Influence of solid oxide fuel cell on power system transient stability

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Abstract: Due to its modular, efficient and non-polluting characteristics, solid oxide fuel cell (SOFC) is promising to be widely utilised in the area of distributed generation. Previous studies mainly focused on dynamic modelling of SOFC to analyse its load following behaviour, however, the influence of SOFC on power system transient stability is not yet clear and needs further discussion. In this study, a system-level electromechanical transient mathematical model for SOFC is proposed, based on the circuit structure of SOFC, DC/DC step-up converter and DC/AC converter. Then, a double closed-loop control scheme is designed for the control of SOFC. Finally, the effect of SOFC on the power system’s transient stability is discussed through simulations based on IEEE 3-machine 9-bus standard system. Results show that, under real and reactive power coordinated control strategy, cell current can be adjusted. Therefore, the output power of SOFC can be modulated to help with voltage recovery and power angle stability. The authors’ work reveals the feasibility of using SOFC to enhance power system transient stability.

1 Introduction
A fuel cell is a new type of power generation technology that converts a gaseous or gasified fuel into electricity and heat directly by an electrochemical combination of that fuel and an oxidant. Since it is not burned, the conversion efficiency is relatively high [1]. Therefore, the fuel cell can be used as excellent electrical energy storage devices to smooth the power balance induced by fluctuating renewable wind or solar power generators [2–5].

Solid oxide fuel cell (SOFC) is a third-generation fuel cell, which works in 800 – 1000 °C, namely, it belongs to high-temperature cells. SOFC can use hydrogen, carbon monoxide, or hydrocarbons as fuel, and air (or oxygen) as the oxidant. Plenty of research has been carried out in dynamic modelling of SOFC. Both the detailed model and lumped parameter model were established, and the dynamic characteristics of the two models were compared [6, 7].

Most of the research has focused on its rapid load tracking, as well as load balancing characteristics [8, 9]. In recent years, hybrid fuel cell and new energy supply (such as wind or PV) are brought forward, for that SOFC can stabilise the fluctuation of new energy [10]. However, the influence of SOFC on power system transient stability has been less discussed and not yet clear. Further work is needed to provide some basis for the effect of SOFC on power system stability.

In this paper, a system-level electromechanical transient mathematical model for SOFC is proposed and an active and reactive power coordinated double closed-loop control scheme is designed [11–14]. It is proved that SOFC can improve the power system transient stability, according to simulations conducted on IEEE 3-machine 9-bus standard system.

2 Dynamic modelling of SOFC
2.1 SOFC working principle
Fig. 1 is the schematic diagram of SOFC. At the porous cathode, the oxygen in air stream undergoes a reduction reaction to generate oxygen ions $O^{2-}$, which reach the anode via the solid oxide electrolyte. Hydrogen infiltrates the anode, synthesising water vapour with oxygen ions $O^{2-}$ and losing the electrons. The electrons return to the cathode through an external circuit, which forms the load current.

The electrochemical reaction equations are as follows:

\[
\text{Anode: } H_2 + O^{2-} \leftrightarrow H_2O + 2e^- \tag{1}
\]

\[
\text{Cathode: } \frac{1}{2}O_2 + 2e^- \leftrightarrow O^{2-} \tag{2}
\]

![Fig. 1 Schematic diagram of SOFC](image)
2.2 SOFC mathematical model

2.2.1 Equation of state: According to the ideal gas state equation, the molar flow of hydrogen meets the following equation:

\[
q_{H_2} = q_{H_2}^{in} - q_{H_2}^{out} - \dot{q}_{H_2}
\]  

where \(q_{H_2}^{in}\), \(q_{H_2}^{out}\), \(\dot{q}_{H_2}\) represent input, output and reaction of hydrogen flow, respectively. On the basis of SOFC electrochemical reaction, the relationship between the gas and the current is obtained

\[
q_{H_2} = \frac{N I}{2 F} = 2 K_I I
\]

where \(N\) is the number of single cells, \(I\) is the current of SOFC, \(K_I = N/4F\), \(F\) is the Faraday’s constant. The ideal gas state equation \(PV = nRT\) is used to find the partial pressure of the flowing gas through the electrode:

\[
d\frac{d}{dt} P_{H_2} = \frac{d}{dt} \frac{n_{H_2}RT}{V_a} = q_{H_2} \frac{RT}{V_a}
\]

The output hydrogen flow is represented as

\[
q_{H_2}^{out} = K_{H_2} P_{H_2}
\]

where \(K_{H_2}\) is the molar constant of the hydrogen gas valve. In time domain

\[
\begin{align*}
\frac{d}{dt} P_{H_2} &= \frac{RT}{V_a} (q_{H_2}^{in} - K_{H_2} P_{H_2} - 2 K_I I) \\
\frac{d}{dt} P_{O_2} &= \frac{RT}{V_a} (q_{O_2}^{in} - K_{O_2} P_{O_2} - K_I I) \\
\frac{d}{dt} P_{H_2O} &= \frac{RT}{V_a} (q_{H_2O}^{in} - K_{H_2O} P_{H_2O} + 2 K_I I)
\end{align*}
\]

where \(P_{O_2}, P_{H_2O}\) are oxygen, water vapour partial pressures, respectively, \(K_{O_2}, K_{H_2O}\) are the molar constants of oxygen, water vapour valve, respectively.

With the help of the Laplace transformation, the following expression can be obtained:

\[
\begin{align*}
P_{H_2}(s) &= \frac{1}{1 + \tau_{H_2} s} (q_{H_2}^{in} - 2 K_I I) \\
P_{O_2}(s) &= \frac{1}{1 + \tau_{O_2} s} (q_{O_2}^{in} - K_I I) \\
P_{H_2O}(s) &= \frac{1}{1 + \tau_{H_2O} s} (q_{H_2O}^{in} - 2 K_I I)
\end{align*}
\]

with \(\tau_{H_2}, \tau_{O_2}, \tau_{H_2O}\) are dynamic response time constants, given as \(\tau_{H_2} = (V_a/k_{H_2} RT), \tau_{O_2} = (V_a/k_{O_2} RT), \tau_{H_2O} = (V_a/k_{H_2O} RT)\).

2.2.2 Output voltage of SOFC: SOFCs are typically formed by connecting a plurality of columns in parallel, and each SOFC cell can be approximated as consisting of many identical single cells in series with an output voltage

\[
V_{out} = N(E - V_{ohm} - V_{act} - V_{con})
\]

where \(E\) is the single-cell Testers reversible potential, \(V_{ohm}, V_{act}, V_{con}\) are the single-cell ohmic polarisation voltage, active polarisation voltage and concentration polarisation voltage, respectively.

The reversible potential is the open-circuit voltage of a single cell when the fuel cell output current is zero

\[
E = E_0 + \frac{RT}{2F} \ln \frac{P_{H_2} P_{O_2}^2}{P_{H_2O}^2}
\]

The ohmic polarisation voltage is related to the material properties of the electrode and electrolyte and is affected by temperature

\[
V_{ohm} = n_f \exp \left[ \frac{1}{1 + \frac{1}{T}} \right] I
\]

The chemical reaction in the fuel cell electrode must first overcome the energy barrier, thus forming into the active polarisation voltage

\[
V_{act} = \frac{RT}{2F} \ln \left[ 1 + \left( \frac{I}{\tau_{act}} \right) \right]
\]

As the reactants and products pass through the porous electrode, the resistance of the mass transport stream causes a change in concentration, resulting in the generation of a concentration polarisation voltage

\[
V_{con} = \frac{RT}{2F} \ln \left[ 1 - \left( \frac{I}{\tau_{con}} \right) \right]
\]

2.3 Characteristics analysis of SOFC

SOFC has two typical steady-state operation strategies, i.e. fixed flow control and fixed fuel utilisation control. In this paper, the fixed flow control strategy is selected, under which the hydrogen and oxygen input flow rate of SOFC are constant.

2.3.1 Steady-state characteristics analysis: A list of simulation parameters for an SOFC lumped model is given in Table I [7].

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| \(T\)     | 1273 K| \(\tau_{L}\)| 2.91 s |
| \(F\)     | 96487 C/mol | \(\tau_{H_2O}\)| 78.3 s |
| \(N\)     | 450,000 | \(T_e\)| 0.8 s |
| \(K_I\)   | 0.996 \times 10^{-3} | \(T_I\)| 5 s |
| \(U_{out}\)| 0.85 | \(\tau_{H_2-O}\)| 1.145 |
| \(K_{H_2}\)| 0.843 mol/(s \cdot atm) | \(r_0\)| 0.126 Ω |
| \(K_{O_2}\)| 2.52 mol/(s \cdot atm) | \(\alpha\)| -2870 |
| \(K_{H_2O}\)| 0.281 mol/(s \cdot atm) | \(I_L\)| 300 A |
| \(\tau_{H_2}\)| 26.1 s | \(I_i\)| 12.112 A |

2.3.2 Dynamic performance analysis: For a lumped SOFC model with parameters in Table I and \(\dot{q}_{H_2} = 0.4\) mol/s, supposed that the steady-state output current is \(I = 100\) A. At \(t = 100\) s, load current increases to \(I = 150\) A. Simulation results are shown in Fig. 3, where the output voltage decreases tardily, and the power surges first and then gradually drops to a new steady value.
3 Control strategy

A system-level electromechanical transient mathematical model for SOFC is shown in Fig. 4, which mainly includes SOFC, DC/DC step-up converter and DC/AC converter.

As for the control strategy, a double closed-loop control scheme for SOFC is proposed in this paper, based on the coordination between the real power modulation and reactive power compensation functionalities. The double closed-loop control scheme contains an outer control loop and an inner control loop [14]. The outer control section mainly works for voltage and current detection, sampling feedback, numerical calculation and regulator design. In addition, the output of the outer loop provides an inner loop section with reference for real power and reactive power. The inner control part includes variables decoupling, calculation and closed-loop controller design, which realises the adjustment of real power and reactive power by regulating the real and reactive output current.

3.1 Steady-state operation

In steady-state operation condition, the output power of SOFC is a fixed value. The reactive power injected into the system is typically zero, designed to make the most of the device capacity. Assuming that in steady state, the real power generated by SOFC is \( P_{\text{steady}} \), then the reference value of real power is \( P_{\text{ref}} = P_{\text{steady}} \). Meanwhile, the reactive power reference is \( Q_{\text{ref}} = 0 \). Therefore, steady-state current reference values are

\[
\begin{align*}
    i_{\text{dref}} &= \frac{2P_{\text{ref}}}{3V_g} \\
    i_{\text{qref}} &= 0
\end{align*}
\]  

(14)

3.2 Transient operation

In the event of a system failure, the bus voltages will drop abruptly, which would threaten the stability of the power system [15–17]. With the reactive power regulation, SOFC can provide suitable reactive power to support the voltage recovery. According to the proposed control method, reactive power control is realised by adjusting the reactive current. The reference value of reactive power is given by the control strategy shown in Fig. 5a. The voltage controller compares measured bus voltage \( v_g \) with reference bus voltage \( v_{\text{ref}} \) (\( v_{\text{ref}} \) refers to the voltage at PCC),
and passes the difference through a PI controller. Then, reactive current reference \( i_{q_{\text{ref}}} \) is obtained as the quotient of the reactive power reference \( Q_{\text{ref}} \) divided by bus voltage \( v_{\text{ref}} \).

When power system suffers from large disturbances, the balance between the mechanical torque of the prime motor and the electromagnetic torque of the generator will be broken, causing the acceleration or deceleration of the generator rotor. Therefore, the reference value of the SOFC active current can be calculated according to the difference between a measured neighbouring generator speed and its reference speed. The control strategy is shown in Fig. 5b.

As shown in the following equations, \( i_d \) is not only related to \( v_{d1} \) and \( v_{q1} \), but also influenced by \( i_q \). Namely, coupling is introduced, during Park transformation. In order to facilitate closed-loop current control, it is necessary to introduce state feedback decoupling link

\[
\begin{align*}
v_{d1} &= G_{d}(s) \cdot (i_{d\text{ref}} - i_d) - \omega L_1 i_q \\
v_{q1} &= G_{q}(s) \cdot (i_{q\text{ref}} - i_q) - \omega L_1 i_d
\end{align*}
\]  

(15)

According to (15) and the mathematical model of the converter, the state feedback decoupling diagram can be drawn in Fig. 6. And the final synthetic current control scheme for SOFC can be achieved in Fig. 7.

4 Case studies

All cases discussed in this paper are based on the standard IEEE 3-machine 9-bus system. The topology and the detailed data of the system can be found in [18]. An SOFC with a capacity of 30 MW is connected to bus 4, and is named as bus 10 in this paper.

4.1 Case one

Assuming that a three-phase short-circuit fault occurs in line 4 close to bus 9, at \( t = 1 \) s. At \( t = 1.1 \) s, the circuit breakers trip to clear the fault. Then, at \( t = 1.6 \) s, breakers reclose successfully.

The results of the transient simulation are shown in Fig. 8. Compared with the standard IEEE 3-machine 9-bus system, SOFC, with the coordinated regulation between the real power and reactive power, can ameliorate the transient performance of the system.
4.2 Case two

Assuming that a three-phase short-circuit fault occurs in line 3 close to bus 7, at \( t = 1 \) s. At \( t = 1.08 \) s, the circuit breakers trip to clear the fault. At \( t = 1.63 \) s, breakers reclose successfully. The results of the transient simulation are shown in Fig. 9.

Figs. 9a and b show that, when a fault occurs at line 3 close to bus 7 of a standard IEEE 3-machine 9-bus system, the power angle between the generators 1 and 2 constantly increases and bus voltages fluctuate dramatically, leading to instability. However, the power angle swing is gradually attenuated to a constant value in Fig. 9c and voltages are restored in Fig. 9d, once SOFC with the proposed control method is connected to the system. Thus, SOFC is beneficial to the transient stabilisation of the system.

5 Conclusions

In this paper, the steady-state and dynamic operating characteristics of SOFC under the fixed flow control scheme are discussed. Further analysis of the relationship between cell voltage, output power and current is carried out. For the case of SOFC connected to the grid, a double closed-loop control strategy is proposed, which can coordinate the active power of SOFC and the reactive power from its grid-connected inverter. Programs coded in MATLAB are used to make a comparison between the transient stability of an IEEE 3-machine 9-bus system with and without SOFC in the events of power system faults. Results show that the dynamic performance of SOFC in faulted cases can improve the transient stability of the power system. Decoupling control of real and reactive current in SOFC expedites the power angle swing attenuation and provides reactive power support for voltage recovery.

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Fig. 9 Simulation results for a fault at line 3 (bus 7) (a) Rotor angle curve for a system without SOFC, (b) Voltage curve for a system without SOFC at bus 1, (c) Rotor angle curve for a system with SOFC, (d) Voltage curves for a system with SOFC at buses 1–9.
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