Load Following Function of Fuel Cell Plant in Distributed Environment

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Abstract. This paper presents a simplified slow dynamic model for a solid oxide fuel cell. The stand alone performance is analyzed and evaluated. A simple distribution feeder is penetrated by two fuel cell plants, and this is used as an example to evaluate the load following performance. The simulation indicates a restricted capacity of locally supply step load changes of the fuel cells.

Key words

Distributed Generation, fuel cell, load following functions, slow dynamic simulation.

1. Introduction

The electric market growth, the financial market's development and the accelerated technical progress have made the optimum size in new investments in generation to decrease, in relation to the market's size and to the private financial capacity [1]. Additionally, the deregulation processes that have been appearing in the whole world have made this possible by promoting competence in generation. All this, opened the opportunities for on-site power generation by electricity users using smaller generating system with emergent technologies. The distributed energy resources (DER) - small power generators typically located at users' sites where the energy (both electric and thermal) they generate is used - have emerged as a promising option to meet growing customer needs for electric power with an emphasis on reliability and power quality. The portfolio of DER includes generators, energy storage, load control, and, for certain classes of systems, advanced power electronic interfaces between the generators and the bulk power provider [2]. Several technologies are being used in distributed generation (GD) applications with a varied degree of success. Some of them are: wind turbines, mini and micro hydraulic plants, biomass, micro turbines, photovoltaic system, and fuel cells (FC). Micro turbines and fuel cells show particular promise as they can operate multiple fuels with low emissions, high efficiency and high reliability [3]. The FC is a technology of generation with hurried development. They have many characteristics that make them favorable as energy conversion device: high efficiency (35-60%), low to zero emissions, quiet operation, and high reliability due to the limited number of moving parts [3]-[6]. FC is an electrochemical device that converts the chemical energy of a reaction directly into electrical energy. The basic physical structure or building block of a FC consists of an electrolyte layer in contact with a porous anode and cathode on either side [4] (Fig. 1).

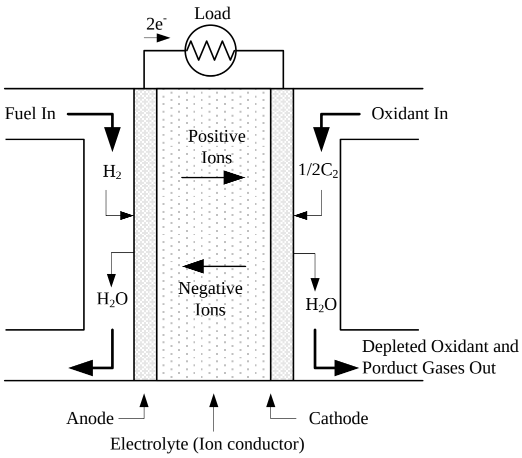

Fig. 1. Schematic of an Individual FC

In a typical FC, gaseous fuels are fed continuously to the anode compartment and an oxidant (i.e., oxygen from air) is fed continuously to the cathode compartment; the electrochemical reactions take place at the electrodes to produce an electric current. The effectiveness of this process is strongly dependent upon the electrolyte to create the chemical reactivity needed for ion transport [3]. The fuel cells can be classified by use of diverse categories, depending on the combination of type of fuel and oxidant, whether the fuel is processed (external or internal reforming) the fuel cell, the type of electrolyte, the temperature of operation, whether the reactants are fed to the cell by internal or external manifolds, etc [4]. The most common classification of fuel cells is by the type of electrolyte used in the cells and includes: polymer electrolyte fuel cell (PEFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), intermediate temperature solid oxide fuel cell (ITSOFC), and tubular solid oxide fuel cell (TSOFC). Some technologies have been successfully commercialized and other still in developing today, and are expected in the near future.

FC power plants can become a large part of the generation mix in the future, would be interconnected to the distribution network and expected to introduce and potentially dominate local dynamic modes resulting from the following.

- The response of the various control loops of the plant.
- The plant's interaction with the inertia and controls of other types of distributed generators (e.g., gas-turbines).
- The interaction of the combined distributed generation with the transmission system [8], [9].

An important issue in planning of FC generation is, therefore, the effect on system stability that its increasing size could have [10]. In order to carry out planning studies, appropriate dynamic models for FC plants are required, which combined with other types of distributed generation may provide a suitable dynamic model for assessing stability. Transient models have been developed for autonomous power plants of various fuel cell types [3], [5]–[7], [10]–[12]. This paper show a slow dynamical model for FC power plant, adequate to the load-following functions, and the model capability is demonstrated with simulation in a distribution system. Conclusion are presented in the last section.

2. Modelling a Fuel Cell System

A power generation fuel cells (FC) plant has following parts [4]:

- *Fuel Processor*. This converts a conventional fuel (natural gas, other gaseous hydrocarbons, methanol, naphtha, or coal) is cleaned, then converted into a gas containing hydrogen and byproduct gases.
- *Power Section*. Generates the dc electricity by means of individuals cells combined in stack or bundles. A varying number of cells or stacks can be matched to a particular power application.
- *Power Conditioner*. This converts dc power to ac power output and includes current, voltage and frequency control.

Although a variety of fuel cells are in different stages of development, this paper is focused on SOFC system modeling with the expectation that the response of other types would be similar [3].

A. Modelling of SOFC System

The SOFC power section dynamic model used for performance analysis during normal operation is clearly known [3], [4] [13].The electrochemical reactions occurring in SOFCs utilizing H_2 and O_2 are [4]:

$$\mathrm{H_2 + O^{=} \rightarrow H_2O + 2e^{-}} \text{ (anode)} \quad (1)$$

$$\frac{1}{2}\mathrm{O_2 + 2e \rightarrow O^{=}} \text{ (cathode)} \quad (2)$$

The overall SOFC reaction is:

$$\mathrm{H_2}\frac{1}{2}\mathrm{O_2 \rightarrow H_2O} \quad (3)$$

So the stoichiometric ratio of hydrogen to oxygen is 2 a 1 [3]. The ideal performance of SOFC is defined by its Nernst potential represented as cell voltage, this equation provides a relationship between the ideal standard potential (E_0) for the cell reaction and the ideal equilibrium potential (E) at other temperatures and partial pressures of reactants and products [4]. The corresponding Nernst equation is:

$$E = E_0 + \frac{RT}{2F}\ln\left(\frac{P_{H_2}\left[P_{O_2}\right]^{1/2}}{P_{H_2O}}\right) \quad (4)$$

The performance of SOFC depends on the electrochemical reactions that occur with the fuel and oxygen. Carbon monoxide (CO) and hydrocarbons such as methane (CH_4) can be used as fuels in SOFCs. SOFC designs for the direct oxidation of CH_4 have not been thoroughly investigated in SOFCs in the past [14],[15] nor lately (no significant work was found) the direct oxidation of these fuels is favored less than the water gas shift of CO to H_2 and reforming of CH_4 to H_2. For reasons of simplicity in this paper, the reaction of CO is considered as a water gas shift rather than an oxidation. The CO-shift reaction is:

$$\mathrm{CO + H_2O \rightarrow CO_2 + H_2} \quad (5)$$

On other hand, reactant utilization and gas composition have major impacts on fuel cell efficiency, and indicator of it is fuel utilization (U_f). It refers to the fraction of the total fuel or oxidant introduced into a fuel cell that reacts electrochemically.

$$U_f = \frac{q^r_{H_2}}{q^{in}_{H_2}} \quad (6)$$

The hydrogen flow reactant and the output current can be related by [3], [13]:

$$q^r_{H_2} = 2K_r I^r_{fc} \quad (7)$$

The electrochemical reaction in the SOFC, restring the current demand of the cell, this is given by the input hydrogen flow, and the maximum and minimum fuel utilization.

$$U_{\min} q^{in}_{H_2} \le 2K_r I^r_{fc} \le U_{\min} q^{in}_{H_2} \quad (8)$$

The real output current in the SOFC system can be measured, and closed loop control can be used to adjust de input hydrogen flow to satisfy a U_f at U_{opt}.

$$q_{H_2}^{in} = \frac{2K_r I_{fc}^r}{U_{opt}} \quad (9)$$

The fuel processor in SOFC system exhibit usually a slow chemical response, this is associated with the time to change the chemical reaction parameters after a change in the flow reactants. This dynamic response is simulated by first-order transfer function. In against part, the electrical response of the SOFC system is generally fast and associated mainly with the speed at witch the chemical reaction is capable to restoring the charge that has been drained by the load. A first-order transfer function is used to simulate the electrical dynamic response of the SOFC. Base on [3], [4], and [13] and the above discussions, the SOFC system dynamic model is given in Fig. 2.

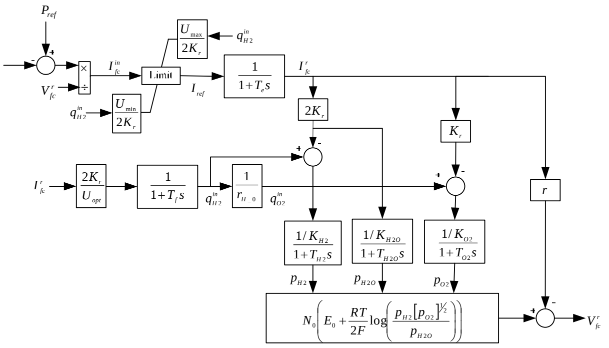

Fig. 2. SOFC system dynamic model

1) *Model Parameters*

For the examples studied in this paper, assume the rated power of the SOFC is 100 kW. The model parameter are updated of the ref [3], and listed in Table I.

TABLE I. - Parameters in SOFC system model

Parameter	Representation	Value
P_{nom}	Rated Power	100 kW
P_{ref}	Real power reference	100kW
T	Absolute temperature	1273°K
F	Faraday's constant	96487 C/mol
R	Universal gas constant	8314 J/(kmol-°K)
E_0	Ideal standard potential	1.18 V
N_0	Number of cells in series in the stack	384
Kr	Constant, $K_r = N_0/4F$	0.996×10^{-6} kmol/(A-s)
U_{max}	Maximum fuel utilization	0.9
U_{min}	Minimum fuel utilization	0.8
U_{opt}	Optimal fuel utilization	0.85
K_{H2}	Valve molar constant for hydrogen	8.43×10^{-4} kmol/(s-atm)
K_{O2}	Valve molar constant for Oxygen	2.52×10^{-3} kmol/(s-atm)
K_{H2O}	Valve molar constant for water	2.81×10^{-4} kmol/(s-atm)
T_{H2}	Response time for hydrogen flow	26.1 seg.
T_{H2O}	Response time for water flow	78.3 seg.
T_{O2}	Response time for oxygen flow	2.91 seg.
R	Ohmic losses	0.126Ω
T_e	Electrical response time	0.8 seg.
T_f	Fuel processor response time	5 seg.
r_{H_O}	Ratio of hydrogen to oxygen	1.145

2) *Stand-alone Performance*

The dynamic model of the SOFC system was simulated in stand-alone operation model, all parameters are same as shown at Table I. Initially the fuel cell system is operating with constant rated voltage 333.8 V (1.0 p.u), and power demand of 70 kW (0.7 p.u) and suppose the steady state electrochemical, at t = 0s, a step increase of power demand from 70kW to 100 kW.

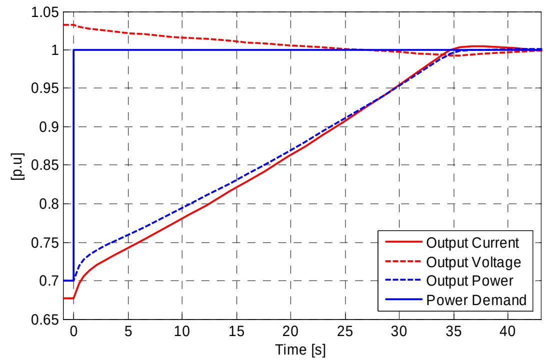

Fig. 3. Response of P_d, P_{fc}, V^r_{fc}, I^r_{fc}, to step in increase of power

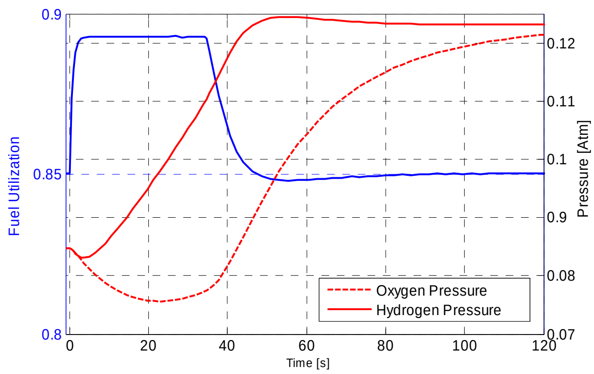

Fig. 4. Response of P_{H2}, P_{O2} and fuel utilization, to step in increase of power

The Fig. 3 and 4, show the dynamic response of this system to step increase of power. Initially the time response of the SOFC is fast, first 2 or 3s the output power has a fast increase due to the fast electrical response time of the FC. Then, a slow transient in the electrical power is evident. The slow chemical response produces an increase slowly and continuously until reaching the demanded power. The slow dynamic of the fuel processor dominated this transient. In total, the response of the SOFC to step of power demand requires 30s, to change the output power from 70kW to 100 kW. The Fig. 4, show the fuel utilization, during the step of power demand, a evident maximum fuel utilization is reached at 5s, staying at this value during 25s, it decreases to optimal utilization in about 20s.

Assume now, the SOFC in stand-alone operation mode, in electrochemical steady state, at rated voltage and power demand equal to rated power. At t =0s, a ramp descent the power output, with a 5kW/s slope. The dynamic response to this demand change is shown in Fig. 4 and 5. The fast electrical response time in the fuel cell, and the slow chemical response time in the fuel processor is evident. In the first 2 or 3s, the output power tries to follow down the demand ramp, due the fast electrical response the FC, but subsequently the output power cannot decrease as same rate like power demand, the dynamical is dominated by the fuel processor, and the minimum fuel utilization is reached in about 3s, and still there about 20s, to decrease to optimal value at 55s.

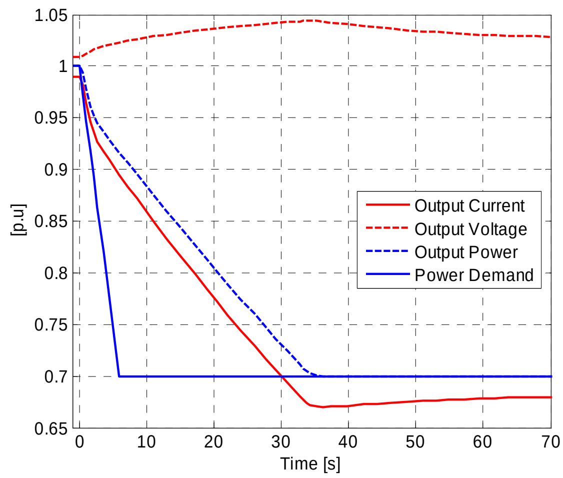

Fig. 5. Response of P_d, P_{fc}, V^r_{fc}, I^r_{fc}, to ramp on decrease of power

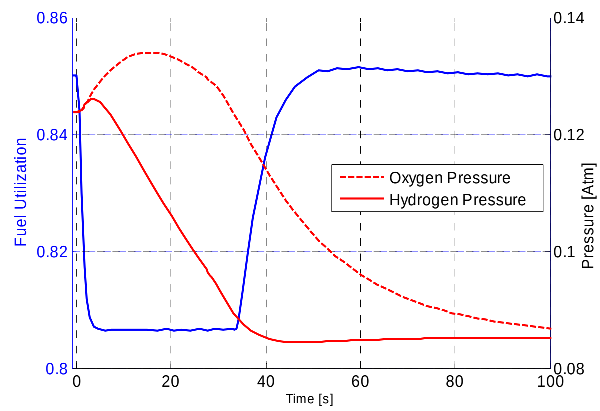

Fig. 6. Response of P_{H2}, P_{O2} and fuel utilization, to ramp on decrease of power

3. Load-Following

The FC will likely become major DRs in the future, an important operation uses is the provision of interconnected operation service (IOS), or ancillary services, under deregulation. IOS identifies the following seven services [16]: regulation, load following, contingency reserve (spinning or supplemental), reactive power supply from generation sources, frequency response, and system black start capability. Regulation is mainly used for maintaining interconnection frequency, minimizing differences between actual and scheduled tie-line power flows, and matching generation to load within the control area at the minute time scale. The load-following is the provision of generation and load response capability, including capacity, energy, and maneuverability, that is dispatched within a scheduling period by the operating authority [16]. The key distinction between load following and regulation is the time scale over which fluctuations occur (10 minutes or more). Regulation responds to rapid fluctuations and load following responds to slow changes of load patterns.

1) Load-Following Performance

Numerical simulations are performed on a typical four buses distribution feeder, shown in Fig. 5.

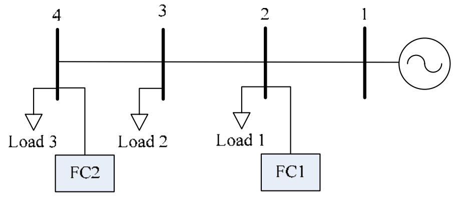

Fig. 5. Distribution System Diagram

For simplicity, only real power is consumed by the load, and they are modelled by impedance constant. Two fuel cell plants are included, FC1, FC2, at buses 2 and 4 respectively. Each plants consist a SOFC with P_{rate} = 500kW and V_{rate} = 6.600 V. The unit parameters are not due to space limits. Thought the power conditioner of the fuel cell system can output not only real power, for simplicity only real power output is consider to the inverter, and due the response time of the power conditioner is les than 10ms, it not necessary to include its detailed model in slow dynamic fuel cell system. The units FC1 and FC2, mainly provide some peak shaving compatibility and ancillary services for the feeder. The man interest on this dynamic simulation is the load-following function on the plants FC1 and FC2. Suppose at a certain time, the total load in this distribution system is P_{load} = 1.25MW. , and t = 0 s, occur a step increase of 25% on Load 3, then at t = 200s, another step increase the Load 1 in 25%. Fig. 7 show de dynamic response of tie-line flow, real power output of FC1 and FC2.

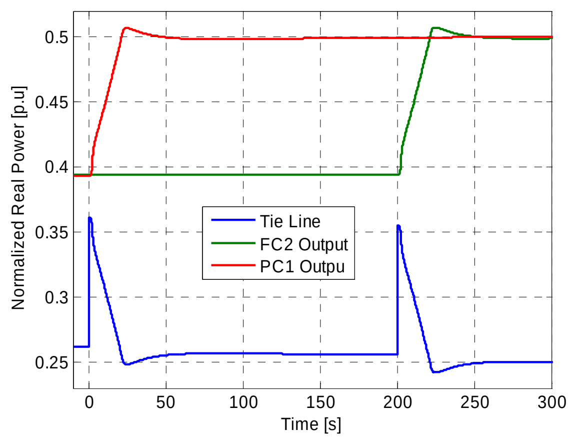

Fig. 7. Load-following performance of FC1, FC2, 25% increase of Load

The fuel cells plants are installed to supply load following function locally, communication does exist between these. The power limits of the plants, limits the following characteristic.

Initially the tie-line flow is 0.26 p.u., when the load changes occurs, the slow time response of power out in the fuel cells plants, cannot supply instantaneously the sudden increase in the power demand. Fig. 7 shows the change in the tie-line flow to compensate the slow time response on output power of FC1 and FC2.

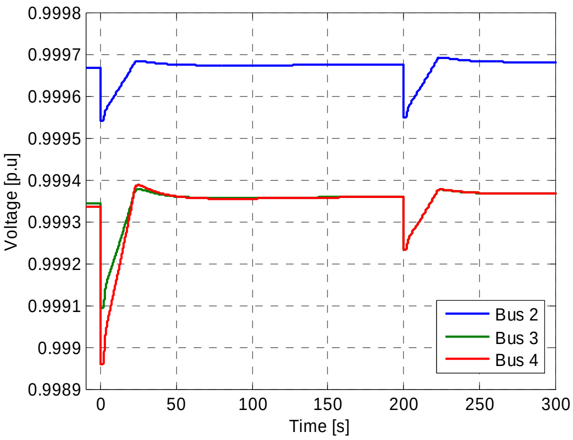

Fig. 8. Bus Voltage during 25% load change

The load-following involves electro chemicals chances in the FC, during load chances, the voltage, fuel utilization, and pressures of hydrogen and oxygen and shown in Fig. 8, 9, 10.

The load-following capability of the fuel cells plants are limit by the rated power. A load increase of 50% on Load 3 and 1, produce the maximum output power of the both fuel cells plants, and the remaining power to supply the load must be imported by the tie-line. This situation is evident in the Fig. 11, and the Fig. 12 shows the bus voltages at this condition.

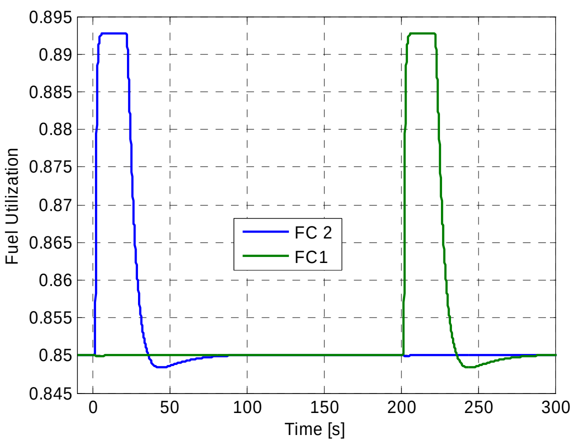

Fig. 9. Response of fuel utilization of FC1 and FC2, 25% increase of Load

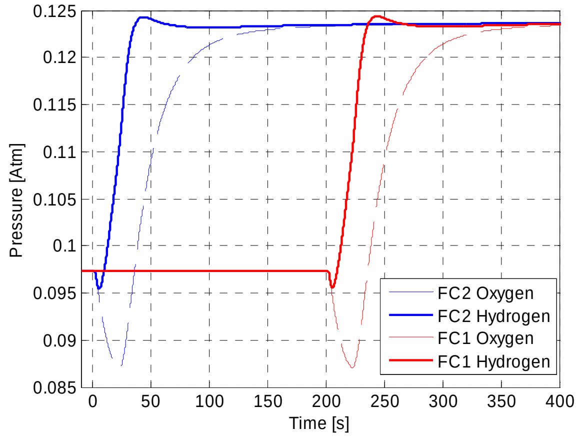

Fig. 10. Response of P_{H2}, P_{O2}, for FC1 and FC2, 25% increase of Load

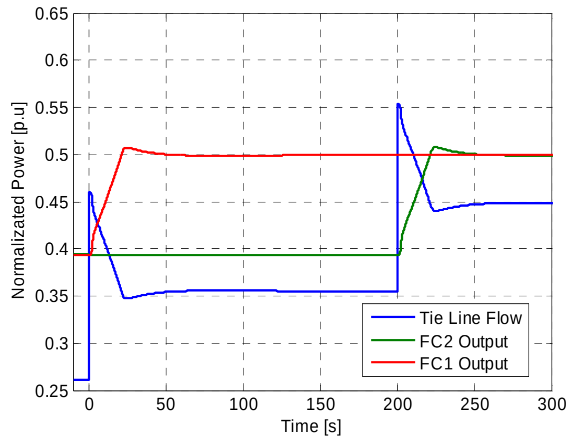

Fig. 11. Load Following performance of FC1, FC2, 50% increase of Load

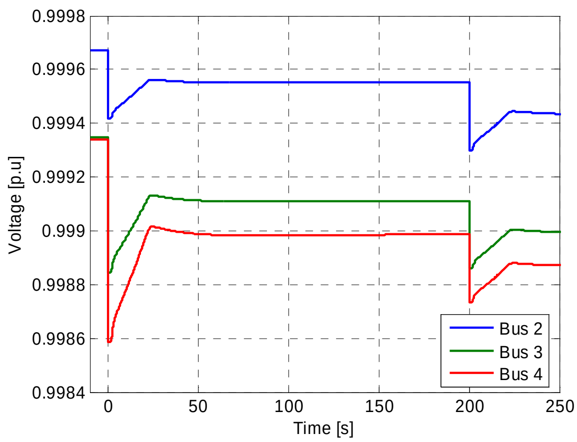

Fig. 13. Bus Voltage during 50% load change

4. Conclusion

In this paper a slow dynamic model of SOFC is developed. Stand alone evaluations of the model show the capability to simulate the slow dynamic performance with reasonable and suitable results. A simple distribution system was simulated with the model developed, and did evident the slow dynamic response to load changes of the fuel cells plants, and the important limitations in the load-following performance. During step changes on the load, the fuel cells plants cannot supply the sudden increases on power demand, and increases in the tie-line flow must be done. In distributed energy resources ambient, bilateral contract to load following function maybe done to keep the lie line flow between limits of bilateral contract.

Acknowledgement

The authors would like to thank Prof. Kevin Tomsovic for valuable collaboration in the development of this paper.

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