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DYNAMIC MODELLING OF REVERSIBLE SOLID OXIDE CELL FOR GRID STABILISATION APPLICATIONS

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ABSTRACT

In this work, the dynamic modelling of a system based on reversible solid oxide cell (rSOC) is developed so that it can be integrated with the grid for power balancing. The focus is on the compatibility with profiles of wind electricity production. In addition, the effect and challenges of such a dynamic operation on the system and stack itself are studied. Detailed operation strategies are defined during the switching process from one operational mode to another and are implemented on the dynamic process model. Simulation results show that when the rSOC system is operated in solid oxide electrolysis cell (SOEC) and solid oxide fuel cell (SOFC) modes alternatively, energy balancing can be continuously implemented. In this process the results show that rSOC system operates in the safe operating range and does not deviate from the system limits. This is due to the accurate strategies developed for the switching process. It is also observed from simulation results that the switching time significantly is influenced by the initial power of one operational mode and the final power of another operational mode.

Keywords: rSOC system, grid stabilization, SOEC mode, SOFC mode, switching

NONMENCLATURE

Abbreviations

BoP	Balance of plant
RES	Renewable energy source
rSOC	Reversible solid oxide cell
SOEC	Solid oxide electrolysis cell
SOFC	Solid oxide fuel cell

Symbols

E_{max}	Maximum cell voltage
E_{rSOC}	Cell voltage
i_{max}	Maximum current density
r_1	Area specific internal ionic resistance
r_2	Area specific internal electronic resistance
η_f	Fuel electrode gas utilisation

1. INTRODUCTION

Reversible solid oxide cell (rSOC) technology is envisaged to play a major role in the field of energy storage. rSOCs however cannot be used for frequency regulation of the grid instead they can be used for grid stabilisation applications. rSOC is an operationally

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flexible energy conversion device, which can operate in both power generation (solid oxide fuel cell, SOFC) and fuel producing (solid oxide electrolysis cell, SOEC) modes [1]. In this regenerative operation mode, the rSOC system is able to better use and support the electricity grid. This work aims at investigating transient behaviours of rSOC system coupled with the renewable energy sources (RESs) in switching mode conditions using a mathematical modelling approach. The research goal is to assess the suitability of rSOC connected to the grid for grid balancing when rSOC is switched from one operational mode to another.

2. DESCRIPTION OF SYSTEM PROCESS

In this process, a system with rSOC is connected to a RES such as wind, aiming to facilitate the integration of RESs into the grid. In this process, hydrogen from hydrogen storage tank is expanded to system pressure from its storage pressure of 350 bar. The required water which is stored at atmospheric pressure and 90 ℃ is pumped to the evaporator and superheater units. The superheated steam is then mixed with the hydrogen from the hydrogen storage tank. Air is supplied from ambient to the system to provide the required oxygen for the SOFC mode. In the SOEC mode, the air flushes out the produced oxygen from electrolysis reactions of SOEC.

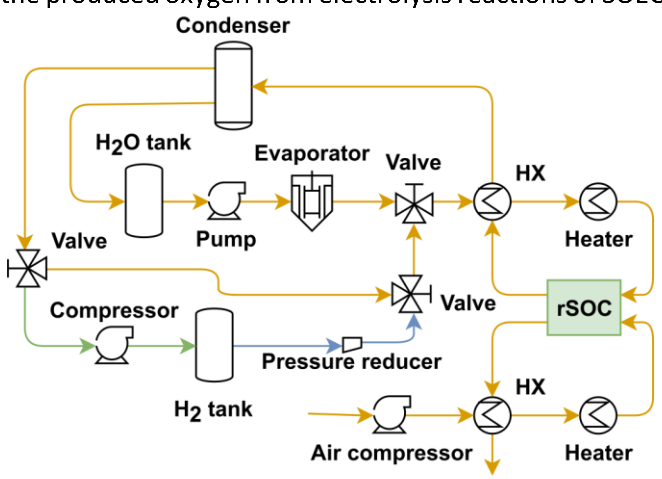

Fig 1 Process flow diagram for rSOC system.

Furthermore, it acts as a medium that carries heat to or from the stack to meet the boundary conditions. It is preheated in the heat recovery unit. Both streams exit the stack while hydrogen recirculation is fixed at 80% in SOFC mode. In both SOFC and SOEC modes, the fuel utilisation is fixed at 80 %. The heat generated in SOFC due to the exothermic reaction is employed to preheat the air stream. The remaining portion of the streams are sent to the heat recovery system to preheat the fuel stream and the evaporator unit. In the SOEC mode, the final fuel product is separated from the steam, compressed and is sent to hydrogen storage tank condition. Separated steam on the other hand, is condensed and cooled down to 90 ℃ and is sent into the water tank. The process flow diagram for the rSOC system is shown in Fig 1.

3. MODEL DESCRIPTION

3.1 *Model description of rSOC system*

Dynamic lumped model of an rSOC integrated process is developed using MATLAB/SIMULINK. The mathematical models used in this study for pump, blower, heat exchanger and condenser are adapted from models reported earlier [2].

3.2 *Model description of rSOC stack*

The dynamic model of the rSOC stack is based on a representation of a solid oxide cell with an equivalent electric circuit. The representation of the equivalent circuit for SOFC and SOEC modes is given in Fig 2.

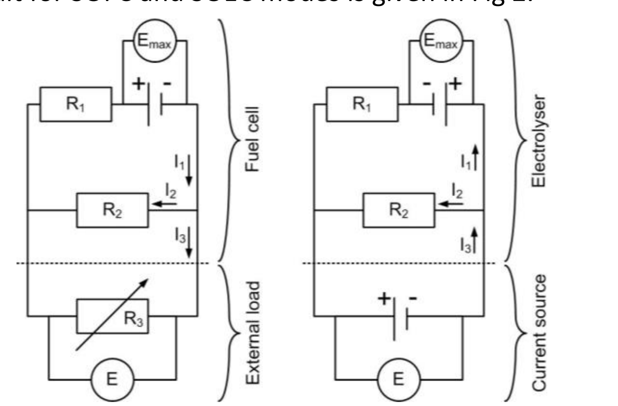

Fig 2 Electric circuit equivalent of SOFC (left) and SOEC (right).

The representation of rSOC as an electric circuit is related with adequate calculation of ions and electrons flows in the electrochemical module. Based on the Ohm's and Kirchhoff's Laws, the voltage in both operational modes (as fuel cell or electrolyser) can be determined, given by equation (1)

$$E_{rSOC} = \frac{E_{max} \pm i_{max} r_1 \eta_f}{\frac{r_1}{r_2}(1-\eta_f)+1} \tag{1}$$

The used methodology for rSOC stack dynamic model does not include use of empirical or semi-empirical equations and parameters, and every element in the implemented equations have physical explanations. The proposed methodology was described in detail elsewhere [3-5]. Concept of the dynamic model of the rSOC stack relies on representing a number of cells with a quasi-1D model, which was designed and implemented in Aspen® Hysys 8.8 software. The concept of the model is shown in Fig 3.

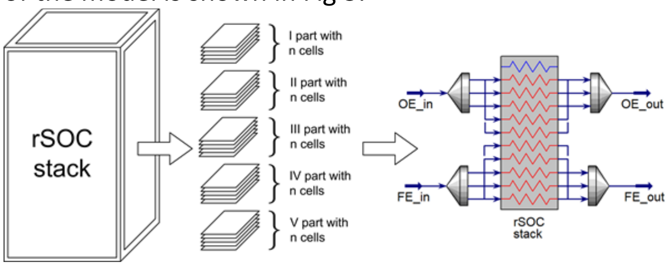

Fig 3 rSOC stack dynamic module concept.

The stack is divided into 5 parts, where each comprises of cells grouped in packages. The reference stack which was used for validation of rSOC stack electrochemical module consists of 25 Ni-YSZ supported cells with single cell active area of 100 mm x 100 mm. In order do scale-up the reference stack for the power generation unit with 1 MW electrolyser, the number of cells was increased to 1400 cells per module, 7000 cells in total. The heat exchange between the neighbouring packages is included in the vertical position along the height of the stack while composition of the reagents, working parameters in the electrodes compartments as well the voltage and current density are resolved using a lumped volume model at the level of each package of cells.

4. RESULTS AND DISCUSSIONS

4.1 Dynamic results of rSOC system

The input wind power profile is equal to the power output of the rSOC . It is assumed that the power is quasi-steady state, therefore, the system is able to track the wind power profile. Fig 4 shows the total generated power from rSOC, the load demand as well as the consumed electrical power of the balance of plant (BoP) for both SOEC and SOFC operational modes. Fig 4 is used to indicate which mode should be activated or deactivated. When rSOC power is positive, it means there is excess power available for hydrogen generation, which will result in the activation of the SOEC mode. In the case of negative power of rSOC, it switches from SOEC operational mode to SOFC mode to supply the power deficit.

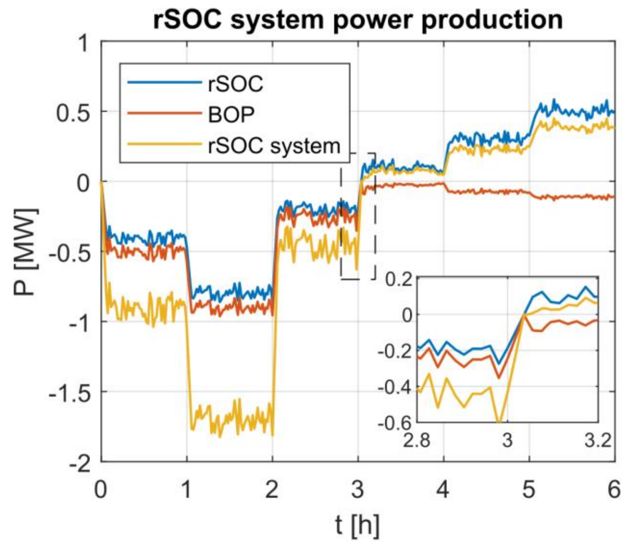

Fig 4 Power production/consumption of the rSOC, BoP, and rSOC system (Negative power indicates power consumption).

The power signal enforced on the rSOC is made up of consecutive ramps for which the slope changes 50 times per hour, which means a new ramp every 69 seconds. The BoP power consumption includes the power consumption of the pump, compressors, condenser and the net amount of energy that needs to be supplied by electric heaters. The results show that the electrical power consumption of BoP at SOEC mode is significantly higher than SOFC mode. Air heater has the main contribution which accounts for 74% of the net power consumption of the BoP when rSOC operates at SOEC mode. This is due to the endothermic operation of SOEC. The rest of the power in SOEC mode is consumed by the compressors 19%, pump 21%, the fuel heater (5-6%), and heat requirements of the other parts (1-1.5%). In SOFC mode, the net power consumption of the BoP is lower than in SOEC mode, because the exothermic operation allows for better heat integration, reducing the amount of heat that needs to be supplied by electrical heaters. The air heater takes up 64 to 71% of the net power consumption, while the compressors and pump make up 29 and 36% of the power consumption, respectively. The fuel heater is not used, because the fuel channel outlet stream is able to provide the necessary heat to heat the fuel channel inlet stream. Fig 5 presents the changes in rSOC voltage as well as current density changes corresponding to the power profile throughout the simulation period.

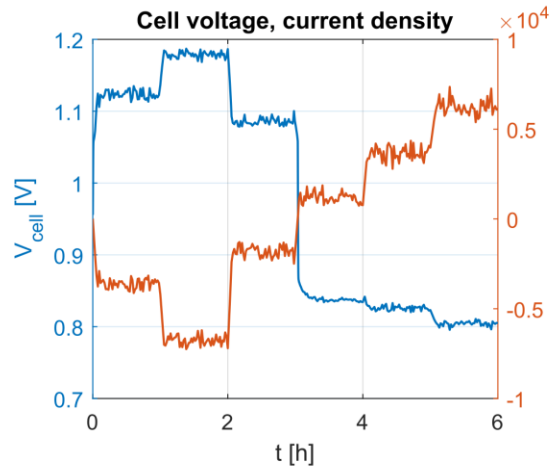

Fig 5 Cell voltage and current density.

4.2 Dynamic results of stack model

For the dynamic model of the rSOC stack, several simulations were performed in order to determine the temperature changes in the stack during the complete thermal cycles while operating in SOFC in SOEC modes. An example of such cycle with operating temperature at 700°C with 5 A/min current change rate is shown in Fig 6.

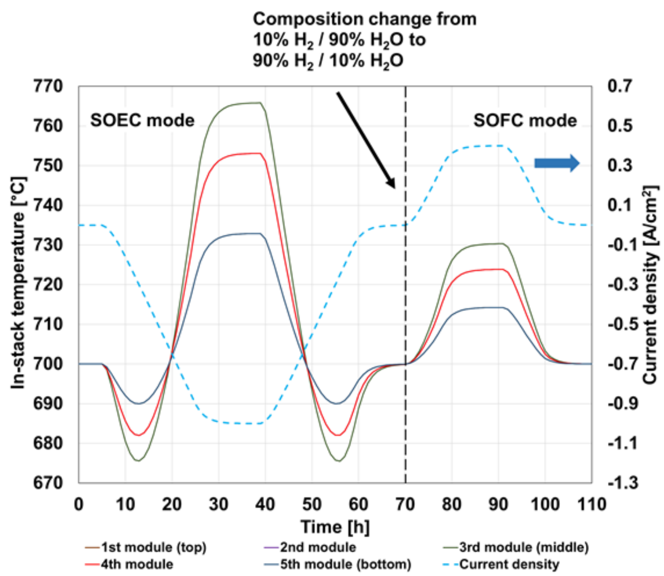

Fig 6 Results of dynamic simulation of rSOC stack performance both in SOFC and SOEC modes at 700°C with 5 A/min current rate.

5. CONCLUSION

A dynamic model of a rSOC process system is developed to integrate the grid balancing service with a focus on compatibility with wind electricity production profiles. In addition, the effect and challenges of such dynamic operation on the system and stack itself are studied. Detailed operation strategies are defined during switching process from one operational mode to another and are implemented in the dynamic process model. Simulation results show that when the rSOC system is operated in SOEC and SOFC modes alternatively, energy balancing can be continuously implemented. This is due to the fact that the electrochemical reactions are generally fast reactions. In this process the results show that rSOC system operates at the safe operating range and does not cross the system limits. This is due to the defined accurate strategies for switching process from one operational mode to another mode. It is also observed from simulation results that the switching time is significantly influenced by the initial power of one operational mode and the final power of another operational mode. The results from the current analysis of rSOC system behaviour will be used to optimise the control strategy of the system, enabling a fast transition between modes. Performed simulations allowed to determine the optimal operating parameters for the rSOC stack in order to not exceed thermal gradients along the cell above the allowed value.

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