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Solid oxide fuel cell architecture and system design for secure power on an unstable grid

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Abstract

In a power grid with significant components of distributed generation and insufficient spinning reserve, the quality of delivered power may not meet the requirements of advanced manufacturing. A system design for power quality security which uses solid oxide fuel cell (SOFC) technology is described. Critical parameters for system performance are continuous supply voltage at the nominal voltage and frequency. The grid chosen for this study has significant voltage fluctuations and periodic voltage drops and surges, including total power loss. A supply of methane from a sewer sludge digester is scrubbed of CO_2 and used for continuous standby operation, with excess stored to enable 8 h operation of an uninterruptible power supply (UPS). The system employs a modular, thermally coupled, SOFC architecture that includes steam reforming of the methane fuel, a rectifier, power controls, and control system. Continuous operation of a 125 kW tubular SOFC stack maintains operating temperature and steam for fuel reforming in a secondary SOFC stack, by exhausting through it before a gas turbine expands the exhaust to supply the plant air and fuel compression. Modelling of the energy balance of the system demonstrates the standby and full power operating modes. The system is sized at 250 kW to supply secure power for a manufacturing facility.
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Keywords: Solid oxide fuel cell; Uninterruptible power supply; Sustainable energy system; Power quality; Steam reforming; Unstable grid

1. Introduction

The motivation for this study was to investigate the possibility of utilizing solid oxide fuel cells (SOFCs) to provide an uninterruptible power supply (UPS). This is a technical study to evaluate the feasibility of an original idea for SOFC architecture conceived at the University of Canterbury. The approach is focused on developing a total system concept (TSC) for a power plant to meet a specific energy demand scenario within the context of a particular environment. Several of the technologies modelled in this study are still in the development stage. The goal is to propose the design space for an innovative combination of components. By investigating the energy system in context, the intention is to provide momentum for technological development for a clearly defined application.

The purpose of a UPS system is to keep critical loads under power in the event of an outage in a typical alternating current (ac) grid. The present investigation takes the function of a UPS system one step further in that it also provides power-conditioning in an unstable ac grid that has frequent power dips and surges. Hospitals, police, and military installations have employed back-up diesel generators for many years. There is now a rapidly growing demand for UPS systems for manufacturing facilities where a power outage could mean heavy losses in productivity or risks of damaging equipment. Modem high-tech manufacturing facilities and financial institutions can suffer heavy losses from disruptions in the voltage or the power factor. UPS loads can range from 5 kW for a critical computer network, to several megawatts for manufacturing.

A major motivation for this investigation arises from two factors: the sensitivity of many activities to power loss and power quality, coupled with decreasing spinning reserve in large grid networks as peak demands approach generation capacity. The target application for the design of an SOFC-based UPS system is a manufacturing facility in Singapore. The local grid is based on numerous distributed generators, with no large baseline power plants. Surges, dips, single-phase disruptions, and outages are becoming a serious concern for the economic future of the country's high-tech and financial industries [1].

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Conventional UPS systems provide instantaneous (<1 ms), constant, ac power by automatic discharge of capacitors through a solid-state inverter. A drop in grid voltage triggers the switch to a bank of charged batteries. Lead–acid batteries typically have a continuous discharge time of up to 6 h. If the risk of power outages longer than the battery charge is significant, then a diesel generator may be included in the UPS system. Supercapacitors are now becoming available to provide a short-term ride-through capability for the UPS rather than to switch directly to batteries. These supercapacitors can provide up to 15 s of power. The new supercapacitors, together with power sensors, switches, rectifiers and power electronics that are commonly used in modern UPS systems, have been incorporated into the SOFC–UPS system design.

The energy resource for the SOFC–UPS system for Singapore was considered to be an important part of the TSC. Singapore has no native resources of fossil fuels. Moreover, as the country lies on the equator, it does not appear to be a likely position to utilize wind power. Ullegerg and Morner [2] have modelled a solar–hydrogen with long-term storage for remote-area power generation of very low loads [2]. The equatorial location of Singapore suggests an abundance of seasonally invariant solar energy. There is, however, significant cloud cover and precipitation in this region. There is also a very high population density with an accompanying scarcity of land area for large collector banks. The issue of storage of sufficient hydrogen gas to supply a 250 kW load at 65% conversion efficiency for 8 h has placed the focus of this investigation on the design of SOFC technology fuelled by methane derived from waste material.

Methane generation from microbial digestion of sewage sludge is a process utilized at wastewater treatment facilities to generate electricity and heat for processing. The simple system comprises combustion of the biogas, typically around 40% CO_2, to fire a boiler for a standard steam-power cycle. Wastewater outflows from city populations are relatively season invariant, and represent a potential stable and cost-effective source of energy in Singapore. Additional considerations for the use of methane gas in a SOFC–UPS power plant is the global net chemical balance, removing methane (a high impact greenhouse gas compared with CO_2) from the atmospheric system, and producing potable water from the exhaust of the SOFC.

2. Background

2.1. Operating principles of solid oxide fuel cells

The SOFC is a three-layer, solid-state device constructed of ceramic materials and housed in a high-temperature pressure vessel. The UPS plant design is based on the most well-known SOFC, the tubular architecture developed by Siemens–Westinghouse, as shown in Fig. 1. The anode material is zirconia–nickel cermet, the electrolyte is

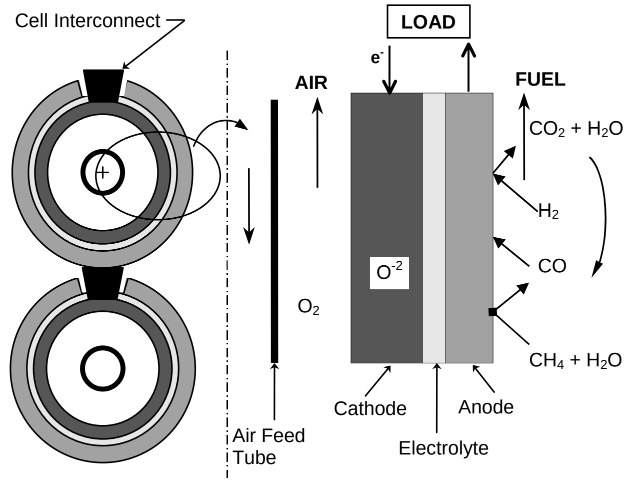

Fig. 1. High-temperature SOFC based on tubular architecture used by Siemens–Westinghouse with internal reforming of methane fuel.

yttria-stabilized-zirconia (YSZ), the cathode is strontium-doped lanthanum manganite, and the interconnect is lanthanum chromite [3]. If roughly half of the spent fuel is re-circulated into the inlet fuel, then steam is available for the internal reforming of methane, which takes place on the catalytic nickel surfaces. This is a two-step process, steam reforming of the methane, followed by the shift reaction, i.e.

$$CH_4 + H_2O \rightarrow CO + 3H_2, \quad \Delta H = 224.9\,\text{kJ/mol} \tag{1a}$$

$$CO + H_2O \rightarrow CO_2 + H_2, \quad \Delta H = -34.8\,\text{kJ/mol} \tag{1b}$$

Hydrogen and carbon monoxide are then reduced with oxygen, which has been ionized on the cathode, and ionically conducted through the electrolyte, according to the basic SOFC reactions:

Cathode:

$$O_2 + 4e^- \rightarrow 2O^{2-} \tag{2a}$$

Anode:

$$H_2 + O^{2-} \rightarrow H_2O + 2e^-, \quad \Delta H = -247.8\,\text{kJ/mol} \tag{2b}$$

Anode:

$$CO + O^{2-} \rightarrow CO_2 + 2e^-, \quad \Delta H = -282.6\,\text{kJ/mol} \tag{2c}$$

The voltage delivered by the SOFC is a function of the reversible open-circuit (Nernst) voltage, E, which depends on the fuel and oxygen partial pressures, P_{H_2} and P_{O_2}, respectively:

$$E_{H_2} = E^0_{H_2} + \frac{RT}{2F}\ln\left(\frac{P_{H_2}P^{1/2}_{O_2}}{P_{H_2O}}\right) \tag{3a}$$

$$E_{CO} = E^0_{CO} + \frac{RT}{2F}\ln\left(\frac{P_{CO}P^{1/2}_{O_2}}{P_{CO_2}}\right), \tag{3b}$$

where

$$E^0 = \frac{-\Delta \bar{g}^0_f}{2F}$$

The voltage of the fuel cell is reduced by irreversible losses of anode and cathode activation, electrical resistance, and other factors that depend on the specific materials and stack design, manufacture and operation. The resulting drop in cell voltage, V, is mostly a function of increasing current density, I, and can be modelled by an equivalent cell resistance, R [4], i.e.

$$V = E - (i + i_n)r - A \ln\left(\frac{i + i_n}{i_0}\right) + B \ln\left(1 - \frac{i + i_n}{i_l}\right) \quad (4a)$$

$$V = E - IR_{\text{eq}} \quad (4b)$$

Characteristic values of the constants in Eqs. (3) and (4) are available in the literature for various SOFC architectures and materials. While cost and manufacturing remain areas for development, the Siemens tubular SOFC power plant has been demonstrated in the 200 kW to 1 MW range [5].

The dynamic electrical response of an SOFC plant can be modelled using Eqs. (l)–(4) [6]. A fundamental operating requirement of an SOFC to avoid breakage of the ceramic material is to avoid temperature gradients and temperature fluctuations. Assuming that the SOFC can be maintained at a constant temperature above 1000 °C, then it is possible to operate at different power ratings. Indeed, as can be seen in Eq. (4), the SOFC has high voltage at low current with high efficiency due to low irreversibility. The time constant of voltage response to a step increase in current appears to be limited by diffusion of fuel to the anode and into the pores of the anode [7].

2.2. Gas turbine power plant integrated with solid oxide fuel cells

Studies in the literature have demonstrated that gas turbine technology can be coupled with the SOFC to generate power for a grid with overall theoretical efficiency in the range 65–80%. Harvey and Richter [8] investigated an integrated fuel cell with recycled off-gasses used as oxygen carriers and fed back into the fuel cell. A design was presented for a 100 MW power plant which fed into grid using a 61.2 MW SOFC, and a 63 MW gas turbine with 24.3 MW compressor load. Modem developments in microturbine materials and design continue to increase performance, with efficiencies approaching 30%. Massardo et al. [9] coupled a 50 kW microturbine to a pressurized SOFC and proposed a 389 kW grid connected power plant with overall efficiency of 60%. Microturbines are not, however, currently available in the power range required for a 250 kW system.

One of the attractive features of the SOFC from the viewpoint of reduced energy loss, is substitution of electrochemical oxidation for combustion in conventional power systems. Internal-reforming SOFCs provide a means for directly utilizing the high temperatures resulting from the exothermic oxidation reactions to provide the heat for the endothermic reforming reaction which occurs on the catalytic surface of the anode [10]. The performance, efficiency, power density and current density have been analyzed by Hartvigsen et al. [11] across the spectrum of operational parameters, and Campanari [12] has investigated the full- and part-load performance of a combined SOFC and microturbine system for distributed power.

The common design theme appearing in the literature is a high-pressure SOFC power plant operating at full power with excess fuel and air (fuel utilization factor, $U \leq 85\%$). The risk of cell damage due to fuel starvation is often noted. In the Seimens SOFC, exhaust is mixed at the exit near the top of the fuel cell in a combustion plenum. The products of combustion are expanded through a gas turbine. The turbine is coupled with compressors which supply the air and fuel to a recuperative heat-exchanger, and on to the fuel cell. The remainder of the power from the turbine is used to generate electricity. It appears that all of the SOFC power plant designs reported in the literature are conceived to supply base-load power to the grid. Thus, network parameters must be used to control the inverter and the power electronics on the generator so that the power can be synchronized with the grid. The plant must also respond to variable load on the grid, and must be capable of rapid shunting of load off the grid in case of power-line failure to protect utility workers.

3. SOFC–UPS power plant

3.1. Total system concept

In this study, an investigation is made of the feasibility of an SOFC-based power system for a specific critical load in a specific location. A TSC approach is adopted. First, the characteristic problems with the local grid and representative critical loads are determined. Next, an inventory of local and imported energy and environmental resources and conditions is performed. This allows the design criteria for the load to be determined and an approached to be made to the design of a solution with sustainable resource and impact criteria.

The target application is a factory which produces electronic components and has a critical load of 250 kW. The critical load is assumed to be continuous, and on an isolated circuit. The environmental conditions are such that refrigeration cooling is required for the proper function of computers, electronics, machines, and workers. Thus, while the electric UPS load is 250 kW, it is also important to have continuous air-conditioning through a power failure.

SOFC power plants are usually envisioned for continuous base-load power generation. The plants have several attractive features, which include augmented total efficiency through coupling with a gas turbine. The goal is to conceive a system design that will ensure the thermal stability of an SOFC plant, while providing power conditioning for a facility on a national grid with daily electrical quality fluctuations, weekly power dips and surges, and monthly

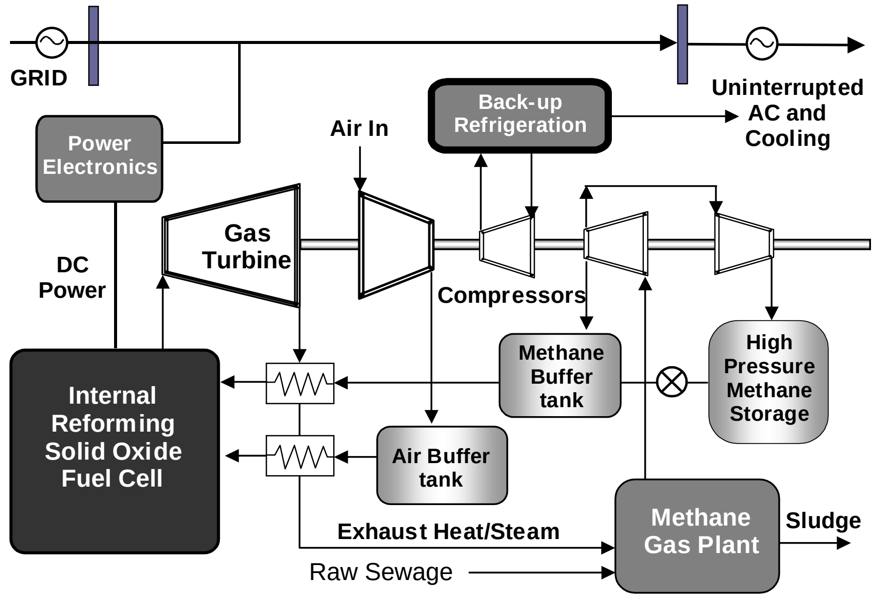

Fig. 2. Conceptual layout of SOFC–UPS system. Inputs to system are screened raw sewage from existing wastewater network, ac grid power, and ambient water and air. Normal outflows from system are 250 kW ac secure power, water, CO_2, and sludge. The gas turbine power plant expands the SOFC exhaust to provide compressor power for fuel and air supply, and air-conditioning during grid power failure.

total outages of up to 8 h duration. A schematic diagram of the SOFC–UPS system is shown in Fig. 2. A gas plant produces methane from a screened extraction from a local raw sewage stream. The methane is sweetened, compressed and fed to a tubular, internal-reforming SOFC. The methane production rate of the gas plant is sized to provide continuous standby operation of the UPS system, plus 8 h of back-up fuel. A combustion plenum at the exit of the SOFC provides complete combustion of any remaining fuel. The high-pressure, high-temperature exhaust from the SOFC is expanded through a gas turbine, then routed to recuperators which preheat the inlet air and fuel, and on to the methane gas processing plant. One of the compressors on the turbine shaft is for refrigerant, which is then expanded to cool water for air-conditioning and for machine and process cooling. The SOFC is essentially a pressurized Siemens–Westinghouse power plant, with one adaptation for part/full-load function. In this system concept, the usual duty of the SOFC plant has been reversed, i.e. from supplying power to a grid, to conditioning grid power for a continuous load.

3.2. Power electronics

When supplying base power to a grid, there are several challenges for the power electronics. The ac inverter from the fuel cell must match the voltage and frequency of the grid. In addition, power from the high-speed gas turbine is often rectified and then inverted to match the grid. On very stable national grids with base-load generation from hydro, coal, or nuclear plants, this is an achievable scenario. On an unstable grid, however, the function of the power electronics to follow the grid parameters may actually increase instability and exacerbate phase anomalies. The present strategy is to generate ac power with the power control unit (PCU) at the voltage and frequency required by the critical load, while using the rectified grid as a power supply to the PCU.

A flow diagram of the power electronics and controls for the SOFC–UPS plant is given in Fig. 3. The ac power from the grid is first rectified to eliminate the effects of voltage variability in the grid. The continuous output of the SOFC is available as a high-voltage dc power source. On a grid with low spinning reserve, voltage dips and surges can occur when large inductive loads are turned on or off. The power input from the SOFC is used to buffer these short-term dips and spikes. As a further buffer, an array of supercapacitors is used to supply up to 15 s of constant current, i.e. a function similar to that now performed by supercapacitors in battery–UPS systems. The conditioned dc power is then fed to the PCU which produces up to 250 kW at 415 V, 50 Hz.

The SOFC–UPS controller uses parameters from the network, the power electronics, and the load to control the SOFC supply current and, in the case of a larger power fluctuation, to open the fuel and air flows to the secondary cell array in the SOFC. It is envisioned that the controller will use both the actual signal and the differential signal to try to anticipate an outage. The SOFC architecture is structured so that excess fuel and air do not pose any risk to the stack or other components. Thus, the controller can be set up to err on the side of caution, and to initiate a full-load sequence based on the rate of change in the network voltage signal which can drop to near zero in less than 100 μs if the mains are shorted out.

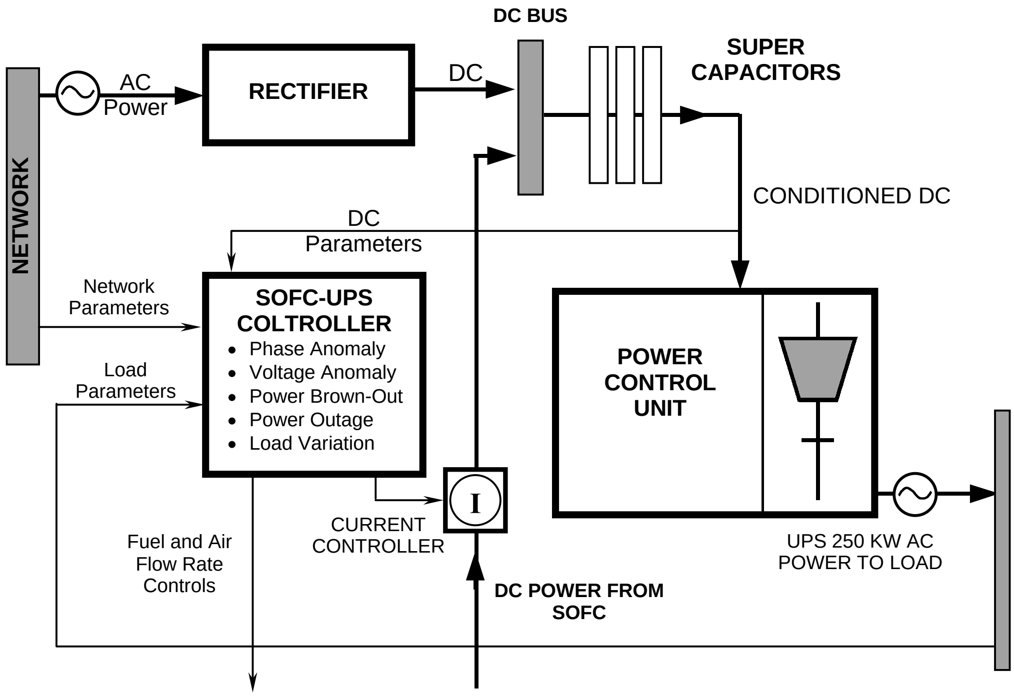

Fig. 3. Schematic diagram of power electronics for SOFC–UPS system. Unstable ac grid power is first rectified, then buffered by current-controlled SOFC power and supercapacitors. The PCU delivers 250 kW continuous voltage and frequency ac power to critical load.

3.3. Solid oxide fuel cell power unit

The SOFC power unit is shown in Fig. 4. Compressed air and fuel are preheated by turbine exhaust gas and fed into the SOFC. The Siemens–Westinghouse tubular SOFC design is structured into bundles of 24 tubes, which are arranged into rows to form the stack. There are two seals for each bundle, namely, at the tops of the air tube and at the fuel inlet in the top of the pre-reformer. A portion of the spent fuel/steam is re-circulated into the pre-reformer to supply water to initiate the reforming reaction shown in Eq. (1). The partially reformed fuel is then fed into the pressure vessel, which houses the array of tube bundles. An air-feed tube runs down the length of the each SOFC and delivers fresh air at the bottom of the tube. Since not all of the fuel is consumed in the SOFC, the excess fuel and air are allowed to mix in the exit chamber where the remaining fuel is oxidized and the product gases exit the pressure vessel.

The adaptation proposed for the SOFC architecture is designed to couple thermally an active stack to a dormant stack. The *primary stack* is operated with excess fuel and with the current-controller maintaining the power output at about 80% of full power. The current is limited to the amount of power that must be generated to keep the SOFC thermally and chemically stable. If the stack is operated at too low of a load, it will not produce sufficient steam to reform the methane fuel, nor sufficient heat to maintain the stack temperature and the gas turbine cycle. The primary stack comprises sufficient tube bundles to generate 125 kW at full power.

During standby operation, the primary stack operates near full power, and functions according to the original Siemens–Westinghouse design. The modification to the plant comes in coupling the primary stack to a *secondary stack* for power generation in the case of a total grid outage. The secondary stack is maintained at the operating temperature by passing the exhaust of the primary stack through the fuel pre-reformer and into the fuel side of the cells. The design calls for both stacks to be housed in the same unit and fully insulated. In standby mode, the secondary stack is open-circuited, and the air and fuel flows are off. This is accomplished with external controls and valves. The only internal adaptation is the connection of the primary stack exhaust to the secondary stack pre-reformer. In this connection line, simple flap valves, like those found in internal combustion engines, ensure one-way flow.

When a grid fault is detected, the current from the primary stack is ramped up to full power, the circuit to the secondary stack is closed, and the fuel flow is ramped open. There is adequate steam for pre-reforming of the fuel in the secondary stack, because of the presence of the primary stack exhaust. After a short time delay to ensure that adequate fuel has entered the secondary stack, the air supply is ramped open, and a limiting valve on the primary stack exhaust to the combustor is gradually opened. Thus, the response time for full power operation will be related to the time required for the gas flow into the secondary stack.

At this point, it could be asked: why not just build an SOFC power plant for continuous power to supply the manufacturing facility? As will be indicated in Section 3.5, the

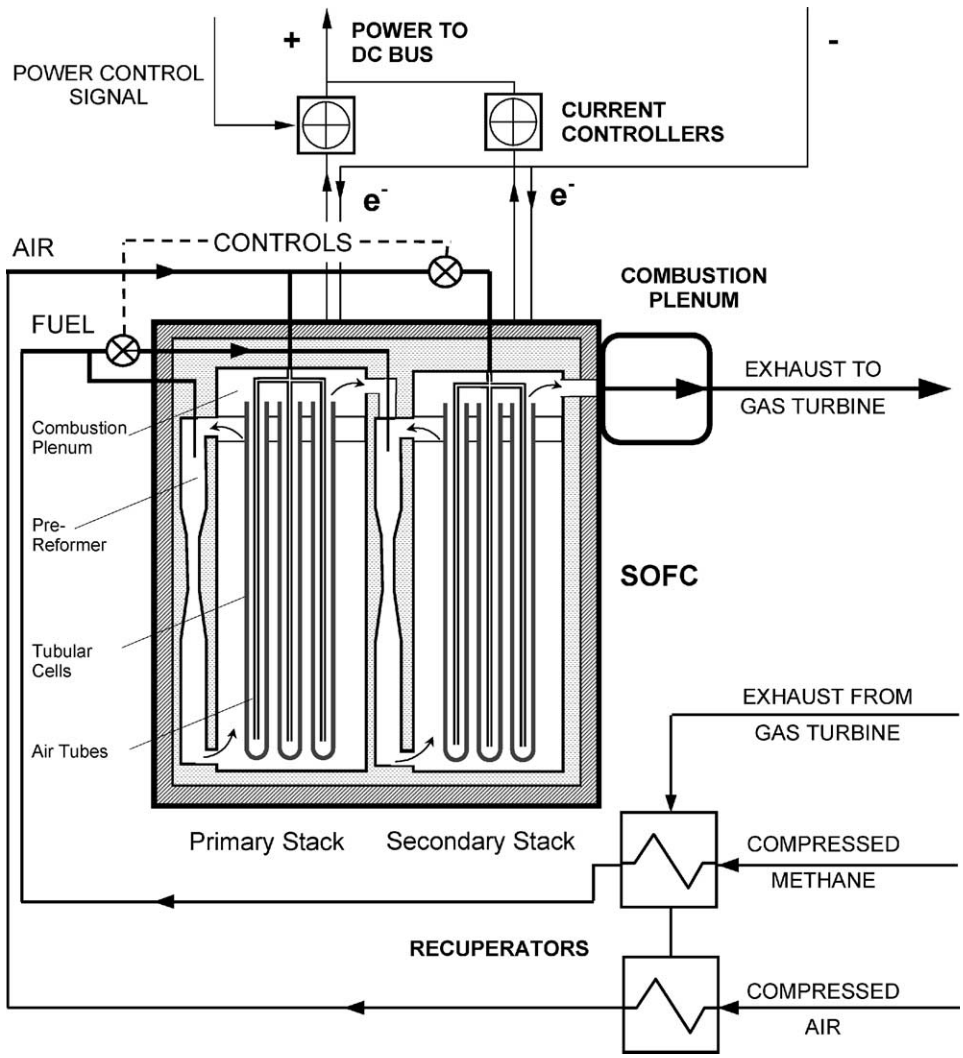

Fig. 4. Component and flow diagram for UPS architecture SOFC which features current control on tubular stack bundles, and two fuel and air manifold configurations for standby and full power modes.

methane consumption rate for 250 kW continuous power supply would require a very large waste gas plant. The present design is based on the premise that the methane fuel source is available at a rate that is roughly half that necessary to supply the critical load. With total outage frequency set at 30 days, it is easy to determine the amount of excess fuel production required in order to store 8 h worth of fuel for full load. Standby load fuel supply, plus the full load supply spread out over 30 days, gives the necessary fuel production rate for the system.

3.4. Gas turbine power unit

In the hybrid SOFC-GT power plants referenced previously, the power rating of the gas turbine is roughly the same as that of the fuel cell. About half of the turbine power is used to compress the feed air and fuel, and the remaining shaft work is used to generate electricity. Because the power plant is actually in the same location as the load, the turbine power can be used directly to provide shaft work. The components of the gas turbine power unit are shown in Fig. 2. In this scheme, the turbine will provide the air and fuel compression for the high pressure SOFC, and the additional capacity will be used for high-pressure storage of methane for operation during power outages, and for cooling.

During standby operation, a small flow rate of methane from the first-stage compressor, pressure ratio 4:1, is directed to a second-stage compressor and to a high-pressure storage vessel. The remaining turbine capacity provides refrigerant compression. There are storage tanks in the system for both air and fuel, which have diaphragm baffles to maintain constant pressure delivery to the SOFC. When a power outage is detected, the controller opens the valve between the high-pressure methane reserve and the operating pressure supply tank. This increases the fuel flow available for the SOFC to ramp up to full generation capacity. The back-up storage at 10 MPa would be roughly 5 m^3. On the

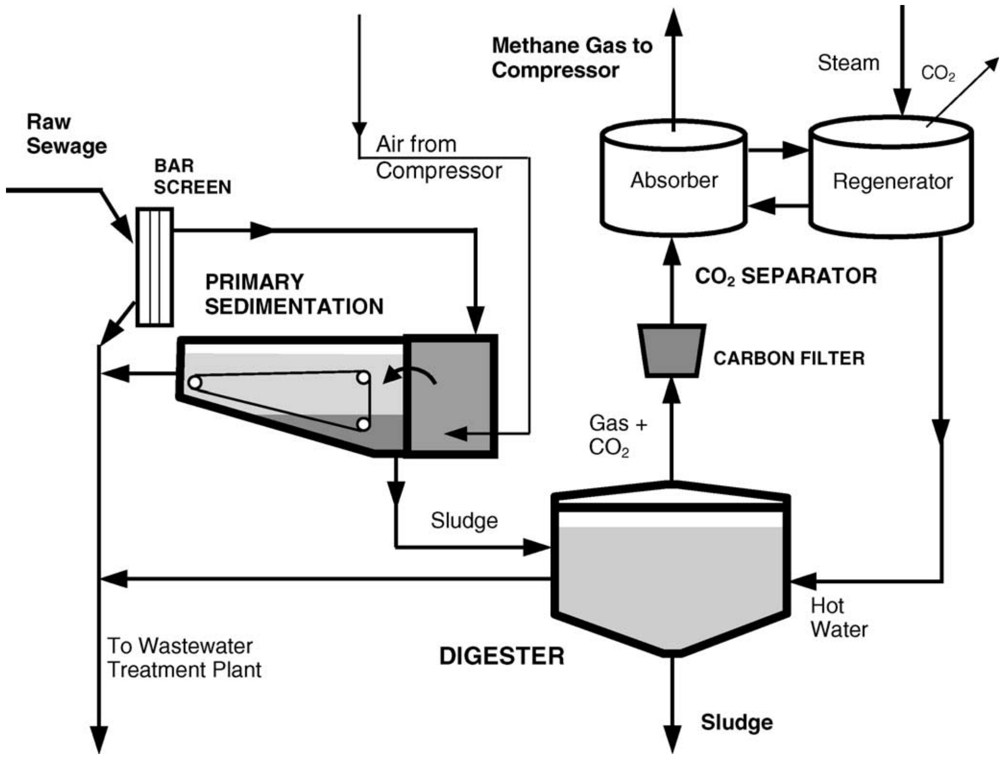

Fig. 5. Schematic diagram of biogas plant which uses a portion of the organic solids in the wastewater stream, exhaust steam from the gas turbine exhaust, and compressed air to provide methane to the compressor.

air circuit, the full-power condition supplies additional work due to the increasing flow rate through the turbine. The mass flow rate through the refrigeration compressor is initially decreased, with the work going to ramp up the air supply, then increased to match the increased power available from the gas turbine.

The operating conditions of the gas turbine unit are calculated for both standby and full-power conditions. In future work, the optimization of using a gas turbine running at off-design point for one of the operation modes will be investigated. The total system efficiency and stability are modelled for various shaft and cycle configurations in order to fully develop this design concept [13].

3.5. Methane gas plant

The energy source for the SOFC–UPS power plant is the product of biological digestion of sewage. While improvements in this process continue to develop, the basic process is well known. A flow diagram of a typical gas plant is presented in Fig. 5. A main sewer line is passed over a bar screen, and a portion of the solids separated and fed to the plant. Compressed air from the turbine plant is used to break up the solids, which are then fed into the digester. Hot water from the turbine plant is circulated through the digester to maintain optimum temperature of 55 °C. The resulting sludge is delivered to a fertilizer plant. While Singapore has only 2% arable land, the use of greenhouses to grow fresh produce may provide a market for the sludge. The product gas from the digester is 60–80% methane. The gas is passed through an activated carbon filter to remove any trace of hydrogen sulphide. A CO_2 separation process is then used to deliver pure methane to the power plant. The separation process is typical of commercial CO_2 production. Steam from the turbine plant is used to regenerate the absorbent solution, which is typically alkanolamine [14].

A sewage gas plant typically produces 0.3–0.5 m^3 of methane per kilogram of solids. The energy requirement for the SOFC–UPS power plant design would require 32 m^3 of methane per hour. This represents the gas production rate generated from wastewater for a population of 40 000 people, or 1% of Singapore's population.

4. Thermo-chemical model of SOFC–UPS

The first-level analysis of the feasibility of the SOFC–UPS concept was accomplished by examining two critical energy and mass balances. First, the basic function of the primary SOFC stack was investigated to determine possible operating regimes. Then a total energy balance on the SOFC–UPS plant was performed using representative performance characteristics for each component of the system. The general energy analysis provided the starting point for further

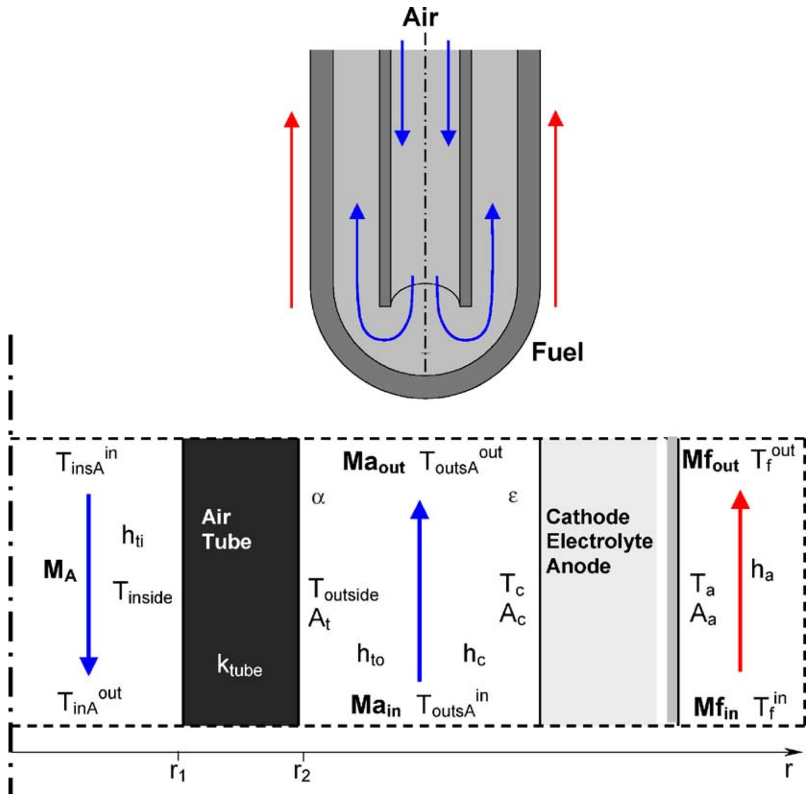

Fig. 6. Energy and mass balance on an elemental volume along SOFC tube length. Air and fuel enter at bottom of the tube and flow toward the exit and re-circulation ports at top.

research by identifying any changes that must be made to the total system concept, and in defining the global design parameters.

4.1. Primary SOFC tube reforming, reaction kinetics, and thermal analysis

The control volume for the thermal analysis of the progressive reforming and reduction reactions is defined in Fig. 6. The model predicts the composition of the molar flow rate through out the length of the cell, and the temperature of the flow and air tube based on the following assumptions:

- surface temperatures of the anode and cathode are constant and known,
- uniform potential along the stack based on typical operating conditions,
- uniform current density due the electrochemical oxidation of carbon monoxide and hydrogen,
- radiation heat exchange between the cathode and air tube only (not to the gases),
- internal reforming,
- equilibrium shift reaction.

Taking advantage of the long thin shape and symmetry, a l-D model was formulated. A single tube was divided into finite length sections, where mass and energy balances were performed. There are four reactions occurring in the fuel stream, namely, reforming, shifting, and the electrochemical reaction of hydrogen and carbon monoxide. The total current is due to the electrochemical oxidation of the hydrogen and to some extent carbon monoxide, giving currents i_c and i_h, respectively, for a finite section of the tube.

The rate of reforming is expressed by [15]:

$$n = k_{CH_4} A_a \exp\left(\frac{-E_{CH_4}}{RT}\right) \quad (5)$$

The shift reaction proceeds at a rate such that equilibrium is maintained, i.e., the partial pressures of the gases satisfy:

$$k_{shift} = \frac{P_{CO_2} P_{H_2}}{P_{CO} P_{H_2O}} \quad (6)$$

The temperature-dependent equilibrium constant is given empirically by [10]:

$$\log(k_{shift}) = AT^4 + BT^3 + CT^2 + DT + E \quad (7)$$

The resulting molar flow rate vector of the fuel entering ($\mathbf{Mf}_i$) and exiting ($\mathbf{Mf}_o$) a finite section of the tubular cell is:

$$\mathbf{Mf}_o = \mathbf{Mf}_i + \frac{i_h}{2F}\begin{pmatrix}0\\-1\\0\\0\\1\end{pmatrix} + \frac{i_c}{2F}\begin{pmatrix}-1\\0\\1\\0\\0\end{pmatrix} + n\begin{pmatrix}1\\3\\0\\-1\\-1\end{pmatrix} + m\begin{pmatrix}-1\\1\\1\\0\\-1\end{pmatrix}, \quad \mathbf{Mf} = \begin{pmatrix}CO\\H_2\\CO_2\\CH_4\\H_2O\end{pmatrix} \tag{8}$$

A similar expression for the air flowing on the outside of the air tube is obtained, i.e.

$$\mathbf{Ma}_o = \mathbf{Ma}_i + \frac{i_h}{4F}\begin{pmatrix}-1\\0\end{pmatrix} + \frac{i_c}{4F}\begin{pmatrix}-1\\0\end{pmatrix}, \quad \mathbf{Ma} = \begin{pmatrix}O_2\\N_2\end{pmatrix} \tag{9}$$

The thermal profile of the tubular cell, given the reaction rate profiles calculated from above, is then determined from the elemental energy balance as a function of position along the cell. Well mixed, fully developed, laminar conditions were assumed, hence an energy balance for the four surfaces, anode, cathode, inner and outer air tube can be written. The following equations are for a finite section of the tube, with the over bar indicating the average value. Variables are as defined in Fig. 6, and $\boldsymbol{C}_i$ are vectors containing the specific heats.

Anode surface:

$$h_a A_a (T_a - \overline{T_F}) = \boldsymbol{C}_F \cdot \overline{\mathbf{Mf}} (T_F^{out} - T_F^{in}) + n\,\Delta h_r + m\,\Delta h_s \tag{10a}$$

Cathode surface:

$$h_c A_c (T_c - \overline{T_{outsA}}) = \boldsymbol{C}_A \cdot \overline{\mathbf{Ma}} (T_{Aout} - T_{Ain}) + A_t \delta\varepsilon\alpha (T_a^4 - T_{outside}^4) \tag{10b}$$

Outside air tube:

$$\frac{k_{tube}(T_{inside} - T_{outside})}{\ln(r_2/r_1)} = \varepsilon\alpha\sigma r_2 (T_c^4 - T_{outside}^4) + r_2 h_{ot} (\overline{T_{outsA}} - T_{outside}) \tag{10c}$$

Inside air tube:

$$\frac{k_{tube}(T_{inside} - T_{outside})}{\ln(r_2/r_1)} = r_1 h_{it} (T_{inside} - \overline{T_{insA}}) = \boldsymbol{C}_A \cdot \boldsymbol{M}_A (T_{insA}^{out} - T_{insA}^{in}) \tag{10d}$$

The gas composition and temperature solutions are coupled, hence Eqs. (8)–(10) are solved simultaneously in an iterative fashion using Matlab until a steady state is achieved. The result for an SOFC with realistic values for current density, initial flow and temperatures is shown in Fig. 7 for partial pre-reforming.

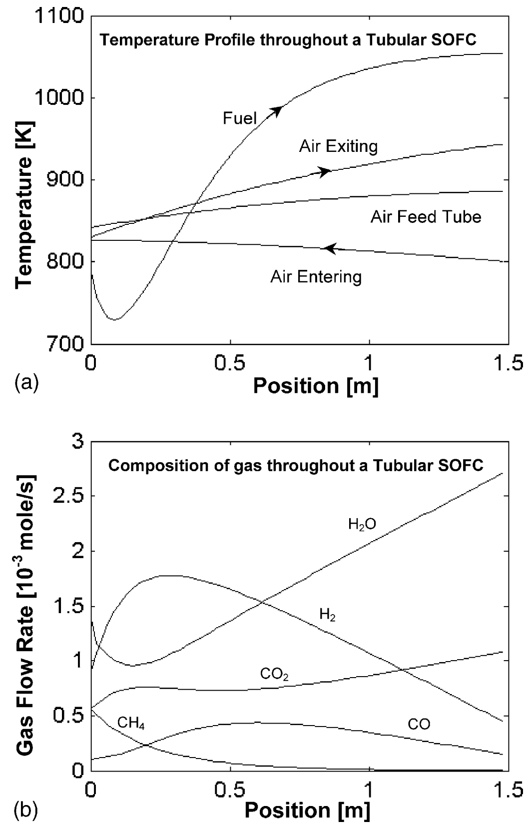

Fig. 7. (a) Thermal analysis of SOFC tube from energy balance on elemental volume given as temperature of each gas flow stream and air feed tube. (b) Species concentration as function of position along SOFC tube.

4.2. System performance

The analysis from Section 4.1 was used to model the SOFC stack behaviour in the investigation of possible operating strategies for the system. Generic models were employed for other system components such as turbines, compressors, and heat exchangers. Typical efficiencies were assumed. This process is iterative. Where an operating scheme is proposed, the kinetic chemical–thermal model is used to determine feasibility, then basic system energy and mass balances are performed to determine operating points. The independent parameters for the SOFC–UPS system are given in Table 1. The results for one possible operating

Table 1
SOFC–UPS power plant operating points

Parameter	Standby	Full load
Air inlet temperature (K)	800	800
Fuel inlet temperature (K)	800	800
Cell voltage (V)	0.6	0.6
Current density ($A\,m^{-2}$)	4000–5000	5000
Air flow rate (times stoichiometric)	4	4
Fuel utilization	0.65–0.85	0.85
Primary stacks	Full power	Full power
Secondary stacks	Open circuit	Full power
Refrigeration	Boost	Full load
High pressure CH_4 compressor	On-line	Switched to air

Table 2
SOFC–UPS performance points from system energy balance

Parameter	Standby	Full load
Active stacks	Primary	Primary + secondary
Percent of total stack area on-line	50	100
CH_4 flow rate (mol s^{-1})	0.35	0.64
CH_4 energy flow rate (kW)	280	514
SOFC electric power to dc bus (kW)	100–125	250
Total gas turbine power (kW)	80	163
Air compressor (kW)	38.5	77
Fuel SOFC pressure (W)	687	808
Fuel high pressure (W)	26.5	
Refrigeration power (kW)	40.7	85.9
Heat to gas plant (kW)	76	101

scheme are given in Table 2. The primary stack operates at constant fuel and air flow rates, but at variable current density, fuel utilization, and thus variable power. The idea is to run the primary stack nominally at 100 kW, with an excess fuel flow rate to produce 125 kW. This allows rapid response to small and more common voltage dips on the grid without having to change the fuel flow rate. These results demonstrate that it is possible to operate a thermally coupled split SOFC stack in this manner to produce UPS plus emergency cooling.

5. Discussion

The goal of this study has been to develop a system concept for application of SOFC technology for a specific purpose. The application is the need for secure, high-quality power by a high-tech manufacturing facility where the grid is unstable with daily phase anomalies, weekly voltage dips and surges, and monthly total power outages. The total system concept was developed for an electronics manufacturing facility in Singapore with a 250 kW critical equipment load, plus cooling requirements for continued secure and safe operation. Singapore has no indigenous resources of fossil fuels, low-quality solar and wind resources, and a very high population density. The fuel for the SOFC–UPS system was modelled as methane, supplied from the wastewater system by biological digestion of sewage solids. Waste heat and compressed air from the SOFC-gas turbine plant are used to run the gas plant.

A novel SOFC–UPS concept using a continuously operating primary stack to maintain the operating temperature and start-up steam for reforming of a matched secondary stack has been proposed. The primary stack also provides 125 kW of high voltage power for the critical load power, plus conditioning of grid anomalies. Grid power is rectified, conditioned with the SOFC dc power, and subsequently inverted according to plant equipment specifications to supply the critical load. A gas turbine can convert the high-pressure exhaust from the SOFC into shaft work in a typical recuperative cycle. The air and fuel compressors are driven by the turbine and thus matched for variable flow rate as the plant switches from standby to full power operation. There is an additional 41 kW (standby) and 86 kW (full power) available from the gas turbine for cooling of plant operations and machinery via compression of a refrigerant.

Energy and mass-balance modelling is used to investigate the feasibility of the proposed system concept, and to determine system performance at standby and full load for one configuration using 1100 Siemens–Westinghouse SOFC tubes and methane generated from the wastewater solids from 40 000 people. In future work, integrated performance models will be developed for the components, including turbo-machines, heat exchangers, the gas plant and the refrigeration cycle, to characterize fully the system performance and to optimize the system configuration. Additional future work will focus on further development of the modular, flexible modelling technique using the total system concept and the Simulink-Matlab platform for other fuel cell types and other applications.

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