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Utilization of fuel cell energy source for distribution power generation: theory, modeling and review of research work

***Abstract**. The energy crisis is one of the most critical phenomena happening in today's world. The depletion of fossil fuels, the rise in oil prices, and the increase in power demand are the main causes of this problem. Concern over environmental conditions and human health make renewable energy one of the most viable alternative solutions to this crisis. Among various types of renewable energy, fuel cell technology shows a great potential in the electrical energy sector for several reasons, such as high efficiency, clean operation, and immunity to the adverse effects of weather conditions. Recent works prove that fuel cell technology is expected to be a better choice for distributed generation purposes. Distributed generation, which is installed near load centers, can moderate the stress of high electricity demand in the mainstream utility grid. This paper presents an overview of fuel cell technology, with emphasis on fuel cell types, characteristics, and applications. The differences among the various fuel cell types and the dynamic models of each type required for simulation are also discussed. Focus is given to the application of fuel cells in a distributed generation system, the requirements of a fuel cell-based generating system, and issues in distributed generation integration. The present study also discusses the power conditioning unit, which is an important component in the fuel cell-based generating system, as well as its control strategy. Discussion is likewise made on the use of suitable energy storage units for the fuel cell distributed generation system, with regard to battery types and storage control. By adding energy storage units to the fuel cell system, the capabilities of the existing generation system can improve system stability performance.*

Streszczenie.** W artykule zaprezentowano przegląd technologii wytwarzania energii z wykorzystaniem ogniw paliwowych koncentrując się na analizie różnych typów i ich zastosowań. Szczególną uwagę zwrócono na zastosowanie ogniw paliwowych w rozproszonych systemach wytwarzania energii. Analizowano też układ kondycjonowania energii oraz jego sterowanie. **Wykorzystanie ogniw paliwowych w rozproszonych systemach wytwarzania energii elektrycznej – teoria, modelowanie i przegląd prac badawczych

Keywords: Fuel cell, energy storage system, power conditioning unit, distributed generation.
Słowa kluczowe: ogniwa paliwowe, systemy grmadzenia energii, rozproszone systemy wytwarzania energii

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1. Introduction

The increase in energy demand contributes to an increase in fuel used to generate electricity. To overcome the stress of high electricity demand in mainstream utility grids, a combination of renewable energy and decentralized energy system, called distributed generation (DG) has been introduced. In recent years, DG systems which are installed near load centers have seen rapid developments and promise many advantages, such as low investment, high operating efficiency, low loss, and high reliability [1]. The range of produced energy by DG technology is from a few kW up to 100 MW, depending on different application needs, namely, residential, commercial, light industrial and portable power. The various micro-source-based renewable energy technologies available for DG applications can be divided into two different types: controlled sources such as fuel cells and micro turbines, and uncontrolled sources such as photovoltaic, wind, and tidal energy. An uncontrolled source usually depends on the weather and environmental conditions, which are hard to predict. Thus, compared with other renewable sources, the fuel cell (FC) is seen as a better choice for DG application considering its advantages: high efficiency, no combustion, and convenient storage options. An FC is an electrochemical device that converts the chemical energy of a reaction directly into electrical energy without involving moving parts [2]. This feature makes the FC a kind of "silent technology", suitable as a power generation source in proximity to consumers. Moreover, waste heat and water produced from the internal reaction of the FC can be used for district heating, which increases the efficiency of the FC system.

In employing FC technology in a DG system, power conversion processes, which suit the output of an FC with DG requirements, become compulsory parts. The increased use of power electronics equipment is a continuous challenge, mainly in the aspects of modeling and designing the control techniques required to fulfill both grid and islanded modes in a DG configuration. Apart from issues of modeling the FC stack, issues concerning the power conditioning unit (PCU) with the controllers, the load tracking problem, the impact of dynamic behavior of the DG system, voltage disturbance, and overall system stability also become common and critical problems in DG applications involving FC technology as main source. Therefore, presenting comprehensive analyses of DG technology covering all technical and simulation barriers involved in integrating an FC in DG applications is urgently needed. The main objective of the present work is to review distributed FC generation with the aim of solving all the issues related to the simulation design of FC components, PCU, and energy storage system (ESS) for power simulation studies. In Section 2, FC types and characteristics are discussed. The FC types covered in this paper are polymer electrolyte membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC), phosphoric acid fuel cell (PAFC), and molten carbonate fuel cell (MCFC). Dynamic models of the four FC types are given in Section 3, with explanations of the simulation strategies of each model. Recent developments of distributed FC generation, particularly on the hybrid DG system, and the application of an FC as a storage device are explained in Section 4. Section 5 reviews the requirement needed for an FC to operate as a DG system, with particular interest in modeling and solving the issues related to the FC components, PCU, and disturbances in the system.

2. Fuel Cell Types and Characteristics

An FC is a static electrochemical device that converts the chemical energy of a reaction directly into electrical energy. It can be categorized as a first-rate electricity source because of its ability to produce constant power at full load. FC operation is nearly similar to a battery system. However, an FC continuously provides DC electrical power into a system as long as hydrogen gases are supplied, a feature which a battery is not able to perform. An FC generation system needs oxygen and hydrogen to perform chemical reaction and produce electricity in DC form. The oxygen required for an FC comes from the air, which is pumped into a cathode. The hydrogen can be supplied directly or indirectly; it is produced by a reformer from available fuels, such as methane, natural gas, gasoline, and alcohol. Primary products from this chemical reaction are electrical energy, water, and heat. The overall reaction happening inside an FC stack can be described as follows:

$$(1)\quad 2H_2(gas) + O_2(gas) = 2H_2O + power + heat$$

Currently, at least six different types of FCs are under development. Among the various FC types, PEMFC, SOFC, PAFC, and MCFC show great potential in DG applications. Alkaline fuel cell (AFC) is not suitable for electrical power application because it has zero tolerance to carbon dioxide (CO_2) and carbon monoxide (CO) constituents in the fuel, which requires high purity hydrogen and oxygen for internal reactions. Direct methanol fuel cell (DMFC), which can only supply 0.3 V to 0.5 V under loaded conditions, is also not a suitable candidate for DG. DMFC is instead usually used as batteries for cameras, notebook computers, and other portable electronic devices. In this review paper, the scope is limited to PEMFC, SOFC, PAFC, and MCFC, all of which have been reported to be promising DG sources. FCs can be grouped into two categories: low temperature and high temperature FCs. PEMFC and PAFC are examples of low temperature FCs, whereas MCFC and SOFC are high temperature FCs. The characteristics of four main types of FCs mentioned earlier are shown in Table 1.

Table 1. Comparison of fuel cell types

Criteria	PEMFC	PAFC	MCFC	SOFC
Operation temperature	~ 75 ºC (~ 180 ºF)	~ 200 ºC (~ 400 ºF)	~ 650 ºC (~ 1,200 ºF)	~ 1,000 ºC (~ 1,800 ºF)
Operation pressure (atm)	1 – 5	1 – 8	1 – 3	1 – 15
Efficiency (%)	40 – 50	> 40	> 50	> 50
Cell Voltage (VDC)	1.1	1.1	0.7 – 1.0	0.8 – 1.0
Cost	High	Higher	High	High
Self-Reforming	No	No	Yes	Yes
Cogeneration	Unsuitable	Suitable	Suitable	Suitable
Capacity	30 W, 1 kW, 2 kW, 5 kW, 7 kW, 250 kW	100 kW, 200 kW, 1.3 MW	155 kW, 200 kW, 250 kW, 2 MW	1 kW, 25 kW, 5 kW, 100 kW, 250 kW, 1.7 MW
Electrolyte	Solid polymer membrane	Phosphoric acid	Alkali metal carbonate	Ceramic oxide
Anode	Hydrogen	Hydrogen	Hydrogen, Methane	Hydrogen, Methane
Cathode	Pure oxygen, Atmosphere	Oxygen, Atmosphere	Oxygen, Atmosphere	Oxygen, Atmosphere
Power density (p/kW)	8 – 10	~ 25	~ 60	~ 40
Start-up time (hours)	< 0.1	1 – 4	10 +	5 – 10
Applications	Residential, UPS, emergency services (e.g., hospitals and banks) commercial, transportation	Transportation, portable power, commercial, cogeneration	Transportation, industries, utility power plants	Residential, power plant, commercial, cogenerations, portable power
Advantages	High power density, quick start-up, solid non-corrosive electrolyte, higher safety, simple operation, low capital and maintenance cost	Produces high grade waste heat, stable electrolyte characteristic, simplify fuel processing (i.e., less sensitive to CO)	High efficiency, no metal catalysts needed, internal reforming ability	Solid electrolyte, high efficiency, generates high grade waste heat, fuel flexibility, simpler fuel processing
Disadvantages	Expensive platinum catalyst, sensitive to fuel impurities, lower efficiency, no ability for internal reforming, limited cogeneration potential	Corrosive liquid electrolyte, sensitive to fuel impurities, no ability for internal reforming, lower efficiency, high cost	High cost, corrosive liquid electrolyte, slow start up, intolerance to sulphur, poor dynamic characteristics	High cost, slow start up, intolerance to sulphur, poor dynamic characteristics

Table 1 indicates that PEMFC is more suitable for residential and commercial building applications due to its low temperature and fast start-up. PEMFC generation is better done in locations that have available low cost hydrogen gas, such as chemical plants, where hydrogen is normally available onsite. SOFC, MCFC, and PAFC appear to be better choices for medium and large power applications with higher power capacity. However, the efficiency of PAFC is fairly low, and its inability for internal reforming makes PAFC less popular than MCFC and SOFC. Moreover, developer interest in PAFC decreased from 2002 to 2004 because of the following three main factors [3]:

i. Initial cost is much higher than that of other FC types.
ii. The potential for increasing electric generation efficiency to needed levels is limited.
iii. PAFC has low reliability and short life.

Among other fuel cells, SOFC operates at the highest temperature. This characteristic promises several advantages, such as higher efficiency of up to 65%, an increased efficiency of up to 80% with combined heat and power (CHP) operations, and shorter start-up time than MCFC. In addition, due to high temperature operation, SOFC allows direct internal reforming of fuels. However, high temperature corrosion occurs inside the stack, requiring the use of expensive materials, and thus raising the initial cost of SOFC. By designing a hybrid topology of SOFC, the operating pressure can be reduced, which results in increased efficiency and lowered cost. However, current research mainly focuses on designing planar SOFC systems due to their high potential in achieving lower stack and reducing initial cost.

3. FC Models

In power system simulation studies, a simulation model of an FC generation system is important for analyzing the step changes in operating conditions. Simulation models for FCs developed by several researchers can be grouped as mathematical and semi-empirical models. A mathematical simulation model is based on chemical reactions used in evaluating the operation of an FC, whereas a semi-empirical model combines experimental data with parametric equations adjusted by comparison with FC physical variables [4].

3.1 PEMFC model

PEMFC is the most common type of low temperature FCs, aside from AFC and PAFC. Low temperature operations allow a short start-up and a reduction of stack corrosion, thus making PEMFC a suitable candidate for power generation near consumers, as well as for application in vehicles. Simulation models for PEMFC have been discussed in [5 – 12] and are summarized in Table 2.

Table 2. Simulation model of PEMFC

Author	Method	Outcome	Problems
El-Shark et. al. [5]	Present a 5 kW dynamic electrochemical simulation model of grid independent PEMFC consist of reformer, PEM stack and PCU using Matlab/Simulink.	Result shows a fast response of the FC to load changes	- Temperature and oxygen concentration are assumed constant so concentration loss is neglected. - Not connected to grid - Ignored double layer charge effect
Pathapati et. al. [6]	Develop a mathematical model to simulate transient phenomena in PEMFC which include charge double layer capacitance.	Model is capable of predicting transient behavior in molar flow rates, voltages, temperature and pressure profile.	- It is standalone model - Concentration loss is neglected - Not consider rapid load changes
M. Uzunoglu and M. S. Alam [7]	Develop a stand-alone PEMFC model for residential application by incorporating UC to increase power efficiency in the model by using Matlab/Simulink software.	Parallel combination of FC and UC shows good performance for stand-alone residential application during steady-state, load-switching and peak-power demand.	- Not connected to grid - Temperature and oxygen concentration is assumed constant - Concentration loss is neglected - Not consider a short time interruption of load profile
Bibin et. al. [8]	Objective is to investigate PEMFC contact resistance. - Short term model : pressure and temperature are considered constant and only consider double-layer charging effect. - Medium term model: effect of partial pressure is considered, temperature consider constant and ignored double-layer charging effect. - long term model : only temperature effect is considered while pressure and double-layer charging effect are being ignored.	Results show that short-term dynamic PEMFC model can accurately represent the static and dynamic characteristics of FC system and impact of contact resistance is relatively small and can be ignored.	- Validation is only made for short-term dynamic model. - No analysis for medium and long term model is stated. - Simulation is only consider basic simulation of FC - Simulation not considers any variation of loads. - Model not considers combination of pressure and temperature variation with double-layer charging effect.
Jia et. al. [9]	Present a dynamic model of PEMFC with nonlinear control approach based on exact linearization which consists of a combination of linear control GMC, nonlinear controller and specific dynamic PEMFC model in order to keep overall pressure of anode and cathode gases equal to desired value.	Nonlinear control by exact linearization has good transient responses under load variations and it is possible to avoid membrane damage by minimizing pressure difference between electrodes gases.	- Not consider fuel processor, water and heat management. - It is a standalone system and not connected to grid. - Not consider the double-layer charging effect.
Younis et. al. [10]	Develop a dynamic simulation model of PEMFC using Matlab/Simulink with consideration of the three losses.	The output voltage is proportional to the change of the current drawn from FC model.	- Model ignored double-layer charging effect. - Reformer is not included. - Temperature variation is not considered.
Georgakis et. al. [11]	Develop a FC stack with a maximum power of 1kW connected to grid with FC controller, fuel processor, FC stacks, PCU and its control system.	Output response of PCU is fast but the system needs about 20 seconds to reach new value of output power due to inherent delays of FC.	- Double-layer charged effect was ignored. - Simulation is only considered for a step increased of power demand and not a various data.
Tesfahunegn et. al. [12]	Propose a combined steady-state and dynamic model of PEMFC for use in DG. Steady state model depends on V-I measurement over whole-region operation while dynamic part based on inference of dynamic time constants from experimental characterization.	Results show that due to FC dynamics, the model is unable to follow a fast change in power demand where a voltage dip or voltage swell occurs.	- Hydrogen is supplied directly and not through a reformer. - The model ignored double-layer charged effect.

As shown in Table 2, some assumptions are made in several models, including constant temperature and oxygen concentration, causing concentration loss to be neglected. A temperature criterion is important because it affects the performances of FCs. In real cases, temperature characteristics cannot be assumed constant because chemical reaction inside the stack yields net heat generation [13]. Moreover, a double-layer charged effect is also important in FC modeling because the collection of charges at the surfaces of the two electrodes will generate electrical voltage. This layer near the electrode interfaces stores electrical charge and behaves like electrical capacitance [14]. It also has a large value which will affect the FC model. Table 2 further shows that most of the models are autonomous and not connected to a grid. In DG simulation studies, the FC system must be able to perform well not only during autonomous mode, but during grid-connected mode as well. Furthermore, some of the models in Table 2 use available hydrogen supplied directly to the model. However, available hydrogen is difficult to store and distribute and is moderately more expensive than fuels. Thus, a reformer or fuel processor is one of the main important parts in FC modeling, as it converts available fuel, such as methane, into pure hydrogen gases.

3.2 MCFC Model

MCFC and SOFC are two types of high temperature FCs with the ability of internal reforming; they can reform fuels, such as natural gas, within the stack. MCFC is likely to be used in a power plant, and a dynamic simulation model of MCFC has been proposed in earlier research [15 - 19]. W. He presented a simulation model of MCFC to investigate the dynamic performance of an MCFC power generation system in [15]. This MCFC model consists of nine types of component models, including both species and thermal effects. Simulation results indicated that the system output power has a fast response to a current step change and a slow response to a gas flow-rate change. One disadvantage of this model is its external reformer, which can increase costs and waste the MCFC's ability of internal reforming.

Lukas et al. developed a nonlinear mathematical model of an internal reforming MCFC for control system application based on the principles of energy and mass component balances and thermo chemical properties [16]. Simulation results are presented for a transient response to a power plant trip at full load. This standalone MCFC model is detailed and accurate for other studies. The model in [16] is extended in [17] by deriving an explicit set of differential equations for computer simulation. In [17], results were improved by incorporating the FC performance model to account for reversible cell potential and polarization losses. The same authors developed a reduced-order dynamic model of MCFC based on the full-order model in [16] and proposed in [18]. Their MCFC model is simplified by setting the equation under the condition of constant temperature. A comparison between the full-order model and reduced-order model was made by examining gas composition and system DC voltage under severe transient. Simulation results showed that stack temperature changes after 100 seconds, and both terms in the Nernst equation also change due to temperature dependence characteristics.

Leto et al. [19] presented a simulation model of a hybrid system of MCFC and micro-turbine (MT) to provide a reliable analysis for evaluating system performance. However, in their model, contact and polarization resistance of MCFC are negligible. The MCFC models proposed by researchers are fairly limited, and none of them has addressed the process of interfacing an FC to the grid. Future research can focus on this subject to improve the MCFC model for power simulation studies.

3.3 SOFC Model

The SOFC model can be divided into two types, namely, tubular and planar configuration types. Tubular cells are formed into stacks using a tube sheet to support tubes, whereas the planar type is formed by thin plate cells sandwiched between metal interconnecting plates [20]. Both types have their own advantages, which depend on their physical configurations. The tubular design promises robustness, resistance to mechanical damage, and simpler sealing, whereas the planar configuration is more compact and has high power density, which reduces material content, thus lowering cost. The dynamic model of SOFCs has been developed by many researchers to learn SOFC characteristics and behavior for power system simulation studies.

Modeling of the SOFC unit starts with the transient and static models of a 3 kW tubular SOFC, which considers the effect of electrochemical, thermal, and mass flow [21]. The electrochemical and thermal parts of the model have been verified separately before combining these to form the transient model [21]. The model was used to understand the impact of transient behavior during system faults, surge, and switching condition. However, their model does not consider the dynamics of the chemical species. Moreover, the fuel input to the cell has been assumed constant. The transient behavior of an FC in a distribution system is also studied in [22, 23], where a comprehensive nonlinear SOFC dynamic model was developed. The model considers the thermal aspects of chemical reactions inside the FC stack and also introduces a new method for grid interfacing purposes. Li et al. [24, 25] also presented a nonlinear SOFC dynamic model based on electrical and thermal equations to study the dynamic behavior of standalone and grid-connected modes. Their paper also addressed operating issues concerning the fuel utilization factor and the power factor of the FC.

Padulles et al. [26] presented a dynamic model of SOFC for power system simulation and for analyzing power system performance. Their paper also described the initial fuel cell stack and power conditioning model that addresses the trade-off between the factors of the network dynamic requirements issue. Their model only considers the drop of FC electromotive force (EMF) from ohmic loss and ignores the temperature dynamics, concentration, and activation losses. However, [27] and [28] considered all the losses in SOFC. Wang and Nehrir [27] developed a tubular SOFC model based on electrochemical and thermodynamic characteristics. Their model consisted of diffusion, material conservation, electrochemical, and thermodynamic equations, as well as the double-layer charging effect occurring inside the model. Simulation results showed that the terminal voltage in constant fuel flow mode is higher than the constant utilization mode of operation. In [28], Liu et al. proposed a simulation study of an SOFC that was interconnected with a large system when facing load changing performance. This SOFC model considered all the voltage polarization or losses in both electrodes, as well as the fuel utilization process.

A dynamic model of a grid-connected FC power plant suitable for preliminary stability assessment was developed in [29]. The paper also studied the effect of the mixture between an FC and gas turbines on system stability. In this model, the reforming process is done by an external fuel processor. The SOFC model in [30] also used an external fuel processor to reform fuel into hydrogen gases. This SOFC model operated with low pressure and incorporated the electrochemical reaction dynamics, as well as the major voltage losses in SOFC. However, this model ignored the thermal dynamics occurring inside the SOFC stack.

Jurado et al. [31] proposed the Hammerstein nonlinear model for SOFC, which includes a static nonlinear block followed by a linear system, to study the dynamic characteristic of the system. This model was only tested for a step increase of current and did not consider the variations of loads. Moreover, the SOFC in this model was directly supplied with pure hydrogen, and the fuel processor dynamic was not included. Yutong et al. [32] also proposed a nonlinear state space model for tubular SOFC to investigate the dynamic behavior of SOFC for changes in input fuel, air pressure, and temperature. The model considered the dynamic induced by diffusions, inherent impedance, flow, heat exchange, and internal reforming. Simulation results showed that fuel flow inlet pressure and temperature have great effects on the dynamic SOFC performance, with the cathode side air inlet temperature having the most direct effect.

To develop the SOFC model stated earlier, some assumptions are made. Several parts are assumed constant where they will affect the performance of the SOFC model developed and not reflect the actual reaction occurring in the stack. The models in [21 - 26] and [28 - 32] ignored the double-layer charging effect, which is very important in developing FC models for the reasons explained in Section 3.1. The SOFC model in [21 - 32] only focused on tubular SOFC design. The dynamic model of planar solid oxide fuel cell (PSOFC) is limited, and many studies on PSOFC concentrated only on the chemical analysis inside the stack. PSOFC is a new focus in designing an SOFC system, where the system balances cost and promises potential in achieving a lower stack, hence overcoming the high cost problem of the SOFC model.

3.4 PAFC Model

The PAFC is also one of the low temperature types of FCs and has less sensitivity to CO poisoning compared with PEMFC [3]. However, the PAFC model has undergone slower invention progress due to the low conductivity of phosphoric acid [33]. A two-dimensional steady-state model of PAFC was developed in [34] to study the relationship between the performance of the FC and various design options. This model may be needed when the oxygen concentration varies substantially from the flow direction due to the reduction of oxygen and back diffusion of water. Simulation results showed that this model is useful in determining the area of low oxygen concentration and helpful in designing various components of the PAFC stack. PAFC was developed earlier than other FC types and was also the first commercially available FC in the energy sector. After 2000, more attention was given to MCFC, SOFC, and PEMFC. Thus, in 2003, more MCFC units were installed than PAFC units. Consequently, interest in exploring and designing the PAFC model by researchers decreased and more attention was given to other types of FCs.

4. Recent Development of FC in Distributed Genertaion Applications

In recent years, research on expanding DG and simulation to overcome the lack of existing models and several problems in DG have started to become the new areas of focus. In designing a hybrid model, researchers are solving problems such as lack of electrical power during heavy load. Moreover, the need to meet high power applications can also be achieved successfully. Recent developments in applying an FC as storage device in electrical power applications are some of the interesting topics receiving great attention for the reasons discussed in Section 4.2.

4.1 Hybrid System

A hybrid system is necessary when the FC model cannot satisfy the load demand under peak load conditions, which is one major drawback of FC technology. An FC generation system has slow transient response; thus, it is unable to follow load requirement effectively. A hybrid system is a combination of two or more electrical power generation technologies to fulfill high power requirements in DG configuration. Hybrid technologies have been explored and developed by many researchers in both academic and industrial sectors. A hybrid system can be classified into three main configurations: hybrid FC/energy storage, FC multi stack power source, and a combination of renewable energy sources, called hybrid power system, for DG [35]. Each of the succeeding sections explains a configuration.

4.1.1 Hybrid FC/energy storage

In this hybrid configuration, the FC is combined with an energy storage element to respond to the need for high power system applications, thus increasing system efficiency. Normally, renewable energy sources in DG have small generating capacities, and a converter is required to convert the voltage output to suit power system specifications. A source dominated by power electronic interface cannot respond to the initial or sudden power demand. Moreover, an FC system with many components will also cause problems for the fuel flow in following the step changes of load and cause fuel starvation [36]. To overcome all these problems, ESS is necessary for mismatch issues. ESS covers a wide range of power system applications with various technologies, such as ultracapacitor (UC), battery, pumped hydro, compressed air energy storage, and flywheel. UC, also known as supercapacitor (SC) and battery, are the most popular ESSs used in power system applications that supply electrical power fast. By applying ESS in a system, efficiency is improved, stability and reliability of electrical utility is enhanced, voltage disturbances are corrected, and adoption of renewable energy technology in DG is increased. Both technologies have their own characteristics, as stated in Table 3.

Table 3. Ultracapacitor and battery characteristics

Ultracapacitor	Battery
High pulse power capacity	High energy density
High power density	Low power density
Long lifetime	Shorter lifetime
Low equivalent series resistance (ESR)	Types (lead-acid, sodium-sulfur, lithium-ion, nickel-cadmium and others)
Compact in size	Size (0.14 - 2100 kVA)

Although both UC and battery have their own advantages, UC is a better candidate for power quality problem studies due to several reasons. Due to the low power density in the battery, it is not able to release its charge and discharge fast enough during voltage disturbances. Moreover, shorter battery life and high maintenance have been main problems in battery development. However, recent ESS technology combining UC and battery forms a hybrid storage system [37 - 39] that can overcome such problems. Hybrid ESS can extend the life of a battery, increase power capability, and decrease stress on an FC, making it more efficient and economical. Hybrid ESS also offers high power density and high energy density storage to the DG, thereby promising higher performance and a system with lower costs [40].

Azib et al. introduced a hybrid PEMFC-UC system using sliding mode control strategy to improve the robustness and performance of a system [41]. This model can overcome the slow dynamics of an FC and guarantee transient load by carrying out the UC. A hybrid SOFC–battery system is proposed in [42] that uses fuzzy neural control to develop better system efficiency and battery life with tolerable load following capabilities. The same authors [42] replaced the battery with SC to perform a hybrid SOFC-SC system in [43]. This model also used fuzzy controller to control the power flow in DC bus between the FC and energy storage. Simulation results showed that this model increases the life of an FC and improves the system performance under voltage disturbance. Moreover, [44 – 46] also discussed a hybrid FC-energy storage system with their own control strategies to overcome the load tracking issues in an FC generation system.

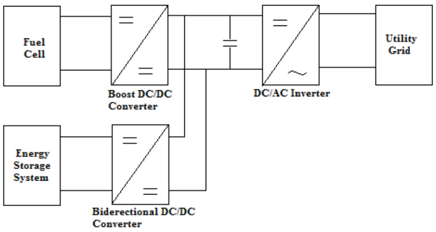

Fig. 1. Parallel structure for hybrid FC-ESS power system

Figure 1 shows the parallel structure for a hybrid power system associating an FC and ESS. This configuration is the simplest structure to implement. Moreover, it promises several advantages, such as less component constraint, good reliability, and easy energy management compared with a system having series and cascade architecture. However, one main problem with parallel architecture is unavoidable losses related to a static converter and reduced FC-delivered power [35]. Some issues in ESS technology include the following:

i)Types of battery

At least five types of batteries at the mature and developing levels can meet the needs of power system requirements [47]. The most common batteries used and studied widely by researchers and power suppliers are shown in Table 4. As seen in Table 4, efficiency, life span, cost, operating temperature, and depth of discharge are the important characteristics of a battery. Among various types of batteries, two are appropriate for large power applications, namely, lead-acid and sodium-sulfur (NaS). The lead-acid battery is the oldest, cheapest, most popular, and mature technology used in larger power applications [48]. However, its bulky size, low energy density, and low efficiency are main limiting factors for it to be considered for DG purposes. A smaller-sized battery, NaS, is also suitable for electrical power application. It promises higher efficiency than the conventional lead-acid battery. NaS performs well at approximately 325 °C with 89% efficiency, but using this battery at high temperature reduces its overall efficiency.

ii)Efficient ESS control

ESS control is an important part in designing a storage system because it interfaces the ESS to the load (either the utility or end-user) and regulates the energy storage charging and discharging processes. Moreover, an appropriate control strategy can help increase the ESS lifespan and reduce the overall lifecycle cost of energy; mistakes in control will decrease overall efficiency and shorten the lifetime of the storage. A unique principle for power electronics equipment for ESS is that they must have the ability of bidirectional conversion, which involves taking power during the charging state and providing power to the utility grid in the discharge state. Furthermore, the placement of ESS also affects DG performance. The location of ESS at either the high voltage side of a DC/DC boost converter or at the low voltage side of a DC/DC boost converter has certain advantages and disadvantages.

Table 4. Comparison of battery types [47 – 48]

	Lead-Acid	Nickel-Cadmium (NiCd)	Lithium Ion (Li Ion)	Sodium Sulfur (NaS)
Cost	Low	Moderate	High	High
Depth of Discharge (%)	75	100	80	90
Life span (cycles)	1000-2000	3000	3000	4500
Efficiency (%)	72 - 78	72 - 78	≈ 100	89
Operating Temperature (°C)	- 5 to 40	- 40 to 50	- 30 to 60	325
Advantages	Safe, mature technology, less robust, economical price	Fast and simple to recharge, economical, mature technology, long shelf life	High efficiency, high lifespan, low maintenance	High efficiency, mature technology
Limitations	Large and heavy, low efficiency, low energy density	Low efficiency, poisonous, heavy, low energy density	Immature technology, expensive, subject to aging	Operate at high temperature, need to be heated at standby mode thus reduce overall efficiency
Applications	Larger power application, UPS system	Biomedical equipment, video camera, power tool	Notebook computer, cellular phone	Ships, electric cars, grid storage

Table 5. Advantages and disadvantages of series and parallel multi-stack FCs

	Series	Parallel
Advantages	Simpler connections, low device count due to less components, less switching loss, lower cost compared to parallel structure	Each subsystem can be designed separately as individual module and combined together as needed, if one FC fails, the system will still operate, increase reliability, each FC module can be controlled separately, any faulty FC can be disconnected for replacement or maintenance without disturbing overall system
Disadvantages	Overall system will collapse if one FC module fails, voltage of FC and load are not controlled, no isolation during overload conditions if the converter is not included	Low efficiency due to more components, higher cost because of the numbers of converters, high devices count due to extra components

4.1.2 FC multi-stack power source

A single module with several cells is not suitable for high power applications. For this purpose, a higher power rating of FC would be required, where a multi-stack of FC power generation can be implemented [49 – 52]. Among several configurations of multi-stack FC, the most popular architectures are series and parallel configurations. A typical configuration of FC generating system is shown in Figure 2, which is actually similar to the multi-stack FC series structure shown in Figure 3.

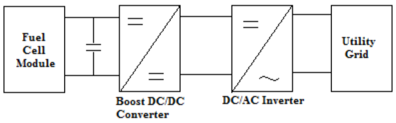

Fig. 2. Typical fuel cell generating system

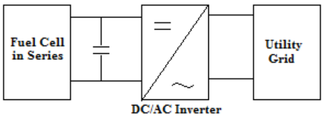

Fig. 3. Series multi-stack fuel cell generating system

These two configurations can provide similar output power, and the only difference between them is that the multi-stack FC does not require a boost converter to increase the voltage because the FC voltage in Figure 3 is enough for the inverter operation. The multi-stack FC configuration will simplify the design as a boost converter and its controller are not needed. However, the main problem with this structure is that the FC voltage is low at full-load and higher at no-load due to the variation of the voltage with the load current [50]. The problem occurs during a no-load condition where the voltage will be high, and higher-rated switches are needed. An alternative solution to overcome this problem is to connect a DC/DC voltage regulator before the inverter, which keeps the voltage at the DC-link constant, thereby removing the dependence of the inverter input voltage on the load current [51].

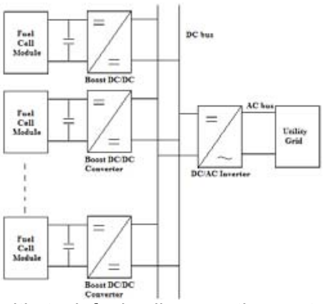

Fig. 4. Parallel multi-stack fuel cell generating system

Figure 4 shows the parallel connection of a multi-stack FC generator with a boost DC/DC converter at each module that increases the FC voltage (the output voltage of the FC is less than the voltage at the DC bus). In a parallel structure, the circulating current problem may arise when instantaneous voltages of FC are not equal. To reduce or prevent this effect, a diode should be placed at the output of every FC module to block any possible reverse current flows. Series and parallel multi-stack FCs have their own merits and drawbacks, as shown in Table 5.

4.1.3 Hybrid power system for distributed generation

Developers and power producers are developing new technology by combining several types of renewable energy to create a hybrid power system (HPS) that would improve the performance and efficiency of DG configurations [53]. HPS is characterized by the combination of two or more renewable power sources, such as PV, FC, MT, wind, and electrolyzers. Many studies related to HPS involve using FC as one of the sources aimed at improving DG operations [54 – 59]. The combination of two FC types with other renewable sources is proposed in [54] with four configurations, which are SOFC-GT, SOFC-Thermo-PV system, PEMFC-solar power, and PEMFC-wind power configurations. These structures are classified based on the need either for improving efficiency or extending the duration of the available power to the load as back-up. For low-temperature FC, the system includes the electrolyzer model, which can be used during peak load periods. In [55], an electrolyzer is also used in the hybrid wind generator, FC, and SC models to make up a long-term storage system. This hybrid system can improve the system performance by providing smooth, consistent power to counter the fluctuating power of the wind generator.

One of the most well-known HPS systems is the combination of FC with MT, which has been explored in most research papers [56 – 59]. A distribution system embedded with both MT and FC plants is proposed in [56] to analyze the load-following capability of the system. In this paper, high-temperature FC is used with a practical control strategy for the analysis of load-following services provided by both systems. Simulation results show that the proposed system can provide load-following service in the distribution system. The model in [50], which also uses hybrid MT and FC DG plant, where the FC model will control the voltage magnitude and the reactive power compensation whereas the MT offers the bulk of the load, follows the criteria. [58 – 59] also discussed HPS technology using both MT and FC as sources with several methods of control strategies.

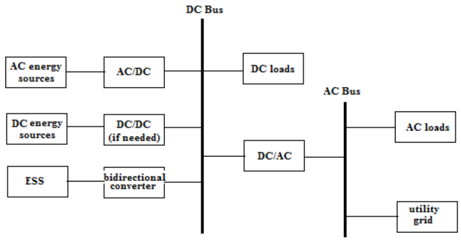

Fig. 5. DC-coupled HPS

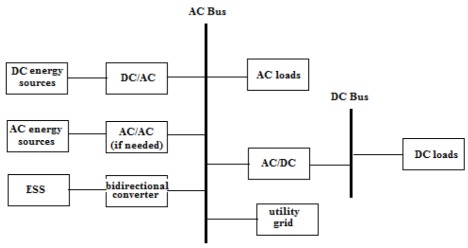

Fig. 6. AC-coupled HPS

HPS can be divided into two main configurations: are DC-coupled and AC-coupled structures [35]. In the DC-coupled structure, the different renewable energy sources are connected to a main DC-bus through appropriate power electronic interfacing circuits, shown in Figure 5. This system will be connected to the utility grid through a main DC/AC inverter [60]. Figure 6 shows a configuration of AC-coupled HPS, whereby all different renewable energy sources are connected to a main AC-bus with appropriate power electronic interfacing circuits. In this system, all the sources will be directly connected to the AC loads or the utility grid and can be connected to the DC load through the AC/DC converter. The DC-coupled and AC-coupled HPS structures in Figures 5 and 6 have several advantages and disadvantages, explained in Table 6.

Table 6. Advantages and disadvantages of DC-coupled and AC-couple HPS

	DC-Coupled	**AC-Coupled**
Advantages	Simpler configurations, no synchronization is needed between grid and sources, higher efficiency due to less conduction losses of inverter, no effects to DC bus if problem arise in the utility grid.	If one of the energy sources fails, system will still operate with the existence of utility grid, the system can utilize existing AC grid technologies, protection and also standards.
Disadvantages	If inverter fails, whole system is not able to supply AC power, problem in protection unit because there is no zero crossing point of voltage in DC system.	Synchronization is needed between the grid and sources, power factor and harmonic distortion correction are needed.

Table 7. Comparison between FC and battery [63].

Criteria	Fuel Cell	Battery
Durability	Long-term energy storage	Short-term energy storage
Power density	Higher	Lower
Charging/ Discharging rate	Not required	Frequently needed
Lifetime	Long	Short
Cost	High cost	Low cost
Output voltage stability	Constant output voltage	Current increase while voltage reduces as battery discharge
Maintenance	Yearly inspection	Regular battery inspection
Start-up	Response depends on FC types (usually takes several period to response)	Quick response (usually about 20ms)

Table 8. Future research issues of FC [66–67]

PEMFC	SOFC	MCFC	PAFC
• Guarantee long-term operation • Operates at Pressure > 1.5atm • Produce 10-20 ppm CO in long-term • Real-world situations • Lowering the cost of the catalyst and membrane	• Cost reduction • Improve system integration • Reduce operating temperature • Long-term mechanical integrity of planar system • Long-term material compatibility of planar system	• Extend stack life • Cost reduction • Increase power density • Improve performance of MCFC components • High volume manufacturing methods to increase commercialization rate • Designed using materials resistance to corrosion	• Cost reduction • Increase anode CO tolerance with operating temperature • Lowering moderate stack temperature to allow quick start-up and shutdown • Reducing the weight and size

In DG applications, the FC generating system is sometimes used as a storage device with other types of renewable energy sources. As explained earlier, FC generates DC power, similar to ESS characteristics. By applying FC as energy storage, the value of renewable energy sources will increase. A reversible SOFC system to be used as a storage device in DG system was developed in [61]. The integration of the SOFC model with a power electronic interface was also been addressed in this paper. Moreover, a design of a green building energy system, which consists of renewable energy resources, FC as energy storage device, and smart energy management, was proposed in [62]. In this design, solar energy and wind generator were used as energy resources of the building, and PEMFC system was considered as energy storage device. Simulation results showed that the energy system in the design is well-managed. The FC system is one of the best candidates as energy storage device in DG applications compared with other common energy storage systems.

Table 7 summarizes the comparison between the FC system and battery and according to Table 7, both FC and battery systems have their own strengths. On the one hand, the battery promises a quick response and offers low capital cost [63]. On the other hand, capital cost in developing FC system is high, and the start-up time for FC is quite slow. However, to overcome the slow response of the FC system, a UC module can be used; the UC module can also compensate for the immediate power fluctuations in the system [64]. A battery system needs charging and discharging processes to operate, which will shorten the lifetime of the battery. Meanwhile, the FC will not be exhausted, and no recharging process is required as long as fuel or pure hydrogen gases are continuously supplied to the anode.

5. Requirement for the FC as distributed generation

To build an FC generation system as DG, several parts need to be studied and modeled, such as the fuel reformer, FC stack, and PCUs.

5.1 Fuel cell reformer

The FC needs oxygen and hydrogen to produce electricity. The oxygen required for FCs comes from the air and pumped into the cathode. The hydrogen is not readily available because it needs to be processed first to obtain pure hydrogen. Hydrogen is difficult to store and distribute. A more convenient approach is for FCs to use fuels that are more readily available. This problem is addressed by a device called a reformer [65]. Unfortunately, reformers are not perfect. They generate heat and produce other gases other than hydrogen. Various devices are used to try to clean up the hydrogen, but even so, the hydrogen that comes out of them is not pure, and this lowers the efficiency of the FC. FC efficiency will also decrease when connected to a high load.

5.2 FC stack

Designing the FC stack depends on the types of the FC itself because different types of FC have their own criteria and operations. Main disadvantage of FC stack is its high capital cost [66] so recent research focuses more on reducing the cost, enhancing the performance of FC and in FC stack development. Focus is also given to various issues, such as preventing severe membrane damage in FC, controlling the large deviations of pressure between electrodes, and controlling the feedback load currents of the FC. Table 8 indicates future research issues involving the four types of FCs.

5.3 Power Conditioning Unit

The FC produces unregulated DC power and cannot be directly used in power applications. The PCU's function is to convert the unregulated DC power source from the FC generator into the required AC level in grid-connected configuration. The major advantages of the PCU design are high efficiency, low ripple current value (by affecting the life span of the FC), electrical isolation, lower cost, high gain (due to the low DC voltage), inverter current control, power grid integration, and reliable operation. Any ripple in the input current and voltage needs to be limited to a small value to reduce the effects on the output current and voltage of the FC [67]. The PCU consists of two main structures: single-stage DC/AC conversion and multi-stage DC/AC conversion [68]. Single-stage DC/AC conversion converts DC power directly into AC power using a DC/AC inverter, whereas in multi-stage DC/AC conversion, a DC/DC converter is located in front of a DC/AC inverter to increase the DC power of the FC generator. Multi-stage conversion is more suitable for FC generation because the FC normally generates low voltage output [69]. Moreover, multi-stage conversion provides isolation between low and high power in a DG system; this feature is important in system protection and for safety purposes. However, the drawbacks of multi-stage conversion, such as high switching loss, low efficiency due to more components, and high-frequency ripples, need to be tackled. Thyristor-based converters were used during the olden days, but this type of converter generates power quality issues, such as harmonics, which affect the DG system. A recent development using high-speed power electronic switches, such as the bipolar junction transistor (BJT), metal-oxide semiconductor field effect transistor (MOSFET), insulated gate bipolar transistor (IGBT), and MOS-controlled thyristor (MCT), has significantly reduced the harmonics problem. The following are issues related to PCUs:

i. DC/DC boost converter

Additional challenges in designing a DC/DC converter include low efficiency and lower converter capacity. Two major objectives in DC/DC converter design are efficiency enhancement and cost reduction [14]. Switching semiconductor devices will determine the cost, so the design will be more focused on converter topology with less switching components. However, this will add complication to the control schemes. Power electronic converter efficiency is determined by the conduction and switching losses [69]; therefore, to improve efficiency, more advanced semiconductors can be used with less conducting and switching losses. Conduction loss is determined by a voltage drop across the device and can be reduced by reducing the usage of the components and operating ranges. Switching loss can be reduced using soft switching techniques, such as zero voltage crossing or zero current crossing. For the limited power rating issues, one of the solutions is to connect smaller DC/DC converters in parallel, and current sharing techniques [70 – 72] need to be studied for parallel power converters because uneven current sharing may result in unbalanced thermal stress, inductor saturation, and also degradation of the converter performance. This issue is also valid for DC/AC inverters.

ii. Synchronization with the utility grid

The PCU must synchronize the frequency of the FC power system with the utility grid to achieve better performance of the system in grid-connected mode. Renewable energy, such as energy obtained from FCs, normally has a slow response and less inertia. However, the existing power system has storage in the generators' inertia, and this will draw a slight frequency reduction in the system. Using ESS can address this issue. Other than that, a better controller can also manage this problem because the frequency of the AC voltage and current for the FC system are established by the inverter controls.

iii. Voltage disturbances

As the injected power of grid-connected DG increases, the power quality and overall system's reliability decline due to voltage rises, voltage sags, and also voltage harmonics problems. A voltage rise effect occurs when extra DGs are connected in a low demand period. By controlling the power factor, reducing the resistance of the lines in the DG, increasing system reactive power, reducing the substation voltage setting, and applying a ring-operated distribution network with respect to DG interconnection, the voltage rise problem can be settled [73]. Other than voltage rise, voltage sag is one of the difficulties occurring in a DG system when disconnection happens in a large DG penetration level. Some researchers used a fuzzy control system as a high-level control algorithm. Fuzzy control manages the power flow to determine the proper power level between the FC stack and energy storage, which allows the system to operate properly when voltage sag occurs in a distributed system and allows the DG system to stay connected to the utility grid [43, 74]. Voltage harmonics is a common problem in a DG system because renewable sources are based on voltage-source converter technology, which will always introduce harmonics in the system to which it is interconnected. All of these mentioned challenges can be managed through a local controller to monitor and control the DG system.

5.4 Control strategies

The output of the FC generator is DC power and is usually supplied to the grid via an inverter at a constant DC level obtained through a boost converter. This PCU configuration is very important to meet the overall system operational requirements. When involving power electronic components, a control scheme is needed to maintain system stability. Various types of control techniques are available and applied in DG configurations, with the most common controllers being droop, PID, and advanced controllers.

5.4.1 Droop control

Droop control is one of the most popular methods used in DG systems to control DG terminal voltage; it is well-known as "real power versus frequency" and "reactive power versus voltage" droop control [75]. The droop control method is based on the flow of power between two nodes. Figure 7 shows an equivalent circuit of an inverter connected to a common bus separated by a line impedance defined as X.

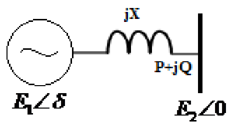

Fig. 7. Power flow in grid connected mode

The power flows into a power line at the terminal; P equals the real power, and Q is the reactive power. Equations can be expressed as

$$(2)\quad P = \frac{3E_1E_2}{X}\sin\delta$$

$$(3)\quad Q = \frac{3E_2}{X}\left(E_1\cos\delta - E_2\right)$$

where *δ* is the power or phase angle, *X* is the magnitude of transmission line impedance, E_1 is the output voltage of inverter, and E_2 is the bus voltage. By considering that the phase angle difference is small, then the small angle formula can be used; thus, sin *δ* = *δ* and cos *δ* = 1. After simplifying the equations, the real power becomes proportional to the phase angle, whereas the reactive power is proportional to the difference of the voltage magnitude. By varying the output frequency and phase angle, the real power is controlled; by altering the output voltage magnitude, reactive power can also be controlled. In [22 – 23], two control loops for load-frequency droop control techniques to enhance the stability in FC based DG systems were developed. Their control scheme aimed for the primary loop to maintain the constant ratio of the stack current to the input fuel flow by controlling the fuel input. By controlling the PCU, the secondary loop could regulate the frequency, and thus track the load. Both loops were for grid-connected DG and did not consider the operation during islanded mode. A new control strategy with load-voltage control was introduced in [76]. The frequency was fixed so frequency droop control was not appropriate. Load-frequency control used frequency variation to determine the power to put into the system. In the load-voltage droop scheme, the system responds to change in current demand with the frequency value stabilized by the inverter. However, this control scheme is for standalone MG and those not connected to the grid. One main advantage of droop control is its easy application in parallel for a number of sources; it is suitable for controlling several inverters in a parallel structure. Several drawbacks of the droop control scheme are the unbalanced harmonic current sharing, limited transient response, and also the fact that it depends on inverter output impedance. These drawbacks can be solved by applying more advanced or modified droop control as available in [77 – 78].

5.4.2 PID controller

The PID controller, which consists of proportional (P), integral (I), and derivative (D) elements, is commonly used in controlling power electronic interfaces in a DG system. This controller can work on either a single element or combination between the three elements, such as PI, PD, as well as PID. In a DG system, the PI controller is widely used by researchers [79 – 81] to control the firing angle (δ) and the modulation index (m) of the converter, as shown in Figure 8.

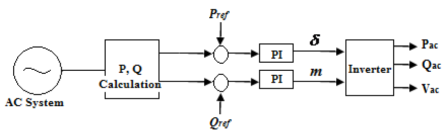

Fig. 8. Basic structure of inverter control using PI controller

Normally, in a voltage source inverter, power control can be achieved by controlling the firing angle, and two PI controllers are sufficient to control the flow of real and reactive powers in power system applications. Research in [79] focused on the modeling, control, and simulation of the PEM FC-based power supply for residential applications. PI-type voltage and active power controllers were implemented by controlling the fuel input to the FC stack and by adjusting the inverter modulation index. Nehrir et al. [80] also presented modeling and control of the PEMFC-based DG system feeding to the AC grid with real and reactive power control capability using conventional PI controller for DC/DC converters and a direct quadrature transformed two-loop current control scheme for the inverter. PI controllers were also used in [81] to control real and reactive power in DC/DC boost converters and sinusoidal pulse width-modulation two-level inverters in PEMFC-based DG models. The main objectives of [81] were to regulate the output voltage from the boost converter and also to alter the output voltage of the inverter at different loading conditions. The PID controller is also used in controlling the DC/DC converter and DC/AC inverter such as in [10]; their results showed that the total harmonic distortion (THD) level for both voltage and current are definitely low.

Most researchers used a PI/PID controller to control three phase inverters, boost converters, and the fuel input to the FC stack. This controller type can perform perfectly under linear and balanced load conditions, and a properly tuned PI/PID controller has been proven to deliver a small value of THD output voltages and current. However, problems arise when the system has to deal with unbalanced linear loads and nonlinear loads where satisfactory performance is not achieved. Moreover, a sluggishness and lack of efficiency in handling the system non-linearity are also other limitations of this type of controller.

5.4.3 Advanced controller

To overcome the lack of conventional control techniques, advanced control methods, such as fuzzy logic control, sliding mode control (SMC), and adaptive discrete time control, look attractive and promise better performance in DG applications. A design of fuzzy logic controller was proposed in [82] and [42] with various types of fuzzy logic design. Jurado et al. presented a design of fuzzy controller using the flux vector control method for the inverter to regulate its terminal voltages [82]. In [42], a Lyapunov-based neuro-fuzzy algorithm was presented to control the FC power plant, DC/DC, and DC/AC converters to control the input fuel flow. However, a fuzzy controller is unable to react to a system with fast dynamic response in DG application, and normally, an advanced controller requires a complex control algorithm, which presents major difficulties in designing a DG system.

The DG control strategy is the main issue closely related to DG applications. Although many control strategies have been introduced and applied, the DG system still has weaknesses. Power quality issues are also important as power electronic converters produce a high level of harmonics in network voltage and current. For this reason, a new or improved control scheme needs to be designed to increase the DG stability as well as its performance. Meanwhile, the control methodologies applied to control the operation of the DC/DC converter, single-phase, and three-phase inverters used in the DG system should be improved. The control strategy in DG applications must take into consideration the type of loads connected: whether they are unbalanced or balanced linear loads, nonlinear loads, sensitive or critical loads, and other types of load. The control strategy must have the ability to control the harmonics produced by the loads and supply enough local generation to meet the demands of the sensitive loads. Other research problems, such as handling inherent uncertainties of renewable sources and also the hierarchical control strategy, must be addressed to support the future DG system. A proper control strategy will solve some issues related to DG, such as dealing with the large transient problem occurring during the transition period, which limits the ripple in input current/voltage to a low level and reduces the effects on the output current/voltage of the fuel cell. A proper control strategy would also ensure that the PCU can synchronize the frequency of the FC power system with that of the grid.

6. Conclusion

The objective of this paper is to provide a general literature review of fuel cell technology as a distributed generation. In this paper, DG applications with four main FC types, namely, PEMFC, PAFC, SOFC, and MCFC, are discussed, and explanations of dynamic models of each type have been given. The components of FC generation-based DG systems, such as the reformer, FC stack, PCU, control strategy, and ESS, together with several issues and challenges, are also discussed. FC technology still suffers from the high initial and capital cost, which reduces any interest in applying FC in DG. However, with sufficient studies in reducing the capital cost and improving the performance of FC, FC will become a successful candidate in electricity generation. The review indicates that improvement in every component of the DG is required for better performance in the future.

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REFERENCES

[1] Guerrero J.M., Blaabjerg F., Zhelev T., Hemmes K., Monmasson E., Jemei S., Comech M. P., Granadino R., Frau J. I, Distributed generation: toward a new energy paradigm, *Industrial Electronics Magazine IEEE*, 4(2010), No.1, 52-64

[2] Nehrir M.H., Wang C., Shaw S.R., Fuel cells: promising devices for distributed generation, *IEEE Power and Energy Magazine,* 4(2006), No. 1, 47-53

[3] Carlson E., Zogg R., Sriramulu S., Roth K., Brodrick J., Emerging technologies: using phosphoric-acid fuel cells, *ASHRAE Journal*, 1(2007),No.1, 50-51

[4] Kristina H., On direct hydrogen fuel cell vehicles-modelling and demonstration, Doctoral Thesis, Department of Chemical Engineering and Technology, KTH- Royal Institute of Technology, Stockholm, Sweden, 2005.

[5] El-Sharkh M.Y., Rahman A., Alam M. S., Byrne P. C., Sakla A.A., Thomas T., A dynamic model for a stand-alone PEM fuel cell power plant for residential applications, *Journal of Power Sources*, 138(2004), No.1-2, 199-204

[6] Pathapati P.R., Xue X., Tang J., A new dynamic model for predicting transient phenomena in a PEM fuel cell system, *Renewable Energy*, 30(2005), No.1, 1-22

[7] Uzunoglu M., Alam M.S., Dynamic modeling, design, and simulation of a combined PEM fuel cell and ultracapacitor system for stand-alone residential applications, *Energy Conversion, IEEE Transactions*, 21(2006), No.3, 767-775

[8] Bibin H., Peng L., Dan W., Fei D., Chengshan W., Modeling and analysis of PEMFC in distributed generation system in sustainable power generation and supply, *SUPERGEN '09. International Conference*, 1(2009),No.1, 1-5

[9] Jia J., Yang S., Wang Y., Cham Y. T., Matlab/Simulink based-study on PEM fuel cell and nonlinear control, *IEEE International Conference*, 1(2009), No.1, 1657-1662

[10] Younis M. A. A., Rahim N.A., Mekhilef S., Dynamic and control of fuel cell system, *Industrial electronics and applications, ICIEA 2008, IEEE Conference*, 1(2008), No.1, 2063-2067

[11] Georgakis D., Papathanassiou S., Manias S., Modeling and control of a small scale grid-connected PEM fuel cell system, *Power Electronics Specialists Conference, PESC '05. IEEE 36th.*, 1(2005), No.1, 1614-1620

[12] Tesfahunegn S.G., Vie P.J.S., Undeland T.M., A combined steady state and dynamic model of a proton exchange membrane fuel cell for use in DG system simulation, *Power Electronics Conference (IPEC), 2010 International*, 1(2010), No.1, 2457-2464

[13] Vielstich W., Lamm A., Gasteiger H.A., Handbook of fuel cells: fundamentals, technology, applications, Wiley, 2003.

[14] Nehrir M. H., Wang C., Modeling and control of fuel cells-distributed eneration applications, New Jersey, Wiley, 2009.

[15] W H., Dynamic model for molten carbonate fuel-cell power-generation system, *Energy Conversion and Management*, 39(1998), No.1, 775-783

[16] Lukas M.D., Lee K.Y., Ghezel-Ayagh H., Development of a stack simulation model for control study on direct reforming molten carbonate fuel cell power plan, *Energy Conversion, IEEE Transactions*, 14(1999), No.4, 1651-1657

[17] Lukas M.D., Lee K.Y., Ghezel-Ayagh H., An explicit dynamic model for direct reforming carbonate fuel cell stack, *Energy Conversion, IEEE Transactions*, 16(2001), No.3, 289-295

[18] Lukas M.D., Lee K.Y., Ghezel-Ayagh H., Reduced-order dynamic model of carbonate fuel cell system for distributed generation control, *Power Engineering Society Summer Meeting, IEEE*, 4(2000), No.1, 1965-1969

[19] Leto L., Dispenza C., Moreno A., Calabrò A., Simulation model of a molten carbonate fuel cell–microturbine hybrid system, *Applied Thermal Engineering,* 31(2011), No.6-7, 1263-1271

[20] Zogg R., Sriramulu S., Carlson E., Roth K., Brodrick J., Emerging technologies: using solid-oxide fuel cells for distributed generation, *ASHRAE J.I*, 1(2006), No. 1, 116-118

[21] Hall D.J., Colclaser R.G., Transient modeling and simulation of a tubular solid oxide fuel cell, *Energy Conversion, IEEE Transactions*, 14(1999), No.3, 749-753

[22] Sedghisigarchi K., Feliachi A., Dynamic and transient analysis of power distribution systems with fuel Cells-part I: fuel-cell dynamic model, *IEEE Transactions on Energy Conversion*, 19(2004), No.2, 423-428

[23] Sedghisigarchi K., Feliachi A, Dynamic and transient analysis of power distribution systems with fuel Cells-part II: control and stability enhancement, *IEEE Transactions on Energy Conversion*, 19(2004), No.2, 429-434

[24] Li Y.H., Rajakaruna S., Choi S.S., Control of a solid oxide fuel cell power plant in a grid-connected system, *Energy Conversion, IEEE Transactions*, 22(2007), No.2, 405-413

[25] Li Y.H., Choi S.S., Rajakaruna S., An analysis of the control and operation of a solid oxide fuel-cell power plant in an isolated system, *Energy Conversion, IEEE Transactions*, 20(2005), No.2, 381-387

[26] Padullés J., Ault G.W., McDonald J.R., An integrated SOFC plant dynamic model for power systems simulation, *Journal of Power Sources*, 86(2000), No.1-2, 495-500

[27] Wang C., Nehrir M.H., A physically-based dynamic model for solid oxide fuel cells, *IEEE Trans. Energy Conversion*., 22(2007), No.4, 887-897

[28] Liu Y.H, Wu Z.Q., Brandon N.P., Application of SOFCs to electric power system, *Power and Energy Engineering Conference (APPEEC), Asia-Pacific*, 1(2011), No.1, 1-4

[29] Hatziadoniu C.J., Lobo A.A., Pourboghrat F., Daneshdoost M., A simplified dynamic model of grid-connected fuel-cell generators, *Power Delivery, IEEE Transactions*, 17(2002), No.2, 467-473

[30] Fleming E.M., Hiskens I.A., Dynamics of micro grid supplied by solid oxide fuel cells, *Bulk Power Systems Dynamics and Control VII*, 1(2007), No.1, 1-10

[31] Francisco J., Manuel V., Manuel G., Identification of hammerstein model for solid oxide fuel cells, *Electrical and Computer Engineering, CCECE '06. Canadian Conference,* 1(2006), No.1, 442 - 445, 2006.

[32] Yutong Q., Biao H., Jingli L., Nonlinear state space modeling and simulation of a SOFC fuel cell, *American Control Conference*, 1,(2006), No.1, 2534-2538

[33] Andújar J.M., Segura F., Fuel cells: history and updating. A walk along two centuries, *Renewable and Sustainable Energy Reviews*, 13(2009), No.9, 2309-2322

[34] Choudhury S.R., Deshmukh M.B., Rengaswamy R., A two-dimensional steady-state model for phosphoric acid fuel cells (PAFC), *J. Power Sources*, 112(2002), No.1, 137–152

[35] Davat B., et al., Fuel cell-based hybrid systems, *Advanced Electromechanical Motion Systems & Electric Drives Joint Symposium, ELECTROMOTION 2009. 8th International Symposium,* 1(2009), No.1, 1-11

[36] Fadali H., Fuel cell distributed generation: power conditioning, control and energy management, Master thesis, University of Waterloo, Ontario, Canada, 2008.

[37] Liu F., Liu J., Zhou L., A novel control strategy for hybrid energy storage system to relieve battery stress, *Power Electronics for Distributed Generation Systems (PEDG), 2010 2nd IEEE International Symposium,* 1(2010), No.1, 929-934

[38] Garcia F.S., Ferreira A.A., Pomilio J.A., Control strategy for battery-ultracapacitor hybrid energy storage system, *Applied Power Electronics Conference and Exposition, APEC 2009. Twenty-Fourth Annual IEEE,* 1(2009), No.1, 826-832

[39] Gao L., Dougal R.A., Liu S., Active power sharing in hybrid battery/capacitor power sources, *Applied Power Electronics Conference and Exposition, APEC '03. Eighteenth Annual IEEE*, 1(2003), No.1, 497-503

[40] Dai H., Chang X., A study on lead acid battery and ultra-capacitor hybrid energy storage system for hybrid city bus,

Optoelectronics and Image Processing (ICOIP), International Conference, 1(2010), No.1, 154-159
[41] Azib T., Talj R., Bethoux O., Marchand C.T., Sliding mode control and simulation of a hybrid fuel-cell ultracapacitor power system, *Industrial Electronics (ISIE), IEEE International Symposium,* 1(2010), No.1, 3425–3430
[42] Hajizadeh A., Golkar M.A., Fuzzy neural control of a hybrid fuel cell/battery distributed power generation system, *IET Renewable Power Generation,* 3(2009), No.4, 402–414
[43] Hajizadeh A., Golkar M.A., Control of hybrid fuel cell/energy storage distributed generation system against voltage sag, *International Journal of Electric Power and Energy Systems,* 32(2010), No.1, 488-497
[44] Jiang Z., Gao L., Blackwelder M.J., Dougal R.A., Design and experimental tests of control strategies for active hybrid fuel cell/battery power sources, *J. Power Sources*, 130(2004), No.1-2, 163-171
[45] Thounthong P., Raël S., and Davat B., Test of a PEM fuel cell with low voltage static converter, *J. Power Sources*, 153(2006), No.1, 145-150
[46] Garcia-Arregui M., Turpin C., Astier S., Direct connection between a fuel cell and ultracapacitors, *Clean Electrical Power, 2007. ICCEP '07. International Conf.,* 1(2007), No.1, 474-479
[47] Divya K.C, Østergaard J., Battery energy storage technology for power systems - an overview, *Electric Power Systems Research*, 79(2009), No.4, 511-520
[48] Coppez G., Chowdhury S., Chowdhury S.P., Review of battery storage optimisation in distributed generation, *Power Electronics, Drives and Energy Systems & 2010 Power India, 2010 Joint International Conference,* 1(2010), No.1, 1-6
[49] Garnier J., De Bernardinis A., Péra M.C., Hissel D., Candusso D., Kauffmann J.M., Coquery G., Study of a PEFC power generator modular architecture based on a multi-stack association, *J. of Power Sources*, 156(2006), No.1, 108-113
[50] Ozpineci B., Tolbert L.M., Zhong D., Multiple input converters for fuel cells, *Industry Applications Conference, 39th IAS Annual Meeting, Conference Record of the 2004 IEEE*, 2(2004), No.1, 791–797
[51] Ozpineci B., et al., Integrating multiple solid oxide fuel cell modules, *Industrial Electronics Society, IECON '03. The 29th Annual Conference of the IEEE,* 2(2003), No.1, 1568-1573
[52] Candusso D., De Bernardinis A., Péra M.C., Harel F., François X., Hissel D., Coquery G., Kauffmann J.M., Fuel cell operation under degraded working modes and study of diode by-pass circuit dedicated to multi-stack association, *Energy Conversion and Management*, 49(2008), No.4, 880-895
[53] Paska J., Biczel P., Klos M., Hybrid power systems – an effective way of utilising primary energy sources, *Journal of Renewable Energy*, 34(2009), No.11, 2414–2421
[54] Rajashekara K., Hybrid fuel cell strategies for clean power generation, *Industry Applications Conference, 39th IAS Annual Meeting, Conference Record of the 2004 IEEE*, 41(2004), No.3, 682–689
[55] François B., Hissel D., Iqbal M.T., Dynamic modelling of a fuel cell and wind turbine DC-linked power system, *Electrimacs Conference 2005*, 1(2005), No.1, 1-6
[56] Zhu Y., Tomsovic K., Development of models for analyzing the load-following performance of micro-turbines and fuel cells, *Electric Power Systems Research*, 62(2001), No.1, 1-11
[57] Ghasemi N., Abedi M., Rastegar H., Gharepetian G., Hybrid distributed generation units PEM fuel cell and microturbine in industrial technology, *ICIT 2008, IEEE International Conference,* 1(2008), No.1, 1-6
[58] Soliman M., Ahmed M.M.R., Safiuddin M., Modeling of fuel cell/microturbine generation scheme with battery storage, *Electric Power and Energy Conference (EPEC), IEEE*, 1(2010), No.1, 1-6
[59] Azmy A.M., Erlich I., Dynamic simulation of fuel cells and micro-turbines integrated with a multi-machine network, *The 2003 IEEE Bologna Power Tech Conf.,* 2(2003), No.1, 1-6
[60] Zhou T., Lu D., Fakham H., François B., Power flow control in different time scales for a wind/hydrogen/supercapacitors based active hybrid power system, *Proc. 13th International Power Electronics and Motion Control Conf., EPE-PEMC 2008, Poznan, Poland,* 1(2008), No.1, 2205-2210
[61] Ren J., Roscoe A.J., Gamble S., Burt G., Modelling a reversible solid oxide fuel cell to be used as a storage device within AC power networks*, Power Electronics, Machines and Drives (PEMD 2010), 5th IET International Conference,* 2(2010), No.CP563, 697-702
[62] Zhenhua J., Rahimi-Eichi H., Design, modeling and simulation of a green building energy system, *Power & Energy Society General Meeting, PES '09. IEEE,* 1(2009), No.1, 1-7
[63] Thomas J., Johan B., Suitability of fuel cell technology for electricity utility standby power applications, *Telecommunications Energy Conference, INTELEC '06. 28th Annual International*, 1(2006), No.1, 1-7
[64] Choi W., Enjeti P., Howze J.W., Fuel cell powered UPS systems: design considerations*, Power Electronics Specialist Conference, PESC '03. 2003 IEEE 34th Annual,* 1(2003), No.1, 385-390
[65] O'Hayre R., Suk-Won C., Whitney C., Prinz F.B., Fuel Cell Fundamental, Wiley, 2008
[66] Jung J.W., Modeling And Control Of Fuel Cell Based Distributed Generation Systems, PhD thesis, The Ohio State University, 2005
[67] Xinhong H., Zhihao Z., Jin J., Fuel cell technology for distributed generation: an overview, *Industrial Electronics, IEEE International Symposium,* 2(2006), No.1, 1613-1618
[68] Blaabjerg F., Chen Z., Kjaer S.B., Power electronics as efficient interface in dispersed power generation systems, *IEEE Trans Power Electronics*, 19(2004), No.5, 1184–1194
[69] Kirubakaran A., Jain S., Nema R.K., A review on fuel cell technologies and power electronic interface, *Renewable and Sustainable Energy Reviews*, 13(2009), No.9, 2430-2440
[70] Thottuvelil V.J., Verghese G.E., Analysis and control design of paralleled DC/DC converters with current sharing, *IEEE Transactions on Power Electronics,* 13(1998), No.4, 635-644
[71] Panov Y., Jovanoiv M.M., Stability and dynamic performance of current-sharing control for paralleled voltage regulator modules, *IEEE Trans. on Power Electronics,* 17(2002), No.1, 172-179
[72] Ponjavic M., Djuric R., Current sharing for synchronized DC/DC operating in discontinuous condition mode, *IEEE Proceedings on Electric Power Applications,* 152(2005), No.1, 119-127
[73] Mahmud M.A., Hossain M.J., Pota H.R., Analysis of voltage rise effect on distribution network with distributed generation, *Proceedings of the 18th IFAC World Congress,* 1(2011), No.1, 14796-14801
[74] Hajizadeh A., Golkar M.A., Intelligent robust control of hybrid distributed generation system under voltage sag, *Expert Systems with Applications*, 37(2010), No.12, 7627-7638
[75] Chandorkar M.C., Divan D.M., Adapa R., Control of parallel connected inverters in standalone AC supply systems, *IEEE Trans. Ind. Appl.,* 29(1993), No.1, 136–143
[76] Zhang Z., Jiang J., Huang X., Wu B., Dynamic characteristics of a micro-grid involving a PEM fuel cell power module, *IEEE International Symposium on Industrial Electronics (ISIE06),* 3(2006), No.1, 2030-2034
[77] Katiraei F., Iravani M.R., Power management strategies for a microgrid with multiple distributed generation units, *IEEE Trans. Power Syst.,* 21(2006), No.4, 1821–1831
[78] Mohamed Y.A-R.I., El-Saadany E.F., Adaptive decentralized droop controller to preserve power sharing stability of paralleled inverters in distributed generation microgrids, *IEEE Trans. Power Electron*., 23(2008), No.6, 2806–2816
[79] Tanrioven M., Alam M.S., Modeling, control, and power quality evaluation of a PEM fuel cell-based power supply system for residential use, *IEEE Transactions on Industry Applications,* 42(2006), No.6, 1582-1589
[80] Nehrir M.H., Wang C., Gao H., Control of PEM fuel cell distributed generation systems, *IEEE Transactions on Energy Conversion*, 21(2006), No.2, 586- 595
[81] Ghareeb W.T., Bendary F.M., Saied E.M., Hegazy Y.G., Investigating the performance of a fuel cell based distributed generation system, *Energy Conference and Exhibition (EnergyCon), IEEE International,* 1(2010), No.1, 462-467
[82] Jurado F., Ortega M., Carpio J., Power quality enhancement in fuel cells using genetic algorithms and ANFIS architecture, *Industrial Electronics, IEEE International Symposium,* 2(2006), No.1, 757–762

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