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Start-Up and dynamic processes simulation of SOFC-MGT hybrid power system

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Abstract. For the start-up process of a hybrid system consisting of a Micro Gas Turbine (MGT) and a Solid Oxide Fuel Cell (SOFC), the surge of the MGT is largely destructive. The MGT, which has a small thermal inertia, can start quickly. However, due to the large thermal inertia of SOFC, starting up SOFC quickly is easily malfunction. Therefore, fast and safe start-up process investigation of the coupling hybrid system is of great challenging and significance. This paper developed a dynamic model of the SOFC-MGT hybrid power systems and studied the rapid start-up process in the case of avoiding gas turbine surge and protecting SOFC by adding other afterburning, auxiliary systems, and bypass valves. The result shows that the bypass from compressor exit to atmosphere can effectively avoid system unstable and the strategy of starting the MGT and SOFC respectively is reasonable. The start-up process simulation provides a reference to the actual SOFC-MGT hybrid power systems.

1. Introduction

Solid oxide fuel cell (SOFC) is a promising technology for generating power with low environment influences. When using hydrogen as fuel, the SOFC system can generate power with zero pollutant emissions. Numerous studies[1-5] have proven that the efficiency of pressurized SOFC is higher than the one works at atmospheric pressure. For improving the efficiency of SOFC, an additional compressor, which is used to raise the pressure of SOFC cathode, is needed. Simultaneously, the SOFC works in a high temperature condition and the fuel utilization is generally below 100%. The high temperature exhaust of the SOFC can be utilized to push the turbine after burning. Therefore, the MGT, which has a compressor, a combustor, and a turbine, is considered to coupling with SOFC[6]. The MGT can provide pressurized air to the cathode of SOFC and can utilize the high temperature exhaust of SOFC. The efficient of SOFC-MGT hybrid power system is higher than independent SOFC power system[7]. However, the thermal inertia difference between MGT and SOFC is huge. The time constant of MGT is second order, but the time constant of SOFC is minute order, sometimes even hour order. The coupling characteristic of the hybrid power system decides the start-up process be complicated.

Some researchers and institutions have done a lot of work about the SOFC-MGT hybrid power system dynamic characteristic and performance analysis[8-12]. U.S. Department of Energy (DOE)/National Energy Technology Laboratory (NETL) has done numerous work about SOFC-MGT[6, 12-14]. The start-up process of the hybrid system also has been investigated[12]. However, the hybrid power system is developed using hardware in the loop simulation. The MGT is an actual system and the SOFC is simulated by a virtual model and some actual tanks and valves. The start-up process is starting up MGT to steady state, adjusting the SOFC model to a nearby boundary condition, and shifting the control signal of fuel valve from MGT to the SOFC model. Therefore, the start-up process of this hardware in the loop simulation was different from the actual SOFC-MGT hybrid power system. Petruzzi[15] developed a three-dimensional geometry code of SOFC to investigate the safe start-up process of small scale SOFC stacks. The result showed that small scale SOFC stacks can start up in 30 minutes without destructing the fuel cell. Some literature[9, 16, 17] have developed the model of gas turbine, including the Capstone MGT C30. This model can investigate the dynamic process of the MGT and can simulate the start-up process of the MGT. Liu[18] built a model of MGT/molten carbonate fuel cell (MCFC) hybrid power system and investigated the start-up process of MCFC-MGT hybrid power system by adding some auxiliary systems. However, this work assumed that the MGT had been started up. Only the start-up process of MCFC and the coupling characteristic was studied. However, when the micro gas turbine starts up, the compressor surge is extremely easy to happen. Some researchers[19, 20] have done a lot of work to avoid surge. The results prove that fast start up is an effective strategy and reducing the pressure ratio of MGT can also keep the MGT safe.

This paper developed a dynamic model of the SOFC-MGT hybrid power system. The MGT subsystem was built based on the prototype of Capstone MGT C30. The SOFC model was developed by referring to the NETL SOFC model. For the SOFC-MGT hybrid power system, in order to avoid the compressor surge during the starting process, to avoid the overheating of the gas turbine inlet and to prevent the temperature of the fuel cell from rising too fast, a supplemental combustion device and an air bypass are added. Then the steady-state validation was carried out. Finally, the safe and fast start-up process simulation of MGT-SOFC was investigated.

2. Mathematical model

2.1 Unit description

The model presented in this paper, the major components of the SOFC-MGT hybrid power system were simulated, including the compressor, heat exchanger, SOFC, combustor, turbine, bypass, etc. The diagram of the SOFC-MGT hybrid power system is shown in Fig.1. When the system is normal operation, the atmospheric air is pressurized by the compressor. Then the pressurized air goes through the heat exchanger, in which the heat of exhaust is retrieved. The heated air flows to the SOFC cathode. The exhaust of the SOFC, which include large heat and part available fuel, goes to the combustor. Next, the flue-gas flows to the turbine to generate power and drive the compressor. Then the exhaust of turbine transfers heat to the low temperature air at the heat exchanger.

In order to start up the hybrid power system, the bypass system is critical. At the initial stage of the start-up process. The MGT and the SOFC should be started up respectively. If all components are started at the same time, the temperature of the SOFC increases quickly. Therefore, the service life of SOFC stack decreases rapidly. So, the bypass valve1 and the SOFC cathode valve can separate SOFC from MGT. And the SOFC temperature can be adjusted by the bypass valve 1. The bypass valve 2 can make the hybrid system more stable by discharging pressurized air to atmosphere.

2.2 Basic equations

The SOFC-MGT hybrid power system model is developed by using the lumped parameter method. The conservation equations of the gas, which are mass, momentum, and energy conservation equations, are simulated by the homogeneous model. The model considers velocities and temperatures in pipe and heat exchanger. Therefore, it is enough that using the homogeneous model simulates the gas flow of the hybrid system.

Mass balance: $\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial z}=0$ (1)

Momentum balance: $$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u^2)}{\partial z}+\frac{\partial \rho}{\partial z}=\rho g_z+F_w \quad (2)$$

Energy balance: $$\frac{\partial(\rho h)}{\partial t}+\frac{\partial(\rho u h)}{\partial z}=\frac{\partial \rho}{\partial t}+Q_w \quad (3)$$

In these equations, Q_w represents heat transferred through walls and F_w is a friction force between the fluid and the wall surface. The space discretization and time discretization are applied to the partial differential equations. The staggered discretization scheme is utilized in the space discretization. Then, in the different space of the mesh, the different parameters are solved. For example, the state parameters are calculated in the middle of the mesh. At the junction of different mesh, the flow related parameters are solved. When calculating the enthalpy, the first order upwind scheme is utilized. Meanwhile, the implicit method is employed in the temporal discretization. The linear equations groups of pressure, void fraction and enthalpy is solved in order[21].

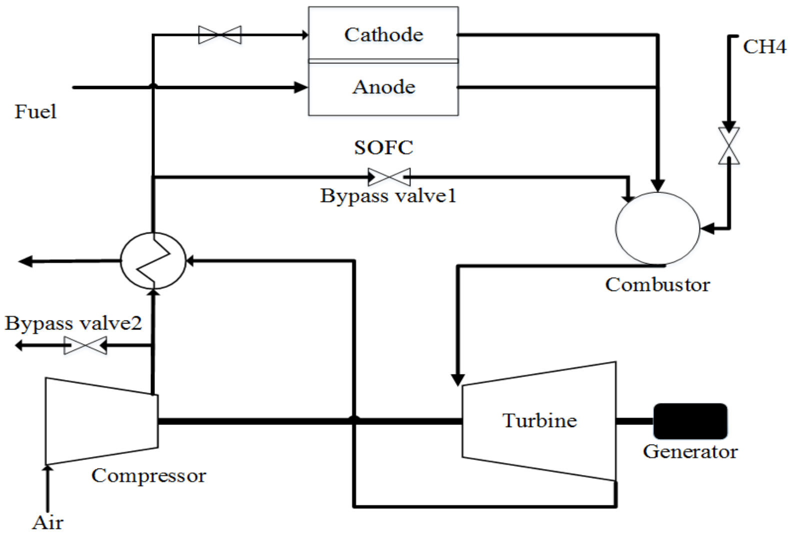

Figure 1. SOFC-MGT hybrid power system diagram.

2.3 Compressor model

The ideal process of the compressor is a definite entropy process. But due to factors such as frictional heat generation, the thermal process in the compressor is more complicated, so the entropy process needs to be corrected to some extent. The adiabatic efficiency of the compressor is introduced, and the adiabatic efficiency is the power consumption ratio of the isentropic process of the compressor adiabatic and the adiabatic entropy process:

$$\eta_{C,S}=\frac{w_{C,S}}{w_C} \quad (4)$$

The power consumption of the ideal process of the compression is:

$$w_{C,S}=\frac{1}{\gamma-1}R_g T_1\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right] \quad (5)$$

Where γ is the specific heat capacity ratio and R_g is the general gas constant.

Compressor outlet temperature is calculated by:

$$T_2 = T_1\left(\frac{\pi_c^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{C,S}} + 1\right) \tag{6}$$

Where π_c is the compressor pressurization ratio.

2.4 Turbine model

The turbine model mainly includes two parts: pressure calculation and enthalpy calculation.

There are different outlet pressures at different flows in the turbine. For this phenomenon, the Stodola formula is used to calculate the front and back pressure of the turbine model. The Stodola coefficient is calculated as follows:

$$K = m\cdot\sqrt{\frac{p_1 v_1}{(p_1)^2-(p_2)^2}} = m_0\cdot\sqrt{\frac{p_{10}v_{10}}{(p_{10})^2-(p_{20})^2}} \tag{7}$$

Where K is the Stodola coefficient, m is the mass flow through the turbine model, and p_1, p_2 is the model inlet and outlet pressure, respectively. v_1 is the model inlet specific volume. The subscript o is parameters under ideal conditions. From the above formula, if the inlet and outlet pressure are known, the mass flow through the model can also be obtained:

$$m_c = K\cdot\sqrt{\frac{(p_1)^2-(p_2)^2}{p_1 v_1}} \tag{8}$$

Practical form loss factor is calculated as follow:

$$k = \frac{2}{\left[K^2 r(1+\frac{p_2}{p_1})\right]} \tag{9}$$

For gas turbines, the working fluid is gas. The model enthalpy difference is:

$$H = m(h_1 - h_2) \tag{10}$$

2.5 SOFC model

For the lumped parameter SOFC model, the voltage of the fuel cell is calculated as follow:

$$V_{cell} = E_{Nernst} - \eta_{conc} - \eta_{act,an} - \eta_{act,ca} - \eta_{ohmic} \tag{11}$$

Where E_{Nernst} is the Nernst voltage. The remaining terms are the polarization losses. The Nernst voltage is given by:

$$E_{Nernst} = -\frac{\Delta G^0_{H_2O}}{2F} + \frac{R_u T}{2F}\ln\left(\frac{p_{H_2} p_{O_2}^{0.5}}{P_{H_2O}}\right) \tag{12}$$

Where the standard potential is E^0. For the model, an equation is established for E^0 as a function of temperature by fitting an equation to the standard change in Gibbs energy for formation of water reaction. The equation for the standard potential voltage is:

$$E^0 = 1.2877 - 0.0002904T \tag{13}$$

The calculation of the gas spices and the concentration polarization calculation refer to the literature[22].

3. Model validation

The model of SOFC-MGT hybrid power system was simulated with the commercial software package APROS developed by VTT Finland. To evaluate the model, the steady state of MGT was validated with the design value. The comparison between the design values and the simulation results is shown in table 1. The design and physical parameters of the fuel cell are based on articles by Aguiar[22]. And the SOFC parameters are compared with the literature[22], which is shown in table 2.

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The MGT parameters comparison between the design value and the simulation results shows a good agreement. And the simulation of SOFC also is similar to the literature[22]. Therefore, the model of MGT and SOFC can be used to develop the model of SOFC-MGT hybrid power system.

Table 1. The MGT parameters comparison between the design value and the simulation result.

Parameter	Simulation result	Design value	Unit	Relative error
Compressor inlet_temperature	15	15	^oC	0.00%
Compressor outlet_temperature	157.6	153	^oC	3.01%
Compressor inlet_pressure	0.97	0.97	bar	0.00%
Compressor outlet_pressure	3.1	3.1	bar	0.00%
Compressor flow rate	0.31	0.31	kg/s	0.00%
Fuel inlet_flow rate	0.0024	0.0024	kg/s	0.00%
Fuel inlet_temperature	25	25	^oC	0.00%
Combustor outlet_temperature	822.2	840	^oC	-2.12%
Combustor outlet_pressure	2.89	2.89	bar	0.00%
Turbine inlet_temperature	822.2	840	^oC	-2.12%
Turbine outlet_temperature	615	620	^oC	-0.81%
Power	29.63	30	MW	-1.23%

Table 2. The SOFC parameters comparison between the literature and the simulation results.

Parameter	Simulation result	literature	Unit	Relative error
Cathode inlet flow rate	0.0013	0.0013	kg/s	0.00%
Cathode inlet temperature	800	800	^oC	0.00%
Anode inlet mass flow rate	0.00012	0.00012	kg/s	0.00%
Anode inlet inlet temperature	927	927	^oC	0.00%
H_2 mole fraction	0.5323	0.5323	/	0.00%
H_2O mole fraction	0.1344	0.1344	/	0.00%
CO_2 mole fraction	0.3333	0.3333	/	0.00%
Current density	0.85	0.85	A/cm^2	0.00%
Voltage	0.712	0.706	V	0.85%
Cell temperature	838	840	^oC	-0.24%

4. Simulation results and discussion

The start-up of the hybrid system is a complicated process. The thermal inertia of the SOFC is different from MGT. To protect the SOFC stack, the start-up processes of SOFC and MGT are separated. Firstly, the MGT needs to be started to the state that its rotation speed reaches nominal speed. Then, the high temperature and pressurized air of heat exchanger outlet flows into SOFC cathode to heat SOFC.

The start-up process of the MGT is a process in which the unit accelerates from shutdown to rated speed, from cold state to hot state. In the start-up process, the parameters in the start-up process should be controlled to maintain a safe range. Before the gas turbine is ignited, the unit is started by the motor to gradually increase the speed of compressor and turbine. After the purge phase, the rotation speed of the gas turbine, which is driven by the starter motor, gradually increases. When the speed reaches 20%n_0, the gas turbine starts to ignite. Then, when the rotation speed reaches the trip speed (60% n_0),

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the driving source of the MGT switches from the starter motor to the turbine. Therefore, after 60%n_0, the kinetic energy of MGT is provided by the power of the turbine. When the rotation speed of the gas turbine reaches the rated speed, the SOFC prepares to be heated. The rotation speed of the MGT start-up process is shown in Fig.2.

After the rotation speed of MGT reaches the nominal speed. The pressure rate of compressor keeps a small range variety. The SOFC cathode valve gradually open. Meanwhile, the bypass valve 1 gradually close to avoiding compressor surge and ensuring the air flow of the system keep constant. The position of the SOFC cathode valve and bypass valve 1 are shown in Fig.3.

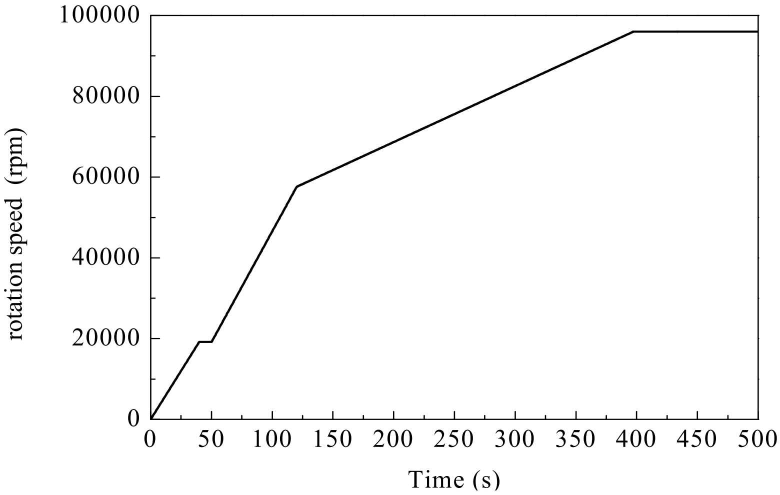

Figure 2. Rotation speed of MGT start-up process.

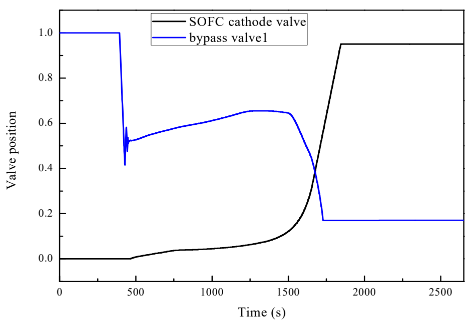

Figure 3. SOFC cathode valve position and bypass valve1 position.

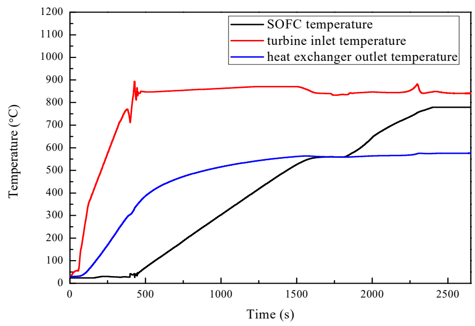

Figure 4. The temperature of turbine inlet, heat exchanger outlet and SOFC.

In order to heat the SOFC to about 600°C, improving the outlet temperature of the turbine is an effective strategy. Therefore, when heat SOFC from atmospheric temperature to start-up temperature, the turbine inlet temperature is improved to 870°C, which is still in the safe temperature range of the turbine. So, the additional heated device is not employed. About 1700s, SOFC generates power by electrochemical reaction. Then, the temperature of SOFC continues increasing with the chemical reaction heat releasing. The temperature of the turbine inlet, heat exchanger outlet and SOFC are shown in Fig.4. In 40mins, the system start-up process is ended.

As shown in Fig.5, when started the hybrid system, the CH_4 is employed to combusting to push the turbine. After MGT reaches nominal rotation speed, the temperature of heat exchanger still increases. Therefore, the CH_4 mass flow reduces slowly. About 1800s, the SOFC starts working. The fuel flow of the SOFC anode gradually increases. The temperature of the SOFC outlet also gradually increase. Therefore, the pressure drop along the pipeline increase. The pressure ratio of compressor increases and the air mass flow of the compressor reduces. The compressor running curve is close to surge line. Therefore, for the purpose of ensuring the safety of the compressor, the bypass valve 2 starts open to increasing air mass flow of compressor and reduce the pressure of the compressor outlet. At the start-up process, the compressor running curve is shown in Fig.6. At the initial stage of the MGT's start-up process, the compressor running curve is from A to B. When the speed of the MGT reaches the nominal speed, the resistance along the pipe increasing as a result of the thermal inertia of the heat-exchanger. Therefore, the compressor running state is from B to C. However, point C, which is close to the compressor surge line, represents that the safety and stability of the system are very severe. Then, the compressor running state changed from point C to D, because the bypass valve 2 is opened. The compressor surge has been avoided.

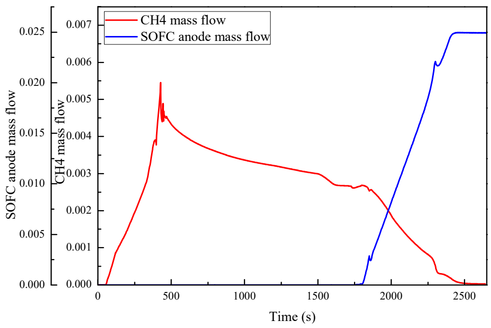

Figure 5. The mass flow of CH4 and the SOFC anode.

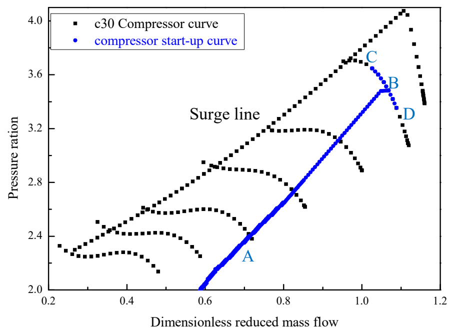

Figure 6. Compressor running

5. Conclusions

In this work, a numerical model of SOFC-MGT hybrid power system is developed. The model includes the compressor, heat exchanger, SOFC, combustor, turbine, and bypass. The MGT model and the SOFC model are validated respectively. Furthermore, the dynamic behaviour of the start-up process have been investigated by starting up the hybrid system from atmospheric temperature. Studies on the start-up process, in which protecting SOFC and avoiding compressor surge are considered, shown that this system can be started in 40 minutes. Moreover, while the temperature of SOFC outlet flue gas increases, the additional bypass valve 2 ensures the system stable. The investigation demonstrates that the hybrid power system can start up safe and fast.

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