A Review of the Optimization and Control Strategies for Fuel Cell Power Plants in a Microgrid Environment

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ABSTRACT
In the recent years, microgrid has been receiving increasing attention as one typical structure in smart grid frameworks. Fuel cells (FC) among other most relevant renewable energy sources have been studied as viable energy alternatives, in terms of them being cleaner and more efficient. Since the academic community and industry started giving attention to FCs, there have been many uplifting achievements in making FC technology more relevant as an energy source and as a result, FCs are increasingly penetrating different fields. The application of FCs into microgrids among other applications has proved advantageous on the performance improvement of microgrids while also inspiring hydrogen energy usage. While this combination of the two technologies carries advantages, there are many challenges that are faced in the process lying on multiple domains. The optimization and control of this combination, and the two technologies individually has been studied greatly in recent years. This paper presents the review of the control of FC based microgrids, where FCs in microgrid environment are looked at after recalling the knowledge background of FCs, the active disturbance rejection controller (ADRC) as a possible controller for some strategies, and the hybrid system and control mechanisms.

INDEX TERMS
Active disturbance rejection control, control systems, fuel cells, optimization, solid oxide fuel cells, microgrid.

ABBREVIATION
AC Alternating Current
ADRC Active Disturbance Rejection control
BFT Boiler Follows Turbine
BOP Balance of Plant
CCS Coordinated Control Strategy
CFD Computational Fluid Dynamics
CHP Combined Heat and Power
CL Catalyst Layers
CP Collector Plates
DC Direct Current
dG Distributed Generation
EM Energy Management
ESO Extended State Observer
FC Fuel cell
FCFI Fuel Cell Follows Inverter
FOA Feasible Operating Area
GDL Gas Diffusion Layers

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I. INTRODUCTION

During the last decades, the development addressing the concerns on energy shortage and security, and the environmental sustainability has proved to be one of the responsible factors critical for the increasing interests in microgrid systems worldwide [1], [2]. Considering how high the rate at which the renewable energy sources penetrate the world in an unorganized manner, numerous technical and operational shortcomings may be encountered, i.e., degraded voltage profiles, low frequency reserves, and overcrowding in power line [3]. Through a microgrid system, there exists a solution that is both favorable and efficient which is achieved by linking various distributed renewable energy sources, energy storage systems, and interlinked loads acting as one manageable unit concerning the power grid [4]. As stated by the USA department of energy, a microgrid is said to be a self-sufficient energy system containing different kinds of distributed energy resources and grouped interlinked loads. It operates as a geographic footprint [4]. The introduction of smart grid addresses most challenges faced by the power grid by ensuring that microgrids are designed and controlled properly where a modernly advanced, high quality, reliable, environmentally friendly, safe, and efficient power can be supplied, which can strengthen the grid dependability and complement the power grid in supplying power to isolated areas [5].

It is now essential to develop more expanded resources of electrical energy for microgrid systems in addition to the current sources namely: solar energy, hydro energy, wind energy, diesel, biomass, and battery technologies. Interestingly, FCs have been increasingly considered as a formidable addition with growing popularity in microgrids during the recent years [2], [6]. This is due to their high operating efficiency and their ability to produce clean energy. FCs are devices that convert the chemical energy of fuel in gas form (usually hydrogen) into electricity, heat, and byproduct (generally water).

Several kinds of FCs exist and are looked at in this paper, but among these types, the proton exchange membrane fuel cell (PEMFC) has had the most widespread use and also received market recognition for compact applications, vehicular applications, as well as residential applications [7], [8]. There has also been a realization of notable research accomplishments in the analysis of performance, control, and modelling of PEMFCs [9]–[11]. The major challenge, however, is that PEMFCs have low efficiency and they depend highly on the fuel input being pure hydrogen which results in them being rarely considered as the first choice for applications involving stationary power. Solid oxide fuel cells (SOFC) are the kind of FCs that has been under intensive research because of its high operating temperature which has made it more appealing to the distributed generation (DG) technology usage where electricity is generated within the vicinity of the load site. Authors of [12]–[15] reported on such SOFC power plants where, [16] reported on the application of SOFC in distributed power generation. Developing this DG technology has major drawbacks, which are the high installation costs, difficulty finding a solution that will result in an improved overall efficiency and finding the approach that will successfully enhance the durability to above 40 000h for stationary power applications. Researchers studied how feasible employing FC power plant for fixed power applications is by reporting in [13], on an integrated SOFC plant dynamic model for power systems simulation, [17] looked at the development of models for analyzing the load following performance of microturbines and FCs, the transient modeling and simulation of a tabular SOFC was demonstrated in [18], and the dynamic and transient analysis of power distribution systems with FC reported on in [19]. Ensuring a successful operation of SOFC in a power system would require assessing if it can track the load [19], and how it impacts the power quality amongst other problems. Important studies deal with finding a credible SOFC plant model, which are detailed in the paper [13], [19].

In spite of the numerous advantages, there exists several key challenges when FCs are integrated into microgrid systems that must first be resolved before they can be used as capable and practical substitutes for current methods. Growing attention from a different viewpoint has therefore been given to overcome the FC’s shortcomings. These shortcomings being: the low durability, and the high costs associated with FCs [20]. Furthermore, issues relating to the system control, hybridization, and energy management (EM) have been signalled, as the prerequisites on resiliency, reliability, and safety of the microgrids tends to be more critical [21].

Traditionally, an understanding is presented in review papers by summarizing the current knowledge of the topic, e.g. most FC control strategies and microgrid review papers discussed some past researches on control strategies and their integration to microgrids where output power, voltage, fuel utilization, FC modelling [22], [23], load following, and real-time optimization control methods were studied, controllers including ADRC [24], [25] among others, and applications of FCs in microgrids [2], [6], [16], [26] were also explored on. However, these needed to be more comprehensive to ensure inclusivity.

- The research papers reviewed in this paper have not been covered in-depth in previous review papers to provide an all-inclusive view.
- Hence, this article includes various aspects such as fuel cells, power generation using them, their modes of operation, optimization, control strategies in a microgrid environment encompassing numerous facets such as FC grid connected system with active power generation and reactive power compensation features [27], experimental real-time optimization of a SOFC stack via constraint adaptation [28], coordinated control strategies for FC power plant in a microgrid [29], a cogeneration system based on SOFC and PEMFC with hybrid storage for off-grid applications [30]–[33] and showing a comparative analysis along with current challenges and recommendations for future research studies.
Therefore, the information presented in this article would contribute greatly to the interested researchers in gaining the understandings in a greater way of recent developments in FC control strategies and microgrid environments.

The outline of the paper is as follows: Section II Focuses on analyzing the theoretical background of FCs and a special attention given to SOFCs, and PEMFCs; Section III concentrates on the FCs in microgrid environment, applications of FCs in microgrid system, and the comparison of those applications; Section IV presents the theory on Active Disturbance Rejection Control (ADRC); Section V concentrates on FCs optimization and control strategies, and also focus on hybrid systems and control mechanisms; Section VI discusses and compares the control strategies and also look at common current challenges and recommendations. Section VII concludes the review paper.

II. BACKGROUND OF FCs

A. FCs HISTORICAL DEVELOPMENTS AND SYSTEM DESCRIPTION

This section presents the FC background with the system description included in the content. As described already, a FC is an electrochemical device. Since the production of hydrogen can be achieved from various sources like biomass-based fuels, renewable sources, and natural gas, using FCs in large scale can minimize the use of fossil fuels and promote the development of renewable power [34]. In numerous applications, FCs possess the ability to mitigate the greenhouse emissions [6]. As such, both the academicians and industry have given recognition to this development, thus realizing some inspiring achievements in FC technology and hence, they have been tied to different fields over the years. The constant supply of the fuel and oxidant is the key to continuously generate energy. There are four major components making FC technologies, namely cathode, anode, electrolyte, and the external circuit. Figure 1 shows these components [2].

The hydrogen fuel undergoes oxidation at the anode and electrons and protons are produced, while oxygen undergoes reduction to form oxides at the cathode, and water and heat are developed [35], [36]. The protons or oxide ions pass through the electrolyte, and the electrons travel on the external circuit to generate an output of direct current (DC). The excess fuel may be re-used by the FC by being fed back through the outlet to the fuel tank as shown in Figure 1.

The FC’s anode reaction, cathode reaction, and the overall reaction are represented by Equations (1) - (3) respectively [37].

\[ 2H_2 \rightarrow 4H^+ + 4e^- \]  
\[ O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \]  
\[ 2H_2 + O_2 \rightarrow 2H_2O + \cdot \cdot \cdot \text{Energy (Electrical + Thermal)} \]

There are limitations to the quantity of the current delivered by FCs which are the results of a minor overlapping space in between the electrodes, electrolyte, and the reactants [2]. The distance between the anode and cathode is another challenge. Therefore, to get the maximum contact area and efficiency of cells, an integration between a thin layer of electrodes and flat porous electrodes is required [36]. To get higher voltage output from FCs, a FC stack made of a series arrangement of cells is needed since facts has it that a single cell can produce an output voltage of as low as 1 V [36].

The arrangement of the FC power plant contains the stack, the balance of plant (BOP), inverter, and if necessary, a fuel reformer [38]. The BOP means the other parts that make up the FC system except the generating component. There exist some similarities between FC systems and battery systems, these basically are their characteristics to convert chemical energy to electrical energy which is the process of electricity generation in such systems. They are like engines also by being capable of continuously generating electricity while using up fuel. However, FCs differ from battery technologies by not requiring to be charged, and they also differ from engines by operating quietly [39]. FCs operations are emissions-free and efficient as compared to engines and battery technologies; although FCs are associated with some form of thermodynamic processes, they are different from thermal engines since thermal engines are limited by Carnot efficiency and FCs are not [39], [40].

There are numerous FC types available that have been studied in recent years which are distinguishable mainly by the electrolyte used. Table 1 [41] shows a summary of basic information about these types. Among these types [41], SOFC and PEMFC are looked at in depth in this review paper. SOFCs possesses high operating temperature, thus they are used mostly in stationary power plant applications due to their ability to reform fuel into hydrogen internally, leading to significant cost savings, while PEMFCs are studied mostly in past research and literature relating to stationary power applications and have had the most exposure among other FCs [7], [19].

B. SOFC

SOFC gained a resurgence of interest in the early 1960s after its development was hindered in 1937 where Baur [42] concluded after numerous failed experiments with various liquid electrolyte types that the SOFC had to be completely dry. Serious material problems resulted from the high temperature and the reducing nature of the fuel gas in some of the
TABLE 1. Types of FCs [41].

| FC Types             | Mobile ion | Operating Temperature | Applications and notes            |
|----------------------|------------|-----------------------|-----------------------------------|
| Alkaline - AFC       | OH⁻        | 50 – 200 °C           | Applicable in space vehicles e.g., Apollo Shuttle. |
| PEMFC                | H⁺         | 50 – 100 °C           | Used and applicable in vehicles and mobile, but also for CHP systems with lower power. |
| Phosphoric Acid - PAFC | H⁺        | 200 °C                | Large number of 200 kW CHP systems in use. |
| Molten Carbonate - MCFC | CO₃²⁻     | 650 °C                | Usually used in medium - large scale CHP systems of up to MW capacity. |
| SOFC                 | O²⁻        | 500 – 1000 °C         | Applicable in all sizes CHP systems, 2 kW to multi-MW. |

experiments conducted by Baur where they were unsuccessful in their search for suitable materials [42]. Advanced ceramic materials were prepared and produced in the 1960s leading to interest in SOFCs being renewed [36]. Numerous patents were then filed for the SOFC technology development. At the time, one of the major challenges was the poor efficiency of SOFCs, where they had high losses due to their internal resistance caused by thick electrolyte layers [36]. Through the 1970s, advances were made continuously in preparing and producing methods leading to thinner electrolytes being developed successfully, which resulted in a remarkable performance improvement. Several SOFC designs have been investigated including tubular and planar designs in the last few decades which resulted in the FC technology gaining popularity among renewable energy sources and received attention from both the academia and industry.

The SOFC is also called ceramic FC because it has a solid ceramic electrolyte which is a metallic oxide. SOFC like all other FCs has fundamental components where in the cathode, the reduction of oxygen into ions occurs where these ions travel under electrical load to the anode through the solid electrolyte. In the anode, these ions react with fuel and produce water, electricity, and heat [36]. This is illustrated in the SOFC schematic diagram in Figure 2 [43].

Despite the fact that for anode reactions pure hydrogen gas is required, light hydrocarbons like natural gas are allowed to be internally reformed into hydrogen (H₂) because of the high operating temperature of the SOFC [42], this also leads to a large cost saving as an added advantage.

In the center of the SOFC study, a credible model with moderate complexity is required. Earlier in [44], a model was proposed which included both thermal and electrochemical characteristics during transient response. The model, nevertheless, was too difficult for control design and analysis due to its complex features. Furthermore, the cell’s fuel input was assumed to be a constant, which led to quite a limited appropriate range of operation around the symbolic condition. Later, a simpler model of SOFC that omitted the thermal aspects was proposed [13]. This model was said to be reasonable because it was shown in [19] that on short-time response the thermal characteristics have little influence, therefore in transient simulation they can be neglected. The model proposed in [13] was then modified further in [17] now including the dynamics of the fuel processor, as illustrated in Figure 3. This model has since then become the benchmark model widely used and popular for control researches; [45] about the analysis of the control and operation of a SOFC power plant in an isolated system, [46] exploring the control strategy of a SOFC power plant in a grid-connected system, [47] data-driven predictive control for SOFCs, [48] predictive control of SOFCs using fuzzy Hammerstein models, and [49] in constrained model predictive control of a SOFC based on genetic optimization, thus proving its feasibility in system level simulations.

C. PEMFC

The PEMFC among other FC types has been given much attention in studies and in the industry due to it being simple, viable, able to start up quick, and possessing a wide range of applications.
of power [50], [51]. It also is one of the FCs that have been studied the most in the literature [6].

Figure 4 shows the fundamental principle of operation of PEMFC. The description of the components as shown in the diagram is as follows [6], [7], [41]:

- Membrane. This is the polymer membrane functioning as the FC’s heart. To gases it is an impermeable membrane while able to conduct protons [6], [53].
- Catalyst layers (CL). These are the two layers containing catalyst particles located on both the left and right sides of the membrane.
- Gas diffusion layers (GDL). These are two sheets of layers covering both the polymer membrane and the CLs. One of their functions is to allow the reactant gases and product water to disperse [6]. Furthermore, GDLs also operate as the thermal conducting mediums and the electric conducting electrodes. Combining the GDLs, CLs, and polymer membrane together forms the membrane electrode assembly (MEA).
- Collector plates (CP). They are situated on either one of the two ends / outermost sides of the PEMFC. The CPs house the gas flow channels (GFCs) as shown in the figure. They can act as the electrical and thermal conductors as well as provide FCs with structural support.

As is known, continuously feeding hydrogen and air into the anode and cathode sides, respectively, is required for an operational FC [7], [50]. Electrochemical reactions take place at the top of the CLs. Hydrogen is oxidized on the anode side with equation:

$$H_2 \rightarrow 2H^+ + 2e^- \quad (7)$$

The positive ions pass through the membrane and the negative ions pass through the CLs, GDLs, and the external circuit and back to the cathode side after performing electrical work [41]. This results in the reduction of oxygen on the cathode side with equation:

$$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (8)$$

Combining the two reactions from the anode side and cathode side, the overall reaction is:

$$\frac{1}{2} O_2 + H_2 \rightarrow H_2O \quad (9)$$

With the electrochemical effect and heat, the water generated as the by-product is dismissed together with air in excess from the cathode side [7], [51].

The maximum electricity generated by a FC resembles Gibbs free energy [6]. Gibbs free energy is said to be the energy used to perform external work, disregarding any work the change in pressure and or volume does. In a FC, the external work involves moving electrons around the external circuit [6] In the reaction (9), let the difference between the reactants and products be $\Delta G$ (measured in eV for one mole of water), the corresponding FC’s theoretical voltage is

$$E = \frac{-\Delta G}{2F} \quad (10)$$

where $F$ denotes the Faraday’s constant. The approximated result of this voltage is around 1.2 V for FC operations less than 100°C [41], but the voltage value is usually less when using a practical FC [7].

As shown in Figure 4, factors like crossover of the reactants causes the distance between the ideal voltage output and the real open circuit voltage. In [6], the polarization curve characterizing the voltage and current relations ship is shown. This curve summarizes the three factors impacting the voltage losses namely the activation losses, ohmic losses, and concentration losses [41], [53].

An important part of the FC that measures its performance is the current density [54]. Current density is the cell output current per active MEA area [54], [55]. In a perfect (reversible) FC, the cell voltage does not depend on the current drawn. Realistically, it is not possible to realize the reversible cell voltage because during the FC operation a lot of irreversibilities emerge [55]. Overvoltage is the distinction between the true cell voltage of a given current density and reaction’s reversible cell voltage [56]. Below are notable overvoltage sources in a FC and their region of polarization are indicated in the current density-voltage polarization curve shown in Figure 5 [6], [55], [57]:

- Mixed potential at electrodes – these arise after inevitable exploitative reactions that results in reduced equilibrium electrode potential. Mixed potential is essentially caused by the fuel crossing over through the electrolyte membrane [55].
- Activation losses – Mainly appear as a result of kinetics at the electrodes. These limitations are often effective at low current densities ($\sim 1$ to 100 mA/cm$^2$) [55], [57].
III. FCs IN MICROGRID ENVIRONMENT

The application of microgrid technologies in electrical systems can be categorized into two: namely, grid connected and grid-independent systems [58]. Understanding that there is more than just a FC stack in a FC power plant is very essential, regardless of whether the FC technology is used in grid-connected or grid-independent environments. This is because supplying reactants (fuel and oxidant) constantly is very important in achieving continuous electrical power production [2], [59]. Therefore, the interest of this section is the connection between FC stack and microgrid. The reactants must meet at a prearranged impurity level ahead of being used to operate the FCs. Therefore, the structure of the FC power plant contains components like fuel processing, electrolyte management, oxidant conditioning, and heat energy management unit, which includes the unit used for reaction product removal, etc. [58].

A detailed schematic of these components was illustrated in [59], but for simplicity in the purpose of this section, a FC microgrid system shown in Figure 6 [2] is used. For illustration purposes, this schematic corresponds with the basic electrical principles and indicate the additional subsystems used in energy processing between the FC stack and the users.

The FC stack produces the output of DC which is supplied to the load. The load is basically the users within the residential, commercial, and industrial premises and most of the appliances of these users are powered using alternating current (AC). Thus, a need for a power conditioning unit (PCU) exists. Normally an inverter also referred to as the DC-AC converter converts the FC stack yield from DC to AC power. For power conditioning purposes, FCs also employ DC-DC converters on top of inverters [60]. The inverter as a power electronic device, has a high efficiency of around 96% for power generation systems rated at MW level [59]. Also, there is waste heat generated at the FC power unit. This energy is sometimes correlated by arranging the FC’s heat exchangers in a certain way to increase both the efficiency and the performance of the system. This waste heat is sometimes also used as an input for combined heat and power (CHP) application or bottoming cycles in some FC technologies for additional electrical power generation [61], [38]. CHP application has added advantages, one being enhancing the FC’s efficiency up to 85% or even higher and the other being the ability to harness the waste thermal energy for household usages especially in heating of water and space, processing food, drying, and preservation, and raising of steam applicable in industries [59], [62].

Types of fuels in FC system are divided into two, the primary and the secondary fuels. The former includes these among other examples; natural gas, methanol, solid waste, heavy oils, low-sulfur extract, coal, biomass, naphtha, etc., while there is only hydrogen and carbon monoxide on the secondary fuels [59]. It is necessary to convert between primary and secondary fuels because the secondary fuels are said to be more electrochemically functional than the primary fuels in the arrangements of FCs [62]. Therefore, this conversion between primary to secondary fuels is done by the FC processor and usually accounts for one third of the weight and capital cost of the plant, especially the hydrocarbon-based plants [59].

The power output, efficiency, heat utilization, water balance, quick start-up, weight, size, long idleness, and supply of fuel are precise requirements for the operation and management of FC technologies [60]. Nonetheless, the major market drivers for applications of power and automobiles are realizing enhanced efficiency and mitigated emissions. The FCs employed in automobiles frameworks are expected to possess an operating lifespan of about 3000 to 5000 hours (not more than a year) while about 40 000 to 80 000 hours (between 5 to 10 years) of operating lifespan is expected from those in stationary applications [38]. The application of...
FCs for stationary purposes is preferred and have significant business and market opportunities because of their longer expected operating lifespan.

The following are applications of FCs in microgrid environments.

- Grid-connected [63].
- Grid-parallel [64].
- Stand-alone power [65].
- Emergency or backup power [66].
- DC microgrid [67].

A. APPLICATIONS OF FCs IN MICROGRID ENVIRONMENTS

1) GRID-CONNECTED

In this application, the energy flows in three unique ways; from the power grid to the users’ load, from the FC microgrid to the users’ load, and from the FC microgrid to the power grid [26], [63], [68]. To meet the maximum electricity demand by the user, the microgrid framework can be planned as a steady energy source by making use of a load-following strategy. In this scenario, the microgrid excess electricity produced may be sold to the power grid. The user in this case may receive energy from two energy suppliers namely the utility grid and the microgrid. The act of selling the excess energy from microgrid to the electrical grid is economical as this results in the electricity bill being reduced from the utility [64].

Figure 7 shows the schematic of a FC’s grid-connected application. As seen on the diagram, both the heat generated and the electric power from the grid supply energy to the total load [2], [26]. From the diagram, the energy meter represented by symbol M is the component used to measure the imported and exported energy to the utility grid. The design of the microgrid framework in Figure 7 assures that both the FC system and the power grid meet the total load required by an average household. Heavy-current load, small or average loads like lighting, TVs, DVD player, etc., and the inductive load all form part of the total load [26]. Linking the electrical system and the electricity grid depending on the configuration and capacity has become a normal practice [58]. A power converter can be used for domestic applications or transformer for heavy applications as this link [2], [26].

2) GRID-PARALLEL

For this application, the purchase of electricity from the power grid to satisfy the load demand is allowed when necessary; however, it is not allowed for the FC microgrid to sell or export any excess energy to the power grid [2]. Therefore, there are only two directions in which energy flows. Balancing the demand is how the microgrid is normally designed, but energy could still be brought in, in case of an unexpected increase in energy demand arrives [64]. It is expected that the energy demand may increase as they can climb the energy ladder [69]. Figure 8 illustrates the grid-parallel application. It is to be noted that a battery system also known as auxiliary power source is omitted in the diagram because the grid is already present and can also provide the start-up requirements.

3) STAND-ALONE POWER

Unlike the previous two applications, there is no interaction between the electrical grid and the users’ load in this application, and there is also no electrical association between the microgrid and the utility grid [70]. Therefore, the power system energy flow from on-site to the users’ load is the only one available. The local power system could range from one source, a FC technology-based stand-alone power system, to a hybrid system combining several energy sources including FCs, solar PV, battery, biomass, diesel generator, microturbines, etc. In [65], the concept of a remote hybrid electrification system is detailed.

Figure 9 - Figure 11 were designed in [2] to illustrate various configurations with other sources of stand-alone power systems based on FCs.

A one-source system based on a FC is shown in Figure 9, while Figure 10 shows hybrid systems containing FCs and PV, and Figure 11 illustrates FCs and Diesel generator [2], [6]. In place of a diesel generator in Figure 11, a microturbine generator may be used which means power sources 1 and 2 might have a solitary essential input of fuel. Besides, a load-following technique is typically utilized in stand-alone power frameworks; thus, the battery storage is incorporated with the energy generation course of action to provide timely response to fast disparities in users’ load demand sometime along the system operation [2], [58].

The stand-alone power system requires technical ability to deal with the start-up necessities of inductive loads like fans, motors, and water pumps. Hence, the model of FC microgrid (FCs + Battery storage) should fulfill highest constant load demand for reasons of reliability. In Figure 9, the FC stack in the system is able to supply the charging current for the battery storage in cases where the users’ load demand is low.
However, in cases where there is a fault in the FC stack or it simply cannot supply power, users will lose energy supply. Figure 10 and Figure 11 addresses this problem by using the corresponding attributes of the hybrid system where the users benefit from other generation resources available [2], [71]. A high level of EM strategy is used in conjunction with the power electronic converters to govern the exchange of energy between the battery storage system and power sources [2].

4) EMERGENCY OR BACKUP POWER

Similar to the stand-alone power system application, the emergency application also requires technical capacity from the microgrid to handle the start-up necessities of inductive loads, but in addition to that there must be a connection to a battery storage or another peaking plant [2], [6]. The battery storage is required for limited backup power for short time (a few seconds to minutes) purposes, while higher backup power in a few or more kW for a period of at least 30 minutes can be provided by the FC stack [63].

5) DC MICROGRID

DC appliances may be powered directly from the DC output of the FC stack without using a DC-AC converter. This DC output may also be used to develop a DC microgrid as shown in Figure 12 connected to the utility grid [67]. The DC microgrid is made up of a FC stack as a voltage source which is connected to the DC-DC power converter to increase or decrease the voltage output based on the design requirements. It is essential to also have the DC-DC power converter for the load as seen from Figure 12, which interfaces the load and the DC bus, by regulating the required load or appliance voltage value. The common voltage levels used for telecommunication systems are 24 V and 48 V [2], [66]. By employing a two-way AC-DC power converter, an essential interface of the existing electrical grid with the DC microgrid is achieved. This interface then provides the possibility for the DC microgrid to purchase and sell electricity from and to the power grid. The DC microgrid will sell the excess electric energy and purchase energy whenever the load demand exceeds what the microgrid system can produce [72]. The gateway unit provides a bidirectional link between the existing grid and microgrid, hence it requires an AC power input.

B. COMPARING THE FC MICROGRID APPLICATIONS

Microgrid technologies are classified into grid connected and grid independent systems. When applying FCs in microgrid systems, understanding that regardless of which system is used, a FC power plant is essentially more than just a FC stack is important. FC systems can be used in grid-independent situations in cases where the load is not very far from the microgrid system. Suppose the sole energy supplier is the FC stack as Figure 7 shows, then there exists a potential for
the microgrid to serve as the electrical grid supply alternative or just supply power for grid-independent purposes [2]. Moreover, the parallel operation of the FC microgrid and the power grid could prove useful in meeting the baseload or peak load requirements, since a property of the energy source is continuous generation.

Types of Fuels in FC systems are divided into primary and secondary fuels where these two types have their own distinctive examples. The conversion between the two types by the FC processor is necessary especially in hydrocarbon-based plants [59]. The FCs used for stationary purposes has more lifespan than those used for automobile purposes hence they are preferred and have greater market opportunities. Thus, different application of FCs in microgrid environments are discussed. The grid connected and grid-parallel applications are comparable with similar aspects. The grid-connected application results in three possible energy suppliers for the user while for the other application, on the three suppliers, exporting power to the grid is disallowed.

A combination with variable energy generation systems to supply power at instances where it is not possible for other systems to power the load [71], is shown in Figure 9. Also, as the backup power supply or emergency generator, the system can be employed where the existing grid or other sources are unable to provide power [2]. The DC microgrid application is similar to most other applications in terms of power trade between the utility grid and the microgrid except that it can only supply power to DC loads.

**IV. ACTIVE DISTURBANCE REJECTION CONTROL**

ADRC has emerged in recent years promising as a control method with the ability to balance the efficiency and complexity. This is a novel control strategy whose exciting performance has been shown by literatures [73]. Since ADRC was proposed by the Chinese scholar Han [74], it has been confirmed to have an intrinsic relationship with PID control in philosophy and methodology [73], [74] and is regarded as the successor of PID controller in the control synthesis of modern industry [74]. However, finding the mathematical relationship between PID and ADRC is a challenge because the original version of ADRC is nonlinear and laborious to analyze [73].

ADRC was proposed initially for the $n$th order process [24]. However, there are usually no accurate model order available in process control. Therefore, preference in practice is usually given to a low-order ADRC controller. Firstly, to make things simple, an unknown system is restructured in the first order form [24], [25],

$$\dot{y} = g(t, y, \dot{y}, \ldots, d) + bu$$  \hspace{1cm} (11)

where $d$ and $g$ represent the external disturbance and the unspecified model respectively, and $b$, a symbol for critical gain which represents the power possessed by the controller output to be able to control $y$, the process variable (PV). With the uncertainty of $b$ and the possibility of it being time-varying, the new plant equation (11) becomes

$$\dot{y} = f + b_0u$$  \hspace{1cm} (12)

where $b_0$ represents an approximation of $b$ and $f = g + (b - b_0)u$ is known as the total disturbance, which consist of some unknown internal disturbances and dynamics [25]. Let $y = x_1$, and make $f$ an extended state $x_2$, thus, equation (12) shown in a state space form becomes

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} b_0 \\ 0 \end{bmatrix} \dot{f}$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$  \hspace{1cm} (13)

and then an extended state observer (ESO) is designed as

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} -\beta_1 & 1 \\ -\beta_2 & 0 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} b_0 \\ 0 \end{bmatrix} \frac{x_1}{y}$$  \hspace{1cm} (14)

If $\dot{f}$ is bounded, then the convergence of ESO is proven [24]. Using the observer bandwidth $\omega_0$, one observer parameter remains [24]

$$\beta_1 = 2\omega_0, \quad \beta_2 = \omega_0$$  \hspace{1cm} (15)

Making use of the total disturbance estimation in the inner loop, shown in Figure 13,

$$u = \frac{u_0 - z_2}{b_0}$$  \hspace{1cm} (16)

an enhanced plant, $u_0 - y$, may be found,

$$\dot{y} = f + b_0 \left( \frac{u_0 - z_2}{b_0} \right)$$

$$\approx f + b_0 \left( \frac{u_0 - f}{b_0} \right) = u_0$$  \hspace{1cm} (17)

which sometimes is approximated as a single integral process.

Figure 13 shows the principle schematic of ADRC [24].

Now the enhanced plant equation can be controlled by a proportional error feedback law [25],

$$u_0 = k_p(r - y)$$  \hspace{1cm} (18)

where $r$ represents set point (SP).

From the equations above, the following closed-loop transfer function is derived,

$$G_d(s) = \frac{y(s)}{r(s)} = \frac{k_p}{s + kp} = \frac{1}{T_d s + 1}$$  \hspace{1cm} (19)

where $T_d$ is reciprocal of $k_p$, the required time constant of the tracking performance in response to a step change in set point [24], [25].

**FIGURE 13. Principle schematic of ADRC [24].**

[Diagram of ADRC schematic]
V. OPTIMIZATION AND CONTROL STRATEGIES

The use of FCs as energy sources has gained popularity in recent years and despite its advantages when integrated with microgrids, the implementation of FCs across the world is still new and faces various shortcomings [1], [2]. On the other hand, most of those FCs already employed in real world systems still provide unsatisfying performance. With all that being said, the introduction of FCs on microgrids contain some new challenges that float out on the microgrid system level [6]. In this section, optimization, and control strategies of both the FCs and the FC-based microgrids that have been studied, experimented on, or tested are discussed.

A. FC SYSTEM MODELLING

The electric-chemical characteristics of a FC operating in one condition can be illustrated by an equivalent circuit model [6]. Figure 14 shows a typical circuit consisting of two resistors ($R_m$ and $R_c$), a capacitor ($C_{dl}$), and a non-linear impedance element ($Z_m$). Such components are tied to the various electric-chemical processes and losses [6], [75]. Since the FC operation entails multi-physics that are firmly connected, the FC modeling from one molecular and pore-level to system level, have received recognition from the research communities. Based on the level of simplicity, there are various classifications of FC models and focus is on multi-dimensional numerical models and 0-dimensional control-oriented [22].

The multi-dimensional models comprise of especially 2-D and 3-D, where numerical studies are done to produce the details of parameters that are hard to obtain on site with normal evaluation processes, like the potential distribution, temperature distribution, reactant and current distributions in single FCs and its aspects [22], [76], [77]. The 3-D multi-phase computational fluid dynamics (CFD) model is broadly used in the design optimization strategies of the individual cell and stack. As is the case, there is a huge connection between the management of water and heat, and to experimentally study the combined managements is difficult and incur costs. Thus, a widely acceptable choice has been to develop a model to optimize water and thermal management [78]. To minimize cost incurred due to the consumption of hydrogen and FC systems, various recent developments have been made in an effort to implement the multi-dimensional, and multi-physics models of FC stacks in live situations [79]. Simulations of hardware-in-loop may easily be done through the real-time FC simulator, and deep studies regarding the effects of control laws and parameter operations may also be carried.

Usually, multi-dimensional modules are unreasonable for the system level control design and investigation, in light of the fact that in a traditional control configuration, limited quantifiable factors just should be controlled to the vital qualities, and the detailed unique disseminations of these factors are not valuable [76]. Furthermore, the implementation of the multi-dimensional model is finished with a time-consuming mathematical computation strategy that is additionally not adjusted to the control configuration [22].

The improvement of control-arranged model is also from multi-dimensional models, however there are yet many parameters to be recognized or known beforehand. For example, in the highly utilized V-I model, around 10 boundaries should be distinguished if a study is centered around an arbitrary FC [80]. Except this, to develop the thermal and fluid models, the definite boundaries on the interior sizes and attributes ought to be known in prior.

Confusing the FCs and FC stacks models with those of FC systems has been occurring regularly until now. Even various simulation plate-form of a few FC applications have been worked out with no consideration given to the system dynamics. A proposal has been made in [81] for a couple of normally utilized general control-situated models. Nonetheless, the development of these models was for some particular FC frameworks which were estimated with boundaries of both FCs and BOP subsystems that were already known. It is typically an assignment that is hard or almost difficult to adjust these models to subjective FC systems. Different works center around the models of one explicit subsystem, and the coupling between the subsystem under study and other subsystems is frequently thought of as powerless [6]. For example, [82] proposes a control-situated humidification model. Two diverse unique control-situated thermal models are additionally proposed in [82], [83] and [84] simplified on a model proposed in [81] and its focus directed to air-fed control problem.

Modelling and simulation are two compelling apparatuses used in investigations pertaining the physical process inside a FC [76]. Some early writing revealed genuine consideration to steady-state transport marvels in the primary segments, which ongoing activities still focus on [22]. Then again, there is a developing interest modelling of different parts of FC activity, similar to transient execution, including start-up/shutdown and freeze-start processes [22]. More and more attention has been attracted by modelling FC degradation from both academic and industrial communities. In [23], the literature proposed some simple degradation models, however, considerably few PEMFC models assimilate such degradation phenomena on account of the complex FC degradation systems related working conditions, which is fairly surprising considering their significance [22].

B. OUTPUT POWER FLOW CONTROL

The research scholars in [46] analyzed the SOFC dynamic conduct in an on-grid climate. They addressed explicitly, working issues identified with the fuel utilization factor and the power factor of the FC plant. They additionally researched the effect the PCU had in assisting with accomplishing their
goals. Firstly, they audit the model determined in [13] and perform the steady-state inspection of a SOFC where they introduced the feasible operating area (FOA) which is the place where the FC should operate inside its rated power and the utilization factor kept inside the suitable range [15]. The FOA is determined after a set of equation derivations and a conclusion is made that any working point not within FOA results in cell life reduction thus, considered unsuitable.

Then on to the examination of controlling the real and reactive power stream from the SOFC plant to the grid. They derived the logical expression relating the power stream to the input of the hydrogen fuel and the control factors in the PCU. In the distributed generation (DG) framework under investigation, utilizing three factors, the generation and transportation of real and reactive powers is controllable [13], [15]. These factors include the input stream rate of natural gas $N_f$ of the BOP, the modulation index $m$, and phase shift $\delta_f$ related to the voltage source inverter (VSI). Under these three variables, the control of fuel input to the stack, the PCU for steady power operation, and the PCU throughout power changes are inspected and a set of derivations is done which brings about the power plant’s general control block diagram illustrated by Figure 15 [46]. In Figure 15, two distinct parts describe the SOFC power framework and its control frameworks. The control framework contains the following.

- Fuel controller
- \( u \) Calculation block
- Strategy block
- VSI controller

From the control scheme in Figure 15 and the use of the three factors that can handle the generation and transmission of real and reactive power, the yield power arrives at the required level $P_{\text{ref}}$ and the control equations are altered to adjust the VSI, so the real yield/output power is kept at $P_{\text{ref}}$ at a steady power factor for the resulting time frames. With this development, the utilization factor introduces its recovery from its transient value ultimately accomplishes the steady state value $u_t$ [15], [27]. It is to be noted that this control plot just relies upon the online terminal data of the FC stack. The data on the internal state of the stack is not required.

The authors in [46] proceed and look at potential techniques in following the power requirement on the FC. Ensuring that the operation of the SOFC is inside the FOA for both constant and transient states and having the necessary change in power in least time while the operation is at a steady power factor with the ac network is the objective. In this segment, the paramount part of the proposed control strategy is the strategy block. Acquiring a proper reference current $I_{\text{FC, ref}}$ achieves the power demand in least time yet it additionally guarantees that all the FC transient run focuses remain inside the FOA [14], [27]. These techniques are looked at for generating the reference current signal.

- Step change in $I_{\text{FC, ref}}$
- Ramp change in $I_{\text{FC, ref}}$
- Simultaneous applications of a step and a ramp in $I_{\text{FC, ref}}$
- Online control of $I_{\text{FC, ref}}$

All these strategies are examined using the calculus theory and the conclusions made are that they are all viable, but some have advantages over others. The first three are concluded to be effective if there is small change in real power demand ($\Delta P$). For large changes of power, the last strategy is the effective one. Not only does it accommodate significant power alterations, but it also does not rely on the model of the fuel processor [27], [46].

The authors then illustrated and compared the real power control schemes through the examples and the simulation tool MATLAB/SIMULINK using the nonlinear model similar to the one on Figure 3 of this paper. The computer simulations confirmed the precision of hypothetical analysis and projection. It is concluded that the control strategies are effective and that for large power ranges, changing the stack current through a feedback control would guarantee that if the required power level is not yet reached, the utilization factor will remain at its cutoff value. Besides, for this strategy, the controller does not rely on the fuel processor model [15], [46].

C. A COMBINED VOLTAGE CONTROL STRATEGY

Controlling the output voltage is crucial in ensuring the power quality of SOFCs, but challenging because of the electrochemical nonlinearity, modelling uncertainties, load disturbances, and actuator constrains. Moreover, throughout the brief voltage regulation, the fuel utilization rate should adhere to limitations within a safety range [85]. Recent research has been attractive to model predictive control (MPC) by constructing the challenges into a constrained optimization problem, however, due to its complex computations, this method has proven troublesome for real-time applications [85]. Sun et al. [31] propose a combined control structure containing fundamental building blocks, with the ability to achieve main objectives with less computation. The control research in [31] centers around a benchmark model of SOFC [17] whose structure is similar to the one on Figure 3. The controlled variable is the stack output voltage $V_{\text{dc}}(V)$, while natural gas flow rate $q_f$(mol/s) is the manipulated variable, and the external load current $I$ (A) is the disturbance variable as Figure 3 shows [17], [31].

An attempt at controlling a nonlinear plant [24] by employing linear control strategy is challenging due to varying operating conditions. Considering this fact, the research scholars in [31] use the ADRC to manage the nonlinearity and parametric uncertainties of the SOFC plant. The interference, uncertainties, and nonlinearity are grouped as the total interference which is successfully approximated and minimized by the ADRC. To increase the disturbance rejection ability, a feedforward control structure is suggested because the current load interference can be measured. The plant equation is derived from a second order ADRC [24]. The fundamental control design of the second order ADRC is shown in [31] with the parameters explained. After the derivation, the research scholars of [31] concluded that the upgraded plant can be said to resemble cascaded integrators and that dependent on the improved plant, configuring the
external-loop control using the proportional-derivative (PD) structure is possible [85]. By parameter turning and verification, Sun et al. [31] concludes that for comparison purposes, ADRC and PID have comparative performances under nominal conditions. Be that as it may, ADRC control system is almost unaffected by the variety of conditions, while there is a significant deterioration in the performance of the PID controller under other working conditions. Consequently, it is confirmed that ADRC contains a solid capacity to manage parametric uncertainties instigated due to the nonlinearity of the system [31].

To further test the effectiveness of ADRC control, the controller constraint is now included. The simulation results shown in [31] indicate how the fuel utilization factor surpasses the bottom safety limit. A complementary strategy is devised and implemented where switching the voltage control by means of ADRC to fuel usage control using PI would be reasonable to avoid fuel usage going over the safety range when it tends to do so. A PI controller would be adequate to ensure that the fuel usage remain at its limits. A simulation scenario dependent on the nonlinear model is made and tested [31]. Firstly, the simulation output of MPC is analyzed, where it is seen through graphical diagrams [31] that as the model stray away from its actual plant qualities, the control framework decays. Also, the severe condition on fuel utilization limitation fails to be fulfilled. With a worse model the problem will persist further [86]. Secondly, the analysis of the results from simulating the proposed control shows that there’s very little degradation on the control performances, showing the more grounded strength than that of MPC.

Comparing the two solutions, the proposed strategy shows that: (i) it is possible to configure the control system by utilizing the fundamental computational parts, where numerical optimization, matrix reversal, and ill conditions are not included; (ii) the controller configuration is unaffected by modelling uncertainties and consequently doesn’t really need a precise model. In outline, the proposed technique exhibits clear prevalence over MPC be it in calculation power or complication acknowledgment [31], [86]. All the ADRC, PI, and logic blocks can simply be designed in the basic industrial controllers utilizing typical components. The paper attempts to address the possibility of realizing a proficient voltage control framework containing straightforward calculation difficulty given that the control design is afforded sufficient concern [31]

Yang et al. [87] achieved the load-following ability of SOFCs by employing a time delay control. The shortcomings of the load following affecting the commercialization of the SOFC system were also identified [87]. Considering this, the authors came up with a time delay control containing an observer in the gas supply framework to enhance the FC’s elements as far as load tracking without reducing or impeding the fuel supply. The primary methodology of a time delay with an observer was improved by incorporating a channel to stop the undesirable results, similar to fuel interruptions, i.e., outside interferences, on the FC’s activity. A 5 kW SOFC was created as an experiment and the report suggested that the proposed control method brought about great powerful display when employed to the fuel section of the framework configuration [87].

The authors in [88] introduced the ideal fault-tolerant control technique in the operation of SOFC. They acknowledged that specific critical concerns, for example, load following, high efficiency, heat management, low capital expense, surplus air proportion, and fault finding are key elements needed for building SOFCs. It was additionally discovered that next to zero research concentrates on the control techniques that depend on improvement and fault finding in SOFCs. According to the report, the proposed control system can follow the electrical, surplus air ratio, and the operating temperature, reaching optimum efficiency, and cost under all conditions [88]

D. EXPERIMENTAL REAL-TIME OPTIMIZATION OF A FC STACK

Bunin et al. [28] propose the experimental verification of a real-time optimization (RTO) technique for the ideal performance of a SOFC stack. This strategy was previously
developed and simulated in [89] and is now verified experimentally for a 6-cell SOFC stack [28]. The constraint-adaptation methodology discussed in [28] has an exceptionally basic yet frequently obvious working principle stating that the optimum of the challenge often lies around the constraints. Thusly, meeting the appropriate set of limitations guarantees the optimality of the process. Because of uncertainty, complementing the estimations of the constrained values provided by the model and those acquired from the real framework will be unlikely. An adjustment done by inserting a bias term to the modelled limitations is utilized to guarantee that the imperatives employed by the optimization strategy are similar to those of the real framework. From that point onward, the RTO iteratively propels the framework to the accurate limitations, with the speed of combination decided by how the bias update is filtered [28].

The study presented in the paper [28] concerns a SOFC short-stack that was built at EPFL for HTceramix-SOFC power [90], [91]. A full detailed description of the stack and an image of its typical construction is found in [91]. The stack was heated at 775°C in a high-temperature heating system and connected to a testing station supplying preheated fuel (∼770°C) and controlled flow rates of air. Controlling the testing station was done via LabVIEW and implementing the RTO algorithm in MATLAB Script function [28].

The efficiency of a SOFC is limited by two key constraints. While the cell might be capable of providing a given electrical power at numerous working conditions, near the highest feasible fuel usage (70-90%) is where to obtain the highest electrical efficiency. To avoid any damage the stack may sustain from local shortness of fuel and re-oxidation of the anode [91], a fuel usage of 75% is predetermined. To keep away from the possibility of internal losses, a base cell voltage of 0.75 V is put to guarantee the stack does not suffer accelerated degradation, which results in the second constraint. The excess air ratio, and the cutoff points on the rate at which inputs are changed are set respectively, and the restrictive laws are imported into the LabVIEW code to ensure that those rates are set to zero if there should be an occurrence of a fuel usage or air ratio breach [28]. For the system presented by the authors in [28], the optimization is highly instinctive and adheres to the accompanying general guidelines: at lower power demands, maximize v (fuel utilization) to maximize efficiency i.e., v is the active constraint; for higher power demands, \( \text{U}_{cell} \) (cell potential) becomes the active constraint, and pushing v to its boundary is no longer optimal [28]. The constraint adaptation algorithm is illustrated by Figure 16 and its full description is on [28].

To test how effective the technique is, a preset power demand profile,

\[
P_{el}^t(t) = \begin{cases} 
0.30 \frac{w}{cm^2} t \leq 90 \text{min} \\
0.38 \frac{w}{cm^2} 90 \text{min} < t \leq 180 \text{min} \\
0.30 \frac{w}{cm^2} t > 180 \text{min}
\end{cases}
\]  

was used to exhibit how the adjustment in active constrains (from v to \( \text{U}_{cell} \)) may take place. Let it be noted ‘that the demand profile acts as a disturbance at the RTO layer: meaning when or how the change in power demand may happen is unknown. An RTO iteration cycle of 30 min was utilized, as it was normally the time the true system takes to arrive at steady state [91].

The first test scenario is the ideal power tracking using various filters, where a preset demand profile case is examined in the SOFC framework with various filter constants values. The results are tabulated in [28], however, it is seen that the optimizer quickly looks to amplify the air proportion for all cases, this is so due to the absence of any parasitic losses to the air blower. A dip is observed in the fuel usage when the power changes which is because in the system the air proportion must be kept beneath its upper limit during the transient to allow for a slow decrease in hydrogen flux to complement a current decrease. This results in short term low fuel usage. Otherwise as anticipated, the convergence speed to the optimum is affected by the filter constants. For the full adaptation case, a quick oscillatory convergence is observed [28].

The second test scenario is the optimal filter design, where improving the power tracking and constraint satisfaction lies in assigning different values to the modifiers [28]. The hardest part is to estimate an ideal filter value for the power demand [91]. For instance, using a value of 0.7 will prompt an insufficient second-iteration step, while using 1.0 results in a far-reaching step. Assuming a value lying somewhere in between is the optimal value, one may choose a value of 0.85. Indeed, implementing this value result in better power tracking. The potential constraint is violated, but due to the large filter value, the potential constraint returns to its bound quickly [28].

An RTO with constraint adaptation for a SOFC stack test was investigated [28]. Evidence showed that even with uncertainty and plant-model inconsistency, the versatile optimization program effectively drove the system to its actual optimum. Additional studies illustrated that when filter values are tuned, quicker convergence and greater performance resulted. The RTO could likewise act as an optimizer and a
controller at the same time. It was recommended that a more thorough hypothetical treatment of the filter tuning is as yet required [28].

Another strategy focused on energy efficiency optimization was presented by authors of [92], where their aim was to build a control system capable of optimizing the FC-based microgrid power delivery and subsequently the efficiency. A microgrid made of two PEMFCs was used to develop and test the effectiveness of the proposed control strategy, the energy performance and to ensure that the integration is optimized [92]. Two boost converters are also employed to boost the FC output voltage and keep it stable. These converters have a certain real-time module controlling them [93].

Before the control strategy was defined, experimental tests were carried out to pinpoint the optimal efficiency of the FCs regarding the generated power and working temperature [92]. Upon realizing the values of these two figures or conditions, a control strategy aiming at producing maximum efficiency of the microgrid was defined with three cases of power demand to be used in order to achieve the desired results. With this, achieving controlling the power delivered by each FC was imminent [94]. Then a control algorithm was also used to detect the difference between the temperature of the stacks. Simulations, tests, and implementations were carried out in LabVIEW and conclusions were drawn. The system showed good but slightly slow response to load and set-point changes. The slowness observed was a result of low proportional PI gain. Increasing this gain would result in greater oscillations occurring the changes in load and set point [92]. The tests also validated and confirmed that the algorithm control implemented did improve the system’s efficiency.

E. FC’s COORDINATED CONTROL STRATEGIES

Some research [95], [96] are dedicated to the efficient controller design of the DC/AC inverter. Despite ongoing studies on the power inverter subsystem in FCs, the correlation of the SOFC and the inverter is rarely thought of. Ordinarily, the association is made in a feedforward way, setting hydrogen input of SOFC to be proportional to the FC yield current $I_{FC}$ [44], [97]. A constant steady-state fuel utilization can be guaranteed in this control strategy. However, as a result, two problems may arise: (i) the rate at which fuel is used may surpass the allowable range in a distant transient load following; (ii) A slow $I_{FC}$ feedforward control response. Sun et al. [29] propose and build two basic coordinated control strategies (CCS) for SOFC power management. In [29], by comparing the working principle of the FC stack with the inverter using Direct Energy Balance (DEB), the problem is handled.

From the operation in the conventional pulverized coal (PC) boiler-turbine unit it is observed that the SOFC inverter unit and the boiler-turbine unit have high similarities [97]. As is notable, as the latest kind of generation type, the SOFC inverter unit is very unique in relation to the conventional boiler-turbine unit in production devices and transformation procedure [29]. Be that as it may, from a control system’s perspective, it is surprising to find similarities in their dynamic qualities. This is shown in Figure 17 [29]. The detailed similarities between the two units are also listed in [29].

Knowing the high correlation between the two units, designing SOFC-inverter control system based on how the boiler turbine unit is controlled would be logical, since the latter has been exposed to world-wide industrial practice corroborating its efficiency, maturity, and security [29]. Currently the boiler-turbine unit has two basic CCS [98], [99]:

(i) boiler following control, i.e., boiler follows turbine (BFT), (ii) turbine following control i.e., turbine follows boiler (TFB). Details on these two CCS are referred to in [29], [98], and [99], and are omitted here. Two corresponding CCS techniques for the SOFC-inverter are designed using information on those CCS of the boiler-turbine unit [29].

The FC follows inverter (FCFI) based on correlated management control is the first of the CCS strategies. The inverter controller ($G_I$ in Figure 17) oversees the quick power following, and the fuel controller ($G_F$ in Figure 17) pulls the fuel utilization factor to the reference value of 0.8 [100]. Solving both the above-mentioned shortcomings, the regular control methodology is improved in 2 steps.

Step 1: Considering the energy balance guideline, processing the power reference is done by means of a switch block used in boiler-turbine BFT plan [100]. Step 2: The fuel controller $G_F$ minimizes the variation of utilization factor $u_f$ through the manipulation of fuel inputs $u_f$. To fast track the process dynamics, the initial feedforward loop is amended as a feedback loop as seen on [29], where designing the fuel controller requires the PI form to eliminate the sluggish pole of the fuel processing unit. Caring out the simulation, the efficiency of the proposed strategy is confirmed [29].

From graphical diagrams in [29] it is evident that in step one the reference is slowed down as a result of the fuel utilization factor edging closer to the limiting margins, thus guaranteeing the safety of the SOFC. Step 2 then obtains a slight settling time from a compelling first control attempt. In this scheme, preference is given to fast tracking ahead of the safe operation of the SOFC. The proposed FCFI-CCS does not depend on the accuracy of the model and does not require a priori information on change in power reference [29].

The second CCS strategy the inverter follows FC (IFFC) based on facilitated control. In this technique the fuel regulator is liable for power management while the inverter reference is intended to provide balance between the DC
supply and AC demand in a manner that results in the fuel utilization factor sustained at 0.8 [29]. Using the same scenario as the previous one, the simulation results shown in [29] evidently proved that in IFFC technique the inverter consistently changes a moderate power quantity into the side of the grid resulting in slower power following than in FCFI technique [100]. In this scheme, preference is given to the safe operation of the SOFC ahead of load tracking.

The research scholars [29] then test the two CCS techniques in a grid-dependent microgrid [29], and the total harmonic distortions (THD) are examined using the inverter switch. This research is also applicable in a stand-alone microgrid where instead of the power grid a battery is used. In the paper [29] an attempt is made to set the total power trade between the microgrid and the power grid to be zero. This results in the combination of the microgrid having next to zero effect on the power grid and subsequently the long-range power transfer can be minimized. In a balanced condition, the SOFC power reference will follow its own yield power [97]. The details on how the CCS are simulated and tested are in [29]. It can be concluded however, that the simulation in a hybrid microgrid indicates how proficient the two CCS proposed are. The two procedures and a supervisory power management technique are exceptionally easy to carry out and they require no a priori information and precise plant model [44]. It is recommended also by the authors of the paper that in future along the said exploration line, an advanced controller needs to be used in an attempt to minimize the THD in higher power level working conditions [29].

F. HYBRID SYSTEMS AND CONTROL MECHANISMS

As discussed earlier, FCs can be applicable in both grid-dependent and grid-independent frameworks. Employing the FC microgrid as a solitary power source in a grid-connected system insinuates that there may be a purchase of electricity from the power grid when the demand of electricity is higher than the supply to the microgrid. An arrangement like this is achieved due to the complementing aspects of both the FC and the grid as energy sources [2]. Nonetheless, there are some constraints encountered when innovation like SOFC’s is utilized as the just or single power source in off-grid applications [70]. The deterioration of the framework’s life expectancy reflects these situations, particularly in dynamic operations, with high capital expense, which influences the long life of the FC system [30]. Thus, unavoidably, the durability of the FC is affected by this degradation of life span. In stationary applications, these factors were notable among others that afforded hybrid systems an advantage over solitary-source systems. It is in this manner, important to implement some control techniques for the coordination of the microgrid system’s operation based on multiple energy systems [97].

Baldi et al. [30] considered a CHP system based on SOFC and PEMFC combined with a hybrid storage setting for grid-independent system purposes. By using this proposed hybrid CHP solutions, the authors aimed to get the better of the constraints highlighted above, then the SOFCs satisfies the system’s baseload, while incorporating the purification unit and the system arrangements results in the pure $H_2$ being produced and stored from the SOFC anode off-gas [30]. The $H_2$ put in storage may be used to drive PEMFCs when the power demand reaches peak. Applying the hybrid energy storage framework, battery storage and $H_2$ in this instance, to limit maximum energy demand, was the main objective of doing this research, this enhanced the SOFC’s normal load and decreased the installation size, which led to an almost steady load operation of the SOFC and an enhanced durability [2], [30].

Integrating a SOFC with an organic Rankine cycle and absorption chiller frameworks proves useful in achieving the dynamic power and cooling generation for residential use. Author in [32] proposes a dynamic, physical model integrating the systems mentioned above to imitate the household’s dynamic loads. A report was made that the hybrid plan integrating unique models of organic Rankine cycle and ingestion chiller could follow the electrical dynamic load and using the SOFC dynamic waste heat to produce more household electrical power or cooling [32]. Such a study had an idea of exploring the high thermal property of the SOFCs together with bottoming cycles (as illustrated in Figure 7), in producing additional electrical energy, heat energy, or cooling in an attempt of increasing the efficiency of the system now as compared to when a single system is operated in a stand-alone configuration [2].

Taleb et al. [33] achieved a directed hybrid design of PEMFC surface with small aqueous supercapacitors. The fact that the PEMFCs possess a high-power density was already established, but the degradation of this property may come from the weight and size of the affiliated supports needed in managing and controlling the air flow rates, $H_2$, and the steaminess [33]. Several researchers introduced a hybrid design based on ultracapacitors or batteries to overcome the limitation challenges of FC dynamics by fuel supply mechanism having the compressor, flow control device, and/or the humidifiers [33]. Nonetheless, the researchers postulated that there are technical questions raised from enhancing the performance of the hybrid design offered-FC system with supercapacitors regarding the best design and control techniques. Thereafter, sacrificing the durability and reliability of the FC operation in the implementation of hybrid designs was not desirable [2].

The complexities of the capital cost of the system need to be rationally moderate, although some exceptions can be made in certain situations [33]. In most studies for power management, a single or two DC-DC power electronic converters are usually included in the FCs/super capacitor hybrid systems. There is also a possibility of having a plan that links FCs directly with super capacitors without employing a power management mechanism and the power converters connected to it. A design of this kind is called a passive hybrid design, and the authors in [33] proposed an idea of using...
this design to improve the reliability and performance of the system containing high varying yield demand [33].

The hierarchical EM is proposed in [101] for the hybrid design containing solar PV, battery island and $H_2$ DC microgrid systems. Han et al. [101] first presents a few of the advantages of DC microgrids such as that power quality issues, flow of reactive power, and synchronization have no negative effect on them as they do very commonly on the design of AC microgrids. Such advantages among other factors gave the motivation that prompted an introduction of a strategy that would improve the performance of electrical system through its cost effectiveness and robustness. This EM system contains the local control (LC) and the system control (SC) layers. The management and control of the DC microgrid components is done on the LC layer based on their feature and working characteristics, on the other hand, the SC layer devises a strategy to minimize the associated fuel usage, as well as the energy exchange between the battery and FC [101].

Han et al. [102] also realizes a dual-level EM technique for solar PV, FCs, and battery systems-based DC microgrid system. The conventional, distributed control method had its drawbacks as mentioned by authors that they generally failed to satisfy the EM operational requirements for the DC microgrid framework with multiple sources. The two EM strategies proposed in [101] and [102] are similar to one another, but the one in [102] has two divisions being the device control and the SC. At the device control level, the introduction of the peak point-droop, droop control, and dual mode control enhances the chances of the microgrid system being reliable, while only the management of the flow of power between the FC and the battery is done at SC level [102]. Comparing the dual-level EM approach and the PI and the state machine control methods in reducing the $H_2$ fuel usage, the authors predicted that the proposed dual-level EM technique would succeed.

VI. DISCUSSION AND COMPARISON OF THE CONTROL METHODS REVIEWED

The control methods reviewed in this paper are compared in Table 2 in terms of their merits/demerits. It is challenging to balance controlling all aspects of FC power plants in a microgrid, as while ensuring one aspect is under control and operates efficiently, the other aspects may lead to inefficient plant operation, thus compromising the safety of the plant and its components. CCS may be used to help balance controlling most if not all aspects of the FC power plant, and this technique can be applied to other research topics and studies as well [29]. Usually, PI controller is sufficient to perform fundamental duties. – integrate with other controllers to achieve desired results or use different controllers all together. The researchers [29] recommended an advanced controller to help minimize THD in higher power level working conditions and it would be a practically sound recommendation to use ADRC in a quest to minimize the THD because it is the most promising control method with the ability to achieve greater controlling results than the famous PID and can keep the efficiency and complexity balanced in the modern industry of control advancements [73]. Furthermore, ADRC among others is used to assist in preventing the act of controlling a nonlinear plant using a linear control method by minimizing the total disturbances. Thus, it would be a good fit to solve such shortcomings. However, other modes controllers may also be explored with an appropriate optimization technique.

The main aim of the paper [31] was to control the output voltage of the SOFC using the MPC as is sometimes used but in this case integrating it with ADRC to help minimize the total disturbances [31]. The results showed that using ADRC improved the plant operation, efficiency, and safety. Observing the results obtained, it is evident that integrating controllers and/or using different and more advanced controllers can achieve the desired control objectives and results. This, however, does not take anything away from individual controllers or any use of them. Nonetheless, it highlights that a different controller can help produce different results which may contribute to major breakthroughs in research and fill the gap currently present in the FC studies and implementation.

The constraint adaptation technique presented in [28] is the first to be applied in RTO studies (with many other techniques being experimented and applied before in RTO studies) and is reviewed in this paper for the very first time. As [28] present current developments in RTO studies, this paper contributes to reviewing these current developments in studies, by exploring, summarizing, and pointing out the merits and/or demerits where the most important take away was that: the system reached its actual optimum with an inconsistent plant model and some uncertainties when a RTO using constraint adaptation technique was applied. Further studies, however, are still required when tuning filter values. Since this constraint adaptation technique is still new, along this research line [28], future studies may focus on sophisticated SOFC problems for improvement of the proposed technique; these may include problems involving co-generation, parasitic losses, steam reformers etc.

Based on the presented research, it is evident that employing FCs as only power sources in the microgrid environment [30], however, hybrid systems are used to reduce the negative impacts of obvious challenges in the process [97]. Considerations at many hybrid sources which had the potential and improved the operation of the microgrid systems were given. However, it is noticeable that controlling mechanisms are still a problem in these systems, it is recommended that going forward more studies are essential to ensure complete understanding as there is still limited knowledge regarding control mechanisms of hybrid systems which also have limited applications and implementations in real life situations with many challenges still to be addressed. This will ensure that integration of these sources is safe and result in efficient, durable, and reliable in connection with FC operation in the microgrid.
### TABLE 2. Control Methods and Merits and Demerits.

| Ref | Year | Control Method | Merits/Demerits |
|-----|------|----------------|-----------------|
| [17] | 2002 | FC system modelling (SOFC). | The benchmark model widely used for SOFC studies. It omits the thermal characteristics and has the dynamics of the fuel processor. |
| [11] | 2004 | FC system modelling (PEMFC). | The PEMFC type is considered to be simple, viable, and has a quick start up ability among other FC types. A major challenge however is that it has low efficiency and depends highly on pure hydrogen, hence its limited applications. |
| [80] | 2018 | FC system modelling | The improvement of control-oriented model is from multi-dimensional models, however there are yet many parameters needed to be known or recognized prior including the definite boundaries on the interior sizes and attributes in order to develop thermal and fluid models. |
| [46] | 2007 | Output power flow control | To generate the reference current signal for the power control, four techniques are looked at and a conclusion is made that all are viable, but some have advantages over others. The last strategy is the effective one. Not only does it accommodate significant power alterations, but it is also not dependent on the model of the fuel processor. |
| [27] | 2020 | Output power flow control | The computer simulations confirmed the precision of hypothetical analysis and projection. It is concluded that the control strategies are effective and that for large power ranges, changing the stack current through a feedback control would guarantee that if the required power level is not yet reached, the utilization factor will remain at its cutoff value. For this strategy, the controller does not rely on the fuel processor model. |
| [31] | 2017 | Output voltage control | There are challenges in controlling the output voltage of the SOFC power plant which include the electrochemical nonlinearity, modelling uncertainties, load disturbances, and actuator constrains. Moreover, throughout the brief voltage regulation, the fuel utilization rate should remain within a safety range. ADRC is employed to manage the nonlinearity and parametric uncertainties of the SOFC plant. |
| [31] | 2017 | Output voltage control | Comparing the two solutions, being the use of ADRC together with PID for some purposes against the MPC, in outline, the proposed technique exhibits clear prevalence over MPC be it in computation power or complication acknowledgment. |
| [28] | 2021 | Real-Time optimization | Testing an RTO with constraint adaptation for a SOFC stack showed that even with uncertainty and plant-model inconsistency, the versatile optimization program effectively drove the system to its actual optimum. Further studies illustrated that when filter values are tuned, quicker convergence and greater performance resulted. The RTO could likewise act as an optimizer and a controller at the same time. |
| [92] | 2013 | Real-Time optimization | An energy efficiency optimization strategy was presented where the aim was to build a control system capable of optimizing the FC-based microgrid power delivery and subsequently the efficiency. Using three cases of power demand, the power delivered by FCs was controlled. Implementing the control algorithm through LabVIEW resulted in the system showing good response to load and set-point changes. |
| [29] | 2018 | Coordinated Control Strategies | Two fundamental coordinated control strategies (CCS) for SOFC power management are built. In the first strategy which is FCF scheme, preference is given to fast tracking ahead of the safe operation of the SOFC while in the second strategy called IFFC scheme, preference is given to the safe operation of the SOFC ahead of load tracking. |
| [29] | 2018 | Coordinated Control Strategies | The two CCS techniques are tested in a grid-dependent microgrid, and the total harmonic distortions (THD) are examined using the inverter switch. It is concluded that the simulation in a hybrid microgrid indicates how proficient the two CCS proposed are. The two procedures and a supervisory power management technique are exceptionally easy to carry out and they require no a priori information and precise plant model. |
| [30] | 2019 | Hybrid Systems and Control Mechanisms | The CHP system based on SOFC and PEMFC combined with a hybrid storage setting for grid-independent system purposes was proposed. Applying the hybrid energy storage framework, battery storage and H2 in this instance, to limit maximum energy demand, enhances the SOFC’s normal load and decreases the installation size, which leads to an almost steady load operation of the SOFC and an enhanced durability. |

### A. CURRENT CHALLENGES AND RECOMMENDATIONS
Integration of FCs into microgrids has demonstrated great advantages through recent research and implementation, however, there are still many challenges being faced mainly because FCs penetration into the world is still new and is yet to be fully comprehended [6]. The FCs already in
service provide unsatisfying performance, while also new shortcomings are encountered when integrating FCs into microgrids systems [2]. There are many factors affecting the FC performance which results in the following challenges:

- FC system performance depends on the FCs themselves and multiple BOP components [38], so it is required that all these components which are equally important as the FC be controlled accordingly which can be challenging.
- The FC operation involve many domains namely thermal, electrochemical, and fluidic domains [6]. Therefore, numerous physical variables are analysed in order to control and monitor the system.
- High non-linearity and uncertainty in FC systems. The polarization curve shown in Figure 5 illustrating the V-I nonlinear characteristics when building thermal and fluidic models, some nonlinear properties are observed [6], [55], [57]. These provide challenges to the modelling and control of the FC system.

Considering the challenges mentioned above, taking efforts in the following direction can enhance the FC system performance [6].

- Improvement of material and assembling of FCs: materials play an important role in improving the FC performance and allowing it to be widely commercialized. The advanced materials especially, are key to the durability improvement, while also reducing the FC cost [20]. Each material type contains strengths and weaknesses, but the idea is maintaining the electrical conductivity and mechanical properties balanced.
- Improving performance of auxiliary components: as the applications of FCs increase, it is evident that a cost-effective FC BOP system with high reliability and durability is as important as the FC itself [103]. However, the issue would be that the components with high quality are difficult to obtain as they are only made by few manufactures worldwide [104].
- FC system modelling: modelling and simulations are two effective ways of assessing the physical aspects inside the FC. There have been many studies in the past focussing on FC modelling especially concerning the steady-state transport. However, recent studies are being attracted to modelling other parts of FC operations like transient performance, with freeze start and start-up/shutdown processes [19].
- Progressive mentoring and measurements: online or offline measurements are taken for the purpose of controlling and monitoring FCs. These measurements are divided into two; the ordinary in-situ and the measurements to FCs in particular. The in-situ measurements may include the fluidic sensors for pressure and flow rates management, and the thermal sensors for temperature management. For the FC-specific measurements, specialized sensors may be used in addition to various standard experimental techniques [105].
- System integration and control: controlling FC system is done in two levels. The first one involves auxiliary sub-system control which consists of thermal and water management control, and reactants control [83], [84], [106]. The second level entails the integration of FC system with components like energy storage units and power converters. This is done by coordinating various energy sources in the hybrid FC system. Evidently [71], relying on FCs as the sole energy source in the microgrid often results in increased cost, thus delaying commercialization of FC technologies even further [20]. To minimize the system cost and provide adequate reliable energy, hybridization of FCs with other renewable energy sources is the solution. PV/FC/battery microgrids are said to be the most commonly used hybrid systems [107]. Other studies [108] also considered wind/PV/FC microgrids. With FCs, having most known information highly depended on research findings, and little reference given to practically installed systems, it is recommended that hybridization techniques be assessed further and proposed for future implementation into modern microgrids.

VII. CONCLUSION

This paper presented a detailed review of the topic: Optimization and Control Strategies for Fuel Cell Power Plants in a Microgrid Environment. A theoretical background of FC technologies was discussed where its historical developments especially on SOFC was highlighted as well as a theory on PEMFC because both these FCs are generally used in stationary applications involving FC microgrid systems.
A description of FC systems was given with its basic diagram, the anode, cathode, and overall reactions, the different FC types were looked at with their basic information tabulated as well. The paper looked at FC technologies in microgrid environment and their applications in such systems. The applications included grid-connected, and DC microgrid configurations among others which both the on-grid and off-grid microgrid frameworks had interest in. The advantages of these applications were presented, the comparison and the technical drawbacks in connection with each system’s operational mode.

ADRC has emerged in recent years as a new control technique that possessed signs of achieving the balanced efficiency and complexity. A theoretical review was done to this control method since as an added interest to explore its effectiveness in controlling FC based microgrids. The ADRC has been confirmed to have a relationship with PID control and regarded as its successor, however, there are still many challenges around it, one is where finding the mathematical relationship between the two which is a tedious process. It was nonetheless analyzed in this paper where its brief theory especially the part where a derivation of plant equation based on its principle schematic was done.

Optimization and control strategies of both the FCs and the FC-based microgrids that have been studied, experimented, and tested were discussed. The FC system modelling was looked at first since most if not all FC technology studies are centered on and requires a credible model with modest complexity. A glance at models developed for some FC systems in particular that were measured with variables of FCs and BOP subsystems was given, and a focus on SOFC technology model was done. All the studies and conclusions of model developments leading to the benchmark SOFC model were looked at. Output power flow control strategies were reviewed where the dynamic behavior of the SOFC in a grid-connected microgrid was investigated. Issues focused on were the operating drawbacks related to the fuel utilization factor, and the power factor of the FC plant. A look at what role the PCU plays in achieving these objectives was given.

Other control strategies looked at include: a combined voltage control strategy, experimental RTO control of a SOFC stack via constraint adaptation, the CCS for FC power plant in a microgrid, and the hybrid systems and control mechanisms. Hybrid systems were said to have an advantage over single-source systems in stationary applications, since when technology like SOFCs operate in grid-independent applications as the only power source, their durability and consequently their lifespan is affected. Challenges currently being faced in the research domain and recommendations were detailed with focus given to hybridization of FCs.

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