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Design and Implementation of Models for Analyzing the Dynamic Performance of Distributed Generators in the Micro Grid Part I: Micro Turbine and Solid Oxide Fuel Cell

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Abstract. *This paper implements models of two important distributed generators. The first developed model describes and simulates the dynamic performance of a Single Shaft Micro Turbine, while the second model simulates the dynamic behavior of a Solid Oxide Fuel cell (SOFC). Increasing and reducing the power produced by these micro sources is also simulated. The two developed models can test the dynamic response for the power demand change from 0% to 120% of the rated value. The stand alone dynamic performance of the two developed models is analyzed and evaluated. Results proved the effectiveness and robustness of the developed models. The two developed models can be used to describe the behavior of a Micro Grid (MG) under different disturbance conditions like islanding from the main grid, load following, load shedding, unbalanced loads, failure of one micro source and so forth. Also, we developed models for those micro sources for building a complete model that can describe the overall dynamic performance of the Micro Grid (MG). The developed models of the Micro Turbine and the SOFC are inserted in a complete MG system to prove the validation of those models. Investigations of the MG system under different disturbance conditions are performed. Results proved the validation and effectiveness of the two developed models in the studying and analysis of the transient dynamic response of MG. All models and controllers are built in the Matlab® Simulink® environment.*

Keywords: *Micro turbine; SOFC; Dynamic response; Distributed generators; Micro grid; Islanding.*

INTRODUCTION

There are four realities facing future power systems that require rethinking the distribution system, the use of Distributed Energy Resources (DER) and the smart grid. The realities require that the transmission and distribution system must [1-2]:

- Provide for load growth with enhanced stability and with minimal growth of the transmission system.
- Make greater use of renewable energies, such as wind and photovoltaic systems.
- Increase energy efficiency and reduce pollution and greenhouse gas emissions.
- Increase the availability of high power quality for sensitive loads.

A micro grid can be defined as a LV distribution system to which small modular generation systems are to be connected [3]. Generally, a micro grid corresponds to an association of electrical loads and small generation systems through a LV distribution network. This means that loads and sources are physically close [3]. Micro generation systems can include several types of device, such as fuel cells and renewable generators such as wind turbines or Photovoltaic (PV) systems, as well as micro turbines powered by natural gas or bio fuels [3].

Among such Distributed Energy Resources (DER), micro turbines and fuel cells show particular promise, as they can operate on multiple fuels with low emissions, high efficiency and high reliability [4].

Micro turbines are small and simple-cycle gas turbines with outputs ranging from around 25 to 300 kW. They are part of a general evaluation in gas

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turbine technology. There are essentially two types of micro turbine. One is a high-speed single-shaft unit with the compressor and turbine mounted on the same shaft as the electrical alternators; turbine speeds mainly range from 50,000 to 120,000 rpm. The other type of micro-turbine is a split-shaft design that uses a power turbine rotating at 3600 rpm and a conventional generator connected via a gearbox [4-6].

Fuel cells are another rapidly developing generation technology. Fuel cell features have the potential for high efficiency (35-60%), low to zero emissions, quiet operation and high reliability due to the limited number of moving parts. They produce power electrochemically by passing a hydrogen-rich gas over an anode, air over a cathode and introducing an electrolyte in-between to enable exchange of ions. The effectiveness of this process is strongly dependent upon the electrolyte to create the chemical reactivity needed for ion transport. As a result, fuel cells are classified by the electrolyte type [4-5]:

- Polymer Electrolyte Fuel Cell (PEFC);
- Alkaline Fuel Cell (AFC);
- Phosphoric Acid Fuel Cell (PAFC);
- Molten Carbonate Fuel Cell (MCFC);
- Solid Oxide Fuel Cell (SOFC).

As micro turbines and fuel cells will likely became major Distributed Energy Resources (DERs), dynamic models are necessary to deal with issues in system planning operation and management. Micro turbines and fuel cells have several unique properties from a modeling viewpoint. Micro turbines have extremely low inertia and damping. In fuel cells, the electrical response time of the power section is generally fast, being mainly associated with the speed at which the chemical reaction is capable of restoring the charge that has been drained by the load. Conversely, the chemical response time of the reformer is usually slow, being associated with the time for the fuel cell stack to modify the chemical reaction parameters after a change in the flow of reactants. Accordingly, it is necessary to develop new models appropriate for investigating such performances.

To study the dynamic response of each one of the Distributed Energy Resources (DERs), the theory of operation of each micro source must be studied. Mathematical models that describe the dynamics of induction and synchronous generators, converters, wind energy conversion systems, photovoltaic systems, fuel cells, micro turbines, battery energy storage systems and super capacitors are mainly addressed in [5]. Reference [4] developed mathematical models for micro turbines and fuel cells. Matlab® Simulink® models developed in this paper are modeled according to the mathematical description provided by [4,5].

Most papers which discussed the dynamic behavior of micro grids, used (EMTP/ATP) and (PSCAD/EMTDC) software packages to simulate micro grid components. However, those packages are designed to analyze large conventional power systems, and when they are used to simulate MG components many assumptions are taken into consideration. The main goal of our work is developing a complete model that can simulate MG components more accurately. In [7], we developed Matlab® Simulink® models to simulate the inverter with its various controllers that are used to connect Distributed Generators (DG) to micro grids. In this paper, we developed Matlab® Simulink® models to simulate a micro turbine and fuel cell.

MICRO TURBINE MODELING

As previously mentioned, there are essentially two types of micro turbine model. One is a high-speed single-shaft model with the compressors and turbine mounted on the same shaft as the alternator. Another is a split-shaft model that uses a power turbine rotating at 3600 rpm and a conventional generator connected via a gearbox. The parts of the models are [4]:

- **Turbine.** There are two kinds of turbine: high-speed single-shaft turbines and split-shaft turbines. All are small gas turbines.
- **Alternator or induction machine.** In the single-shaft design, an alternator is directly coupled to the single-shaft turbine. The rotor is either a two or four pole permanent magnet design, and the stator is a conventional copper wound design. In the split-shaft design, a conventional induction or synchronous machine is mounted on the power turbine via a gear box.
- **Power electronics.** In the single-shaft design, the alternator generates a very high frequency, three-phase signal ranging from 1500 to 4000 Hz. The high frequency voltage is first rectified and then inverted to a normal 50 or 60 Hz. In the split-shaft turbine design, power inverters are not needed [7].
- **Recuperator.** The recuperator is a heat exchanger, which transfers heat from the exhaust gas to the discharge air before it enters the combustors. This reduces the amount of fuel required to raise the discharge air temperature to that required by the turbine.
- **Control and communication systems.** Control and communications systems include full control of the turbine, a power inverter and start-up electronics, as well as instrumentation, signal conditioning, data logging, diagnostics and user control communication.

In this paper, we are mainly interested in the dynamic performance of the micro turbine. Based on this, our simplified micro turbine model is found in the following assumptions:

- The system operation is under normal conditions. Start-up and shut down are not included.
- The micro turbine electric-mechanical behavior is our main interest. The recuperator is not included in the model as it is only a heat exchanger to raise engine efficiency. Also, due to the recuperator's very slow response time, it has little influence on the time-scale of our dynamic simulations.
- The gas turbine temperature and acceleration controls are of no significance under normal system conditions. They can be omitted in the turbine model.
- Most micro turbines do not have governors and, so the governor model is not considered.

Modeling of Split-Shaft Design

Figure 1 shows the diagram of a split- shaft design [6]. The main blocks of this micro turbine are shown in Figure 2. The details of these blocks with all parameters are given in the following subsections.

Control System

We are mainly interested in the real power control function of the control systems, so, the control systems are simplified as a real power Proportional-Integral (PI) control function, as shown in Figure 3. The controlled real power, P_{in}, is applied to the turbine.

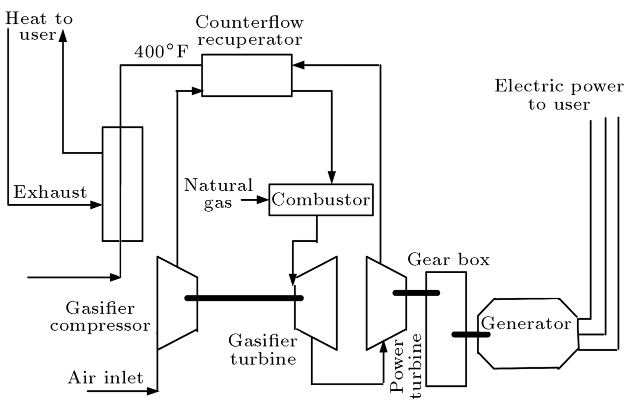

Figure 1. Power works micro turbine diagram.

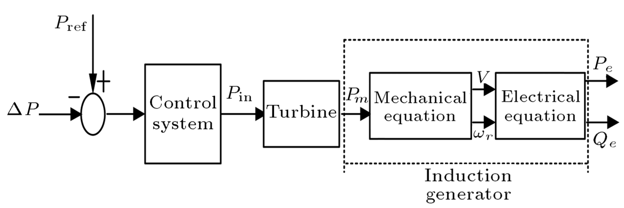

Figure 2. Main blocks in micro turbine model.

Turbine

In the split-shaft design, although there are two turbines, one is a gasifier turbine driving a compressor and another is a free power turbine driving a generator at a rotating speed of 3600 rpm; there is only one combustor and one gasifier compressor. This is largely different from the twin-shaft combustion-turbine, which has two combustors and two compressors [8]. So, it is more suitable to model this split-shaft turbine as a simple-cycle, single-shaft gas turbine. The GAST turbine-governor model is one of the most commonly used dynamic models of gas turbine units. The model is simple and follows typical modeling guidelines [9]. For simplicity and wider acceptability, the turbine part in this micro turbine design is modeled as a GAST model without the droop, as shown in Figure 4.

Mechanical Formulation of the Generator

The mechanical equation of the generator in Figure 2 is:

$$2H\frac{d\omega_r}{dt} = \frac{P_m}{\omega_m} - P_e - D_{\text{gen}}(\omega_r - 1). \qquad (1)$$

With $\omega_r = \omega_m$ and $\omega_m = \frac{\omega_m}{\omega_b}$, ω_b is the base speed.
We have the following mechanical equation:

$$2H\frac{d\omega_m}{dt} = \frac{\omega_b^2}{\omega_m}P_m - \omega_b P_e - D_{\text{gen}}(\omega_m - \omega_b), \qquad (2)$$

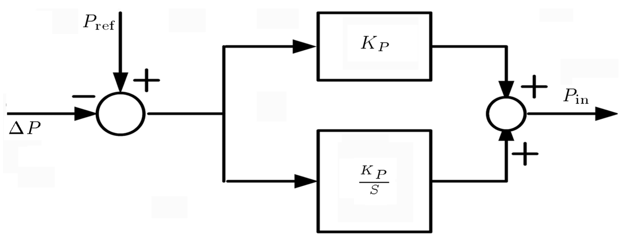

Figure 3. Control system model.

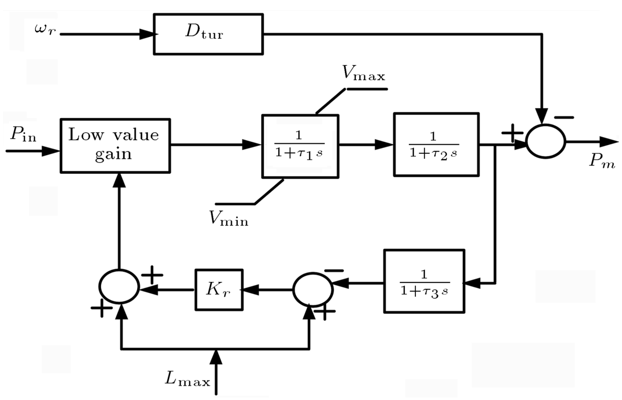

Figure 4. Turbine model.

where:

P_m mechanical output power of the turbine which inputs to the generator shaft (Watt);

Pe output electrical power (Watt);

D_{gen} generator damping coefficient.

Electrical Equations

The electrical equations are the equations which describe the operation of the induction generator [5]. The generator, coupled with the Micro Turbine in our case, is a squirrel-cage induction generator that can be directly connected to the micro grid or may be operated in stand-alone mode. In this paper, we used a stand-alone mode and a capacitor bank is used for generator excitation.

Model Parameters

In this paper, we assume that the rated power of the micro turbine is 3.73 kW and the rated line voltage is 380 V. The parameters of this micro turbine model are listed in Table 1 [8-9].

Matlab Simulink Model of Integrated Split-Shaft Micro Turbine System

Details of the model developed for implementation of a micro turbine and its generator is in Figure 5. Figure 6 shows the model's block diagram with input and output terminals. The input terminal is P_{ref} (required power). Output terminals are the mechanical power of the Micro Turbine (or mechanical torque), which are applied to the input of the generator, and the terminals of the generator are connected with the MG. The reference power represents the amount of power demand from the Micro Turbine. As we will describe later, in the complete MG system section the value of P_{ref} is determined by the frequency deviation of the MG. If there is a drop in MG frequency, this means that the load inside the MG is more than the generation and

Table 1. Parameters of split-shaft micro turbine model.

Parameter	Representation	Value
P_{rate}	Rated power	3.73 kW
V_{rated}	Rated voltage	380 V
P_{ref}	Real power reference	1 p.u.
K_P	Proportional gain in PI control	1
K_i	Integral gain in PI control	1.08
D_{tur}	Damping of turbine	0.03
T_1	Fuel system lag time constant 1	10.0 s
T_2	Fuel system lag time 2	0.1 s
T_3	Load limit time constant	3.0 s
$L_{\max}$	Load limit	1.2
$V_{\max}$	Maximum value position	1.2
$V_{\min}$	Minimum value position	-0.1
K_T	Temperature control loop gain	1
p	Num ber of poles	4
R_S	Resistance of stationary part	0.1 Ω
R_r	Resistance of rotor circuit referred to the stationary circuit	0.1 Ω
L_S	Inductance of stationary circuit	0.0059 H
L_r	Inductance of rotor circuit referred to the stationary circuit	0.0059 H
L_m	Mutual inductance	0.2037 H
D_{gen}	Damping of generator	0.1
J	Generator inertia	0.02 kg.m^2
F	Generator friction	0.0057 N.m.s

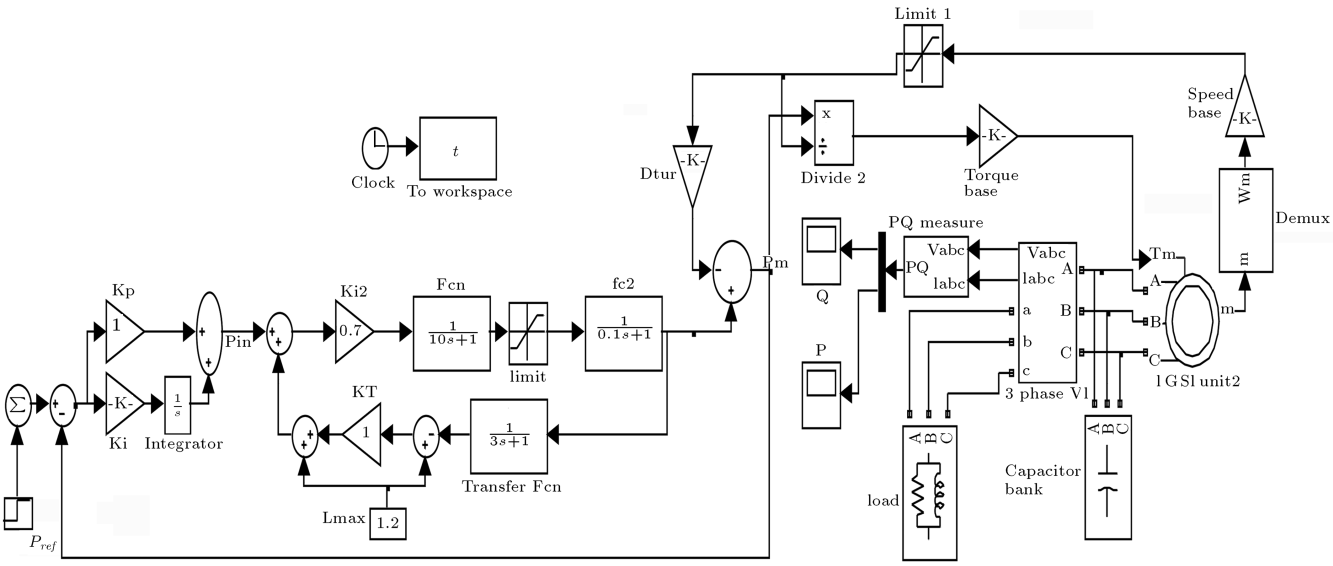

Figure 5. Matlab®/Simulink® model for micro turbine system.

P_{ref} must be increased until balancing occurs. If MG frequency increases, this means that the load is less than the generation and P_{ref} must be reduced. The control loop that decides the value of P_{ref} is shown in Figure 7.

Assume this micro turbine has 120% peak power capacity, So $L_{\max} = V_{\max} = 1.2$.

EVALUATION OF STAND-ALONE PERFORMANCE

Assume a split-shaft micro turbine system is operating with a constant rated voltage, 1.0 p.u. (380 V), and a power demand, 0.7 p.u. (2.6 kW). All parameters are the same as listed in Table 1. At $t = 60.0$ sec, there is a step increase of the power demand from 0.7 p.u. (2.6 kW) to 1 p.u. (3.73 kW). Figure 8 shows the dynamic response of the mechanical power, P_m, and the total three-phase electrical power output, P_e. Figure 9 shows the dynamic response when decreasing

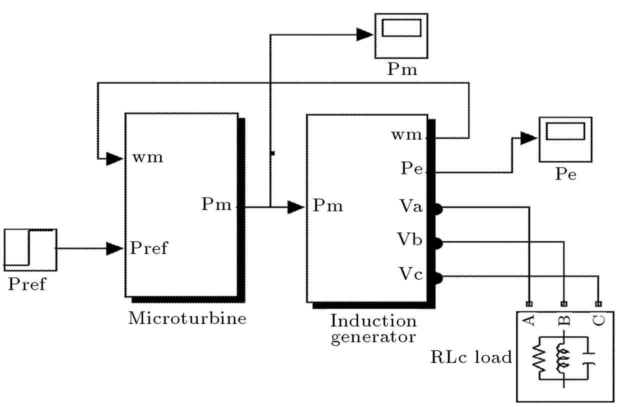

Figure 6. Micro Turbine system model.

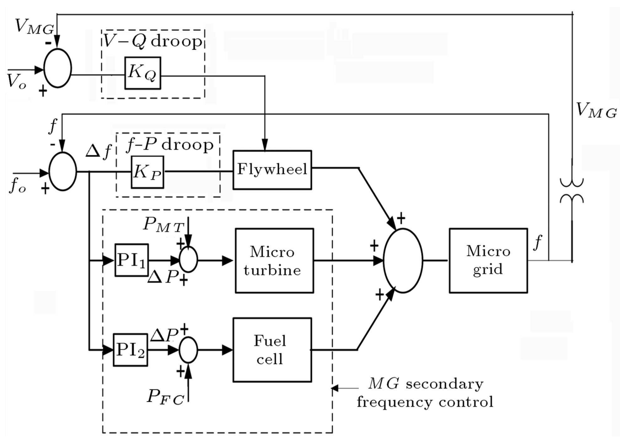

Figure 7. Frequency control using Micro Turbine and SOFC.

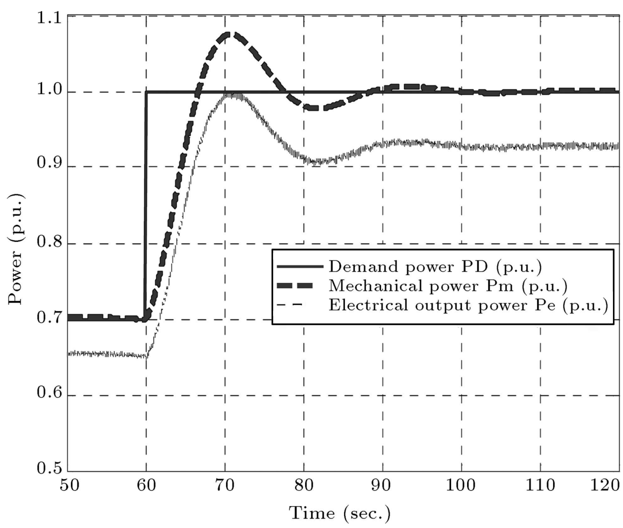

Figure 8. Dynamic response of Micro Turbine when increasing power demand from 0.7 p.u. to 1.0 p.u.

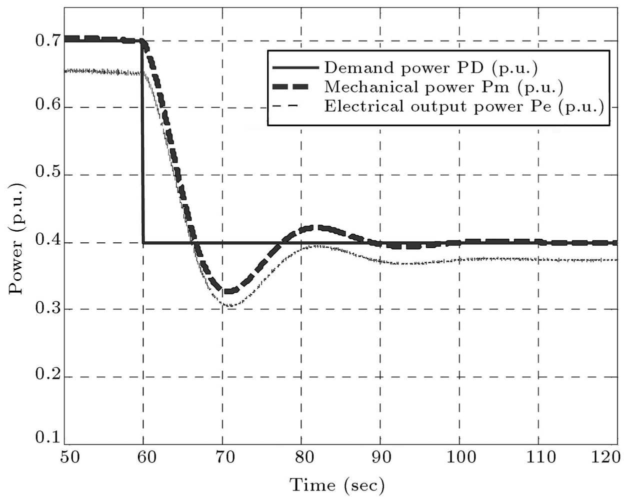

Figure 9. Dynamic response of Micro Turbine when decreasing power demand from 0.7 p.u. to 0.4 p.u.

the power demand from 0.7 p.u. (2.6 kW) to 0.4 p.u. (1.5 kW).

From simulation results, the following points can be raised:

- The initial response time for the step change is around 10 sec; this delay mainly due to the turbine response time.
- The oscillation in P_m and P_e is significant with a time period around 20 sec; this is mainly due to the small inertia and damping of the Micro Turbine.
- A Micro Turbine is the most suitable micro source for dealing with the load following in the micro grid.
- The efficiency of the Micro Turbine ($P_{\text{elec}}/P_{\text{mech}}$) at full load (Figure 6) is equal to 93%, while efficiency at 40% of the full load is equal to 92.5% as shown in Figure 9.

INTEGRATED FUEL CELL SYSTEM MODELING

A power generation fuel cell system has the following three main parts:

- **Fuel processor.** The fuel processor converts fuels, such as natural gas, to hydrogen and byproduct gases.
- **Power section (fuel cell).** The power section generates electricity. There are numerous individual electrochemical fuel cells in the power section.
- **Power conditioner (Inverter).** The power conditioner converts DC power to AC power output.

In this study, we focus on the Solid Oxide Fuel Cell (SOFC) system modeling, with the expectation that the response time of other types of cell will be similar.

Modeling of SOFC System

Padulles and Aulf [10] provided a basic SOFC power section dynamic model used for performance analysis during normal operation. Based on that, some control strategies of the fuel cell system, response functions of the fuel processor and the power section are added to model the SOFC power generation system (all symbols are defined in Table 2):

- Although CO can be a fuel in SOFC, the CO-shift reaction is chemically favored with the present designs and operations if the fuel gas contains water. The CO-shift reaction is:

$$\mathrm{CO} + \mathrm{H_2O} \rightarrow \mathrm{CO_2} + \mathrm{H_2}. \quad (3)$$

Based on this, we assume that only H_2 and O_2 enter into the fuel cells.

- Fuel utilization is the ratio between the fuel flow that reacts and the input fuel flow. Here, we have:

$$U_f = q^r_{\mathrm{H_2}}/q^{\mathrm{in}}_{\mathrm{H_2}}. \quad (4)$$

Typically, there is 80-90% fuel utilization. Reference [9] gives the following equation:

$$q^r_{\mathrm{H_2}} = \frac{N_o I^r_{fc}}{2F} = 2K_r I^r_{fc}. \quad (5)$$

For a certain input hydrogen flow, the demand current of the fuel cell system can be restricted in the following range:

$$\frac{0.8\ q^{\mathrm{in}}_{\mathrm{H_2}}}{2K_r} \leq I^{\mathrm{in}}_{fc} \leq \frac{0.9\ q^{\mathrm{in}}_{\mathrm{H_2}}}{2K_r}. \quad (6)$$

- The real output current in the fuel cell can be measured, so that the input fuel flow can be controlled to control U_f (fuel utilization) at 85%, so:

$$q^{\mathrm{in}}_{\mathrm{H_2}} = \frac{2K_r I^r_{fc}}{0.85}. \quad (7)$$

- The overall fuel cell reaction is:

$$\mathrm{H_2} + \frac{1}{2}\mathrm{O_2} \rightarrow \mathrm{H_2O}. \quad (8)$$

So, the ratio of Hydrogen to Oxygen is 2 to 1. Oxygen excess is always taken in to let Hydrogen react with Oxygen more completely. Simulation in our fuel cell system shows that $r_{\mathrm{H-O}}$ (ratio of Hydrogen to Oxygen) should be kept around 1.145, in order to keep the fuel cell pressure difference below 4 kPa under normal operation. So, the input Oxygen flow is controlled to keep $r_{\mathrm{H-O}}$ at 1.145 by speed control of the air compressor.

Table 2. Parameters of SOFC model.

Parameter	Representation	Value
P_{rate}	Rated power	100 kW
P_{ref}	Real power Reference	100 kW
V_{rate}	Rated voltage	333.8 V
T	Absolute Temperature	1273 K
F	Faraday's constant	96487 C/mol
R	Universal gas constant	8314 J/(kmolK)
E_0	Ideal standard potential	1.18 V
N_0	Number of cells in series in the stack	384
K_r	Constant, $K_r = N_0/4F$	$0.996 * 10^{-6}$ kmol/(sA)
$U_{\max}$	Maximum fuel utilization	0.9
$U_{\min}$	Minimum fuel utilization	0.8
U_{opt}	Optimum fuel utilization	0.85
K_{H_2}	Valve molar constant for hydrogen	$8.43 * 10^{-4}$ kmol/(s atm)
$K_{\text{H}_2\text{O}}$	Valve molar constant for water	$2.81 * 10^{-4}$ kmol/(s atm)
K_{O_2}	Valve molar constant for oxygen	$2.52*10^{-4}$k mol/(s atm)
τ_{H_2}	Response time for hydrogen flow	26.1 s
$\tau_{\text{H}_2\text{O}}$	Response time for water flow	78.3 s
τ_{O_2}	Response time for oxygen flow	2.91 s
r	Ohmic loss	0.126 Ω
T_e	Electrical response time	0.8 sec
T_f	Fuel processor response time	5 sec
$r_{\text{H-O}}$	Ratio of hydrogen to oxygen	1.145
PF	Power factor	1.0

- The chemical response in the fuel processor is usually slow, as it is associated with the time to change the chemical reaction parameters after a change in the flow of reactants. This dynamic response function is modeled as a first-order transfer function with a 5 sec time constant.
- The electrical response time in the fuel cells is generally fast and mainly associated with the speed at which the chemical reaction is capable of restoring the charge that has been drained by the load. This dynamic response function is also modeled as a first-order transfer function, but with a 0.8 sec time constant.
- Through the power conditioner (inverter), the fuel cell system can output not only real power but also reactive power. Usually, the power factor can be in the range of 0.8-1.0. Based on [10] and the above discussions, the SOFC system dynamic model is given in Figure 10 where $q_{\text{O}_2}^{\text{in}}$is Oxygen input flow.

The fuel cell demand current (I_{fc}^{in}) is calculated by dividing power demand by fuel cell voltage (V_{fc}). Equation 6 determines the limits of the fuel cell demand current as shown in the block diagram. The fuel cell demand current is treated through a transfer function with time constant Ts which represents the electrical time constant. The fuel cell demand current multiplied by ohmic resistance (r) determines the internal voltage drop. The fuel cell demand current multiplied by constant $2K_r$ ($K_r = N_0/4F$), treated through a transfer function of gain equal to ($1/K_{\text{H}_2\text{O}}$) and a time constant equal to $T_{\text{H}_2\text{O}}$ determines the pressure of water as shown in the block diagram. With the same method, fuel cell current can be treated through transfer functions with time constants dependent on the valve molar constant of Oxygen and Hydrogen and with time constants equal to the response time of Oxygen and Hydrogen flow; this method can decide the pressure of Oxygen and Hydrogen inside

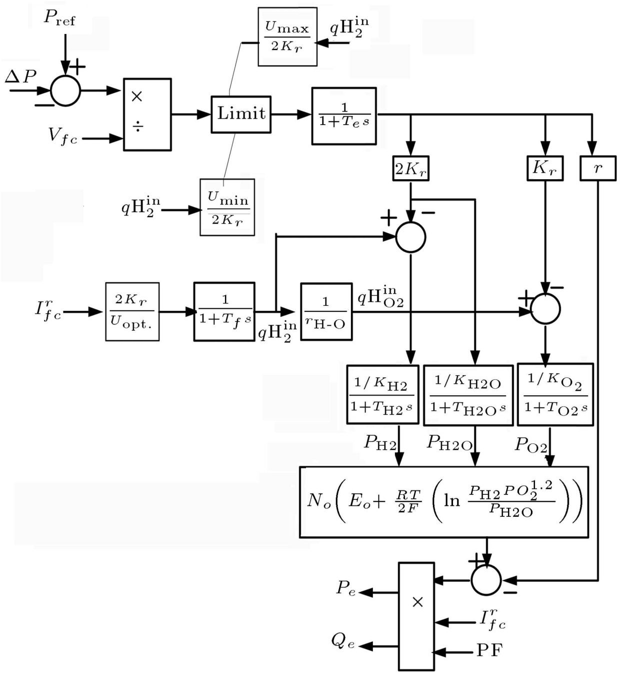

Figure 10. SOFC system dynamic model.

the fuel cell. By knowing water, Oxygen and Hydrogen pressures, voltage produced inside the fuel cell can be calculated, as shown in the block diagram. If the internal voltage drop caused by ohmic resistance (r) is subtracted from the voltage produced inside the fuel cell, net output voltage can be calculated. By knowing the fuel cell load current (current output from the fuel cell), the active power produced by the fuel cell is calculated. Reactive power can be decided by the power factor of the inverter, which is used to interface the fuel cell to the MG.

Model Parameters

In this paper, the rated power of the SOFC system is 100 kW. All model parameters are listed in Table 2.

Matlab Simulink Model of SOFC

Details of the developed model for implementation of the SOFC in the Matlab® Simulink® environment are shown in Figure 11. Figure 12 shows the model block diagram, input and output terminals. The input terminals are P_{ref} (desired power) and rated voltage, V_{ratd}. The output terminals are the fuel cell electrical output, active and reactive power. The amount of reactive power depends on the power factor of the inverter that is used to interface the SOFC with the MG. The reference power, P_{ref}, of the SOFC is determined by the same method as described in the Micro Turbine and also indicated in Figure 7.

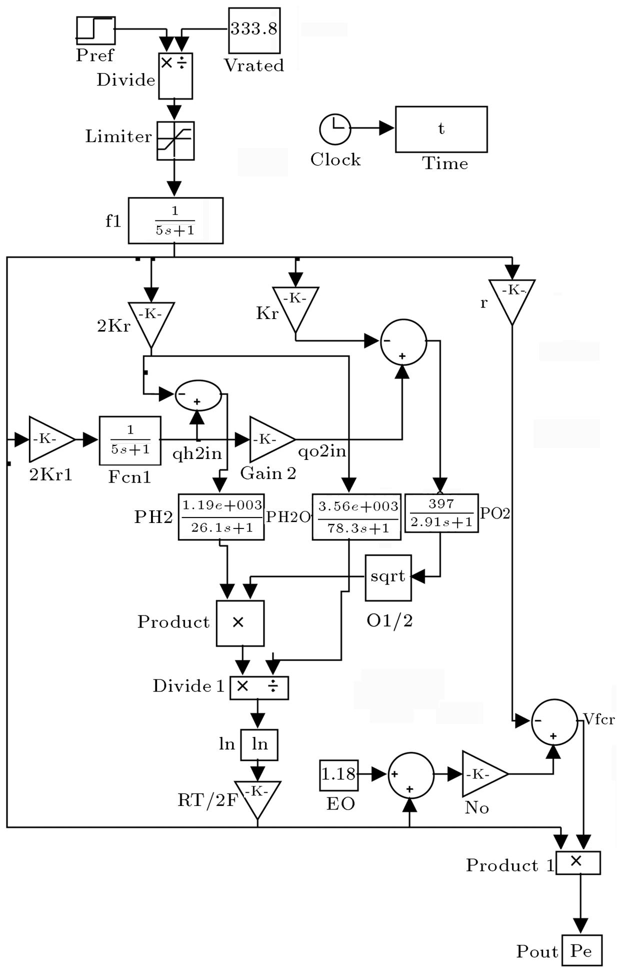

Figure 11. Matlab®/Simulink® model for SOFC system.

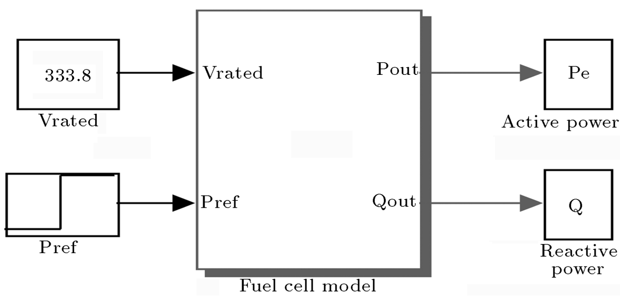

Figure 12. SOFC system model.

EVALUATION OF STAND-ALONE PERFORMANCE OF SOFC

It is assumed that the stand-alone SOFC system is operating with constant rated voltage, 1.0 p.u. (333.8 V), and power demand, 0.7 p.u. (70 kW). All parameters of the system are the same as in Table 2. At $t = 100$ sec, there is a step increase of the power demand from 0.7 p.u. (70 kW) to 1.0 p.u. (100 kW). Figure 13 shows the dynamic response of this system. Figure 14 shows the dynamic response of the SOFC when there

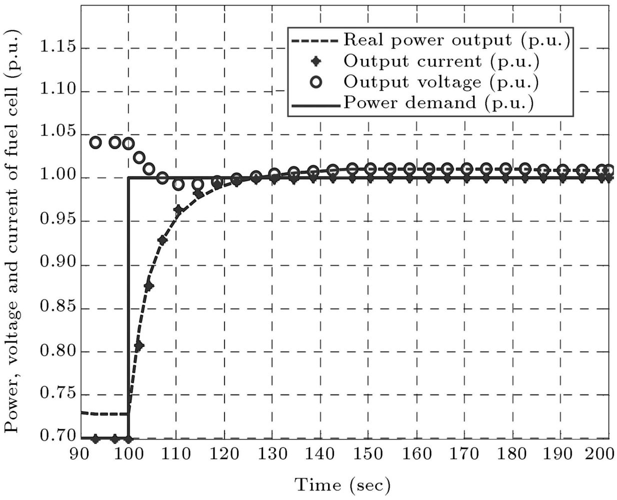

Figure 13. Response of SOFC when increasing power demand from 0.7 p.u. to 1.0 p.u.

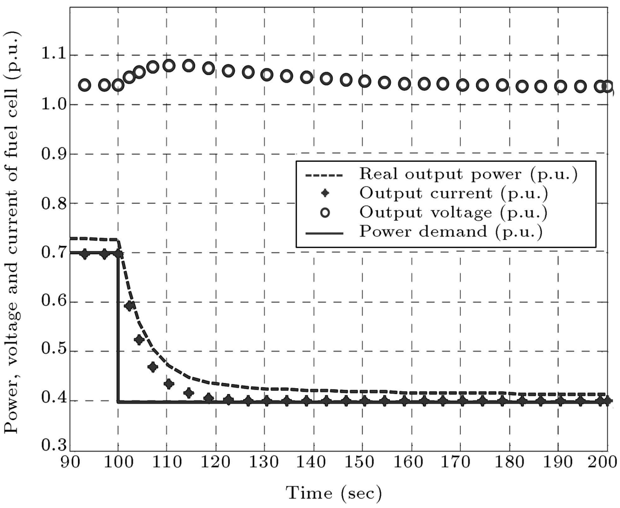

Figure 14. Response of SOFC when decreasing power demand from 0.7 p.u. to 0.4 p.u.

is a decreasing in power demand from 0.7 p.u. (70 kW) to 0.4 p.u. (40 kW).

From simulation results, the following points can be raised:

- P_e (output electrical active power) increases slowly and continuously until reaching the demand power.
- From Figure 14, P_e will decrease slowly until reaching the desired value.
- In both cases, the response time of the fuel cell is about 25-30 sec This is roughly three times that of the micro turbine response time (10 sec).
- In the first case, the output voltage of the fuel cell suffers from some decreasing, especially during power raising; while, in the second case, the voltage has some increasing during power decreasing.
- Results show that the SOFC has some slow dynamic response, so that using SOFC alone may be not suitable for systems that need a fast dynamic response. In this case, the Micro Turbine can be used with the SOFC to deal with a fast system response.

PERFORMANCE OF MICRO TURBINE AND SOFC MODELS INSTALLED IN A COMPLETE MICRO GRID SYSTEM SUBSEQUENT TO SEVERE AND MULTIPLE DISTURBANCES

The two previous described models of the Micro Turbine and SOFC are inserted in a complete model of the Micro Grid (MG). The developed MG system also contains a wind generation system, two photovoltaic panels, a flywheel and two types of inverter. Figure 15 shows a single line diagram of the developed MG system. All the micro sources ratings and load values are shown through that figure. The performance of the MG is investigated under several disturbances. The first disturbance is islanding from the main grid at $t = 60$ sec The second disturbance is the failure of the inverter, which interfaces the SOFC (at bus 7) at $t = 80$ sec The third disturbance is wind speed and

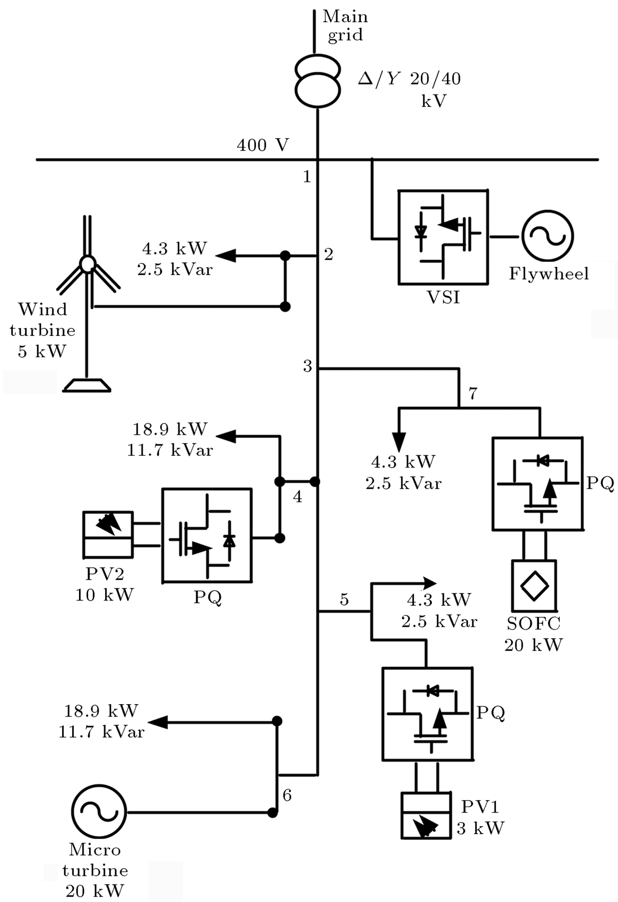

Figure 15. Single line block diagram of the developed MG.

solar irradiance fluctuations, which cause fluctuations on the frequency and voltage of the MG's subsequent islanding from the main grid. The frequency of the MG during and subsequent to all these disturbances is shown in Figure 16. Performances of the Micro Turbine and SOFC are indicated in Figures 17 and 18, respectively. Voltage at bus 6 (Micro Turbine bus) is shown in Figure 19. The power injected by the flywheel is shown in Figure 7.

From Figures 16 to 20, performance of the MG can be summarized in the following points:

- Before $t = 60$ sec, MG is at its steady state and its frequency is equal to the nominal value, as shown in Figure 16. The Micro Turbine generates about 40% of its rating (20 kW), as shown in Figure 17, while SOFC produces about 43% of its rating (20 kW), as shown in Figure 18. Both the Micro Turbine and SOFC are at their steady state.

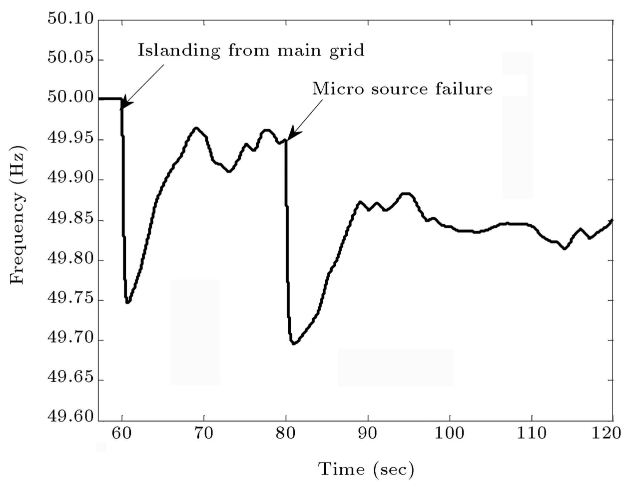

Figure 16. MG frequency during and subsequent three disturbances.

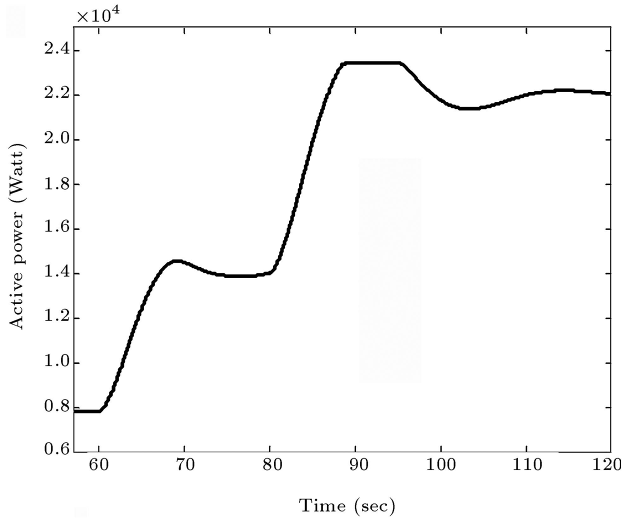

Figure 17. Micro turbine response.

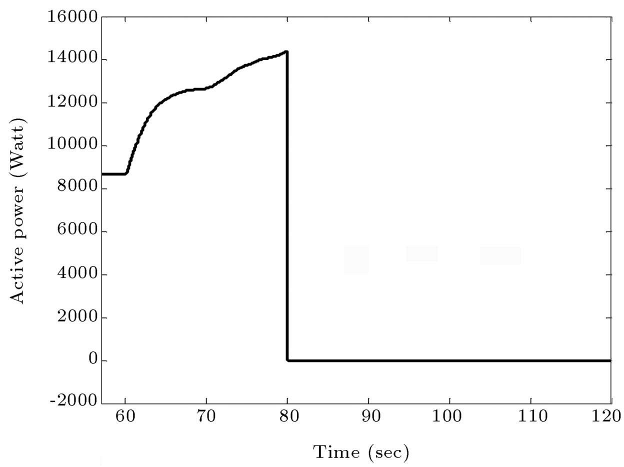

Figure 18. SOFC response.

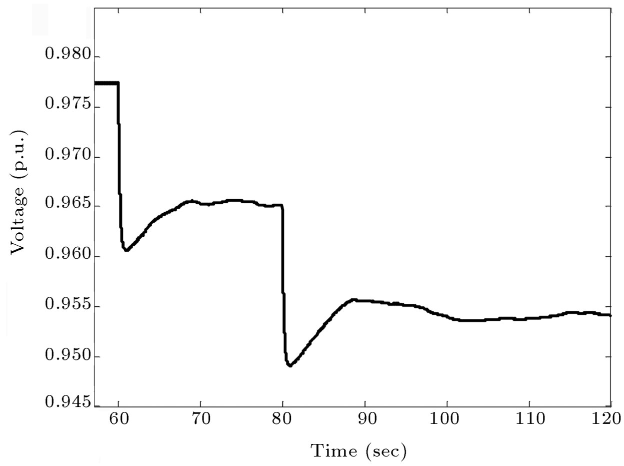

Figure 19. Voltage at bus # 6 (Micro Turbine bus).

- At $t = 60$ sec, the MG islanded from the main grid, which led it to lose certain active and reactive powers supplied by the main grid. Islanding led to frequency and voltage drop, as shown in Figures 16 and 19, respectively.
- Frequency deviation is used to adjust the generated power of the SOFC and Micro Turbine (as shown in Figure 7) to balance load and generation inside the MG. Powers generated by the Micro Turbine and SOFC increase, as shown in Figures 17 and 18, respectively. The response of the Micro Turbine and SOFC is shown in Figures 17 and 18 and has little difference from the response shown in Figures 8 and 13. This is because in Figures 8 and 13 there is only one constant step change on the power demand (from 0.7 p.u. to 1 p.u.) while in Figures 17 and 19, the reference power of the Micro Turbine and SOFC continuously change (Figure 7), because it depends on frequency deviation that decreases with time as shown in Figure 16.
- The storage device (flywheel) will inject power to

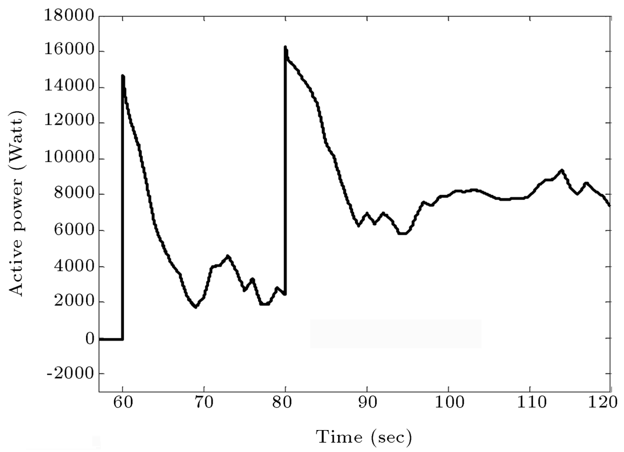

Figure 20. Power injected by flywheel.

balance the load and generation inside the MG during the period needed by the Micro Turbine and SOFC to raise their generations as shown in Figure 20.

- Fluctuations on the frequency are caused by continuous fluctuations of power generated by renewable sources (wind and solar) due to continuous variations of wind speed and solar irradiance.
- At $t = 80$ sec, the inverter interface SOFC is failed and the MG faces a severe disturbance due to loss of active power generated by SOFC. Frequency and voltage have a high drop as shown in Figures 16 and 19, respectively. Frequency deviation acts to raise the power of the Micro Turbine (Figure 17) and tries to balance the load and generation inside the MG. At $t = 90$ sec, the Micro Turbine reaches its rated power and cannot generate any extra power. The frequency is still less than the nominal value; the storage device will inject power (Figure 20) until its storage energy is totally consumed and the MG will go to blackout unless a load shedding strategy is used.
- Results shown in Figures 16 to 20 validate the developed model of the Micro Turbine and SOFC for investigating the transient dynamic performance of MG under severe disturbance conditions.

CONCLUSIONS

In this paper, Matlab® Simulink® dynamic models of a split-shaft Micro Turbine and SOFC are developed. Evaluation of those stand-alone models shows that they are reasonable and suitable for dynamic simulations. It is found that a Micro Turbine can increase or reduce its output mechanical power (30%) with a response time of nearly 10 sec The output mechanical power of the Micro Turbine suffers from some oscillation due to the small inertia of the Micro Turbine. Also, SOFC can increase or reduce its electrical output power (30%), but with a relatively long response time (25-30 sec) compared to the Micro Turbine (10 sec). It is demonstrated that Micro Turbines and fuel cells are capable of providing a load-following service in the distributed generation system, but the Micro Turbine is more suitable than the fuel cell for systems that need a fast dynamic response; for that system, both micro turbines and fuel cells can be used simultaneously to ensure a good response. The two developed models of the Micro Turbine and SOFC are inserted in a complete MG system to deal with the system fast response. The MG system is studied under several disturbance conditions such as islanding from the main grid and failure of a dominant micro source in addition to wind speed and solar irradiance fluctuations. The obtained results prove that a Micro Turbine and fuel cell can deal with load changes in the micro grid.

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