A Review of Fuel Cell to Distribution Network Interface Using D-FACTS: Technical Challenges and Interconnection Trends

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***Abstract*—Today, the worldwide public interest in reducing power quality issues and greenhouse gas emissions is a key driver to study fuel cells (FCs) connected to distribution network systems (DNs) based on distributed flexible alternating-current transmission systems (D-FACTS). DNs will need to develop a better performance on Power Quality (PQ) while providing a more efficient energy technology. This study reviewed in-depth the interface of DN to FC systems. By focusing on the FC interface and the associated technical challenges, this review may help reduce the risk of DNs, minimizing the consumption of fossil fuels for power generation, lowering the emission of hazardous gases while dramatically increasing electrical power loads, improving PQ and stability. Besides, the study deliberated aspects of FC power technology with DNs interfacing based on D-FACTS. Specifically, the discussion encompassed the configuration structures of FC power technology and DNs connection based on D-FACTS, technical challenges of DNs, and its trends to determine the diagnosis, integration, and optimization for FC power technology.**

***Index Terms*—Fuel cell, distribution network integrated, D-FACTS, configuration structures, technical challenge, interconnection trends**

I. Introduction

Energy systems play an essential role in many processes, such as distribution networks, transmission networks, power-generation plants, demand load, and industry [1]-[3]. The electric Distribution Network (DN) has a fundamental design to distribute electricity to the demand loads. For the uninterrupted and smooth functioning of an electrical grid, it must be augmented with a stable power source [4]. The most promising renewable systems in clean energy generation are fuel cells (FCs), wind turbines (WTs), and photovoltaic toward a sustainable energy future. In this respect, the FC is one of the technological innovations in energy systems that have been considered a potential candidate for solving the future energy crisis [5]-[7] because it could guarantee adequate supplies of energy according to load demand [8]-[10].

Applying FCs provides several advantages for DN, such as permitting a substantial increase in power stability and better economic performance [11], [12] Specifically, FCs enable the flattening of the peak of a load (load leveling) and the removal of the peak of a load (peak shaving) when the system load is low, frequency regulation, damping energy oscillations, and high electrical efficiency while improving power quality (PQ) and reliability [13], [14] when used to feed alternating-current (AC) loads. World-wide, electricity is exclusively produced from power-generation plants, which often encounter power insufficiency, especially during prolonged drought. In this respect, a dynamic load demand is equal to the total use of power and energy density, efficiency, and lifetime [15], [16].

On the other hand, DN development is considerably constrained by increasing power consumption [17], [18]. Power losses are a growing concern over the safety and resistance of bus voltages. Therefore, through the deliberation on FC technology, this study may help identify a reliable technology for sustainable and adequate energy supply because FCs could operate in extreme environmental conditions, such as intense radiation environments or low temperatures. Also, because the technology of FC power directly converts the chemical energy stored in the hydrogen and oxygen into electricity [19]-[21].

The International Energy Agency (IEA) is reported the hydrogen and fuel cell have been utilized by an unprecedented momentum in taking actions to address an important element of clean as well as secure energy future [22]. In this context, hydrogen and fuel cell technologies continued strong momentum in 2019, with strong interest among policymakers. Moreover, the fuel cell trade nearly doubled up due to outstanding achievement and expansion in some countries such as Korea, Japan, and China. However, by taking into consideration low-carbon production capacity kept comparatively steady. To more elaborate, this still stays

Manuscript received January 10, 2021; revised April 25, 2021; accepted May 27, 2021.

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doi: 10.18178/ijeetc.10.5.319-332

outside the framework of the Sustainable Development Scenario (SDS). More to the point, low-carbon hydrogen production, 2022, 2023, and 2030, announced and in the SDS, by 0.86 Mt/y, 1.45 Mt/y, and 7.92 Mt/y, respectfully. Hydrogen and fuel cell technologies can help to solve the future energy crisis remarkably by taking more intensive activities such as scale-up to minimize costs; substitute high-carbon by low-carbon hydrogen in current applications; and increase hydrogen usage to new applications [22].

The next sections of the study have been explained in the following. Section II discussed the configurations: fuel cells to DNs interface. Section III, shows the distribution networks connection, D-FACTS, Interfacing DNs components of FC power technology, DC-DC converters, DC-AC converter, Filter, and transformer. Section IV, shows the energy storage technologies, Hybrid Energy Storage System (HESS), HESS energy management, and control. Section V discussed the technical challenges, power quality issues, and power flows control. Section VI, presented interconnection trends, diagnosis, model-based method, and on-model-based method. Section VII indicates the conclusions of the study.

II. Configurations of FC to DN Interface

The FC power technology has been widely electrical grid employed to deal with DNs based on distributed flexible AC transmission system (D-FACTS) devices. For example, distributed static synchronous compensator (D-STATCOM), dynamic voltage restorer (DVR), unified power flow controller (UPFC), sub-synchronous series compensator (SSSC), and Thyristor controlled series capacitor (TCSC) in the industrial applications energy system, especially in developed countries. However, evaluating the performance of FC power technology can be very challenging, largely because the software of the evaluation substantially varies among different DNs. Fig. 1 shows the interfaces of FCs and D-FACTS in DNs, in which various elements. Such as direct-current-direct current (DC-DC) and DC-AC converters, filter, and step-up transformer could be combined to interface with DNs.

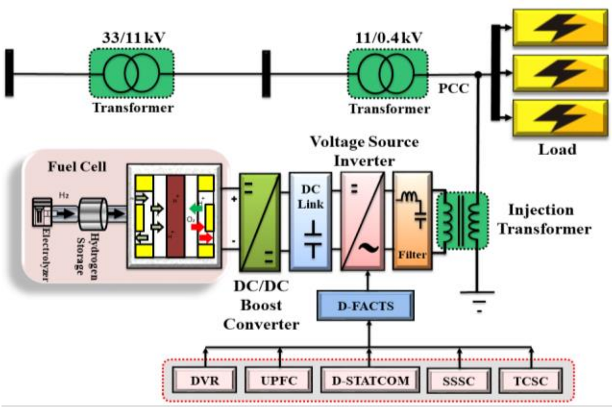


Fig. 1. DNs with fuel cell interfacing to D-FACTS.

A. Types of FC and Operations

In general, the FC is an electrochemical cell consisting of two electrodes, the anode, and cathode. These are used to generate electricity via a pair of reduction-oxidation (redox) reactions. In this respect, the FC is one of the most widely regarded hydrogen energy and has received special attention in the chemical energy system. Hydrogen energy is being made in the interests of safety and efficiency, energy density, and attempts to achieve greater performance in air pollution [23], [24]. There are several types of FCs, depending on the composition of their electrolyte, the operating temperature, and the type of fuel applied [25]-[29]. The most widely studied FCs are proton exchange membrane fuel cells (PEMFC), alkaline FCs (AFC), solid oxide FCs (SOFC), and molten carbonate FCs (MCFC). Table I shows the common types of FCs used in power technology. The operating temperature of FCs varies greatly, depending on their type. PEMFC has the lowest operating temperature, i.e., between 50 ℃ to 80 ℃. However, AFC, SOFC, and MCFC could operate only between 600 ℃ and 850 ℃.

TABLE I: The Common Types of FC used in Power Technology

FC type	Temp (℃)	Electrolyte	Application
PEMFC	50–80	Flexible polymer	▪ Distribution network ▪ Clean power generation ▪ Electronic throttle valve ▪ DC motors ▪ Servo control ▪ Robotics
AFC	600	Solution of potassium hydroxide in water	▪ Space ▪ Rail transportation ▪ Transit network
MCFC	600–700	Melton alkali metal carbonates	▪ Grid power stabilization ▪ Distributed generator ▪ Power generator ▪ Heating production ▪ Cooling production
SOFC	650–850	Solid ceramic oxide	▪ Electrical power ▪ Clean water provision ▪ Hydrogen generation ▪ Diesel-based engines ▪ Gas turbines

In general, the FC power technologies are categorized by their materials, major components of the cells, and the types of electrolytes they comprise [30]. Overall, PEMFCs show a broader application in the electrical power system (Table I).

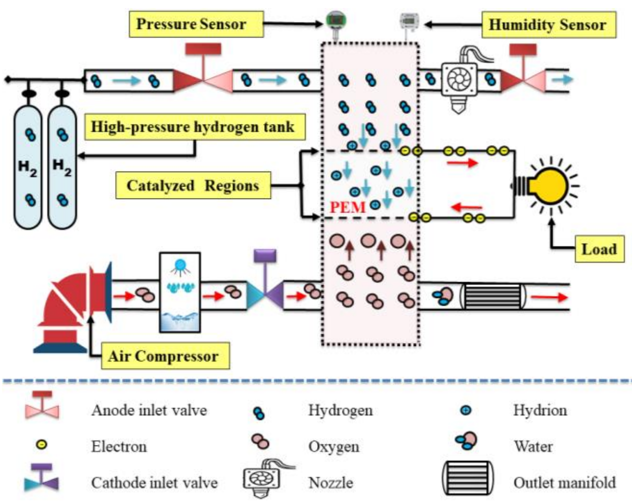


Fig. 2. A PEMFC power technology with additional components.

Low-cost bipolar plates have been developed to increase the corrosion resistance and productivity of the FC, thereby enhancing the durability of the Proton-Exchange Membrane (PEM) while optimizing the operating parameters to dynamic characteristics [31]. Fig. 2 shows the PEMFC power technology and additional components such as a high-pressure hydrogen tank, air compressor, anode inlet valve, cathode inlet valve, outlet manifold, nuzzle, pressure sensor, and humidity sensor.

Several ingredients have combined to create the PEMFC power technology including a high-pressure hydrogen tank, air compressor, anode inlet valve, cathode inlet valve, outlet manifold, nuzzle, pressure sensor, and humidity sensor. Moreover, some PEMFC power technology combines elements of the system, intercoolers, and humidifiers. In this context, the dynamic air supply system model generally uses control-oriented and can be split up the PEMFC electrochemical model, air compressor model, cathode model as well as manifold model. The protons are the ionic charge carrier in PEMFC. An essential ingredient in PEMFC power technology is air compressors. The air compressor promises to bring more efficiency to the power density and cost. When hybridized with energy storage systems (ESS), the DN utilizes the energies of the FC, and a battery bank to supply the demand loads through a combination of electric and magnetic feeders [32].

In particular, PEMFCs are widely used because they have many advantages to DNs, such as a substantial positive impact on power density, minimal temperature performance, rapid start-up, and zero-emission zero of hazardous gases [33]-[36]. Moreover, PEMFC stacks in effect are equivalent to unit cells, which would substantially increase the output voltage of cells. As for chemicals reaction within a PEMFC, the hydrogen oxidation reaction (HOR) below summarises the partial redox reaction that takes place at the anode:

$$H_2 \rightarrow 2H^+ + 2e^- \tag{1}$$

where e denotes an electron.

Together with another partial redox reaction at the cathode, the hydrogen reacts with oxygen to generate water, electricity, and heat, as shown in (2) and (3) below:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{2}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{Electricity+Heat} \tag{3}$$

Fig. 2 shows the operation of PEMFC, current densities, and output voltages, in which the difference between the theoretical maximum and the output voltage is known as polarisation, and it can be measured by Equation 4 below:

$$E = -\frac{\Delta G}{nF} \tag{4}$$

where ΔG (J mol^{-1}), refers to the Gibbs free energy, i.e., the difference between the product and reactant for one mole of hydrogen; n, refers to the number of electrons transferred in a hydrogen-oxygen electrochemical reaction, and F refers to the Faraday's constant.

Therefore, the total energy (the enthalpy difference, ΔH) can be calculated as expressed.

$$\Delta H = \Delta G + T\Delta S \tag{5}$$

where $T(K)$ refers to the temperature in Kelvin, and ΔS (J mol^{-1}), refers to the entropy difference between the product and reactant for one mole of hydrogen. Thus, the maximum energy efficiency ($\eta_{\max}$) of FC power technology could be calculated by Equation 6 below:

$$\eta_{\max} = \frac{\Delta G}{\Delta H} \tag{6}$$

In general, the PEMFC energy has improved efficiency performance by nearly 83% at a temperature of 25 ℃. Taken together, PEMFC cell voltages E_{cell} can be computed by Equation 7:

$$E_{\text{cell}} = E_{\text{OCV}} - \eta_{\text{act}} - \eta_{\text{ohm}} - \eta_{\text{trans}} \tag{7}$$

where E_{ocv} = open-circuit voltage; η_{act} = activation loss; η_{ohm} = loss of electrical resistance, and η_{trasns} = mass transport loss.

The open-circuit voltage, E_{ocv} , in Equation 7 could be less than the reversible cell potential (~ 1.2V) as a consequence of slight electron conduction (by membranes), comprising the major cause of voltage loss through internal currents and hydrogen crossover.

Meanwhile, η_{act} is responsible for activation loss, which has a long-term effect on the chemical reactions taking place on the surface of electrodes. On the other hand, η_{ohm} drops more slowly and nearly linearly even in an ideal PEMFC polarisation curve, leading to the loss of electrical resistance. Another source of voltage loss is mass transport loss, which happens when the voltage reduces quickly.

III. Connection of Distribution Networks

The power system is a dynamic system, where various active system elements connect and directly interact through transmission networks and distribution networks. In essence, DNs must effectively deliver a stable supply of energy to the demand load, which is highly critical to the long-term future of the electric utility (Fig. 1). Thus, the PQ and reliability of power supply to demand loads must be enhanced in the overall operation as well as the planning of the entire electrical power system because DNs strongly influence the location and density of demand loads. Also, DNs determine the extent of the fault levels and network strength, transformer ratings, and source of impedances. In the vast majority of cases, DNs expand rapidly due to the availability of more and more reliable, sustainable growth, and highly efficient and environmentally friendly energy supply.

A. D-FACTS

The efficient concept of FACTS was introduced in the late 1980s, and the technology of FACTS has taken advantage of efficient energy utilization, voltage stabilization, demand control, power factor correction voltage sag mitigation, and harmonic mitigation for its rapid development [37]-[40]. Thus, the fundamental concepts of FACTS technology are based on the understanding of using high-voltage power electronics to regulate the transmission system. As the demand for electricity continues to increase [41]. Table II shows different types of D-FACTS controllers and the parameters they regulate.

Meanwhile, the D-FACTS leads to the injection of both active and reactive power to DNs via the supply of ESS. In shunt D-FACTS, the D-STATCOM is closely related to a voltage-source converter, which has been used to compensate for the reduction of PQ, for example, voltage sag, voltage unbalance, unbalanced load, harmonic, and voltage fluctuation. The same can be said on DVR. Meanwhile, the shunt-series D-FACTS compensators integrate another piece of equipment known as unified power quality conditioners (UPQC) to improve dynamic active and reactive power regulation, voltage flicker, voltage mitigation, voltage unbalance, and harmonics. In recent decades, due to an ever-increasing demand for electricity in most countries, the need to build new transmission lines and electricity posts has tremendously increased with huge capital investment. Thus, finding effective solutions to reduce the costs for electric companies has been a great challenge.

Moreover, a recent study on PQ concluded that voltage sag and swells in the medium voltage DNs are strongly considering as the most regular form of PQ issues. These PQ issues can have a huge negative effect on the sensitive loads and cause main financial losses to millions of dollars. In this context, Dynamic Voltage Restorer (RVR) based on a bidirectional DC-DC converter is utilized to defend the demand loads against such PQ disturbances.

Needless to say that one of the recent trends in DVR structure is to instantly suppress the DC-DC converter, which enables the hardware and software required and the losses in the conversion operation to be reduced Furthermore, DC-DC converter has a significant role to play in providing the voltage between the energy storage system and the voltage source inverter (VSI). In this context, the DVR can an adjustable DC-link voltage utilizing a DC-DC converter. Thus, the output voltage of the DVR has the capability to reach the maximum level for compensation in DNS.

TABLE II: THE DIFFERENT TYPES OF D-FACTS CONTROLLERS AND THE PARAMETERS THEY REGULATE [42], [43]

Type of D-FACTS	Characteristics	Controlled Parameters	Devise
Shunt	Control susceptance	Real & reactive power	▪ Distributed static synchronous compensator D-STATCOM ▪ Static synchronous compensator (STATCOM) ▪ Static VAR compensator (SVC) ▪ Dynamic voltage restorer (DVR)
Series	Control reactance	Real & reactive power	▪ Sub-synchronous series compensator (SSSC) ▪ Thyristor controlled series capacitor (TCSC)
Series- Series	Control V&δ	Real & reactive power	▪ Interlink power flow controller (IPFC) ▪ Generalized interlink power flow controller (GIPFC)
Shunt-Series	Control X,V and δ	Real & reactive power	▪ Unified power flow controller (UPFC) ▪ Unified power quality conditioners (UPQC)

B. Interfacing FC to DN

Although DNs could gain electrical power from the FC power technology through D-FACTS (Fig. 1), the DC produced by FCs will need the installation of power electronic devices for effective delivery into the power system. In this regard, FCs to the DN interface is provided through power electronic converters and other electrical components. At the utility scale, the FC power technology consists of four parts, i.e., DC-DC boost converter, DC-AC converter, output filter, and step-up transformer.

1) DC-DC converters

There are many industrial applications for DC-DC converters to generate high step-up voltage gain, for example, in D-FACTS and renewable energy systems, as well as other non-conventional energy sources, such as due to their high DC output voltages.

A conventional boost converter cannot provide such high-voltage gains because its duty-cycle is narrow, [44].

The boost converters with higher voltage gains can theoretically be realized with an extreme duty-cycle design and application. In the FC power applications, the output voltage and load power are variable, and they highly depend on operating conditions. Thus, DC/DC power converters are usually used to maintain a constant voltage, matching the subsequent power bus. Due to the nonlinear characteristics of the FC and load profiles, therefore, a more robust design for power converters is essential [45]. These applications are developing fast in the distributed power grid [46]. The DC-DC converter can handle bidirectional power flow. Fig. 3 shows the topology of a conventional boost converter connected to FC power technology, while Fig. 4 shows the topology of an interleaved boost converter connected to FC power technology.

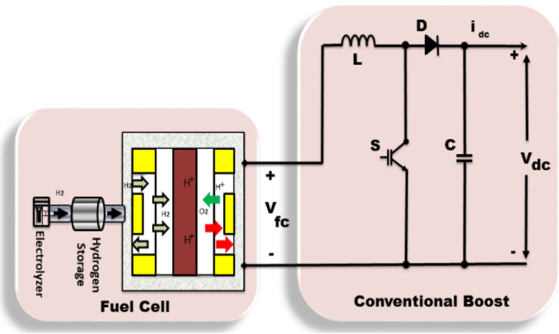


Fig. 3. Topology of a conventional boost converter.

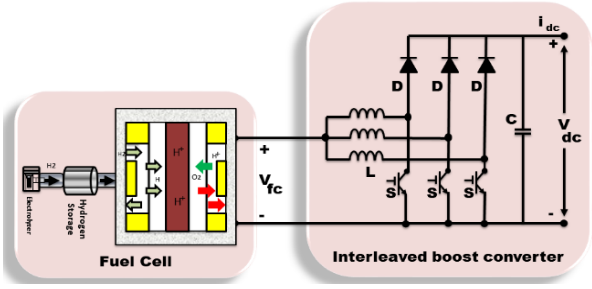


Fig. 4. The topology of an interleaved boost converter

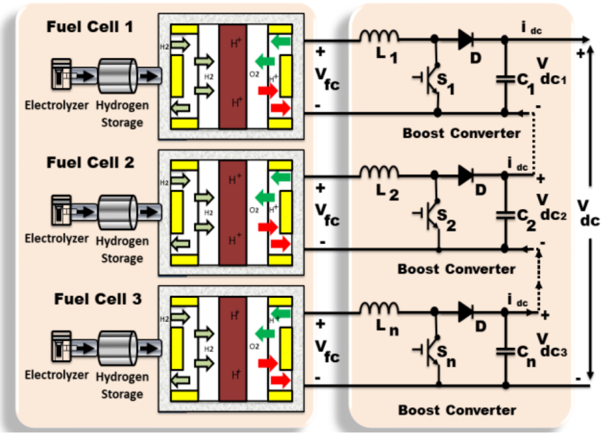


Fig. 5. The topology of a Multi-input single-output converter.

In DC-DC converters, the interleaved boost converter topology is employed in classical designs to eliminate the disadvantages that may occur in driving a high-frequency semiconductor switch [47]. The interleaved DC-DC converter aims to minimize the input current ripples as well as the switching losses. In this case, the efficiency of the converter system can be substantially increased. Unlike other types of converters, this interleaved DC-DC converter uses small electronic components. Also, this new technology interleaved DC-DC converter could be applied to FC power technology by multi-input single-output (MISO) dc-dc converters (Fig. 5).

Meanwhile, the effect of passive circuit elements such as inductors and capacitors on circuit performance is crucial in DC-DC power converter circuits, in which duty ratio values and the switching frequency of the active element power semiconductor affect the output voltage ripple, which, in turn, may vary depending on load conditions. Furthermore, voltage doubler boost converters with four parallel phases (Fig. 6) are now widely implemented in FC power technology to gain a high step-up voltage. Fig. 7 shows the topology of a voltage doubler boost converter based on the isolation transformer.

In the studies of isolated DC-DC converters, bridge converters are more commonly used to stabilize the output voltage. Fig. 8 shows the topology of a dual half-bridge dc-dc converter in FC systems based on the isolation transformer. Power control in this converter is simpler compared to other DC-DC converters although dual the full-bridge converter is more complex and expensive. Current-fed dual half-bridge and voltage-fed dual half-bridge converters are alternative bridge-based DC-DC converters used in this study [48], [49], respectively.

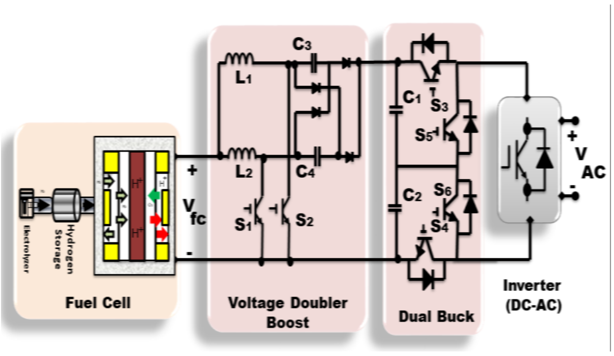


Fig. 6. The topology of voltage doubler and boost and dual Buck converter.

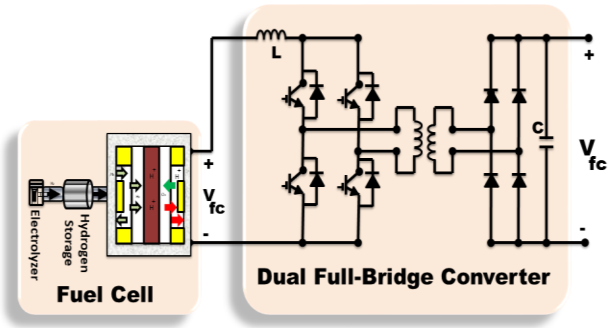


Fig. 7. The topology is based on the isolation transformer.

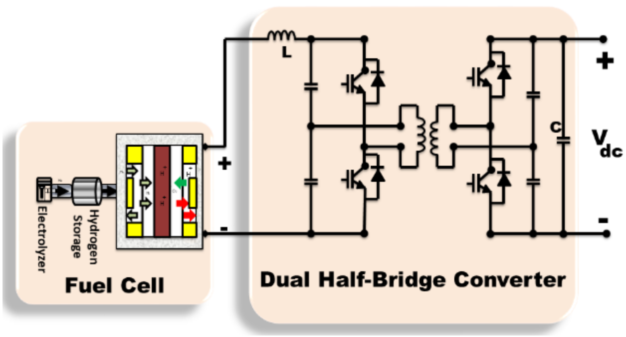


Fig. 8. The dual half-bridge converter in FC systems

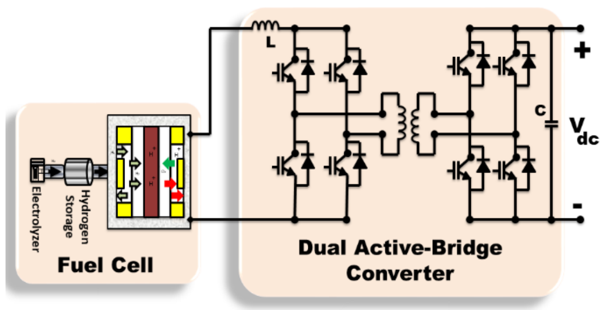


Fig. 9. The circuit of a dual-active bridge converter.

Also, the dual active bridge is an example of bridge converters used in FC systems for grid interconnection. Fig. 9 shows the circuit of a dual active bridge converter.

Fig. 10 shows the circuit of a forward converter, which provides galvanic isolation using a transformer, while Fig. 11 shows the high step-up coupled inductor converter. Besides, a high step-up coupled inductor converter and zero-voltage transition are two other topologies with a considerable voltage conversion ratio. Fig. 12 shows the zero-voltage transition DC-DC converters connected to a FC system.

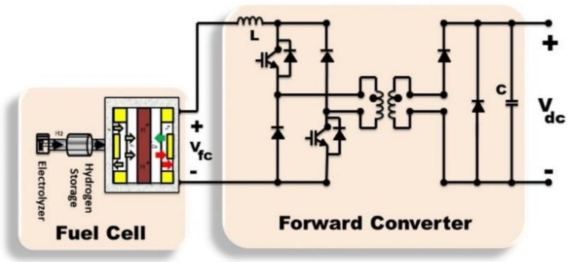


Fig. 10. The circuit of the forward converter.

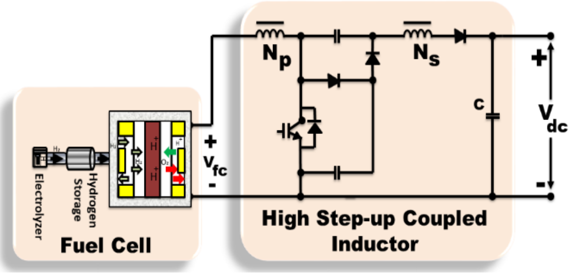


Fig. 11. The high step-up coupled inductor converter.

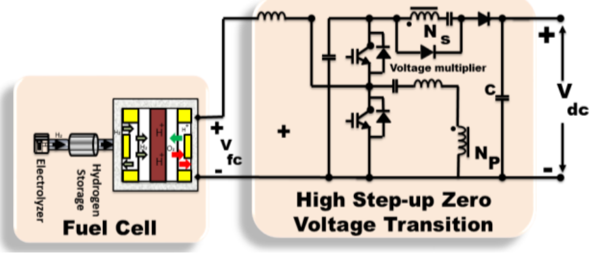


Fig. 12. The zero-voltage transition DC-DC converters are connected to a fuel cell system.

2) DC-AC inverter

A voltage-source inverter (VSI) works as a power interface between the PEMFC stack and a DN system, converting the DC electricity to the sinusoidal AC form, and three-phase waveforms can be obtained using the DC/AC inverter. The inverter modulates the electricity via six semiconductor switches with an on-off state controlled by the duty ratio of bipolar pulse-width modulation (PWM) [50]. With the integration of many power inverters, the network characteristics would certainly change, leading to new technical challenges, such as complex control systems, complicated stability analysis, as well as systematic protection [51]. These inverters primarily serve to control the real and reactive power between the FC power technology and DN interconnections. From this perspective, the inverter could be considered as one of the major components of the DNs connected FC power technology. In this case, VSIs were applied to the D-FACTS devices to interface FCs to DNs (Fig. 1).

3) Filters

Filters play an important role in harmonic mitigation, reactive power compensation, load balancing, neutral current compensation, and reducing flickers [52]. The filter-connected VSI is related to improved attenuation performance and consequently a decrease in size, volume, and cost [53], [54]. Passive filters are widely used in electrical systems for PQ improvements, and they were first installed in the 1940s. Their advantages such as compensation of voltage harmonics, compensation of current harmonics, balancing of mains voltages in three-phase, and balancing of mains currents in three-phase make them an attractive and standard solution up to these days. A particular issue in harmonic distortion is the line current generated from non-linear loads. A high level of harmonics, also known as total harmonic distortion (THD), could cause many consequences, such as conductor overheating, voltage distortion, malfunction of transformers, unnecessary protection device trip, and interference in the telecommunication network. Based on the Institute of Electrical and Electronics Engineers (IEEE) Standard 519-2014, if the level of THD exceeds 8% at the point of common connection (PCC) at low voltage levels, the system should be investigated.

Moreover, IEEE Standard 1547 has limited the THD of the injected current by 5% [55]. Meanwhile, filters are classified into two categories, namely passive, and active filters. The passive filters affect the economics of countermeasure in power issues related to harmonics [56]. There are various designing techniques of passive filters, i.e., first-order series filter, second-order shunt filter, third-order single tuned filter, fourth-order double-tuned filter, fifth-order low pass filter, sixth-order high pass filter, seventh-order LCL filter, and eighth-order LLCC filter. Fig. 13 shows different types of passive filters at DNs connected with FC power technology.

This discussion deliberated some instances of filters, which can be extensively used as an interface among DNs, D-FACTS, and FC power technology. The process of harmonic LC traps, rather than the LCL filter capacitor, is more commonly used to maximize the benefits for industry, due to its potential for reducing or even taking out the network-side filter inductor. The trap filter suggested for single-phase DNs-interface converters is LLCL filter, which uses a small inductance on the DN-side of the filter. From this perspective, active filters are widely distributed through series types and shunt types, and they are known as power electronic devices for controlling the voltage harmonic and current harmonic sources, which are a useful function as harmonic mitigation and reactive power compensation [57], [58].

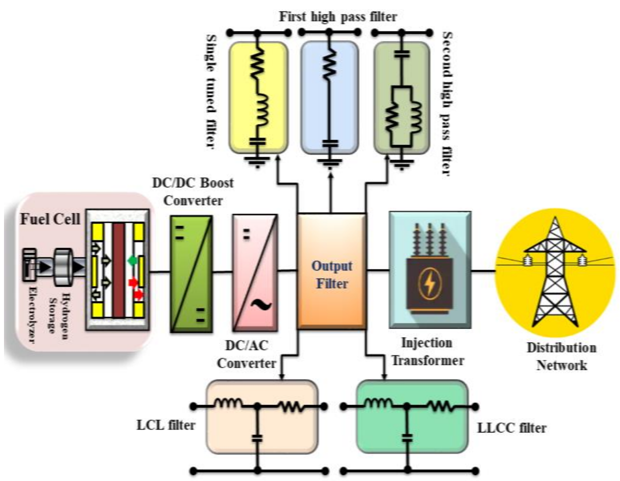


Fig. 13. Different types of passive filters at DNs connected with fuel cell power technology.

4) Transformer

In recent times, the energy efficiency of DNs connected to FC power technology becomes increasingly clear, in which an improvement in the performance of power systems is accompanied by a reduction in operational costs, enhanced signal quality, and a reduction in adverse environmental effects. For these reasons, the transformer stations of D-FACTS have become a common element in all power systems. Moreover, distribution transformers are put forward to the last stations to supply electrical feeders, bringing more efficiency to the distribution chain [59].

In this case, achieving specific and effective progress on standards is one of the determining factors influencing the demand and supply balance and success of the network process that will, in turn, determine the proper operation of the system. The electrical power demand of the distribution network has been analyzed in detail using distribution transformers, which also gives accurate predictions for DN systems. In this respect, transformers, which operate under very difficult circumstances, and have made enormous damage to undesirable high-frequency impulses because of circuit breaker operation, direct lightning impulse, system faults [60], [61].

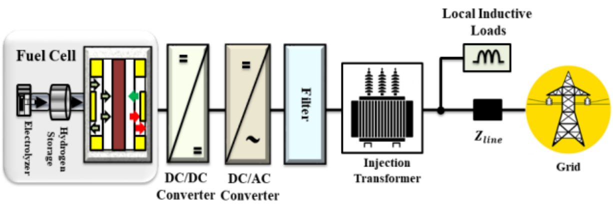


Fig. 14. The single-line diagram of a DNs-interfaced FC power technology [62]

In this context, the conventional DNs-interfaced systems, FC power technology ensure the generated power into a single DN feeders and control the DN-bus by interfacing elements of the entire system [62]. In this case, interline fuel cell (I-FC) power technology shares a DC-DC converter connected FC at the base of inverters which is designed to eliminate the further FC power technology and DC-DC converter in a multi-feeder system. For this aim, FC power technology is interfaced to multi-feeders through separate inverters, thereby distributed electrical power into the feeders and attenuates the effects of the harmonics at DN-side currents. In this direction, the aim of the system provides an economical way for the attenuation of DNs issues for multi-feeders. Fig. 14 shows the single-line diagram of a DNs-interfaced FC power technology.

To achieve the functional abilities of I-FC power technology, dual-functional control is separate that can be applied in the electrical grid inverters. Last but not least, the I-FC power technology is devoting the active power to both feeders, and an ever-reduces amount of the current harmonics through DNs power demands from the utility-grids.

IV. Energy Storage System Technologies

Energy storage systems (ESSs) can be an effective solution to smooth fluctuation for improving the stability of the DN. Electrical energy storage (EES) is a process of converting electrical energy into other forms of energy that can be stored for converting back into electrical energy when needed. One can categorize the storage technologies by storage duration (long-term, short-term storage), by the kind of storage (electrical, mechanical, chemical, thermal, etc.) [62], [63], or by other criteria such as capital cost, capacity, efficiency, and environmental impact. Table III shows the classification of energy storage technologies by the form of stored energy.

TABLE III: The Classification of Energy Storage Technologies by the Form of Stored Energy

Ref.	Energy Storage Technologies	Classification	Type
[64]-[72]	Chemical	Fuel Cell (Hydrogen)	PEMFC SOFC MCFC AFC
	Electrical	Supercapacitor	-
		Superconducting Magnetic (SMES)	
	Mechanical	Pumped Hydro (PHS)	-
		Compressed air (CAES)	
		Flywheel (FES)	
	Thermal	High Temperature	PCM
			CSP
		Low temperature	Aquiferous
			Cryogenic
	Electrochemical	Electrochemical Batteries	Lead Acid
			Nickel-based
			Sodium-based
			Li-ion
		Flow Batteries	Redox flow
			Hybrid flow
	Thermochemical	Solar fuel	-

V. Technical Challenges in DN

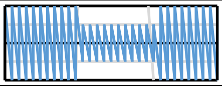
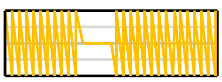
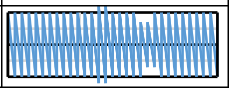
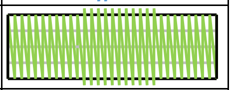
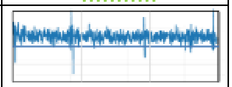
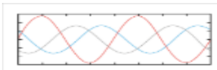
The electrical DNs, together with the associated technical challenges, are rapidly evolving. These challenges encompass aging power quality (PQ) issues and the integration of FC power technology in the DNs based on D-FACTS. Also, the influx of FC power technology in DNs, which was not initially planned to deal with more energy, could result in extensive bottlenecks in DNs. Thus, D-FACTS is to provide high PQ and reliable integration for DNs. In this respect, PQ issues, and waveform are investigated for FCs to DNs connection.

A. Power Quality

At the present day, the power devices of customers have received special attention from both utilities and researchers. As a result, the electric sector has become very innovative and dynamic with increasing competition and hence efficiency. Thus, the notion of PQ has become increasingly crucial for both utilities and consumers [73], [74]. 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 [75]-[77]. Unless these underlying deficiencies of PQ issues are rectified the distribution system can never be efficient. Table IV shows PQ issues and waveform.

To overcome the PQ challenge, the distribution system responds to the demands of the installation equipment such as the series unit (SEU) and shunt unit (SHU), which are placed in each bus of a DN, their effects on improving the power loss and PQ indices of a DN were discussed. For that purpose, the D-STATCOM, DVR, Active Power Conditioner (APC), Active Voltage Conditioner (AVC), were beneficial to improve the PQ due to disturbances, such as voltage sag/swell, interruptions, and harmonics. Furthermore, three-phase current and power factor could be maintained using Static Var Compensation (SVC) and active filters with the application of reactive power compensation to improve the PQ [78]. Therefore, it was important to determine the requirements for a safe and reliable DN operation to overcome the above-mentioned challenges. The combination of D-FACTS technology for the DN connected to FC able to overcome the PQ challenge.

TABLE IV: PQ ISSUES, DESCRIPTION, AND WAVEFORM

Ref.	PQ issues	Description	Waveform
[78], [79]	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.	
[80]	Short interruptions	▪ Total interruption of electrical supply for a duration from few milliseconds to one or two seconds.	
[80]	Long interruptions	▪ Total interruption of electrical supply for a period greater than one to two seconds.	
[80]	Voltage spike	▪ Very fast-changing of the voltage rate for durations from several microseconds to few milliseconds. Even in low voltage, these variations may reach thousands of volts.	
[80]	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.	
[80]	Voltage fluctuation	▪ Oscillation of voltage value, amplitude modulated by a signal with a frequency of 0–30 Hz.	
[80]	Voltage Unbalance	▪ A voltage variation in a three-phase system in which the three voltage magnitudes or the phase angle differences between them are not equal.	

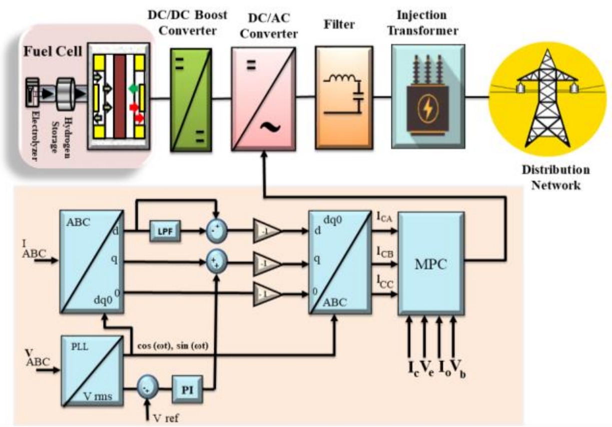


Fig. 15. The system configuration with the reference current detection and power MPC is based on D-FACTS.

B. Power Flows Control

Due to a substantial increase in the usage of FC power technology and nonlinear demand loads, the quality of power in modern DNs has been directly affected especially by voltage sag, swell voltage, and harmonics [81]. Although D-FACTS devices integrated with FC power technology were sufficient to resolve the PQ issues, intelligent control [81]-[83] was also included in ESS, which could be attained through the inverter of D-FACTS devices by controlling both active and reactive power from the FC power technology and DNs. Meanwhile, the energy resources can be made available through the system of DN (e.g., hybrid energy storage system) to resolve the PQ issues.

Once voltage sag occurs, it can cause an enormous economic loss due to the trip of industrial processes and demand loads, and the fault scenario would certainly impact the point of common coupling (PCC) voltage waveforms. In this respect, D-FACTS could substantially enhance the performance of DNs, because it can rapidly raise the exchange of active and reactive power. Fig. 15 shows the system configuration with the reference current detection (RCD) and model predictive control (MPC) based on D-FACTS devices, in which the system control performance can monitor the reference current and the reactive power and output currents.

The D-FACTS is known as a shunt-connected system, and it can inject current to provide compensation for maintaining the downstream performance, especially when the current drawn from the point of an upstream source is sinusoidal as well as in phase with the voltage. In this regard, the topology of the direct matrix converter (DMC) can be widely implemented in system applications. The DMC is composed of bidirectional switches, each comprised of two insulated-gate bipolar transistor and diode pairs connected in an anti-parallel fashion to encourage bidirectional current flowing through the system.

Additionally, filters in the D-FACTS system would reduce the high-order harmonics generated by converter switching. Taken together, the D-FACTS system convincingly demonstrates its effectiveness in resolving PQ issues, such as voltage sag, swell, harmonics voltage unbalance, and instability of the system. Besides, for the D-FACTS system composed of a neutral current, the zero-sequence current control loop can gain a competitive advantage over the traditional direct current control method, leading to achieving a neutral-point voltage balance on D-FACTS. Fig. 16 shows the proportional-integral (PI) controller and neural network (NN) based on D-FACTS, while Fig. 17 presents the PI controller and artificial neural network (ANN) based on D-FACTS.

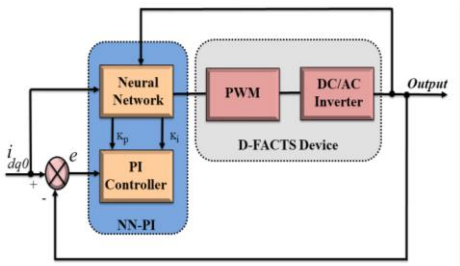


Fig. 16. The PI controller and neural network (NN) is based on D-FACS.

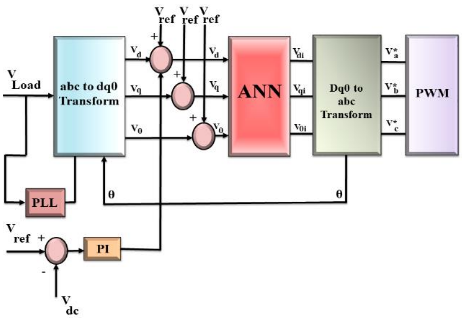


Fig. 17. The PI controller and artificial neural network (ANN) are based on D-FACTS.

The goal of the PI controller and neural network was to improve the efficiency of the control precision for the D-FACTS. In this respect, the backpropagation neural network (BP-NN) performs an important role in the structure of D-FACTS. The BP-NN statue is enclosed within a structure of the input layer, the hidden layer, and the output layer, allowing the neural network of the PI controller to serve a useful function to control the voltage and current for D-FACTS. After the *dq0-axis* current is created, the neural network of the PI controller starts enhancing the precision of control. Eventually, the output *dq0-axis* regulated (or directed) voltages are transformed through a three-phase AC modulating signal.

The D-FACTS devices can then be combined to create two control strategies of the PI controller and ANN controller. Fig. 16 shows the PI controller and ANN-based on D-FACTS. The ANN control approach encompasses three neuron layers, i.e., the input layer, hidden layer, and output layer. The input layer unit is provided by load signal in the voltage of DN bus as direct-quadrature axis voltage and V_{dq0} forwards the signal to the hidden layer unit. An output layer unit is essentially a learning process unit, and it is to be continually supplied output signal. The output signal unit, including the V_{di}, V_{qi}, and V_{0i}, forwards the voltage to phase voltages V_a^*, V_b^* and V_c^* through the generation of the PWM signal to an inverter of the D-FACTS system.

However, some studies suggest that can be improved the harmonics extraction approach using Instantaneous Power Theory (IPT), using indirect current-controlled, neutral point diode clamped using three-level, shunt active power filter (SAPF) based on the inverter. In this regard, The SAPF has high flexibility to mitigate current harmonics. Besides that, the SAPF design allows dealing at peak efficiency with dynamic state conditions. In the other operational process, the SAPF is performing a function due to unbalanced electrical grid conditions using a Virtual Input Signal (VIS). VIS-based IPT generates the compensation signals composing of harmonic and/or reactive currents [83]-[85]. By taking into account that the reference signal generation is obtained for each phase by calculating powers of multiple-phase inverse, separately.

VI. Interconnection Trends

In this section, this study has researched fuel cell power technology connected to DNs based on D-FACTS. Moreover, the study on fuel cell power technology has led to some important advances at DNs to enhance the PQ. To be elaborated further, including for diagnosis, integration as well as optimization, which can be elaborated in the following sections.

A. Fault Diagnosis of FC

The accurate diagnosis also plays an important role in protecting the FC power technology while increasing the operational lifetime of FC, improving the system, and optimizing maintenance costs. A combination of these elements poses a major challenge to researcher and science, their stability, and security in DNs. Thus, a remaining technical challenge is its high power requirements [85].

Various fault methods have been proposed for the diagnosis of the FC power technology, and these primarily encompass the model-based and non-model-based methods. Table V summarises different fault diagnosis approaches for PEMFC. In general, the fault diagnosis procedure is considered effective when the FC power technology system continues surveillance on all the parts and subsystems of each type of delivery system. This diagnosis would reduce the time spent on faults while increasing the productivity of the system by taking into account the cost of maintenance.

B. Integration

The FC power technology is regarded as one of the most promising power solutions for distribution network DNs, and heavily on several added features, such as high efficiency, high energy density, as well as zero-emission of hazardous gases. In this respect, reliable, high-density, and efficient power electronic systems are required for

DNs integration. For this purpose, the FC power technology integration can be implemented in several ways based on the selected type of FCs, advantages, and overall efficiency of these systems. Table VI shows the classification of DN-connection FC power technology.

The energy generation and storage systems used in FC power technology can be connected to hybrid energy storage systems (HESS). In these DN systems, FC power technology, photovoltaic systems, and WT can be particularly useful for enhancing the power system areas. This study introduced different maximum outputs of FC power technology, such as 100W, 300W, 1.2kW, 6kW, and 8.04kW. This study also provided the modeling of PEMFC power technology implemented using PSCAD/EMTDC for steady and transient regimes, which had been applied for equivalent electrical circuits. This model considered the activation, concentration, and Ohmic losses of a PEMFC, as well as its thermodynamic behaviour that can influence the behaviour of FC power technology through DNs. Also, the integration of PEMFC power technology to the main electrical network via a boost DC/DC converter and a DC/AC converter was deliberated in this discussion.

TABLE V: SUMMARY OF DIFFERENT FAULT DIAGNOSIS APPROACHES FOR PEMFC

Ref.	Approaches	Method	Category	Element
[85]-[87]	Fault diagnostic	Non model-based method	Artificial Intelligence method	Fuzzy logic controller, Neural network, expert system.
			Statistical method	Voltage measurement, impedance spectroscopy, polarisation curve interpretation, spatial current density, pressure drop.
			Signal processing method	Magnetic resonance, imaging, acoustic emission, magmatic field, neutron radiography, the wavelet transform.
		Model-based method	Quantitative approach	Analytical redundancy, Observers statistic method, and Kalman filter.
			Qualitative approach	Structural analysis and Causal model.

TABLE VI: THE CLASSIFICATION OF DN-CONNECTION FUEL CELL POWER TECHNOLOGY [85]-[88]

Power (kW)	Connection	FC power technology type	Simulation Software	Advantage	The overall efficiency of the system (%)
8.0	Grid	PEMFC	PSCAD/ EMTDC Simulations	• Reliability and energy quality in a steady state. • Fuel flexibility. • Rapid response to load changes when compared to the other types of FC. • To evaluate PEMFC as a backup source, obtaining the algorithm for maximum power tracking, and testing new topologies for the interface of grid-connection.	50%
0.1	Grid	PEMFC	MATLAB Simscape Power System toolbox	• Eigenvalue analysis was performed to examine the stability of the integrated PEMFCs for grid connections. • Sensitivity analysis was conducted to investigate potential instability problems associated with DC/DC converter design or inverter parameters.	40%
1.2	Distribution network	PEMFC	MATLAB	• To simulate DNs with three optimization techniques namely, modified flower pollination algorithm (MFPM), electromagnet-tic field optimization (EFO), and harmony search (HS), for the optimal gain scheduling of two the PI control parameters. • To enhance the power issue through FC-connected DNs.	53%
8.04	Distribution network	PEMFC	Matlab Simulink	• High efficiency in the power plant. • Improving the fuel cell performances on energy/ exergy efficiency. • Enhance the efficiency of the electrical power to optimize the operating parameters of the PEMFC system using MOEA/D and achieve maximizing the system efficiency and power.	79%
6.0	Smart grid applications	PEMFC	Matlab Simulink	• Aim to increase the efficiency of the model by implying the load tracking capability of the fuel cell system and yielding good agreement with ANN-predicted results.	60%

C. The Optimisation of HESS

The optimization is an appropriate subject matter for hybrid systems of energy generation, and it encompasses FC power technology, photovoltaic (PV), supercapacitor (SC), diesel generator, battery, and wind turbine (WT).

In this perspective, improvement of performance and equipment protection are the major majors of HESS optimization. The optimization methods offer a clear advantage to DNs and D-FACTS by gaining a competitive advantage over its maintained reliability while providing a maximum output power at a relatively low cost. The FC power technology has attracted the attention of HESS in terms of a longer lifespan, easier maintenance, cost reduction, and minimization of hazardous emissions. Nevertheless, the effective hybridization of energy systems is crucial to achieving the maximum power output from renewable energy sources (RES). Table VII summarises the optimization studies in HESS, including FC power technology type, HESS components, approach, purpose, and simulation software. The energy generation and storage systems used in FC power technology can be connected to hybrid energy storage systems (HESS). In these DN systems, FC power technology, photovoltaic systems, and WT can be particularly useful for enhancing the power system areas. This study introduced different maximum outputs of FC power technology, such as 100 W, 300 W, 1.2 kW, 6 kW, and 8.04 kW.

TABLE VII: THE SUMMARY OF OPTIMIZATION STUDIES IN HESS [89]-[92]

FC type	HESS Components	Approach	Purpose	Simulation Software
PEMFC SOFC	Fuel Cell Water-gas shift (WGS) Thermal swing adsorption (TSA)	A novel biogas-fed hybrid system	• To implement PEMFC-SOFC hybrid system, WGS reaction, and TSA, to increase the efficiency of power generation. • To reveal and develop a roadmap for the PEMFC & SOFC hybrid power-generation technology under different regions.	Numerical Simulation
PEMFC	Fuel Cell Super Capacitor Battery system	Salp swarm algorithm (SSA) Mine-blast optimization (MBO)	• The purpose is to design analyses of SSA and MBO strategies of FC power technology, SC, and battery storage systems due to highly fluctuating load conditions.	Matlab Simulink
PEMFC	CHP-PEMFC, WTs, Photovoltaic	Modified teaching learning-based organization (MTLBO)	• To implement the MTLBO method with the operation of combined heat and power (CHP) units and other RESs. • To enhance the performance of 33 bus DN base on the MTLBO algorithm.	Matlab Simulink
PEMFC	Fuel Cell Wind power	Model and predictive control (MPC).	• Aim to implement a hybrid system management model and predictive control (MPC). • Improving and taking contingency measurements to avoid disturbing the network or even improving the network at the connection point.	Matlab Simulink
FC	Fuel Cell Photovoltaic Wind Turbine	General regression neural network (GRNN) Radial basis function network-sliding mode (RBFNSM)	• To propose effective GRNN methods and RBFNSM to deal with various disturbances and system uncertainties such as various loading conditions and severe faults with a better transient response and more stability.	Matlab Simulink
PEMFC	Fuel Cell Solar Cell Battery	Coulomb counting method (CCM)	• To design power management strategies for a sustainable operation to achieve root mean square errors of 0.06℃ and 0.07 A based on the coulomb counting method (CCM).	SimPower System/ Matlab

Due to the growth in demand for batteries, the charging process of battery systems will need to be well managed through the optimization of controlled energy in managing the entire system. To resolve this issue, optimization control is introduced with FC power technology, PV, and WT. On the contrary, the implementation of FC power technology with the simultaneous generation of heat and power (FC-CHP), wind, and PV has shown a substantial improvement with the optimally coordinated scheduling of renewable energy resources and thermal units. In this respect, the optimization algorithm and artificial intelligent controller are useful techniques for the enhancement of DNs.

VII. CONCLUSION

This study had discussed the FC power technology in-depth, encompassing the chemical and electrical aspects of the FC. Different types of FCs available in the electrical power system and their working principles were deliberated, and this investigation was against DNs applications of the D-FACTS. The current and research challenges in the FCs and their solutions were also addressed. Different topologies of the power electronic converters used for FC applications were discussed. The issues of PQ and DNs connected to FC-based power systems were reviewed, and the deployment of Energy Storage Systems (ESS) was a crucial avenue for maximizing the energy efficiency of DNs, while the overall network performance could be enhanced by their optimal placement, sizing, and operation. This discussion summarised different fault diagnosis approaches for PEMFC, including approaches, method, category, and element. This study also examined the classification of DN-connection FC power technology studies, including power quality, connection, FC power technology type, simulation software, advantages, and overall efficiency of the system. Overall, optimization methods were able to provide maximum output power at a low cost with reliable maintenance. Finally, the PQ issues and power control were explored for the integration of FC power technology and DNs based on D-FACTS.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

M.M.K., contributed theoretical approaches and preparing the article; M.R.A., S.M.Z., A.A.A, and M.M.G. contributed to supervision; M.R.A., and S.M.Z contributed to article editing. All authors have read and agreed to the published version of the manuscript.

REFERENCES

[1] H. He, E. Dub, N. Zhanga, C. Kanga, and X. Wang, “Enhancing the power grid flexibility with battery energy storage

transportation and transmission switching," *Appl. Energy*, vol. 290, May 2021.

[2] G. Brunaccini, F. Sergi, D. Aloisio, N. Randazzo, M. Ferraro, and V. Antonucci, "Fuel cells hybrid systems for resilient microgrids," *Int. J. Hydrogen Energy*, vol. 44, no. 38, pp. 21162–21173, 2019.

[3] S. Koohi-Fayegh and M. A. Rosen, "A review of energy storage types, applications and recent developments," *J. Energy Storage*, vol. 27, Feb. 2020.

[4] V. Kannan, H. Xue, K. A. Raman, J. Chen, A. Fisher, and E. Birgersson, "Quantifying operating uncertainties of a PEMFC E Monte Carlo-machine learning based approach," *Renew. Energy*, vol. 158, pp. 343–359, May 2020.

[5] D. Wu, C. Peng, C. Yin, and H. Tang, "Review of system integration and control of proton exchange membrane fuel cells," *Electrochem. Energy Rev.*, vol. 3, pp. 466–505, May 2020.

[6] M. Tanrioven, T. Akfidan, and M. S. Alam, "Demonstration and assessment of dynamic performance of a hybrid power system based electric passenger cart," *Int. J. Hydrogen Energy*, vol. 44, no. 41, pp. 23348–23359, 2019.

[7] L. Xu, C. Liu, D. Paire, and F. Gao, "An observer-based switch open-circuit fault diagnosis of DC – DC converter for fuel cell application," *IEEE Trans. Ind. Appl.*, vol. 35, no. 3, pp. 2737–2763, 2020.

[8] M. Inc and O. Türksoy, "Review of fuel cells to grid interface : Configurations, technical challenges and trends," *J. Clean. Prod. J.*, vol. 213, pp. 1353–1370, Dec. 2019.

[9] F. Alvarez-Mendoza, P. Bacher, H. Madsen, and C. Angeles-Camacho, "Stochastic model of wind-fuel cell for a semi-dispatchable power generation," *Appl. Energy*, vol. 193, pp. 139–148, Feb. 2017.

[10] R. Kapoor, R. Gupta, L. H. Son, S. Jha, and R. Kumar, "Detection of power quality event using histogram of oriented gradients and support vector machine," *Meas. J. Int. Meas. Confed*., vol. 120, pp. 52–75, May 2018.

[11] N. Chettibi and A. Mellit, "Intelligent control strategy for a grid connected PV/SOFC/BESS energy generation system," *Energy*, vol. 147, pp. 239–262, Mar. 2018.

[12] S. Choudhury, P. Bhowmik, and P. K. Rout, "Economic load sharing in a D-STATCOM integrated islanded microgrid based on fuzzy logic and seeker optimization approach," *Sustain. Cities Soc*., vol. 37, pp. 57–69, Feb. 2018.

[13] Y. Han, G. Lv, and E. Mokaramian, "A review modeling of optimal location and sizing integrated M–FACTS with wind farm and fuel cell," *J. Clean. Prod.*, vol. 268, no. 20, pp.1-25, 2020.

[14] S. Soltani, M. Rashidinejad, and A. Abdollahi, "Balancing considering distributed energy resources," *IEEE Syst. J.*, vol. 12, no. 3, pp. 2866–2877, 2018.

[15] B. Singh and R. Kumar, "A comprehensive survey on enhancement ofsystem performances by using different types of FACTS controllers in power systems with static and realistic load models," *Energy Reports*, vol. 6, pp. 55–79, Nov. 2020.

[16] R. Lin, X. Xi, P. Wang, and B. Wu, "Review on hydrogen fuel cell condition monitoring and prediction methods," *Int. J. Hydrogen Energy*, vol. 44, no. 11, pp. 1–11, 2018.

[17] M. Inci and A. Caliskan, "Performance enhancement of energy extraction capability for fuel cell implementations with improved Cuckoo search algorithm," *Int. Journal Hydrog. Energy*, pp. 1–12, 2020.

[18] Y. Guo, X. Guo, H. Zhang, and S. Hou, "Energetic, exergetic and ecological analyses of a high-temperature proton exchange membrane fuel cell based on a phosphoric-acid-doped polybenzimidazole membrane," *Sustain. Energy Technol. Assessments*, vol. 38, pp. 1-11, Apr. 2020.

[19] J. C. Mayo-Maldonado, J. E. Valdez-Resendiz, V. M. Sanchez, J. C. Rosas-Caro, A. Claudio-Sanchez, and C. P. Freddy, "A novel PEMFC power conditioning system based on the interleaved high gain boost converter," *Int. J. Hydrogen Energy*, vol. 44, no. 24, pp. 12508–12514, 2019.

[20] K. H. Al-Hamed and I. Dincer, "A novel ammonia molten alkaline fuel cell based integrated powering system for clean rail transportation," *Energy*, vol. 201, no. 15. pp. 1-12, 2020.

[21] M. Ramezanizadeh, M. Alhuyi, M. Hossein, and L. Chen, "A review on the approaches applied for cooling fuel cells," *Int. J. Heat Mass Transf.*, vol. 139, pp. 517–525, May 2019.

[22] IEA, "Tracking Energy Integration 2020," 2020.

[23] A. Lysik, *et al*., "Silver coated cathode for molten carbonate fuel cells," *Int. J. Hydrogen Energy*, vol. 45, no. 38, pp. 19847–19857, 2020.

[24] A. M. Haghghi, M. Shamsaiee, S. G. Holagh, A. Chitsaz, and M. A. Rosen, "Thermodynamic, exergoeconomic, and environmental evaluation of a new multi-generation system driven by a molten carbonate fuel cell for production of cooling, heating, electricity, and freshwater," *Energy Convers. Manag.*, vol. 199, no. 1, pp. 1-15, 2019.

[25] U. M. Damo, M. L. Ferrari, A. Turan, and A. F. Massardo, "Solid oxide fuel cell hybrid system : A detailed review of an environmentally clean and ef fi cient source of energy," *Energy*, vol. 168, no. 1, pp. 235–246, 2019.

[26] M. Ali, N. Chitgar, O. A. Oyewunmi, and C. N. Markides, "Working-fluid selection and thermoeconomic optimisation of a combined cycle cogeneration dual-loop organic Rankine cycle (ORC) system for solid oxide fuel cell (SOFC) waste-heat recovery," *Appl. Energy*, vol. 261, no. 1. pp. 1-20, 2020.

[27] S. Chugh, C. Chaudhari, K. Sonkar, A. Sharma, G. S. Kapur, and S. S. V Ramakumar, "Experimental and modelling studies of low temperature PEMFC performance," *Int. J. Hydrogen Energy*, vol. 45, no. 15, pp. 8866–8874, 2020.

[28] K. Ou, W. Yuan, M. Choi, S. Yang, S. Jung, and Y. Kim, "Optimized power management based on adaptive-PMP algorithm for a stationary PEM fuel cell/battery hybrid system," *Int. J. Hydrogen Energy*, vol. 43, no. 32, pp. 15433–15444, 2018.

[29] S. Zhuo, S. Member, and A. Gaillard, "Extended state observer-based control of DC-DC converters for fuel cell application," *IEEE Trans. Power Electron.*, vol. 35, no. 9, pp. 9925–9934, 2020.

[30] K. Emami, H. Ariakia, and T. Fernando, "Estimation technique for grid connected solid oxide fuel cells," *IEEE Trans. Energy Convers.*, vol. 33, no. 1, pp. 96–105, 2018.

[31] F. Wang, T. Mamo, and X. Cheng, "Bi-directional long short-term memory recurrent neural network with attention for stack voltage degradation from proton exchange membrane fuel cells," *J. Power Sources*, vol. 461, no. 15. pp, 1-8, 2020.

[32] A. Aktaş and Y. Kırçiçek, "A novel optimal energy management strategy for offshore wind/marine current/battery/ultracapacitor hybrid renewable energy system," *Energy*, vol. 199, pp. 1–26, 2020.

[33] J. Shen, Z. Tu, and S. H. Chan, "Evaluation criterion of different flow field patterns in a proton exchange membrane fuel cell," *Energy Convers. Manag.*, vol. 213, no. 1. pp. 1-7, 2020.

[34] Z. Yuan, W. Wang, H. Wang, and A. Yildizbasi, "Developed coyote optimization algorithm and its application to optimal parameters estimation of PEMFC model," *Energy Reports*, vol. 6, pp. 1106–1117, Apr. 2020.

[35] Z. Galias and S. Member, "Probabilistic model for studying blackouts in power networks," *IEEE J. Emerg. Sel. Top. Circuits Syst.*, vol. 7, no. 2, pp. 218–227, 2017.

[36] Y. Li, W. Li, X. Shi, and X. Chen, "An efficient numerical method for computing eigenvalue sensitivity with respect to operational parameters of large-scale power systems," *Electr. Power Syst. Res.*, vol. 174, pp. 1-7, Sept. 2019.

[37] F. H. Gandoman, *et al.*, "Review of FACTS technologies and applications for power quality in smart grids with renewable energy systems," *Renew. Sustain. Energy Rev.*, vol. 82, pp. 502–514, Feb. 2018.

[38] S. Devassy and B. Singh, "Design and performance analysis of three-phase solar PV integrated UPQC," *IEEE Trans. on Industry Applications*, vol. 54, no. 1, pp. 73–81, Jan. 2018.

[39] M. Farhadi-kangarlu, E. Babaei, and F. Blaabjerg, "A comprehensive review of dynamic voltage restorers," *Electr. Power Energy Syst.*, vol. 92, pp. 136–155, Nov. 2017.

[40] J. A. L. Franklyn, B. Moreno, J. E. Palacios, and J. Posada, "Implementation and evaluation of a new DVR topology with AC

link for series compensation," *Electr. Power Syst. Res.*, vol. 181, pp. 1-11, Apr. 2020.

[41] M. I. Mosaad and H. S. Ramadan, "Power quality enhancement of grid connected fuel cell using evolutionary computing techniques," *Int. J. Hydrogen Energy*, pp. 1–15, 2018.

[42] C. K. Sundarabalan and K. Selvi, "Real coded GA optimized fuzzy logic controlled PEMFC based dynamic voltage restorer for reparation of voltage disturbances in distribution system," *Int. J. Hydrogen Energy*, vol. 42, no. 1, pp. 603–613, 2017.

[43] T. A. Sivakumar and M. M. Linda, "Improving the dynamic performance of grid connected wind farms using modern UPFC," *Microprocess. Microsyst.*, vol. 74, pp, 1-36, Apr. 2020.

[44] I. M. A. Mehouachi, M. Abbes, and S. Chebbi, "Design of a high power D-STATCOM based on the isolated dual-converter topology," *Electr. Power Energy Syst.*, vol. 106, pp. 401–410, Mar. 2019.

[45] A. Jalilian, S. B. Naderi, M. Negnevitsky, and M. T. Hagh, "Controllable DC-link bridge-type FCL for low voltage ride-through enhancement of converter interfaced DG systems," *Int. J. Electr. Power Energy Syst.*, vol. 95, pp. 653–663, Feb. 2018.

[46] D. Peng, M. Huang, J. Li, and J. Sun, "Large-signal stability criterion for parallel-connected DC-DC converters with current source equivalence," *IEEE Trans. Circuits Syst. II Express Briefs*, vol. 66, no. 12, pp. 2037–2041, 2019.

[47] K. Sabanci and S. Balci, "Development of an expression for the output voltage ripple of the DC-DC boost converter circuits by using particle swarm optimization algorithm," *Measurement*, vol. 158, no. 1. pp. 1-9, 2020.

[48] H. Lee, B. Kang, W. Kim, and S. Yoon, "Reduction of input voltage/current ripples of boost half-bridge DC-DC converter for photovoltaic micro-inverter," *Sol. Energy*, vol. 188, pp. 1084–1101, Aug. 2019.

[49] L. Sun, Y. Jin, L. Pan, J. Shen, and K. Y. Lee, "Efficiency analysis and control of a grid-connected PEM fuel cell in distributed generation," *Energy Convers. Manag.*, vol. 195, pp. 587–596, Sept. 2019.

[50] A. L. Nascimento, I. Yahyaoui, and F. Tadeo, "Modeling and experimental validation of a PEM fuel cell in steady and transient regimes using PSCAD/EMTDC software," *Int. J. Hydrogen Energy*, vol. 45, no. 55, pp. 1–12, 2020.

[51] G. San, W. Zhang, X. Guo, C. Hua, H. Xin, and F. Blaabjerg, "Large-disturbance stability for power-converter-dominated microgrid: A review," *Renew. Sustain. Energy Rev.*, vol. 127, pp. 1-12, July 2020.

[52] R. N. Beres, X. Wang, F. Blaabjerg, M. Liserre, and C. L. Bak, "Optimal design of high-order passive-damped filters for grid-connected applications," *IEEE Trans. Power Electron.*, vol. 31, no. 3, pp. 2083–2098, 2016.

[53] S. Jiang, Y. Liu, W. Liang, J. Peng, and H. Jiang, "Active EMI filter design with a modified LCL-LC filter for single-phase grid-connected inverter in vehicle-to-grid application," *IEEE Trans. Veh. Technol.*, vol. 68, no. 11, pp. 10639–10650, 2019.

[54] D. Li, K. Yang, Z. Q. Zhu, and Y. Qin, "A novel series power quality controller with reduced passive power filter," *IEEE Trans. Ind. Electron.*, vol. 64, no. 1, pp. 773–784, 2017.

[55] N. Rasekh and M. Hosseinpour, "LCL filter design and robust converter side current feedback control for grid-connected proton exchange membrane fuel cell system," *Int. J. Hydrogen Energy*, vol. 45, no. 23, pp. 13055–13067, 2020.

[56] I. D. Melo, J. L. R. Pereira, A. M. Variz, and P. F. Ribeiro, "Allocation and sizing of single tuned passive filters in three-phase distribution systems for power quality improvement," *Electr. Power Syst. Res.*, vol. 180, pp.1-12, Mar. 2020.

[57] A. Kouchaki and M. Nymand, "Analytical design of passive LCL filter for three-phase two-level power factor correction rectifiers," *IEEE Trans. Power Electron.*, vol. 33, no. 4, pp. 3012–3022, 2018.

[58] A. Karadeniz and M. E. Balci, "Comparative evaluation of common passive filter types regarding maximization of transformer's loading capability under non-sinusoidal conditions," *Electr. Power Syst. Res.*, vol. 158, pp. 324–334, Jan. 2018.

[59] A. Akgündo, I. Öz, and C. P. Uzuno, "Signal quality based power output prediction of a real distribution transformer station using M5P model tree," *Electr. Power Syst. Res.*, vol. 177, #106003, 2019.

[60] A. Patel, H. D. Mathur, and S. Bhanot, "Electrical power and energy systems an improved control method for unified power quality conditioner with unbalanced load," *Electr. Power Energy Syst.*, vol. 100, pp. 129–138, Feb. 2018.

[61] M. Erdogan and M. K. Ekerb, "Analysis of lightning impulse voltage distribution for a dry-type transformer using three different winding types," *Electr. Power Syst. Res.*, vol. 188, pp. 1-10, Nov. 2020.

[62] M. Inci, "Interline fuel cell (I-FC) system with dual-functional control capability," *Int. J. Hydrogen Energy*, vol. 45, no. 2, pp. 891–903, 2020.

[63] M. C. Argyrou, P. Christodoulides, and S. A. Kalogirou, "Energy storage for electricity generation and related processes : Technologies appraisal and grid scale applications," *Renew. Sustain. Energy Rev.*, vol. 94, pp. 804–821, Jun. 2018.

[64] Z. Wu, *et al.*, "Study of MW-scale biogas-fed SOFC-WGS-TSA-PEMFC hybrid power technology as distributed energy system: Thermodynamic, exergetic and thermo-economic evaluation," *Int. J. Hydrogen Energy*, vol. 46, no. 19, pp. 1-16, 2020.

[65] T. H. Kwan, *et al.*, "Comprehensive review of integrating fuel cells to other energy systems for enhanced performance and enabling polygeneration," *Renew. Sustain. Energy Rev.*, vol. 128, pp. 1-17, Aug. 2020.

[66] H. Lu, J. Chen, C. Yan, and H. Liu, "On-line fault diagnosis for proton exchange membrane fuel cells based on a fast electrochemical impedance spectroscopy measurement," *J. Power Sources*, vol. 430, pp. 233–243, May 2019.

[67] J. Chen, Q. Song, and S. Yin, "On the decentralized energy management strategy for the all-electric APU of future more electric aircraft composed of multiple fuel cells and supercapacitors," *IEEE Trans. Ind. Electron.*, vol. 67, no. 8, pp. 6183–6194, 2020.

[68] Z. X. Zheng, X. Y. Xiao, X. Y. Chen, C. J. Huang, L. H. Zhao, and C. S. Li, "Performance evaluation of a MW-class SMES-BES DVR system for mitigation of voltage quality disturbances," *IEEE Trans. Ind. Appl.*, vol. 54, no. 4, pp. 3090–3099, Jul. 2018.

[69] S. Hajiaghasi, A. Salemnia, and M. Hamzeh, "Hybrid energy storage system for microgrids applications: A review," *J. Energy Storage*, vol. 21, pp. 543–570, Feb. 2019.

[70] S. M. Mousavi, F. Faraji, A. Majazi, and K. Al-Haddad, "A comprehensive review of flywheel energy storage system technology," *Renew. Sustain. Energy Rev.*, vol. 67, pp. 477–490, Jan. 2017.

[71] C. K. Das, O. Bass, G. Kothapalli, T. S. Mahmoud, and D. Habibi, "Overview of energy storage systems in distribution networks : Placement, sizing, operation, and power quality," *Renew. Sustain. Energy Rev.*, vol. 91, pp. 1205–1230, Mar. 2018.

[72] A. Colmenar-santos, A. Linares-mena, J. Fernández, and D. Borge-diez, "Energy-efficient three-phase bidirectional converter for grid-connected storage applications," *Energy Convers. Manag.*, vol. 127, pp. 599–611, Sept. 2016.

[73] M. A. Amini and A. Jalilian, "Modelling and improvement of open-UPQC performance in voltage sag compensation by contribution of shunt units," *Electr. Power Syst. Res*., vol. 187, pp. 1-12, Oct. 2020.

[74] E. A. Nagata, *et al.*, "Real-time voltage sag detection and classification for power quality diagnostics," *Meas. J. Int. Meas. Confed.*, vol. 164, pp. 1-50, Nov. 2020.

[75] G. S. Elbasuony, S. H. E. Abdel Aleem, A. M. Ibrahim, and A. M. Sharaf, "A unified index for power quality evaluation in distributed generation systems," *Energy*, vol. 149, pp. 607–622, Apr.2018.

[76] T. Thomas and P. A. Michael, "Mitigation techniques of power quality issues from materials," *Mater. Today Proc.*, vol. 33, no. 3, pp. 1701-1705, 2020.

[77] J. Kaushal and P. Basak, "Power quality control based on voltage sag/swell, unbalancing, frequency, THD and power factor using

artificial neural network in PV integrated AC microgrid," *Sustain. Energy, Grids Networks*, vol. 23, pp. 1-52, Sep. 2020.

[78] Y. Wang, H. Luo, and X. Y. Xiao, "Voltage sag frequency kernel density estimation method considering protection characteristics and fault distribution," *Electr. Power Syst. Res.*, vol. 170, pp. 128–137, May 2019.

[79] A. Sharma, B. S. Rajpurohit, and S. N. Singh, "A review on economics of power quality: Impact, assessment and mitigation," *Renew. Sustain. Energy Rev.*, vol. 88, pp. 363–372, May 2018.

[80] D. Thomas, G. D. Hoop, O. Deblecker, K. N. Genikomsakis, and C. S. Ioakimidis, "An integrated tool for optimal energy scheduling and power quality improvement of a microgrid under multiple demand response schemes," *Appl. Energy*, vol. 260, pp. 1-16, Feb. 2020.

[81] H. M. A. Ahmed, A. S. A. Awad, M. H. Ahmed, and M. M. A. Salama, "Mitigating voltage-sag and voltage-deviation problems in distribution networks using battery energy storage systems," *Electr. Power Syst. Res.*, vol. 184, pp. 1-11, July 2020.

[82] Y. Mohammadi, M. H. Moradi, and R. Chouhy Leborgne, "Employing instantaneous positive sequence symmetrical components for voltage sag source relative location," *Electr. Power Syst. Res.*, vol. 151, pp. 186–196, Oct. 2017.

[83] Y. Hoon, M. Amran, and M. Radzi, "Control algorithms of shunt active power filter for harmonics mitigation : A review," *Energies*, vol. 10, no. 12, pp. 1–29, 2017.

[84] M. Büyük, M. İnci, A. Tan, and M. Tümay, "Improved instantaneous power theory based current harmonic extraction for unbalanced electrical grid conditions," *Electr. Power Syst. Res.*, vol. 177, pp. 1-12, Dec. 2019.

[85] A. Benmouna, M. Becherif, D. Depernet, and F. Gustin, "Fault diagnosis methods for proton exchange membrane fuel cell system," *Int. J. Hydrogen Energy*, vol. 42, no. 2, pp. 1534–1543, 2017.

[86] H. Yuan, H. Dai, X. Wei, and P. Ming, "Model-based observers for internal states estimation and control of proton exchange membrane fuel cell system : A review," *J. Power Sources*, vol. 468, pp. 1-17, Aug. 2020.

[87] N. R. V Madhusudhan and A. J. Laxmi, "RFLSA control scheme for power quality disturbances mitigation in DSTATCOM with n-level inverter connected power systems," *Energy Syst.*, vol. 11, pp. 753–778, Mar. 2019.

[88] X. Chen, W. Li, G. Gong, Z. Wan, and Z. Tu, "Parametric analysis and optimization of PEMFC system for maximum power and efficiency using MOEA/D," *Appl. Therm. Eng.*, vol. 121, pp. 400–409, March. 2017.

[89] H. Yan, *et al.*, "Techno-economic evaluation and technology roadmap of the MWE-scale SOFC-PEMFC hybrid fuel cell system for clean power generation," *J. Clean. Prod.*, vol. 255, pp. 1-19, May 2020.

[90] H. Rezk, A. M. Nassef, M. Ali, A. Hai, and A. Fathy, "Comparison among various energy management strategies for reducing hydrogen consumption in a hybrid fuel cell/ supercapacitor/battery system," *Int. J. Hydrogen Energy*, vol. 46, no. 8, pp. 1–17, 2019.

[91] M. Bornapour, R. Hooshmand, and M. Parastegari, "An efficient scenario-based stochastic programming method for optimal scheduling of CHP-PEMFC, WT, PV and hydrogen storage units in microgrids," *Renew. Energy*, vol. 130, pp. 1049-1066, Jan. 2019.

[92] Y. Guo, H. Chen, and F. Wang, "The development of a hybrid PEMFC power system," *Int. J. Hydrogen Energy*, vol. 40, no. 13, pp. 4630–4640, 2015.

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