International Journal of Basic Sciences & Applied Research. Vol., 3 (9), 663-670, 2014
Available online at http://www.isicenter.org
ISSN 2147-3749 ©2014

Dynamic Modeling and Simulation of Microturbine Generating System for Stability Analysis in Microgrid Networks

Abbas Khorshidi[1]*, Mahdi Zolfaghari[1], Maryam Akhavan Hejazi[2]

[1]Department of Electrical Engineering, University of Allameh Feiz Kashani, Kashan, Iran
[2]Department of Electrical Engineering, University of Kashan, Kashan, Iran

Corresponding Author Email: Abbaskhorshidi62@yahoo.com

Abstract

This paper presents the dynamic modeling and simulation of a microturbine generation (MTG) system, the nonrenewable source of energy suitable for isolated as well as grid-connected operation in microgrid networks. A microgrid is defined as an independent low or medium-voltage distribution network comprising various DGs, energy storages, and controllable loads. The MTG system consisting of a permanent magnet synchronous generator (PMSG) coupled with a microturbine (MT) which is suitable for stability studies in microgrid networks is modeled and simulated using MATLAB/SIMULINK.

Keywords: Microturbine, Microgrid, Stability.

Introduction

Distributed energy resources (DERs), such as fuel cells, microturbines, and photovoltaic systems offer many advantages for power systems (Jiayi et al., 2008; Lasseter, 2002). For example, they can effectively mitigate peak demand, increase reliability against power system faults, and improve power quality (PQ) via sophisticated control schemes. Accordingly, distributed generators (DGs) have been installed in power systems and tested for better configurations and control schemes. The concept of a microgrid has been proposed in order to solve the common interconnection problems of individual DGs in various power systems (Lasseter, 2002; Piagi & Lasseter, 2004). A microgrid is defined as an independent low or medium-voltage distribution network comprising various DGs, energy storages, and controllable loads that can be operated in three distinct modes: 1) grid-connected, 2) islanded (autonomous), and 3) transition mode (Tsikalakis & Hatziargyriou, 2008; Soultanis et al., 2008).

A microgrid can be thought of as a controllable subsystem to the utility, and can satisfy customer requirements, such as local reliability enhancement, feeder-loss reduction, local voltage regulation, and increased efficiency through the use of waste heat (Hannet & Afzal Khan, 1993a). Some of the operational aspects which require full understanding are voltage control, stability, system protection etc. Such studies require accurate modeling of distributed generation (DG) sources including distribution system (Scott, 1998). Distributed generation using microturbine is a typical and practical solution because of its environment-friendliness and high energy efficiency (Rowen, 1983). Various applications such as peak saving, co-generation, remote power and premium power will make its use worldwide. Generally MTG systems range from 30 to 400 kilowatts (Al-Hinai & Feliachi, 2002; Borbely & Kreider, 2001), while conventional gas turbines range from 500 kW to more than 300 MW (Hannet & Afzal Khan, 1993b; Hajagos & Berube, 2001).

Microturbines are capable of burring a number of fuels at high and low pressure levels. They generally have marginally lower electrical efficiencies than similarly sized reciprocating engine generators. Without a recuperator the overall efficiency of a microturbine is 15 to 17%, whereas with an 85% effective recuperator the efficiency can be as high as 33 to 37%. However, because of their design simplicity and relatively fewer moving parts, microturbines have the potential for simpler installation, higher reliability, reduced noise and vibration, lower maintenance requirements, lower emissions, continuous combustion and possibly lower capital costs compared to reciprocating engines (Goldstein et al., 2003; Malmquist, 1999; Jurado & Cano, 2004). An accurate model of the microturbine is therefore required to analyze the mentioned impacts. Until now, only few works were undertaken on the modeling, simulation and control of micro turbines. There is also a lack of adequate information on their performances. A dynamic model for combustion gas turbine has been discussed in (Lasseter, 2001). The dynamic behavior of the grid connected split shaft microturbine is discussed in (Al-Hinai et al., 2003). Zhu and Tomsovic (2002) the load following performance and modeling of split shaft micro turbine is discussed. A distribution system with some simple but practical control strategies is developed for the analysis of load-following service provided by microturbine (Zhu & Tomsovic, 2002). This paper presents single shaft microturbine generation system model developed in Sim power systems library of the MATLAB software.

Types of Microturbine generating systems

There are mainly two types of microturbine systems available, single-shaft models and two shaft models. In single-shaft designs, a single expansion turbine turns both the compressor and the generator. As a result they operate at high-speeds, some in excess of 100,000 rpm, and generate electrical power at high frequency (in the order of kHz). Two-shaft models on the other hand, uses a turbine to drive the compressor on one shaft and a power turbine on a separate shaft connected to a conventional generator via a gear box which generates AC power at 60 Hz or 50 Hz (Zhu & Tomsovic, 2002) [21]. In a single-shaft design, since the generator provides a high frequency AC voltage source, a power electronic interface between the MTG system and the AC load is required. For a two-shaft design, on the other hand, there is no need for such interfacing. This paper considers the modeling single-shaft type only.

Modeling of Microturbine generating system

The highest efficiency operating speeds of microturbines tend to be quite high, often exceeding 100,000 rpm. The speeds are generally variable over a wide range (i.e., from 50,000 rpm to 120,000 rpm) to accommodate varying loads while maintaining both high efficiency and optimum long-term reliability. The microturbine drives a high-frequency generator that may be either synchronous or asynchronous (or non-synchronous). The caged rotor design in asynchronous (or induction) generators tends to make it a less-costly alternative to synchronous generators. Synchronous generators contain a magnetic rotor that is designed to use either rare earth permanent magnets or coils with additional hardware for delivering current (e.g., slip rings, brushes). Although asynchronous generators are somewhat rare in the industry, they are the generator of choice in wind and hydro generation applications. Power requirements to the generator vary depending on the design.

A synchronous generator with a wound rotor assembly will require dc power for energizing the rotor poles. An asynchronous generator in most microturbine applications will require a 3-phase current to the stator at a frequency correlated well to the rotational speed so that power is produced. In conventional applications, synchronous generators have an advantage where they can be connected directly to the grid if speed is properly regulated. This is generally not the case in high-speed microturbine applications. For all generator types, a 3-phase, high frequency voltage, typically in the range of 1,000 Hz to 3,000 Hz, will be developed that must be converted to line frequency before the generated power becomes usable. Figure 1 shows a general diagram for a microturbine generator system followed by a power converter and a filter. The ac/ac power converter essentially converts high frequency ac to 50 or 60 Hz ac.

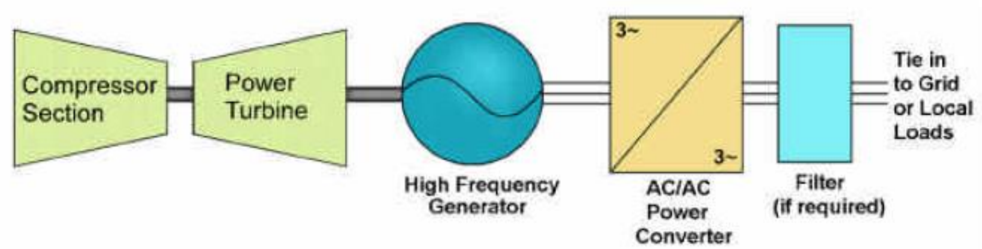

Figure 1. General microturbine diagram.

The power converter can also be designed to provide valuable ancillary services to the power grid or microgrid. These services may include voltage support, sag support, static volt-amp-reactive (VAR) compensation, load following, operating reserve (e.g., spinning or non-spinning), backup supply, and/or start-up power for the microturbine or other local microturbines. Voltage support is common for grid independent operation while load following is used for grid-connected operation. Operating reserve capability may or may not be recognized by the local electricity provider depending on their current tariffs and the capabilities of the microturbine installation. The availability of backup supply and start-up power varies not only by microturbine manufacturer but also by what options may be purchased with the microturbine.

DC Link converter model

The most common power converter topology that is used for connecting microturbines to the grid is the dc link converter. Figure 2 shows a microturbine generator feeding power to an active rectifier circuit (or, alternatively, a passive rectifier) followed by a dc link and inverter circuit. The high frequency power from the generator must be converted to dc before the inverter can reconstruct a three-phase voltage supply at lower frequency required for grid connection. A controller manages the operation of the active rectifier and inverter circuitry by ensuring that functions such as voltage following, current following, phase matching; harmonic suppression, etc. are performed reliably and at high efficiency. The controller may be mostly on-board, pc-based, a processor linked to a pc, etc., depending on constraints and factors such as desired microturbine packaging, desired versatility, type of available features, and the sophistication/maturity of the system design.

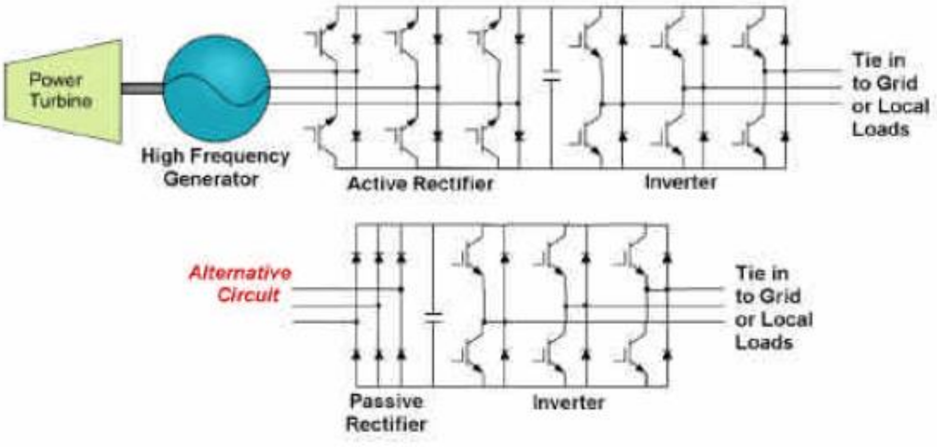

Figure 2. Simplified diagram of a dc link converter.

Power Microturbine model

The working progress of the micro-turbine can be described as follows: Air at the atmospheric pressure enters the gas turbine at the compressor inlet. After compression of the air to achieve the most favorable conditions for combustion, the fuel gas is mixed with the air in the combustion chamber. Then the combustion takes place and the hot exhaust gases are expanded through the turbine to produce the mechanical power. In terms of gas stream during combustion, the chemical energy present in the combustion reactants is transferred to the gas stream during combustion. This energy, measured in terms of gas enthalpy, is then converted into the mechanical work by expanding the gas through the turbine. Thus, the excess to drive the compressor is derived ultimately from the combustion process (Jurado, 2005). The MT model is shown in figure 3.

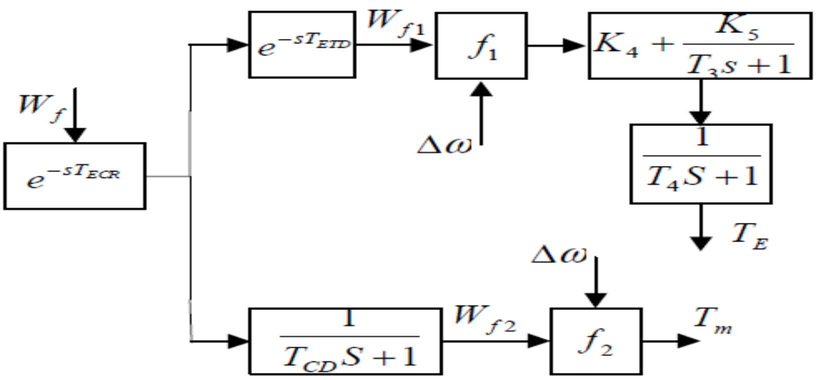

Figure 3. Microturbine model.

The model of the micro-turbine is a complicated thermal dynamic model. It is not realistic to build the exact model because of the existence of nonlinearities and uncertainties. It is important to apply proper control strategy to the model. So speed control, temperature control and fuel control are applied to the model. The temperature control inputs are rated exhaust temperature T_{ref} and measured exhausted temperature T_E. Their error acts on the controller to produce fuel control signal V_f. Usually T_{ref} is higher than TE. The controller keeps the temperature at its maximum temperature. The micro-turbine system is mainly controlled by speed control. And the speed control output is the fuel demand signal F_D. The fuel control inputs are fuel control signal V_f and fuel demand signal FD.

They pass through the "low value select" to produce the demand signal for fuel Vce. The V_{ce} signal is scaled by the gain K_3 and offset by K_6, which is the fuel flow at no load, rated speed condition. Then the signal passes through valve positioner and actuator to produce fuel flow signal W_f. The schematic diagram of the micro-turbine is shown in figure 3. And the fuel system diagram is shown in figure 4. The turbine torque function is giving by:

$$f_2 = a_{f2} - b_{f2}W_{f2} + c_{f2}(1-\omega) \quad (1)$$

And the exhaust temperature function is giving by:

$$f_2 = T_{ref} - a_{f1}(1 - W_{f1}) + b_{f1}(1 - \omega) \quad (2)$$

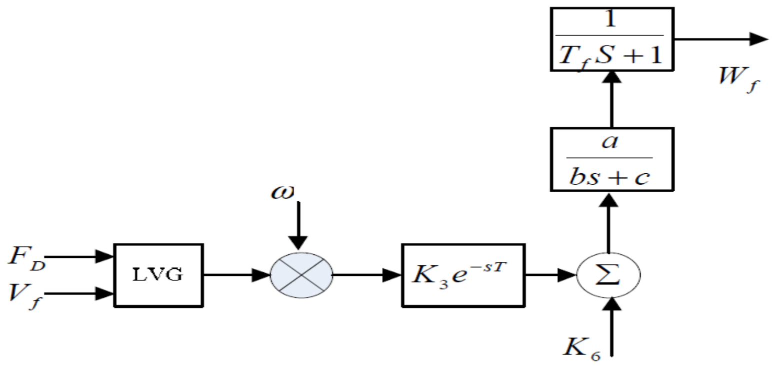

Figure 4. Fuel system diagram.

Permanent magnet synchronous machine model

The model adopted for the generator is a pole permanent magnet synchronous machine (PMSM) with a non-salient rotor (Chee-Mun, 1997). The electrical and mechanical parts of the machine are each represented by a second-order state-space model. The model assumes that the flux established by the permanent magnets in the stator is sinusoidal, which implies that electromotive forces are sinusoidal. The following equations expressed in the rotor reference frame (dq frame) used to implement PM synchronous machine.

Electrical equations:

$$\begin{aligned} \frac{d}{dt} i_d &= \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} p\omega_r i_q \\ \frac{d}{dt} i_q &= \frac{1}{L_q} v_q - \frac{R}{L_q} i_q - \frac{L_d}{L_q} p\omega_r i_d - \frac{\lambda p \omega_r}{L_q} \\ T_e &= 1.5 p(\lambda i_q + (L_d - L_q) i_d i_q) \end{aligned} \quad (3)$$

Mechanical equations:

$$\begin{aligned} \frac{d}{dt} \omega_r &= \frac{1}{J}(T_e - F\omega_r - T_M) \\ \frac{d\theta}{dt} &= \omega_r \end{aligned} \quad (4)$$

Results

In this section, a microturbine generating system is simulated and its performance during a fault on the load bus is investigated. Initially, the system is operating in the normal mode where a single line to ground fault is occurred which is a most common fault in low- voltage microgrid networks. The load is a 10 kW household which was supposed to be supplied by the microturbine generating system. The model considered for the system is shown in figure 1 which contains a microturbine (MT), permanent magnet synchronous generator (PMSG), power converter and filter. The simulation results are shown in Figures 5-8. At t = 0.1 Sec, a single line- to- ground fault was occurred at the load bus. Figure 5 shows that although the MT speed is changed during the fault, but it keeps stability. Figure 6 shows the machine currents increase to about 4.75 pu and figure 7 shows that the field voltage of the PMSG is increased to about 10 pu, while the output voltage is decreased to 0.4 pu as shown in figure 8.

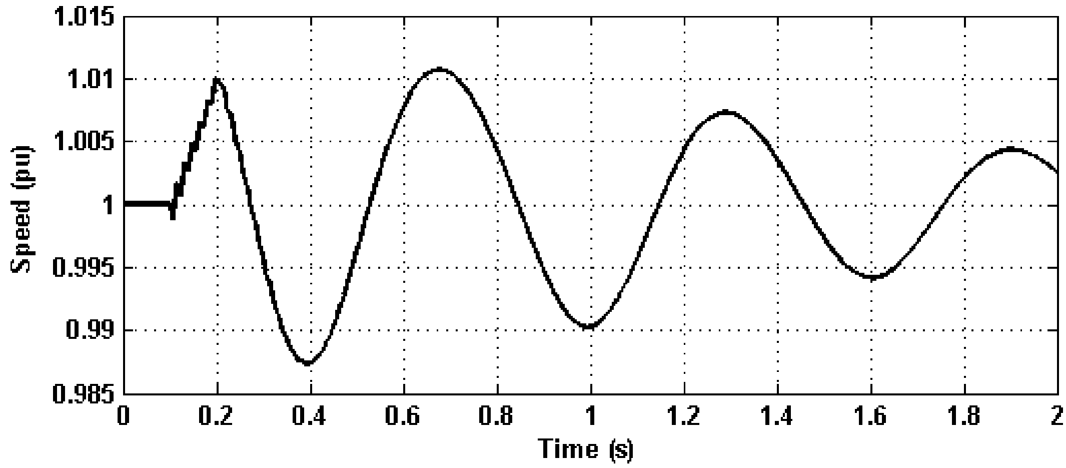

Figure 5. Microtubine speed during a single line to ground fault at t=0.1 Sec. (It's clear that MT speed keeps stability).

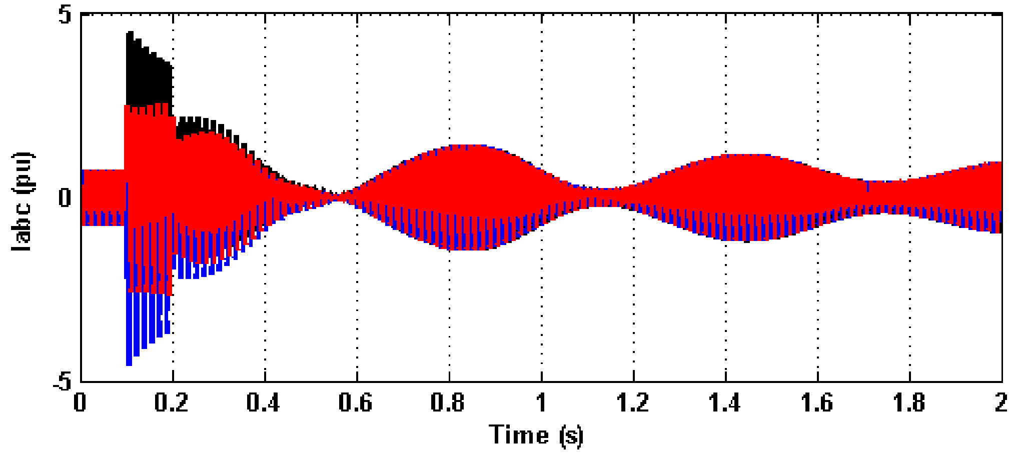

Figure 6. Three phase current of the permanent magnet synchronous machine speed during a single line to ground fault at t=0.1 Sec.

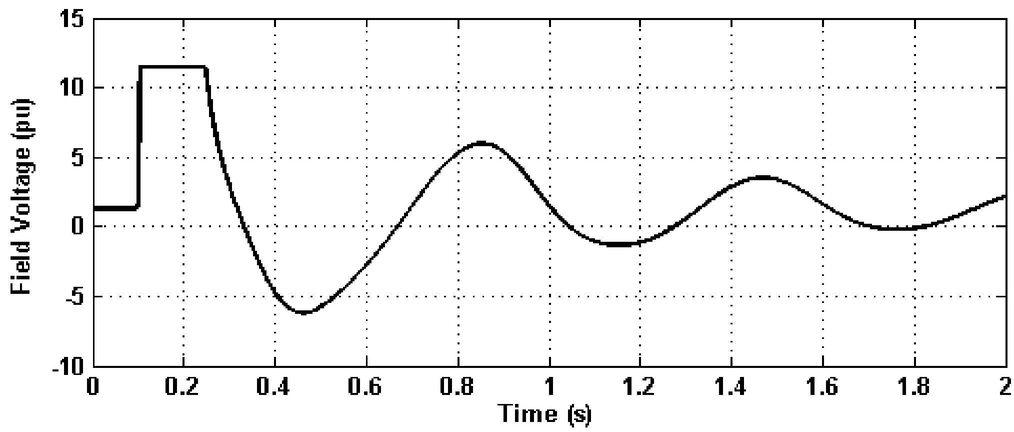

Figure 7. Field voltage of the permanent magnet synchronous machine speed during a single line to ground fault at t=0.1 Sec.

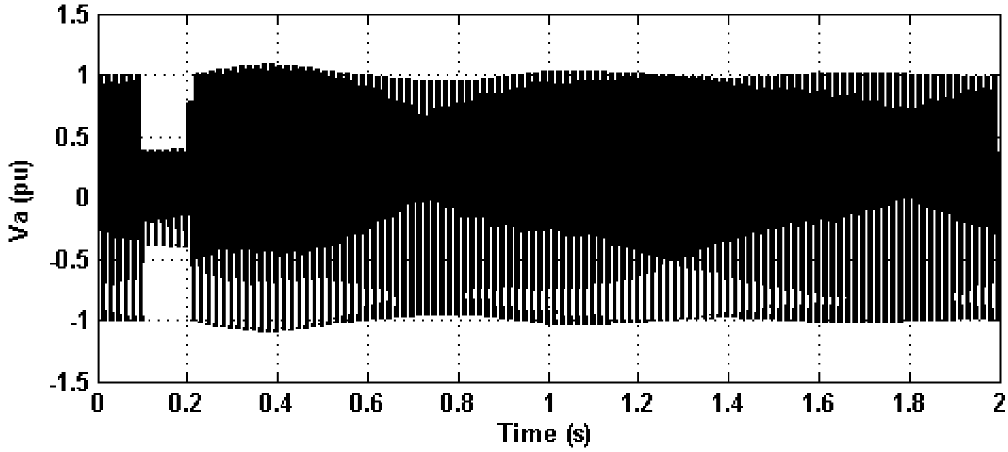

Figure 8. Phase a voltage of the permanent magnet synchronous machine speed during a single line to ground fault at t=0.1 Sec.

Conclusion

In this paper, the dynamic model of microturbine generator (MTG) was introduced that is suitable for stability analysis of microgrids. In this MTG the permanent magnet synchronous generator (PMSG) is employed. The PMSG operates with maximum efficiency by optimizing the decomposition of the dq-xes armature currents in the synchronous reference frame. The simulation results confirmed the proposed model.

The modeling of a single-shaft microturbine generation system suitable for isolated DG applications is presented in this paper. First mathematical modeling of the control systems of the microturbine is given and following that the detailed simulation model of the MTG system is developed using MATLAB's Sim Power Systems library. Evaluations of this stand-alone model show that it is reasonable and suitable for slow dynamic simulation studies. The simulation results show that the developed model of the MTG system has the ability toad just the supply as per the power requirements of the load, within MTG's rating. Thus, it can be implemented successfully in real generating systems with varying loads. The MTG system starts as a motor until it attains a predetermined rotor speed, with the help of an external storage or device (such as a battery), and then starts to function as a generating system. These start-up dynamics associated with the MTG system are not considered in this work. Inclusion of these dynamics can help in analyzing the system performance in more detail. Also in the microturbine model, for combined heat and power applications, recuperate or model could be added to increase the overall efficiency.

Acknowledgment

This work was significantly supported by the Abadan oil refining company (A.O.R.C) and research and development center, Iran. The authors are really indebted to the technical section manager of this company for his patience and supportive character.

References

Al-Hinai A, Feliachi A, 2002. Dynamic model of a microturbine used as a distributed generator. In Proceedings, 34th Southeastern Symposium on system Theory, Huntsville, Alabama, March 2002.

Al-Hinai A, Schoder K, Feliachi A, 2003. Control of grid-connected split shaft microturbine distributed generator. System Theory, Proceedings of the 35th Southeastern Symposium. 84-88.

Borbely A, F. Kreider J, 2001. Distributed generation-the power paradigm for the new millennium. US: CRC Press.

Chee-Mun O, 1997. Dynamic simulation of electric machinery using matlab/Simulink. US: Prentice Hall.

Godswill Ofualagba, The Modeling and Simulation of a Microturbine Generation System, IJSER ,Volume 3,Issue 2,February 2012.

Goldstein L, Bruce H, Dave K, Steven I, Richard W, Tom S, 2003. Gas-fired distributed energy resource technology characterizations. National Renewable Energy Laboratory. NREL/TP-620-34783, National Report. 2: 223-456, 2003.

Hajagos LM, Berube GR, 2001. Utility experience with gas turbine testing and modeling. In Proceedings IEEE PES Winter Meeting. 2: 671-677

Hannet LN, Afzal Khan LN, 1993. Combustion turbine dynamic model validation from tests, IEEE Trans on Power Systems. 8: 152-158.

Hannet LN, Afzal Khan LN, 1993. Combustion turbine dynamic model validation from tests. IEEE Transactions on Power Systems. 8: 152-158.

Jiayi H, Chuanwen J, Rong X, 2008. A review on distributed energy resources and microgrid. Renew. Sustain Energy Rev. 12:

Jurado F, 2005. Modeling micro-turbines using hammerstein models. International Journal of Energy Research. 29: 841-85.

Jurado F, Cano A, 2004. Use of ARX algorithms for modeling micro-turbines on the distribution feeder. In IEE Proceedings: Generation Transmission and Distribution. 151: 232-238.

Lasseter R, 2001. Dynamic models for micro-turbines and fuel cells. In 2001 Power Engineering Society Summer Meeting. 2: 761-766.

Lasseter RH, 2002. Microgrids. Proc Power Eng Soc Winter Meeting. 1: 305-308.

Malmquist A, 1999. Analysis of a gas turbine driven hybrid drive system for heavy vehicles. PhD Thesis, Department of Automatic Control, Lund Institute of Technology.

Piagi P, Lasseter RH, 2004. Microgrid: a conceptual solution. Proc Power Electronics Specialists Conf. 6: 4285-4290.

Rowen WI, 1983. Simplified mathematical representations of heavy duty gas turbines. Journal of Engineering for Power Trans.105: 865-869.

Scott WG, 1998. Micro-turbine generators for distribution systems. IEEE Industry Applications Magazine. 4: 57-62.

Soultanis NL, Papathanasiou SA, Hatziargyriou ND, 2007. A stability algorithm for the dynamic analysis of inverter dominated unbalanced LV microgrids. IEEE Trans Power Syst. 22: 294-304.

Tsikalakis AG, Hatziargyriou ND, 2008. Centralized control for optimizing microgrids operation. IEEE Trans Energy Convers. 23: 241-248.

Zhu Y, Tomsovic K, 2002. Development of models for analyzing the load-following performance of microturbines and fuel cells. Journal of Electric Power Systems Research. 62: 1-11.

Appendix

Nomenclature

L_q, L_d	q and d axis inductances
R	Resistance of the stator windings
i_q, i_d	q and d axis currents
v_q, v_d	q and d axis voltages
ω_r	Angular velocity of the rotor
λ	Flux induced by the permanent magnets in the stator windings
P	Number of pole pairs
T_e	Electromagnetic torque
J	Combined inertia of rotor and load
F	Combined viscous friction of rotor and load
θ	Rotor angular position
T_M	Shaft mechanical torque