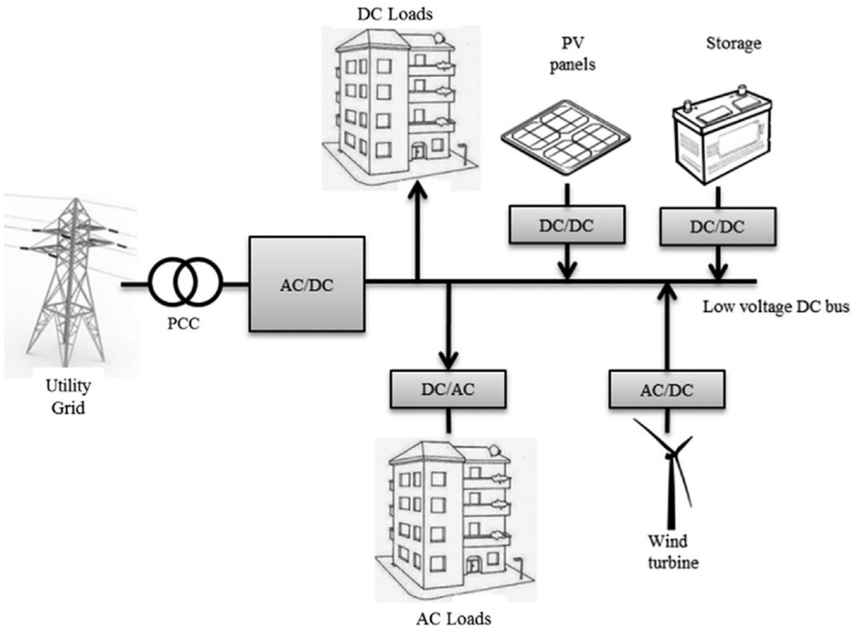

Fig. 1. Structure of a DC microgrid.

Table 2. DC microgrid voltage levels depend on the application [20] (LV – low voltage, MV – medium voltage).

Application	DC voltage (V)	Category based on voltage level
Ships	>1000	LV and MV
Transport	750, 1000, 3000	LV and MV
Data centres	380–400	LV
Buildings	48–400	LV
Lighting applications	24	LV
EV charging	<600	LV
Industry	>600	MV

which are already employed to regulate DC link voltages. As illustrated in Fiugre 2, available controlling techniques can be categorized under four main sections based on their controlling nature [22]:

- Centralized control.
- Decentralized control.
- Distributed control.
- Hierarchical control.

Table 5 represents a detail comparison between the aforementioned controlling techniques employed in DC microgrids.

In DC microgrids, voltage stability will be affected as there is no reactive power flow as in AC microgrids [23]. Significant research has been done to tackle this issue. De-coupled control strategy for energy storage devices based on non-linear PI controller and k-Type compensators has been successfully tested for voltage regulation in a standalone DC microgrid [24]. Dual active bridge (DAB) controllers have been used with the energy storage devices interconnection with the DC bus for providing improved voltage regulation [25]. Fuel cell as a conversion device of Hydrogen energy storage can be utilized for the voltage regulation of DC microgrids[26].

Table 3. Transient voltage standards in DC microgrids.

Transient voltage surges	
Duration (up to)	Maximum allowed voltage (V)
40 s	750, 1000, 3000
60 min	380–400
Transient voltage drops	
Duration (up to)	Maximum allowed voltage (V)
100 µs	0
>100 µs	0
120 s	31
10 s	24

Table 4. Voltage ripple limits in DC microgrids.

Frequency (kHz)	Ripple/noise voltage (pp)
$f < 1$	18 V
$1 \leq f < 30$	6 V
$30 \leq f < 200$	2 V

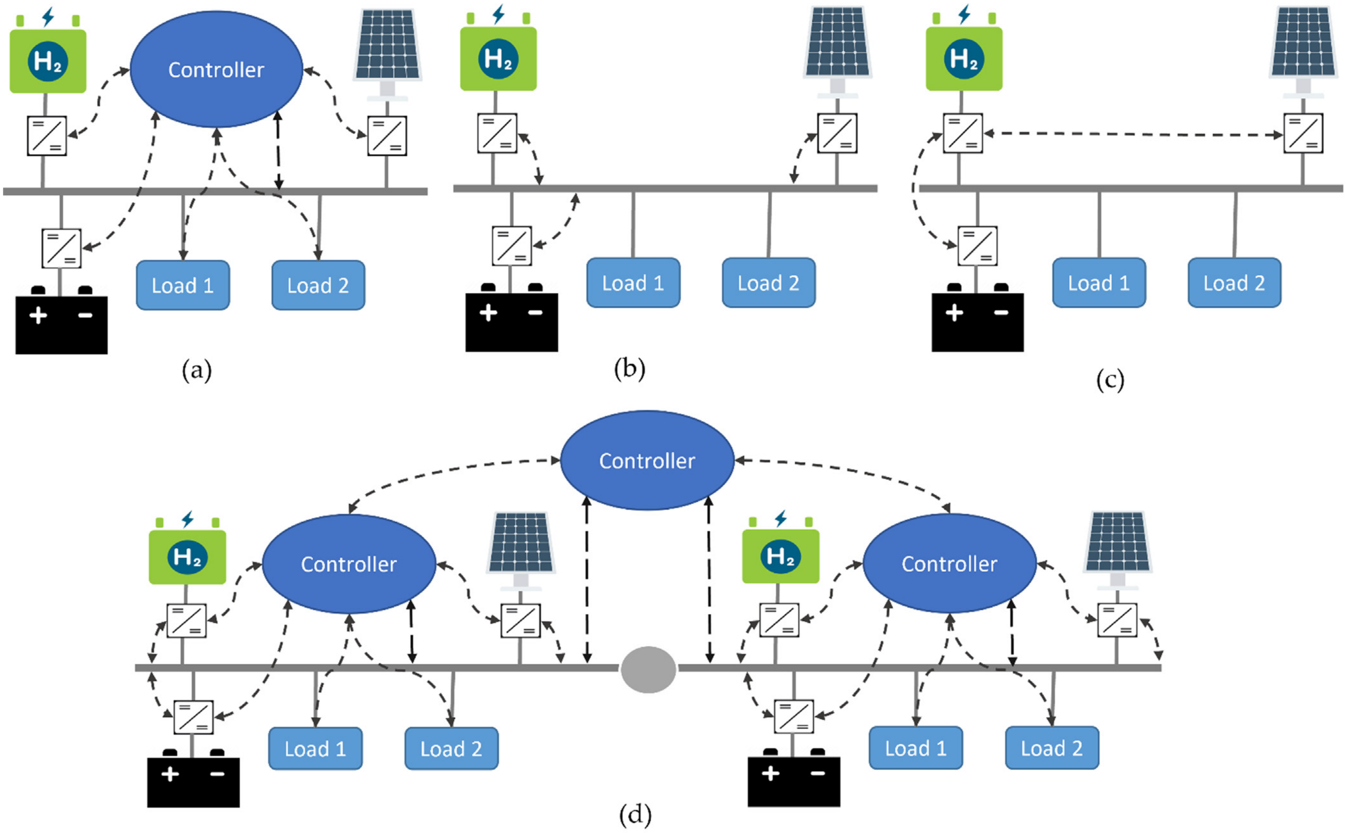

Fig. 2. DC Microgrid controlling techniques: (a) centralized control; (b) decentralized control; (c) distributed control; (d) hierarchical control.

Table 5. Comparison of controlling techniues employed in DC microgrids.

Technique	Advantages	Disadvantages	References
Centralized control	High level of controllability and observability.	High dependency on communication networks. Poor flexibility and expandability.	[29]
Decentralized control	Simplicity. High flexibility for expansions.	Fluctuations can occur due to lack of parameter availability for controlling.	[30] [31]
Distributed control	Low dependency on communication. Enhanced controllability. High expandability.	Inefficient and suboptimal operation. Increased complexity. Potential for instability.	[32] [33]
Hierarchical control	High flexibility for expansions. High robustness. High efficiency.	High complexity High cost Only preferred to use in large scale DC microgrids.	[34] [35]

3 Fuel cells

A fuel cell is DC power supply which convert chemical energy to electrical energy. Fuel cells can generate electricity as long as hydrogen being supplied. As illustrates in Figure 3, hydrogen and oxygen are supplied to the fuel cell and electricity is generated due to the chemical reactions which occur inside the fuel cell. Heat and water are generated as bi-products of these chemical reactions [27]. Efficiency of the fuel cells lies between 40% and 60% and by recovering the heat, efficiency can be further improved up to 80% [28].

Fuel cell contains two electrodes namely anode and the cathode. At the anode hydrogen molecules are split into hydrogen ions and electrons as represented in chemical reaction 1.

$$H_2 \rightarrow 4H^+ + 4e^- \tag{1}$$

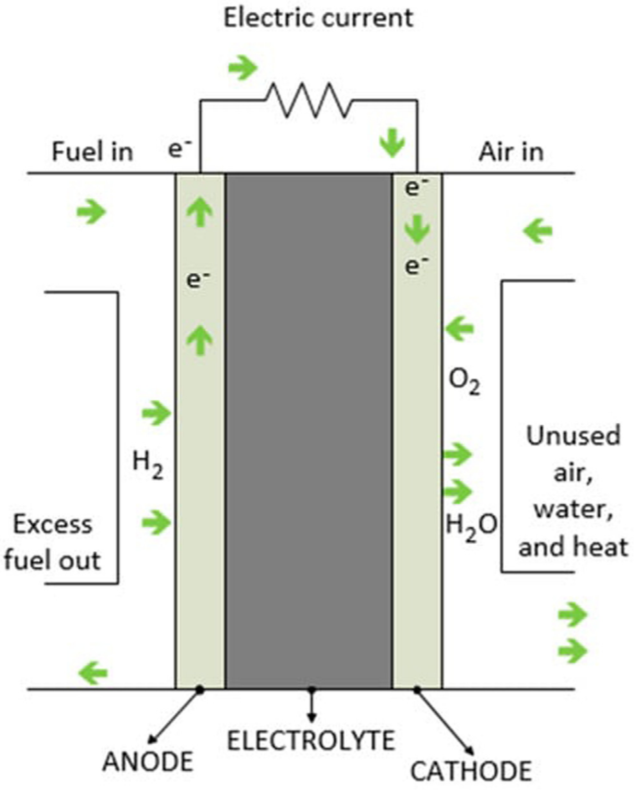

Fig. 3. Basic diagram of fuel cell.

Afterwards, the split hydrogen ions are moved from anode to the cathode via the electrolyte which is known as the membrane. However, the split electrons from hydrogen molecules cannot travel through the membrane due to the internal structure of the membrane. Therefore, split electrons must travel through the external electrical circuit to reach to the cathode. At the cathode, electrons combine with oxygen and produce water and heat as shown in the chemical reaction 2.

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{2}$$

Depending on the materials used to construct the electrolyte, various types of fuel cells are available. Commonly employed fuel cell types include:
- Proton Exchange Membrane Fuel Cell (PEMFC).
- Alkaline Fuel Cell (AFC).
- Phosphoric Acid Fuel Cell (PAFC).
- Direct Methanol Fuel Cell (DMFC).
- Solid Oxide Fuel Cell (SOFC).
- Molten Carbonate Fuel Cell (MCFC).

Table 6 represents a detail comparison of commonly available fuel cells [36].

PEMFC is the widely employed fuel cell type in residential and vehicle applications due to their high power density, rapid start-up and low-temperature operating capabilities [37]. PEMFC consist of a thin ion-conducting polymer as the electrolyte [38].

PEMFCs can be classified into two types considering the operating temperature [39].
- Low temperature PEMFC (LTPEMFC) – Operating in range of 60–80 °C.
- High temperature PEMFC (HTPEMFC) – Operating in range of 110–180 °C.

Nafion, which is a Teflon based material has been used as the standard material for electrolytes in LTPEMFCs. For HTPEMFCs, Nafion and Polybenzimidazole doping with phosphoric acid have been used as electrolyte material [40].

3.1 Electrical characteristics of the PEMFC

As shown in Figure 4, the current density vs terminal voltage characteristic curve of PEMFC has a nonlinear relationship [41]. There are three major voltage losses directly associated with the characteristics of PEMFC, which are:

- Activation voltage losses due to electrochemical reactions.
- Ohmic voltage losses due to the ionic electronic condition.
- Concentration voltage losses due to mass transport.

Activation voltage losses normally occur at low current densities as shown in the red curve in Figure 5. The slow rate of chemical reactions at electrodes is the main cause behind the activation losses and this is also known as the required voltage to start a chemical reaction. Activation losses occur at both anode and cathode electrodes, however, activation losses at the cathode are more significant [42].

Ohmic voltage losses are the second type of voltage loss in PEMFC. As shown in the blue curve in Figure 4, Ohmic voltage losses are a linear voltage drop [42].

Internal resistances are the cause behind the ohmic losses and there are two types of resistance which consist of:
- Resistance for electrons when transferring through the electrodes and outer circuits.
- Resistance for protons when travelling through the proton exchange membrane.

The last type of voltage loss in PEMFC is concentration voltage loss. As shown in the orange curve in Figure 4, concentration voltage losses normally occur at high current densities. The main cause behind the concentration losses is the mass transportation losses of Hydrogen and Oxygen [42].

As expressed in equation 3, the terminal voltage of a PEMFC (V_{fc}) can be mathematically formulated considering the aforementioned voltage losses.

$$V_{fc} = E - V_{act,cell} - V_{ohm,cell} - V_{conc,cell}, \tag{3}$$

where, E is the cell voltage and $V_{act,cell}$, $V_{ohm,cell}$, $V_{conc,cell}$ correspond to the voltage losses due to the activation losses, ohmic voltage losses and concentration voltage

Table 6. Comparison of different types of fuel cells.

Type	Operating temperature	Power range of a stack (kW)	Electrical efficiency	Applications	Advantages	Challenges
PEMFC	<120 °C	1–100	60%	Backup power Portable power Distributed generation Transportation Specialty vehicles	Solid electrolyte reduces corrosion and electrolyte management problems Low temperature Quick start-up and load following	Expensive catalysts Sensitive to fuel impurities
AFC	<100 °C	1–100	60%	Military Space Backup power Transportation	Wider range of stable materials allows lower-cost components Low temperature Quick start-up	Sensitive to CO_2 in fuel and air Electrolyte management (aqueous) Electrolyte conductivity (polymer)
PAFC	150–200 °C	5–400	40%	Distributed generation	Suitable for CHP Increased tolerance to fuel impurities	Expensive catalysts Long start-up time Sulfur sensitivity
MCFC	600–700 °C	300–3000	50%	Electric utility Distributed generation	High efficiency Fuel flexibility Suitable for CHP Hybrid/gas turbine cycle	High-temperature corrosion and breakdown of cell components Long start-up time Low power density
SOFC	500–1000 °C	1–2000	60%	Auxiliary power Electric utility Distributed generation	High efficiency Fuel flexibility Solid electrolyte Suitable for CHP Hybrid/gas turbine cycle	High-temperature corrosion and breakdown of cell components Long start-up time Limited number of shutdowns

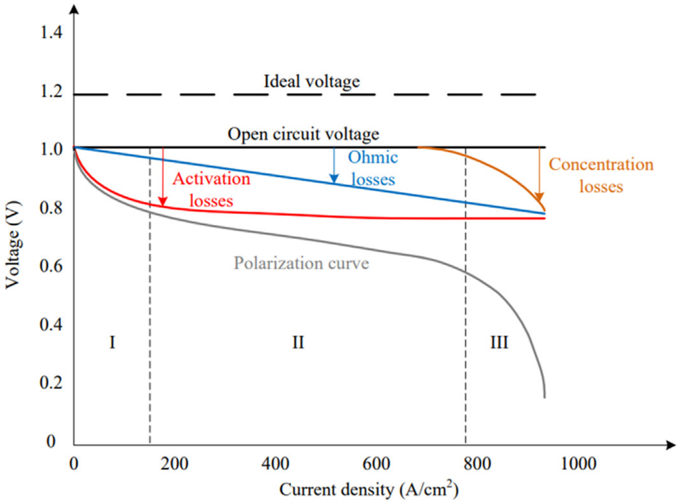

Fig. 4. Characteristic curve of a PEMFC.

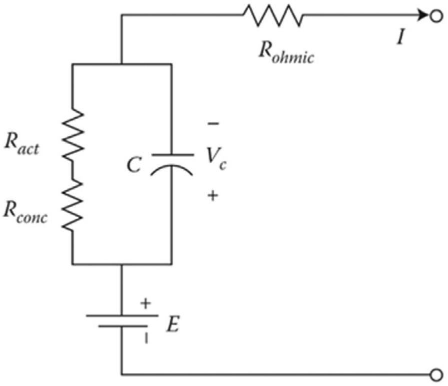

Fig. 5. First order equivalent circuit model for PEMFC.

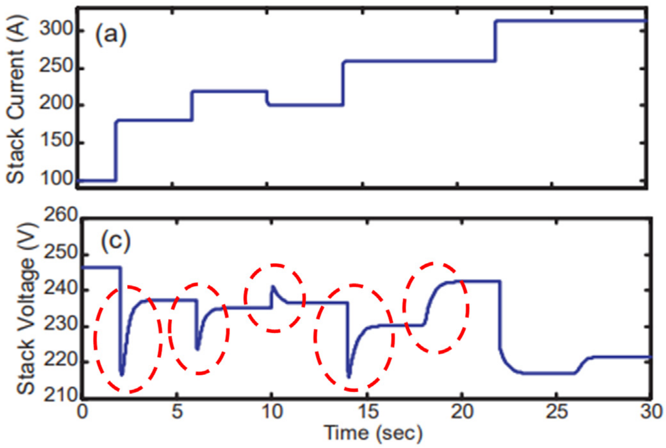

Fig. 6. PEMFC performances under sudden demand variations.

losses respectively [43]. Figure 5 illustrates a first-order equivalent electrical circuit for a PEMFC which is developed using equation 3 [44].

3.2 Fuel cell starvation

In a fuel cell, hydrogen supply is required to increase suddenly in an event of a sudden demand increase. However, due to controlling and mechanical delays, it requires some time to increase the hydrogen supply to match the demand. As a result, there are situations where the anode is in a shortage of hydrogen which is known as fuel cell starvation. Due to the lack of hydrogen the anode is no longer capable of generating the required protons and electrons to satisfy the load demand which leads to water electrolysis and carbon corrosion chemical reaction as represented by 4 and 5 respectively.

$$2H_2O \rightarrow O_2 + 4H^+ + 4e, \tag{4}$$

$$C + 2H_2O \rightarrow CO_2 + 4H^+ + 4e^-. \tag{5}$$

Carbon corrosion leads to damage catalyst layer and weakens the link between Carbon support and Platinum particles which cause degradation of performance in the fuel cell. Furthermore, a significant amount of heat is generated as a result of the high anode potential. Ultimately fuel cell starvation can cause short circuits in membrane electrode assembly and may end up with a catastrophic membrane electrode assembly failure.

In general, fuel cells are not capable of well handling sudden demand changes. Figure 6, illustrates a voltage profile of a PEMFC under sudden demand variations [45]. As shown in Figure 6, voltage response has a delay before settling in its new operating point. Therefore, it is required to have an external assistance for fuel cells during transients to improve the overall voltage response.

4 Fuel cell applications in DC microgrids

Fuel cell applications in DC microgrids are still in the early stages of development. Environmental and economic benefits of employing fuel cells in DC microgrids are analysed in [46–49]. Even though fuel cells have high potential to be employed in DC microgrids, poor transient performance limits the applications of fuel cells in DC microgrids. However, there are some fuel cell applications in AC Microgrids where mostly PEMFS is employed due to its unique characteristics [50]. Current context of the fuel cell applications in Microgrids can be categorized into two sections based on its application.
- Primary power applications
- Backup power applications

In primary power applications, fuel cells are employed to power a section of the microgrid while conventional synchronous generators are maintained the system stability [50]. In backup power applications, fuel cells are employed as an alternative to the conventional batteries due to the very high operating hours of fuel cells (more than hundreds of hours) [51–53]. Fuel cells are commonly employed as backup power source in telecommunication related applications [53].

One drawback in fuel cell is that its slow transient response in sudden load changes [54]. Supercapacitors are commonly utilized in DC microgrids to provide transient support during power fluctuations to reduce the stress on batteries [26,55,56]. With the high-power density, supercapacitors have high potential to assist fuel cells during transients.

Ahmed A. Kamel et al. Presented an integration method of fuel cells with supercapacitors into DC microgrids, which is based on centralized controlling [57]. Fuel cells are employed to compensate for the long-term power shortages caused by solar PVs while batteries and supercapacitors are employed to overcome the short team power shortages. The power flow of the fuel cell and the battery is controlled by the centralized controller. Supercapacitor act as a natural buffer against fluctuations. Authors tried different centralized controlling strategies and found that PI controlling strategy shows better capabilities in improving the power quality of DC microgrids.

Luta et al. [65] developed a DC microgrid which consist of Solar PVs, fuel cells and supercapacitors. Power flow through supercapacitors is also controlled by the centralized controller.

Idoia San Martın et al. [66] presented another centralized controlling method for DC microgrids. Authors proposed a setup where supercapacitors are connected in parallel to fuel to enhance the transient response. However, power flow through the supercapacitors cannot be controlled due to the absence of DC-to-DC controllers. As a result, supercapacitors act as a natural buffer against voltage fluctuations. Recent research conducted in the area of fuel cell integration in DC microgrids has been analysed in Table 7.

Table 7. Recent research conducted in fuel cell integration in DC microgrids.

Energy sources/energy storage devices	Controlling and optimization methodologies	Significant achievements	References
Solar PV, Wind Fuel Cell, Supercapacitor, Battery	Maximum power points of Solar PV and wind has been gained via Artificial Neural Networks Energy management system compromising of fuzzy logic controller. Voltage regulation by non-linear, integral, double-integral and super-twisting sliding mode controllers	DC bus voltage regulation and transient stability of DC microgrid has been achieved. Stress on battery in sudden fluctuations has been significantly reduced by fuel cells.	[58]
Solar PV Battery, Fuel Cell, Supercapacitor	PV system de-rating method has been utilized under low demand conditions. Power supply of fuel cell is controlled by reverse sigmoidal function. Centralized energy management system has been utilized.	System operated properly under transient fault conditions. Battery discharge rate has been limited using fuel cell with supercapacitors in sudden large demand fluctuations.	[59]
Solar PV Battery, Fuel Cell	Multi-port DC-DC converter has been proposed to connect all RES, ESS and loads. Reduce multiple power conversions, voltage boost requirements and elements required.	Significant flexibility has been shown in the proposed buck-boost converter architecture. Maximum power point tracking of RES has also been achieved	[60]
Wind Battery, Fuel Cell, Hydrogen energy storage	Two level control is proposed for the static and dynamic performance of DC microgrid. Centralized energy management and quick reaching law-based global-terminal sliding mode control for device level has been proposed.	Proposed control method had shown a fast transient response with settling time of 0.099 s. Accurate steady-state performance has been observed with 0.071% steady state error.	[61]
AC microgrid coupled with DC microgrid with distributed generation. Battery, Fuel Cell, Supercapacitors	Proposed an adaptive energy management strategy with a modified interlinking converter. Proposed topology improves power transfer in hybrid microgrid.	7.92% voltage improvement has been achieved in AC sub grid. 0.42% voltage improvement achieved DC microgrid.	[62]
Grid connected home DC microgrid. Battery bank, multi stack fuel cell system.	Multi-stage and multi-variable fuzzy logic-based control system has been proposed for power management. Proposed microgrid management system considers microgrid performance, lifespan of energy storage and grid power costs.	Proposed controlling reduces battery bank degradation up to 180% by utilizing multi stack fuel cells. Reduce the cost associated with grid connection by 90%.	[63]
Solar PV Battery, Fuel Cell, Supercapacitors	Integral reinforcement learning-based control algorithm has been used for controlling fuel cell in DC microgrids. Initial stabilization is done by employing twin-delayed deep deterministic policy gradient algorithm.	Proposed topology shows excellent transient and steady state performances with reduced complexity in computation.	[64]

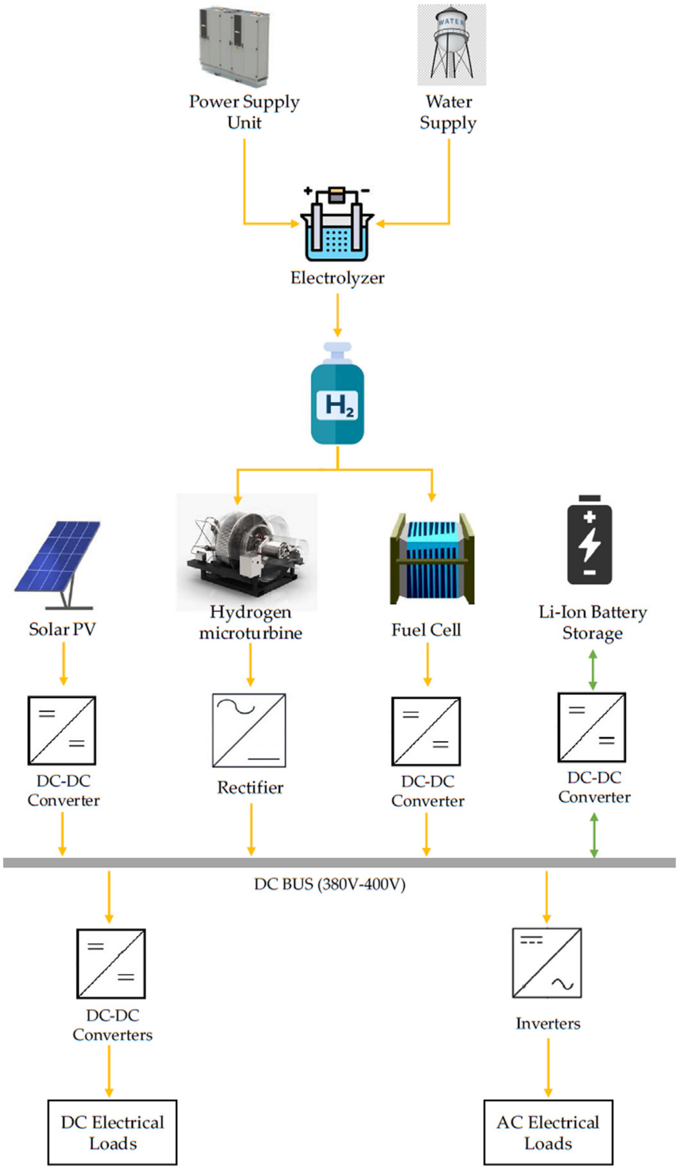

Fig. 7. Schematic diagram of BE CRC DC-microgrid.

Through an analysis of recent research on the integration of fuel cells into DC microgrids, it has become evident that supercapacitors have been employed to enhance the transient response of fuel cells. The successful utilization of fuel cells in conjunction with supercapacitors has proven effective in mitigating stress on battery banks during abrupt transient conditions. This collaborative approach not only enhances the technical performance but also yields significant techno-economic benefits within DC microgrids.

5 Case study: BE CRC's hydrogen-based DC microgrid infrastructure

Blue Economy Cooperative Research Centre (BE CRC) [67] has been established by Australian government to undertake industry focused research and trainings to underpin the broadening Blue Economy in Australia, focusing on two industries: offshore aquaculture and renewable energy. BE CRC ties up government, industry, and research associates in ten countries with expertise in the above.

Aquaculture can be considered as a significant contributor towards the global blue economy, which is a key component in the advancing blue economy in Australia. As the higher growth rates of production in aquaculture farms with higher penetration of sea water, producers are now installing farms far from the mainland to increase productivity [68]. These offshore off-grid operations are now provided mostly by AC generators which are operated using diesel and other fossil fuels. Although these diesel systems are robust and reliable, they carry risks that can be potentially mitigated using renewable energy. High cost of fossil fuel, which is anticipated to increase due to the scarcity, high emission of greenhouse gases, noise of

Table 8. Main components and high-level technical specifications of the BECRC's DC microgrid.

Component	Description
Solar PV System	60 panels at 400W/Panel (3 parallel strings of 20 panels in series)
Electrolyser	700kW from Power Supply Unit and 25kW ancillaries Hydrogen (H_2) Output: 262 kg/day Oxygen (O_2) Output: 2000 kg/day
Water supply for electrolyser	Portable water supply with maximum flow up to 6.5 kl/day
Hydrogen compression and storage	20 bar Hydrogen pressure input from electrolyser is compressed to 165 bar for storage and distribution in tube trailers
Hydrogen microturbine & generator	Output of 65 kW at 400 V DC Overall Efficiency of 20–35% [74]
Fuel Cell	Net system power at 70 kW Idling power at 8 kW Hydrogen supply pressure at 80 bar Peak fuel efficiency of 57%
Battery Storage	114 kWh at 380–400 V DC

the generator operation, and risks of environmental spills are some of the associated risks. Therefore, there is an opportunity to exhibit advancing renewable energy technologies in offshore environments. As most of the electrical loads in aquaculture are in DC domain, DC microgrids can be used to pursue the connection between offshore renewable energy and electrical loads [69]. BE CRC has done an assessment on the energy requirement of offshore aquaculture systems coordinating with Pacific Northwest National Library (PNNL). It has identified that hybrid energy solutions with DC microgrid concept have the capability of increasing the use of renewable energy sources for aquaculture operations by offering clean and reliable ways of supplying power and replace the reliance with diesel [70].

With the increasing availability of renewable energy technologies in offshore environments, ensuring a continuous supply of renewable energy has become a prominent concern. Despite the existence of technologies such as battery storage and thermal storage, each solution faces challenges related to cost, scalability, or geographical limitations. While batteries can be seamlessly integrated into DC microgrids, their storage capacity is finite. When the energy generated from renewable sources exceeds the designated capacity, surplus energy is wasted in battery-integrated DC microgrids. To realize a potential and comprehensive transition to renewable energy sources in aquaculture systems, there arises a need for a system capable of efficiently storing excess energy generated from renewable sources, thereby eliminating waste. This stored energy can then be deployed for critical operations during periods when renewable energy sources are unavailable or when stored battery energy levels have depleted to a certain threshold. Hydrogen energy emerges as a viable solution in this context.

Hydrogen is the ideal component for the storage or delivery of energy, when it is created naturally[71]. It is the fuel that provides most energy per mass. However, it possesses a little volumetric energy content, due to its low density at ambient temperature. Therefore, various production and storage techniques can be taken into consideration to achieve higher target energy density. As mentioned in Section 3, fuel cells can be used to convert stored energy in hydrogen to electrical energy. Utilizing hydrogen in offshore DC microgrids has significant advantages. It can be utilized to provide electrical energy to critical loads when the renewable energy sources are not available to optimize battery storage. Also, it can be employed in vessels to power the engines and in stations where indoor heating is required. Hydrogen plays a key role in BE CRC's offshore renewable energy systems program. They have completed a scoping project to review the options of hydrogen storage and distribution for grid connected and islanded offshore microgrids with high energy [72].

BE CRC has undertaken a demonstration project to design, develop, locate, and operate a hydrogen based offshore DC microgrid, which has the primary target of supporting aquaculture operations. This will be carried out in two phases: onshore and offshore. The onshore microgrid will be an untangled version of the subsequent offshore microgrid. It would supply hydrogen as a fuel for the Metro Tasmania fuel cell bus project [73]. This project is designed together with a bench scale hydrogen-based DC microgrid to carry out analysis in real time and hardware in the loop simulations while determining some important factors like forecasting, fault protection, storage of energy and demand side management. Figure 7 and Table 8 represent the schematic diagram of the proposed demonstration project of Hydrogen bench scale DC microgrid and their technical specifications chosen for to be implemented soon in Tasmania.

There is very little literature available on the technical specifications in hydrogen-based DC microgrids. Providing solid technical specifications for supporting the decision making in development of offshore hydrogen-based DC microgrids is the ultimate objective of this project by the BE CRC.

6 Discussion and conclusion

DC microgrids are gaining rapid popularity, thanks to advancements in distributed renewable power generation technologies. Nevertheless, maintaining a balance between supply and demand within these microgrids poses a significant challenge due to the intermittent nature of renewable sources. While batteries have traditionally served as the primary means of energy storage to ensure a stable electricity supply, their high cost necessitates exploring alternatives.

Fuel cells have emerged as a promising replacement for batteries in DC microgrids, owing to their unique advantages. These benefits encompass high power density, extended operating hours, minimal maintenance requirements, and environmental sustainability. With these attributes, fuel cells have the potential to revolutionize energy storage in DC microgrids.

Despite their promise, fuel cell applications in DC microgrids are still in the early stages of expansion. Currently, centralized control systems are predominantly employed to integrate fuel cells into DC microgrids. However, this approach has inherent drawbacks that limit its practical applicability, including low reliability, limited flexibility for adjustment, restricted adaptability for future expansions, and high operational costs.

Consequently, the use of fuel cells in DC microgrids remains constrained. Additionally, supercapacitors have been utilized as a natural buffer against voltage fluctuations in various applications. Although existing research suggests the potential of employing both fuel cells and supercapacitors as a hybrid unit in DC microgrids, further investigation is needed to solidify this concept. Worldwide initiatives like BE CRC offer an excellent platform for evaluating novel concepts and technologies for integrating fuel cells into DC microgrids.

The application of hydrogen-based power generation has witnessed significant growth alongside the advancement of green power generation in the electrical power industry. Fuel cells have emerged as a key technology for converting hydrogen into electricity. However, the relatively slow transient performance of fuel cells presents limitations that hinder their real-world applications.

Recent research efforts have focused on exploring the potential of combining fuel cells with supercapacitors as a hybrid configuration to enhance the transient performance of fuel cells, and the findings thus far have been promising. Nonetheless, the adoption of fuel cell + supercapacitors as a hybrid unit is still in its nascent stages of development. There exists a noticeable gap in the availability of robust, highly practical, and commercially viable solutions for integrating fuel cells into DC power networks.

Addressing this gap will be crucial in accelerating the utilization of hydrogen-based power generation and ensuring the seamless integration of fuel cells into the evolving landscape of green and sustainable energy production within the electrical power industry.

Implications and Influences

Attention towards addressing the climate change issue on earth, has increased the interest on renewable energy development projects worldwide. With the intermittent nature of the renewable energy sources, energy storage technologies are evolving. Hydrogen storage can be considered as such technology and production of green hydrogen from renewable energy integrates fuel cells and the DC microgrid concept. This review is conducted to identify the current status of the fuel cells and hydrogen storage in DC microgrids.

Hydrogen is considered as a key component in developing blue economy concept in Australian continent. Case study of a hydrogen-based DC microgrid by BE CRC will be done to provide the relevant technological specifications required for DC microgrids in offshore environments.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

Not Applicable.

Author contribution statement

Conceptualization, Methodology – K.G., and N.P.; Writing, Original draft preparation, N.P. and H.J.; Writing—Review and Editing, Supervision: K.G., Investigation, and visualization, K.G., N.P. and H. J. All authors have read and agreed to the published version of the manuscript.

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