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An overview of grid-connected fuel cell system for grid support

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Abstract

Fuel cell (FC) technology has become popular recently for its low-carbon characteristics. Depending on the different structures of the system and controls of the converter, grid-connected FC systems can achieve various goals in supporting the grid. Grid-following (GFL) and grid-forming (GFM) control are normally used for the controller of converters. In this paper, an overview of how the grid-connected FC system can support the grid is presented. The basic grid-connected FC system operation principles are firstly introduced, followed by the comparisons between FC and batteries, which shows the advantages and disadvantages of the FC system. Different functions of the FC system are then reviewed. Renewable sources, particularly wind turbines and photovoltaic farms, have some problems in the integration with the grid during the insufficient wind speed or radians, and FC systems can help renewables achieve better integration with the grid. Moreover, FC cannot only balance the system power as a primary energy source, but provide voltage support during system contingencies as well. Nevertheless, the FC system has some problems with oscillation and harmonics. Finally, the challenges of grid-connected FC systems are presented.

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Keywords: Fuel cell; Grid-connected converter; Grid support; Renewable sources

1. Introduction

Renewable energy systems (RES) have aroused people's attention during the past decades. Different types of energy sources are discovered to support the grid. Fuel cell (FC), wind turbine (WT), and photovoltaic (PV) are very promising technologies in RES [1]. Among these technologies, the FC system has advantages in its cleanness and efficiency, which have become promising and attractive these years [2]. Different from traditional generators, FC does not have moving parts, which means the FC system is very quiet. What is more, traditional generators need a combustion engine to be a prime mover with producing greenhouse gases, while FC is very clean because it does not have those emission gases.

To connect FC with the grid, the DC/DC converters and the controlled voltage source converters (VSC) are required, where the control method determines the role and the performance of the system. Since this paper focuses

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more on the grid-connected operation, DC/DC converters will not be discovered. As for VSC, Grid-following (GFL) converters have been well researched and implemented into the grid for many years. It needs a synchronization unit, normally the phase lock loop (PLL), to estimate the angle of the grid voltage at every moment and output power by injecting active and reactive current to the power system [3]. Therefore, it can be regarded as a current source relying on the synchronization unit from the perspective of the grid, which means it cannot be used in islanding operations. Different from GFL, grid-forming (GFM) converters can output power by controlling the output voltage angle and magnitude. The main advantage of GFM control is its ability to decouple the active power and reactive power control. Some GFM topologies, such as virtual synchronous generator (VSG) with filter-based droop control [4–6], do not need PLL to synchronize with the grid. In the other GFM controls with PLL, the difference between the output power and reference power during a frequency variation can be eliminated by the PLL [7].

FC system is usually not reversible and can only provide power rather than absorb power [8]. Since the GFM control requires the system have the ability to provide and store extra energy from the grid, the additional energy storage determines the grid forming capability of the FC system [9,10]. For example, in over frequency scenarios, the FC system requires an additional energy storage unit to achieve the frequency regulation. This unit can be a power buffer, such as an ultracapacitor (UC), a battery bank or an electrolyzer (ELZ). Moreover, the additional energy storage can also be used to store excess energy from renewable sources to reduce power fluctuations and meet unexpected power demand with a relatively fast response.

The aim of this work is to summarize and overview the controlled VSC-based grid-connected FC system. The main focus is on the various functions the system can have. The rest of the paper is organized as follows. The second section will introduce the basics of the FC system and the comparisons between FC and batteries. The third section summarizes the functions and operations of the FC system in supporting the grid, which includes renewables integration, power balance support, voltage support during contingency and the solutions to solve problems of harmonics and oscillations. The fourth section is the current challenges of the FC system and the last section draws the conclusion.

2. Grid-connected fuel cell system

2.1. Basics of fuel cell

The operation principle of the fuel cell is to generate electricity with the fuel as input. The difference between a battery and a fuel cell is that the fuel cell is not consumed and it can be regarded as a machine to transform the chemical energy from the fuel sources into electricity [8]. Proton exchange membrane fuel cell (PEMFC) and solid-oxide fuel cell (SOFC) are two very popular types of FC. Fig. 1 shows the basic structure (a) and characteristics (b) of a fuel cell.

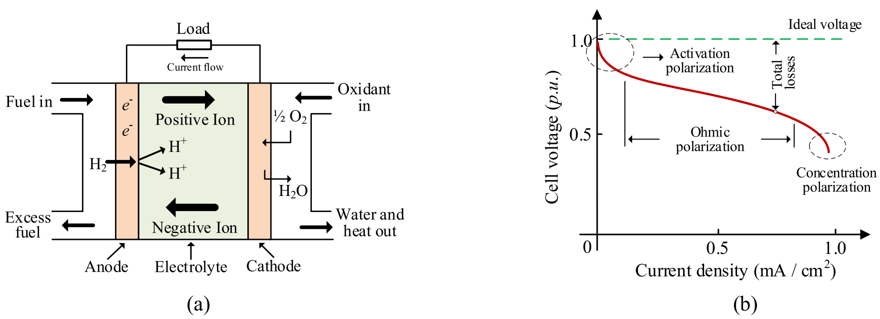

Fig. 1. Fuel cell basics [8]. (a) The structure of a fuel cell. (b) The i–V curve of a fuel cell.

From Fig. 1(a), it can be seen that the hydrogen combustion reaction can be divided into two reactions. The electrons are not allowed to pass through the electrolyte, and this pushes them to flow through the external circuit, i.e., forming the current. In the meantime, the ions flow through the electrolyte. These reactions transform the input hydrogen and oxygen into water, heat and electricity [8].

Fig. 1(b) presents the typical i–V curve of a fuel cell. From Fig. 1(b), the cell voltage will experience a drop when the current increases. The ohmic polarization is a very common operation region where the drop of the voltage

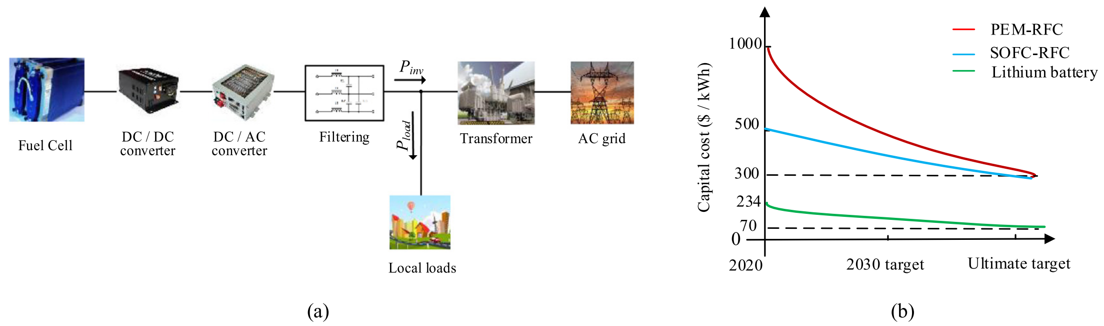

Fig. 2. FC integration and cost. (a) FC integration. (b) Cost reductions of fuel cell and battery [13,14].

is mainly due to the ionic and electronic conduction in the cell. The voltage drop of the fuel cell could lead to a reduction of the DC voltage if there are no proper DC voltage regulation schemes, leading to the overmodulation of the converter between the AC grid and the fuel cell. This will be discussed later. Normally, the main components of an FC system include fuel cell stacks, DC/AC converter, filters, other sources or devices (optional) DC/DC converters (optional) and the grid, which is shown in Fig. 2(a).

2.2. Fuel cell vs battery

When compared with batteries, FC has advantages in energy density [8,11]. If the application requires a large amount of power, the battery stack will become heavy, which may not suit some applications like large-size transportation or shipping. Moreover, FC does not need much time to recharge, because it can operate as long as the fuel source is provided quickly and the refuelling process is fast. For example, an FC based electric vehicle (EV) can be refuelled in 3–5 min which is superior to the recharging of a battery EV [12].

However, the battery also has advantages over the FC. The first merit is efficiency. According to the report provided by Volkswagen [15], the overall efficiency (considering the production of hydrogen and process of compression, liquefaction and filling system) of FC-based EV is only about half of the battery-based EV. Besides, the cost is another advantage for batteries. Currently, the fuel cell is still more expensive than the battery. However, with the development of technology, the price of the FC system is expected to go down significantly in the following decades. Reversible fuel cell (RFC) is the application that combines fuel cell and ELZ, which have the ability to absorb power to generate hydrogen for a fuel cell. Therefore, its function can be seen as the same as a battery. Authors in [14] presented the cost reduction of PEM-RFC and SOFC-RFC, while other researchers in [13] indicated the price of lithium batteries. Fig. 2(b) summarizes the statistics and shows the trend of cost reduction of RFC systems and lithium batteries. In summary, FC has advantages in refuelling time and higher energy density, while battery currently has higher efficiency and lower cost.

2.3. Grid-forming controls and grid-following controls

GFL control usually requires a PLL that detects the grid voltage's amplitude and angle. The angle is used for the d-q transformation and the transformed d-q components can generate the reference current for the current controller according to the reference power [16]. It can control the output power by directly adjusting the output current i_o. For GFM control, it has decoupled active/reactive power regulation. The active power control can adjust the output voltage's angle, while the reactive power control determines the magnitude of that voltage. Fig. 3(a) shows a typical GFL based FC system, and (b) is the system with GFM control.

From the view of the grid, GFL converters act as a current source with a high parallel impedance, while GFM converters operate like a voltage source with a low series impedance [17]. The advantage for GFL converters is the fast response time due to their low inertia, so they usually are regulated by the maximum power point tracking (MPPT) controller, which provides the reference active and reactive power [3]. Since the GFL requires PLL, it cannot operate in island mode if there are no local synchronous generators or GFM converter-based sources providing

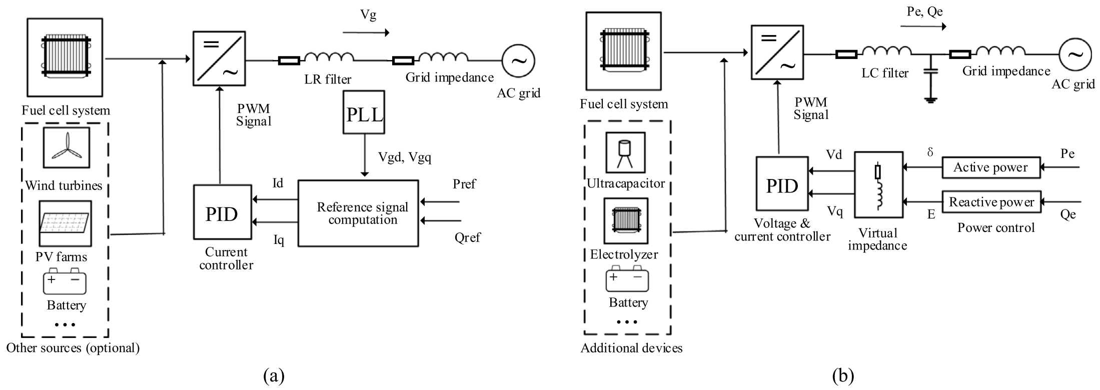

Fig. 3. Typical structures of GFL and GFM systems. (a) GFL control. (b) GFM control.

voltage [3]. Another drawback for GFL is that it cannot actively control the frequency. Although it can adjust the frequency by setting the proper reference power, there exists a delay when compared to the GFM converters' response without the tuning of the reference power [18]. In contrast, GFM control has the advantages of providing inertia, active frequency response [18–20] and voltage regulation [21]. However, the system contingency may cause overcurrent for GFM converters [20,22,23].

3. Grid support

This section will review the literature about grid-connected FC systems to support the grid. FC can be regarded as either an auxiliary or a primary energy source. With different controllers and coordination with other devices, it can achieve various functions.

3.1. Renewables integration

It is known that there are many uncertainties in WT and PV systems due to the variant wind speed and radians. Therefore, the system with the main source such as WT and PV will need an improved control or an additional source. In [25–33], the FC is used to provide this support. This type of system is called the hybrid system. Fig. 4(a) shows a typical hybrid renewable system with FC. To build this type of hybrid system, modelling is the first step of

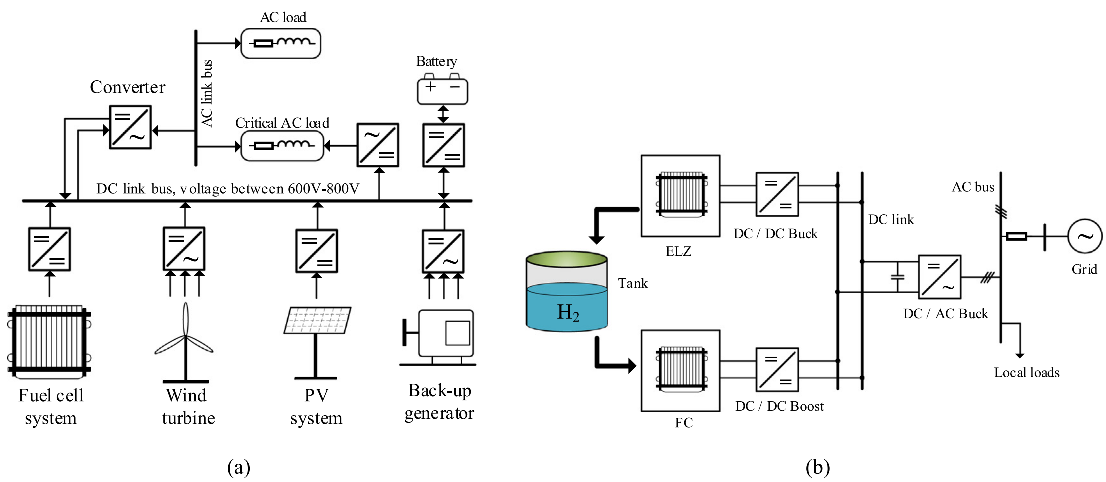

Fig. 4. Structures of power systems with FC. (a) Typical hybrid renewable system with FC [24]. (b) FC–ELZ system [9].

the field. The detailed Simulink model of the PV–FC hybrid system is introduced in [30]. The model is verified by real data and can be further developed due to its flexibility. Apart from the model, size optimization is developed in [27,28]. A detailed mathematical model of the PV–FC system is built in [27] to optimize the capacity, while Okundamiya mainly uses hourly simulations in a computer laboratory to find the best size [28]. Both of the papers are aimed at finding the balance between the least cost of electricity and system robustness to reduce the investment.

After deciding the capacity, the next important issue is to determine the power provided by the FC. The energy management scheme (EMS) is a solution for this, in which the total performance of the system is determined with less cost. Sabir uses Lyapunov theory to design a control system and proposes an EMS to calculate different required power for separate applications, namely the PV and the FC [25]. The PV will operate at maximum power point tracking (MPPT) mode and an additional dump load is used for balancing the output power of the PV. The system also considers its robustness under the voltage sags tests through their simulations. A similar idea is proposed in [26]. This paper also proposes the Lyapunov-based controller to provide MPPT function. Although it does not focus on the contingencies, its scheme can reduce the switching loss of the converter and harmonics in the system. Apart from the PV–FC system, the WT–FC system is introduced in [32,33]. The function of FC in these two papers is to ensure sufficient power when there is no wind. EMS is also proposed in both works. The model in [31] is a smart home system that consists of PV, WT, battery and FC. Traditionally, the FC will operate only when the battery is fully discharged. By comparing the proposed EMS with a traditional scheme, the paper shows the ability of EMS to increase efficiency and reduce the cost of the house.

Besides, the hybrid system with the combination of FC and UC is studied in [24,34]. Different from the WT and PV, the UC can absorb power to provide more support beyond the MPPT function to the grid. Also, the UC can be controlled in a more flexible method compared with the WT and PV. Various structures of the FC–UC hybrid system are reviewed by Ahmed et al. [24]. In this paper, Although UC is not a type of renewables, the paper analyzes the influence of different positions of UC, giving insight into renewables integration modelling design.

In summary, FC can help renewables have better integration with the grid. Due to the variations in wind speed or radians, FC ensures the system has a desired MPPT operation. Furthermore, capacity optimization and EMS are important for the design of this hybrid system. However, most of the current researchers focus on a small-scale grid. In the future, with the demand for high penetration of renewables, a large-scale grid with renewables might be worthwhile for research.

3.2. System power balance

FC system, as an energy source, its first objective is to provide proper power to meet the load requirement and keep the system has a balance in both active power and reactive power, because the active power determines the frequency of the system while the reactive power influences the voltage magnitude [22]. As discussed in the last section, depending on the controls of grid-connected converters, normally there are two topologies, namely GFL and GFM based converters. Both of them can track the reference power, but GFL cannot provide voltage support and frequency response.

There are many papers discussing the controllers for FC system to meet the power balance of the system, including the need for MPPT [26,35,36], matching the load shifting or dynamic load [9,34,37–42] and frequency support [9,29,39]. In [26,35], the single-stage structure for the FC system is adopted with the different converter topologies. A common converter is adopted in [26], while the application in [35] is a multilevel converter. The multilevel converter-based FC system provides more flexibility in integrating other applications, such as other FCs, batteries, PV, WT, etc. They used a proper controller to perform the MPPT function without MPPT application, which reduces the complexity of the system and saves the cost.

To meet the load demand of the system, researchers in [34,37,38] adopted UC to coordinate with the FC system and the structures are similar to Fig. 3(b). They connected the UC with the DC link through a separately controlled DC/DC converter. During the load transition, the FC will respond slowly and the UC can compensate for the power imbalance quickly. This can not only meet the demand but also enhance the FC lifespan. However, UC is relatively expensive when the required capacity is large [38]. The paper compares the FC–UC system and the FC system with a specific scheme that reduces the internal steady-state fuel utilization to make FC response faster. Different from the expensive UC, the power-to-gas (P2G) technology helps people adopt ELZ to form the FC–ELZ system [9,39], which is very clean and efficient. The system is illustrated in Fig. 4(b). The ELZ can absorb power to generate hydrogen for the FC and the excessive hydrogen will be stored in a tank, which enables the system to have the potential to provide frequency support with the grid-forming control. Authors in [9] used the FC–ELZ system to directly feed the grid, while others connect the FC–ELZ system with a DC link of the WT system [39]. With the grid-forming ability of the FC–ELZ system, the WT system is capable of providing frequency support and inertia to the system. Additionally, the excess power generated by high-speed wind will also be reused in ELZ.

From above reviewed papers, it can be seen that the FC system, as a primary energy source, is capable of following and forming the grid. There are many papers discussing the controller design for FC systems to meet the power balance in the grid. The FC–ELZ system is a very promising topology, because it saves the cost of hydrogen production and can achieve a great performance in grid forming.

3.3. Voltage support during contingency

When there exists a grid fault, normally the inrush current will occur. Recall Fig. 2(b), with the large current need, the voltage of cells will drop and this might further influence the DC link voltage, leading to a worse case. The authors in [43] conduct a detailed analysis of the performance of the FC system during the fault. It uses simulations to illustrate that the three-phase system will experience more severe stress than the single-phase system.

Some literature focuses on the control strategies to improve the performance of the FC system, providing voltage support or/and fast recovery during the contingencies [25,44–48]. According to the proposed EMS, Sabir calculates different power references for PV and FC during the grid voltage sages [25]. Through this dynamic reference power, the FC–PV system can provide sufficient support to the grid under an abnormal situation. Authors in [44,45] also mention that adjusting the power output of the FC system is important. They point out that the grid-connected FC system should keep the active power unchanged and increase its reactive power to provide voltage support during the voltage dip. Compared with the work in [44], the improvement about the cancellation of PLL is made by Sabir [45], which is beneficial in the design and saving the cost. The same idea about using adaptive parameters is presented in [46]; however, the unique method is to tune the controller for fast response in normal operation and slow response during faults. The authors find that traditional PI controller tends to be saturated under an abnormal situation, and this saturation can be resolved by applying a slow-responded controller during the fault.

Different from the aforementioned papers, the authors in [47,48] aim at voltage control of the FC system. Authors in [47] show that the voltage support can be realized by increasing the positive voltage and reducing the negative voltage during the fault. Yu et al. use the STATCOM in [48] to combine with the FC system to enhance the voltage stability during grid faults. The proposed dual feedback control strategy shows good voltage regulation results. Islanding is also a dangerous contingency that the FC system might face. Bayrak and Cebeci propose a novel anti-islanding detection in [49] to help the FC system quickly disconnect from the grid.

To conclude, the FC system with a proper controller can support the grid during system contingencies, including voltage sags and grid faults. However, most of the papers do not consider the converters' limit. Since converter normally has a maximum allowable current due to the limit of power electronics, which might be lower than the required fault current during a severe fault. Therefore, further research that considers both FC limits and the converter itself might be interesting.

3.4. Solutions to harmonics and oscillations in FC system

In this part, papers related to harmonics and oscillations issues in grid-connected FC systems are summarized [36,47,50–56].

One main reason for this problem is the insufficient or unstable DC link voltage during load shifting or system contingencies. According to the PWM control theory described in [16], the DC voltage should be twice larger than the grid voltage, otherwise PWM overmodulation will occur. The overmodulation can lead to distortions of the output waveforms. Therefore, the proper selection of DC-bus voltage draws many people's attention. The influence of DC voltage is analysed in [51]. Through simulations, the need for sufficient DC voltage is verified. However, the solution to this is selecting a large value of DC voltage, which is not economical and flexible. Authors in [50] find that in steady state, the reactive power of the FC system determines the AC output voltage, while in the transient process, the rate of change of active power contributes the most. Therefore, a rate limiter for active power is added to prevent overmodulation. Different from directly controlling the DC/DC converter, a novel operation mode that regulates the DC current through the DC/DC converter and the DC voltage by the grid-connected DC/AC converter is proposed by Fuzato et al. [53]. Results show that the oscillations of both the DC voltage and current are smaller than the scheme in [50]. Authors in [54] consider a delay caused by the distance between control units and generation units. This delay leads to oscillation when the load transition occurs. The writers consider the ripple of FC current in [36,55], and Han considers the approach to reducing the ripple of both the voltage and current [56].

In summary, the FC system has some problems with harmonics and oscillations. The reasons for this are normally the unstable DC link voltages, and the delay between controller and generation units. Many researchers improve the controller to minimize the harmonics and oscillations. However, there are also other delays that might cause these problems. For example, the fuel processor in SOFC can be modelled as a delay unit [8], which also can lead to the oscillations of the system. Thus, more considerations of delays in the FC system and other real factors can be investigated in the future.

4. Challenges

Although the aforementioned literature contributes to the development of the FC system, the renewables integration is still limited. It is still a challenging and promising field in the large-scale grid with high penetration of renewable energies. The EMS is also important in allocating the power between the energy sources in the highly integrated FC system.

In the aspect of grid interface, the GFM controls are well developed in the FC system. However, the difference between GFM-based FC and traditional grid and synchronous generator (SG) is still not specified. It would be worthy of understanding whether or not the GFM-based FC can totally replace the functions of SG with the consideration of the limitations of the FC. Since there are still some challenges with the contingency of the GFM-based system, the FC might cause more problems. For example, if the system is experiencing a severe contingency and the current of the converter is saturated. The droop control-based converter will act as a current source instead of a voltage source [57], which leads to an instability problem. Although some solutions are proposed, the limitation of the energy source is not well considered. With the consideration of FC characteristics, the converter stability problem will become more complex.

The development of the FC is also facing challenges. A widely known one is that PEMFC can only accept pure hydrogen as the input. When there are other fuel sources, a mass flow controller (MFC) combined with a mixer or reformer will be needed for converting all the resources into ready-to-use sources. This causes an unavoidable delay in the output of the FC, which might make the difference between SG and FC. Moreover, the controller design needs to consider the i–V curve of the FC, because the FC is not an ideal source with a fixed voltage when the current changes.

5. Conclusions

This paper reviews the grid-connected FC system. It focuses on the electrical aspects rather than the chemical characteristics of FC. The basic operation principles and control structures of the FC system are given. A comparison between FC and battery is also drawn. Subsequently, the papers related to grid support are reviewed. Renewable integration is an important field for the FC system, because the need for high penetration of renewables is urgent in this modern society. With the implementation of GFL and GFM based converters, the FC system can also balance the power of the grid and provide frequency support. Moreover, literature shows the fault-ride-through ability of the FC system, which enhances the robustness of the grid. Apart from the functions provided by the FC system, the quality of FC voltage and current is also a concern among researchers. However, the large-scale grid is still a promising field for FC systems, and the GFM-based FC system still needs to be researched with the consideration of more realistic limitations. To conclude, this paper will give people an insight into what and how the grid-connected FC system can support the grid.

Declaration of competing interest

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

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