Virtual Synchronous Control for Fuel Cell Power Generation System

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Abstract. In this paper, the concept of FC-VSG is proposed to operate a fuel cell power generation (FC) as a virtual synchronous generator (VSG). In order to provide the sufficient frequency and voltage support for the grid, the grid inverter in such a FC-VSG system is controlled to generate an appropriate voltage similar to the conventional synchronous generator. As a result, the overall system behaves like a VSG, which is significantly different from simply controlling the FC as a current source. It is able to provide the hydrogen energy stored in the fuel tank as inertia to support the grid frequency and also to provide reactive power to support the grid voltage. Moreover, the system does not need a phase-locked loop (PLL), and the seamless transition between grid-connected mode and islanded mode can be easily achieved. Simulation results from a 1 MW fuel cell power generation connected to an AC grid is presented to demonstrate the feasibility and effectiveness of the strategy.

1. Introduction

The large-scale utilization of sustainable and clean energy has been regarded as a major means to address sustainability and environmental issues. Hydrogen energy is one of the fastest growing source of clean energy utilized in the world [1]. Fuel cell power generation can directly convert hydrogen energy into electric energy and thermal energy through the chemical reaction of hydrogen and oxygen, which has the advantages of high fuel utilization rate, high power density and environmental protection. Compared with solar energy, wind energy, water energy and other clean energy, fuel cell is not limited by geographical and meteorological factors. With the continuous power generation and convenient installation, it has attracted the attention of many researches and applications.

The U.S., Japan and Europe are at the forefront in the research and application of fuel cell power generation system. Also, in the 13th five-year-plan for the development of national strategic emerging industries in China, it clearly proposed to strengthen the research on basic materials and process mechanism of fuel cell, promote the development of high-performance and low-cost fuel cell materials and key components of the system. China has a wide range of hydrogen source, its industrial by-product hydrogen has reached 8 million tons, while abandoned electricity generated by renewables has reached 100 billion kWh which can produce 2 million tons of hydrogen in 2019. Local governments and enterprises are also actively exploring the development of hydrogen energy industry. In 2019, more than 10 provinces in China including Guangdong and Shanxi have include the development of hydrogen energy in the government work report, to formulate a detailed hydrogen industry development plan.
Most installed fuel cell generation systems adopt the PQ decoupling control strategy to control the current sent to the grid. However, this control method would deprive the hydrogen energy stored in the fuel tank, which can be converted as virtual inertia. Thus, the lack of inertia could cause problems to the grid stability when the penetration of hydrogen energy becomes high. Moreover, the real and reactive power must be injected to the grid according to the phase of grid voltage [2], which often involves the usage of a phase-locked loop (PLL) to track the phase variations. However, it has been known that PLLs suffer from nonlinear structure, time-consuming design and slow performance. It could cause hydrogen energy systems out of synchrony and lead to instability [3].

It is well known that large-scale power plants equipped with synchronous generators are responsible for maintaining the stability of power systems. However, when the penetration of hydrogen energy systems reaches a certain level, there is a need for fuel cell generation systems to take part in the grid regulation. Recent research has shown that grid-connected converters can be controlled to behave like virtual synchronous generators (VSG) to take part in the regulation of system frequency and voltage [4], and the synchronization mechanism of synchronous machines can continue underpinning the grid operation and expansion. The utilization of the VSG technique and the self-synchronization method to fuel cell would ultimately smooth the relationship between hydrogen system and power systems, but this requires deeper research because the working principle of fuel cell involves many interdisciplinary subjects such as material science, electrochemistry, thermodynamics, power system analysis and control theory, the dynamic performance of fuel cell system reveals nonlinear, time-delay and coupling characteristics. Therefore, a more grid-friendly interface for fuel cell generation system is essential.

In this paper, a control strategy is proposed to operate a fuel cell generation system as a VSG without a PLL by operating the fuel flow rate and grid-side converter to generate an appropriate dynamic power for the frequency and voltage support. In order to facilitate this, the fuel cell inverter is equipped with the self-synchronization mechanism of synchronous machines, so there is no need to have a dedicated synchronization. Such a system, denoted as FC-VSG, can support the grid dynamically with the extraction of the hydrogen energy stored in the fuel tank and inject the required power to the grid in the steady state.

2. Modelling of fuel cell generation system

2.1. System principle

The system reaction principle of fuel cell is that the electrochemical reaction between hydrogen and oxygen generates water and releases energy at the same time. The electrode provides the place for electron transfer, while anode catalyzes the oxidation process of fuel (such as hydrogen), and cathode catalyzes the reduction process of oxidant (such as oxygen), and conductive ions migrate in the electrolyte (solid or liquid), then an electric field is formed [5]. According to different electrolytes, fuel cells are divided into different types, but the reaction principle is basically the same. The overall chemical reaction formula can be described as \( 2H_2 + O_2 \rightarrow 2H_2O \).

The electrical part of a typical fuel cell grid connected system includes at least a DC/DC converter and a DC/AC inverter. In addition, in order to ensure the stable and continuous supply of fuel, the fuel cell system also includes the fuel cycle pump and other auxiliary operating systems [6]. Such systems are designed to regulate the flow rate of hydrogen and oxygen, which also has a certain time delay, and it could affect the dynamic power response characteristics of the fuel cell generation system. Seeing that the proton exchange membrane fuel cell (PEMFC) is one the most widely used fuel cell in the markets, this paper takes PEMFC for specific research. A typical grid connected fuel cell power generation system is shown in Figure 1.
2.2. Fuel cell model
In order to build a PEMFC simulation model suitable for dynamic characteristics research, the following ideal conditions are assumed [7]: 1) the input gas is ideal gas, i.e. the fuel is hydrogen, and the oxidant is oxygen; 2) the battery operates at constant temperature and the temperature distribution is uniform; 3) the heat loss of the battery is ignored; 4) the voltage loss can be neglected in the flow tank; 5) the Nernst equation can be used to calculate the terminal voltage of fuel cell; 6) the internal resistance of the battery is constant.

The voltage of PEMFC stack is a function of load current, and the main influencing factors are cathode pressure, gas pressure, temperature and membrane humidity. The commonly used PEMFC voltage $V_{cell}$ equations is as in (1).

$$V_{cell} = N(E_{nerst} - V_{act} - V_{ohm} - V_{con})$$

Where $E_{nerst}$ is Nerst electromotive force of PEMFC, and it can be calculated as in (2). In which $E_{th} = 1.229 - 0.85 \times 10^{-7} (T - 298)$, $R$ is the general gas constant 8.3144J/(mol·K), $F$ is the Faraday constant 96485C/mol, $T$ is the working temperature of the stack, $P_{H_2}$ and $P_{O_2}$ are the system pressure of hydrogen and oxygen respectively. $N$ is the number of cell module connected in series.

$$E_{nerst} = E_{th} + (RT / 2F) \ln(P_{H_2} / \sqrt{P_{O_2}})$$

$V_{act}$ is activation polarization voltage, which reflects the phenomenon when the electrode surface is about to activate the electrochemical reaction as in (3). Where $C_{O_2} = P_{O_2} I (5.08 \times 10^6 \exp(-498/T))$ is the dissolved oxygen concentration on the gas-liquid interface, $I$ is the output current of PEMFC, and $\xi_3$ to $\xi_4$ are the experimental fitting parameters which equals to -0.9514, $2.2 \times 10^{-3}$, $7.4 \times 10^{-4}$ and $1.87 \times 10^{-4}$.

$$V_{act} = \xi_1 + \xi_2 T + \xi_3 T \ln(C_{O_2}) + \xi_4 T \ln I$$

$V_{ohm}$ is the ohmic polarization voltage, which represents the exchange impedance of electrolyte membrane $R_M$ and contact impedance between electrode materials $R_C$.

$$V_{ohm} = I(R_M + R_C) = I \left( \frac{\rho_M l}{A} + R_C \right)$$

Where $A$ is the membrane area, $l$ is the thickness of the membrane, $\rho_M$ and $R_C$ are the empirical value. $V_{con}$ is the concentration polarization voltage, which is caused by the change of gas concentration on the electrode surface.

$$V_{con} = \frac{RT}{2F} \ln(1 - \frac{i}{i_{max}}) = -4.3085 \times 10^{-5} \ln(1 - \frac{i}{i_{max}})$$

In which $i$ is the current density, and $i_{max}$ is the maximum current density. As there is a double-layer charge dynamic voltage $v_d$ generated by the aggregation of electrons and hydrogen ions on the electrode and electrolyte, an paralleled capacitance $C_d$ is chosen to reflect this phenomenon [8]. The equivalent circuit for PEMFC can be represents in Figure 2.
The dynamic performance for a single module can be calculated in (6). Where $\tau$ is electrical time constant, and $C_d$ usually takes 4F.

\[
\begin{align*}
\frac{dv_d}{dt} &= \frac{i - v_d}{C_d} \\
\tau &= \frac{C_d}{v_d + V_{con}} (V_{act} + V_{con})
\end{align*}
\]  

(6)

Moreover, the inflow and outflow of anode gas (hydrogen) and cathode gas (air) as well as the gas consumed in the reaction will affect the gas pressure. From the chemical formula of the reaction of hydrogen and oxygen, it can be seen that the pressures are determined in (7) as follows:

\[
\begin{align*}
P_{H_2} &= (1 - C_{H_2}) H\% \cdot g \cdot P_{H_2} \cdot I_1 \cdot c_{H_2} \cdot F^2 \\
P_{O_2} &= (1 - C_{O_2}) O\% \cdot g \cdot \rho_{O_2} \cdot I_1 \cdot c_{O_2} \cdot F^2
\end{align*}
\]  

(7)

Where $\rho_{H_2}$ and $\rho_{O_2}$ are the gas density of hydrogen and oxygen, $c_{H_2}$ and $c_{O_2}$ are the resistances of pipelines. $H\%$ and $O\%$ are the percentage of hydrogen in the fuel and percentage of oxygen in the oxidant, $C_{H_2}$ and $C_{O_2}$ are the conversion rates of hydrogen and oxygen. According to (1) to (7), the math model of PEMFC can be established.

2.3. Generation system model

On the basis of the fuel cell model above, the air compressor, valve, gas pipeline and other peripheral equipment are needed to provide the fuel, and also the grid-connected inverters are required for the whole power generation system. Generally, the response of the system is realized by adjusting the intake volume of hydrogen and oxygen, which are the functions $Fr(H_2)$ and $Fr(O_2)$ related to the load current. The flow rates of hydrogen and oxygen can be regulated according to the output current of the fuel cell stack, defined as (8).

\[
\begin{align*}
F_{H_2} &= Fr(H_2) \cdot I_1 = RT \cdot I_1 / (2F \cdot P_{fuel} \cdot C_{H_2} \cdot H\%) \\
F_{O_2} &= Fr(O_2) \cdot I_1 = RT \cdot I_1 / (2F \cdot P_{air} \cdot C_{O_2} \cdot O\%)
\end{align*}
\]  

(8)

Where $I_1$ is the output current of single fuel cell module, $P_{fuel}$ and $P_{air}$ are the absolute supply pressure of fuel pump and air pump. Considering the response time and the consumption time of mechanical action, these delays can be uniformly equivalent to a first order delay function, and the time constants for the pumps of hydrogen and oxygen are $\tau_{H_2}$ and $\tau_{O_2}$. Then, on the basis of nominal pressures of hydrogen and oxygen, $P_{H_2}$ and $P_{O_2}$ can be derived from (7). Moreover, this mechanical delay characteristic provides a similar inertial function as in the rotation shaft of synchronous machine. In addition, a boost converter is applied to the output of the fuel cell to generate appropriate DC bus voltage for centralized DC/AC inverter. And this structure enables the system to easily expand the power generation capacity via paralleling the multiple fuel cells at the DC bus through distributed DC/DC converter. Accordingly, the peripheral equipment model and inverter control model can be detailed in Figure 3.
3. Virtual synchronous control design

3.1. Principle of VSG

In the traditional control methods for FC system, PLL is usually used to track the grid voltage vector, and the dynamic performance of output power lacks effective control strategy, which makes it unable to respond to the grid frequency and voltage fluctuations. Thus, in the power system with high hydrogen energy penetration, the stabilities of system voltage and frequency decrease sharply. However, VSG technology is one of the most effective solutions [9], by mimicking the electromechanical dynamic model and excitation model of traditional synchronous generator via inverter control, the dynamic power support capability of the FC system can be realized.

An inverter which can be simulated as a synchronous generator needs to satisfy the droop relationship of active power-frequency and reactive power-voltage [10]. When the line impedance is inductive and the power angle difference is relatively small, the output active power is proportional to the power angle, and the output reactive power is proportional to the voltage amplitude. The droop control can be adopted for the electric network of the fuel cell power generation system, as its impedance characteristics of the output filter naturally meets the above requirements. Then, the VSG control can be applied to such system.

The VSG control model includes four parts as is shown in Figure 4: The virtual synchronous shaft (Part I) generates synchronous frequency, the excitation regulator (Part II) generates excitation voltage amplitude, and the self-synchronization module (Part III) tracks the grid frequency. Finally, the reference value for PWM inverter is constituted by voltage vector synthesis module (Part IV). For the grid connected system, if the voltage support is required, the reactive power can be calculated according to the voltage droop $D_v$, otherwise the output reactive power is regulated according to $Q_v^{ref}$.

![Figure 3. Model of grid-connected PEMFC system.](image)

![Figure 4. Model of VSG control system.](image)
$J \frac{d\omega_s}{dt} = P^m_s - P_e - D_p \cdot (\omega_s - \omega_e)$

$M_i^s i_s = \frac{1}{K_s} (Q^m_s - Q_s)$

$\omega_s = \omega_n + (K_p^m + K_v^m) \cdot D_p \cdot \Delta \omega_s$

$e_s = M_i^s i_s \omega_s \sin \theta_s$

$\sin \theta_s = [\sin \theta_s \sin(\theta_s - \frac{2\pi}{3}) \sin(\theta_s + \frac{2\pi}{3})]^T$

### 3.2. Control of converters

According to the topology proposed in Figure 3, a boost DC/DC converter and three phase DC/AC inverter are required for the grid-connected system for FC system.

Due to the low voltage and high current output characteristics of a single fuel cell, it is necessary to increase the DC bus voltage value to meet the input voltage requirements of DC/AC inverter. Moreover, the multiple low voltage and high current cells are also suitable for the parallel connection on the DC side via respective DC/DC converter, and then connect to the grid via a centralized DC/AC inverter. The open loop voltage transfer function of the boost converter is described in (10).

$$G_d(s) = \frac{V_{cell}}{V_{bus}D} \frac{(k_p s + k_i)(R_p D^2 - L_s s)}{s(L_C R_s s^2 + L_s s + R_p D^2)}$$

In which $D$ is the PWM duty cycle of the boost convert to regulate the $V_{bus}$ voltage. $L_1$ and $C_1$ are the boost inductor and DC bus capacitor, $k_p$ and $k_i$ are the PI parameter, $R_s$ is the equivalent load on the DC bus. The proposed VSG control for fuel cell is applied in the DC/AC inverter. Considering the output power dynamic performance of the fuel cell system is restrained by the mechanical time constant of the fuel pump and the air pump, the virtual inertia and damping coefficient can be set according to the mechanical time constant $\tau_m$ to ensure that the fuel cell can realize the required dynamic response of grid connected power with the capability of frequency and voltage support. The power reference in steady state for fuel cell system can be given in $P^m_s$ and $Q^m_s$ as in (9), the frequency droop factor can be chosen according to the grid code, and the time constant for such VSG system can be calculated as $\tau_e = \frac{J}{D_p}$. Thus, as long as $\tau_e$ is less than $\tau_m$, the output power dynamics can be regulated via virtual inertia and damping coefficient, while the multiple paralleled fuel cell can share an unified power dynamic characteristics with the same VSG parameters. Therefore, the parameter selection method for VSG model can ensure the electrical time constant is adapted with the mechanical response time of the system, and the trip-off fault caused by the extreme low voltage protection of fuel cell under instantaneous high load impact can be avoid.

### 3.3. Self-synchronization control

As is well known, it is crucial to synchronize a voltage source before it is connected to another voltage source. Conventionally, PLL unit is always considered as time-consuming and unstable under sudden frequency change or phase jump events. Even though advanced PLL designs have solved some of the issues, the present paralleled power system actually contains multiple frequencies as each VSG or frequency-voltage regulated source injects its own intrinsic frequency into grid, therefore, makes it more troublesome for PLL unit to generate a stable grid frequency in pre-synchronization period. However, according to the intrinsic frequency $\omega_e$, which generated in VSG, virtual power calculation method is proposed for synchronization to avoid grid frequency fluctuation and impacts of other paralleled frequency-regulated power source in grid. A set of virtual impedance $L_s s + R_s$ is established between the VSG generator terminal voltage $e$ and the grid voltage $u_e = [u_a \ u_b \ u_c]^T$, and it is assumed that the fuel
cell injects power into the grid through this set of impedance. The virtual current $i_v = [i_{va} \ i_{vb} \ i_{vc}]^T$ can be calculated in (11).

$$i_v = \frac{u_s - e_s}{L_s s + R_s}$$  \hspace{1cm} (11)

When the active and reactive power flowing through the virtual impedance are zero, it can be considered that the fuel cell has completed the synchronization process with the grid. Therefore, the active and reactive power reference are both set to 0 during the pre-synchronization, while $P_g$ and $Q_g$ are calculated through grid voltage $u_s$ and virtual current $i_v$ in (12).

$$P_g = u_s i_{va} + u_s i_{vb} + u_s i_{vc}$$  \hspace{1cm} (12)

$$Q_g = \frac{1}{\sqrt{3}} (u_s i_{va} + u_s i_{vb} + u_s i_{vc})$$

After $i_v$ is regulated at 0, the grid breaker can be closed to connect fuel cell to the grid, and $P_g$ and $Q_g$ are calculated through $u_s$ and real output current $i_g$. Thus, the proposed VSG control enables the fuel cell to synchronize with the grid voltage vector, as well as provide frequency support and voltage support autonomously without PLL, just as the conventional synchronous machine.

4. Simulation results

The system shown in Figure 3 with the parameters in Table 1 was simulated to validate the proposed strategy. The PEMFC model is introduced into the VSG system with rated output power of 1 MW is constructed to verify the performance of the system in pre-synchronization mode and grid connected operation mode. The control parameters for VSG control model of PEMFC are listed in Table 2.

| Parameters | Description          | Values   |
|------------|----------------------|----------|
| $P_n$      | Rated power          | 1 MW     |
| $V_n$      | Rated DC voltage     | 625 V    |
| $T$        | Operation temperature| 65℃      |
| $O\%$      | $O_2$ percentage in oxidant| 59.3%  |
| $H\%$      | $H_2$ percentage in fuel| 99.5%  |
| $\tau_{H}$ | time constant for fuel pump | 0.005 s |
| $\tau_{O}$ | time constant for air pump | 0.01 s  |

| Parameters | Description     | Values   |
|------------|-----------------|----------|
| $P_n$      | Rated power     | 1 MW     |
| $U_n$      | Rated AC voltage| 380 V    |
| $f_n$      | Rated frequency | 50 Hz    |
| $U_{dc}$   | Rated DC bus voltage| 800 V  |
| $L_f$      | Grid filter inductance | 0.2 pu |
| $R_f$      | Grid filter resistance | 0.003 pu |
| $D_p$      | P-f droop factor | 0.01     |
| $\tau_i$  | Inertia time constant | 0.02 s |

The simulation was carried out according to the following sequence of actions:
(1) At 1 s, self-synchronization control of VSG were enabled to synchronize the fuel cell with the grid.

(2) At 4 s, the grid breaker is closed, and the output power reference of fuel cell was set to 0.3 MW.

(3) At 8 s, the output power reference of fuel cell was increased to 0.5 MW to simulate its dynamic performance.

(4) At 14 s the grid frequency dropped by 0.5% to simulate its capability of frequency support.

The pre-synchronization and islanded/grid-connected transition simulation results is shown in Figure 5 and Figure 6. As is shown in Fig. 5, self-synchronization control start to operate at 1 s, and regulate the virtual power to 0 within 0.15 s, which represents the amplitude and phase of the three phase voltage vectors on both sides of the grid breaker are the same. Then, the breaker is allowed to be closed at 4 s. As the feedback power of VSG control in self-synchronization mode and grid-connected mode can be altered smoothly, the above process enables the seamless transition for PEMFC system with limited impulse current in Fig. 6.

**Figure 5.** Self-synchronization simulation.

**Figure 6.** Islanded/grid-connected transition.

As is shown in Figure 7, the top-down figures are output active power and reactive power, DC bus voltage and VSG frequency respectively. It can be seen that the output power can track the power reference in steady state. When the active power reference increased 0.2 MW at 8 s, the output power could follow the power reference with the dynamic restrain of the virtual inertia. When the grid frequency decreased to 49.75 Hz rapidly at 14 s, the additional 0.1 MW output active power can be provided by fuel cell to support the grid frequency. As there is no PLL unit to track the frequency automatically, the intrinsic frequency support capability of fuel cell can be released.
5. Conclusion
A control strategy has been proposed to control a fuel cell system behaves like one virtual synchronous generator (VSG) by regulating the real power and reactive power sent to the grid. The grid-connected inverter is equipped with the self-synchronization function, so there is no need to have a dedicated synchronization unit, such as a phase-locked loop (PLL). Therefore, it can release the energy stored in the fuel cell to support the system frequency and also to provide reactive power to support the system voltage. Simulation under self-synchronization mode and normal operation mode have demonstrated the feasibility and effectiveness of the proposed control strategy. The results reveals that the fuel cell under the proposed VSG control can not only play an important role in peak load shaving, auxiliary grid service, emergency power supply, but also can improve the frequency and voltage stability of power system with high penetration of hydrogen energy.

A Simulink simulation model consisting of a PEMFC stack, boost converter and three phase inverter was developed for the performance analysis of a 1 MW PEMFC system. The obtained simulations results indicate that the output characteristics of PEMFC can be regulated as a conventional synchronous machine embedded with frequency support capability.

The future research work needs to consider experimental verification of the mathematical modelling, design and simulation results of the proposed VSG control for PEMFC.

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