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Modeling, Control and Simulation of Microturbine Generator for Distributed Generation System in Smart Grid Application

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Abstract

Microturbines system (MTS) are currently being deployed as small scale on-site distributed generators for microgrids and smart grids. In order to fully exploit DG potentialities, advanced integrated controls that include power electronics facilities, communication technologies and advanced modeling are required. Significant expectations are posed on gas microturbines that can be easily installed in large commercial and public buildings. Modeling, control, simulation of microturbine generator based distributed generation system in smart grid application of buildings for both grid-connected and islanding conditions are presented. It also incorporates modeling and simulation of MT with a speed control system of the MT-permanent magnet synchronous generator to keep the speed constant with load variation. Model and simulations are performed using MATLAB, Simulink and SimPowerSystem software package. The model is built from the dynamics of each part with their interconnections. This simplified model is a useful tool for studying the various operational aspects of MT and is also applicable with building cooling, heating and power (BCHP) systems

Key Words : Microturbine(MT), MATLAB, Simulink and SimPowerSystem, PMSM, P-Q controller, Dynamic Model of MT, Distributed generation

1. Introduction

DEREGULATION of the electricity market has created a novel interest in the generation operating parallel with the distribution network. Distributed generation (DG), which includes fuel cells, microturbine(MT), wind turbine generators, photovoltaic cells and reciprocating engines relies on power electronics components for functioning and interfacing with the distribution network. These interface devices make the sources more flexible in their operation and control compared to the conventional machines [1]. However, due to their disturbances. The progress of DG, as an important energy option in the present scenario is the result of the high efficiency of the energy conversion process, combination of utility reconstructing, technology evolution and recent environmental

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policies [2]. These situations, together with market liberalization and introduction of DG generation technologies, predict reverberation on the management of the distribution network to which new generation plants will be connected. In order to achieve a significant penetration of DG potentially susceptible to oscillation resulting from network in power systems, important issues have to be regarded: (1) the integrated management of different distributed resources characterized by unpredictability in generation as renewable sources and building cooling, heating & power (BCHP) system; negligible physical inertia they also make the system (2) the adoption of suitable data and control network technologies; (3) the need for interconnection rules and for new protection methodologies and technologies [3-4].

A microgrid can be operated either in grid connected mode or in standalone mode. In grid connected mode, most of the system level dynamics are dictated by the main grid due to the relatively small size of MT. In the standalone mode, the system dynamics are dictated by MT themselves, their power regulation control and by the networks itself. They are generally considered to be less than 100MW in capacity and not centrally planned or dispatched.

DG using MT is a typical and practical solution because of its environment-friendliness and high efficiency. Microturbines have the potential for extremely low emissions. Because MT is able to meet key emissions requirements with this or similar built-in technology, post-combustion emission control techniques are currently not needed. MTs using lean premix combustion are designed to achieve the objective of low emissions at full load. Various applications such as peak shaving, co-generation including BCHP system and district area, remote power and premium power will make its penetration wide spread. An accurate model of the MT is therefore required to analyze the mentioned impacts. Until now, few works were undertaken on the modeling, simulation and control of MT, There is a lack of adequate information on their performance. Dynamic combustion gas turbine has been discussed in [5-7]. In these references, a combustion gas turbine model was used to represent the gas turbine dynamics, including speed, temperature, acceleration and fuel controls. However their works deal with heavy-duty gas turbine. Model of MT was studied in [8] where authors developed a generic model of the grid connected MT converter. A liberalized model was adopted and compared to the first order transfer function [9]. The dynamic behavior of the grid connected split shaft MT generation system is presented in [10]. The evaluation of the electromagnetic transients of a grid connected MTG system that includes an AC_DC_AC converter is done in [11]. All most of these works consider a one way frequency converter AC-DC-AC with a diode rectifier that interfaces the high frequency alternator and DC bus. The study deals with the dynamic models of generator, converter, power system and the thermodynamic model of MT system. Modeling of MT and its advanced controls for grid connected and islanding conditions with privileged loads are developed and presented in [3].

In this paper, a single shaft MTG system model is developed in Simulink/SimPowerSystems of the Matlab. The developed model considers bidirectional power flow between and MTG system. Two configuration of alternator operation (motoring and generating) are considered. Two interface controls are designed such as one for normal operation and the other for islanding operation are given. Simulation results of a 30[kW] MT connected to a distribution network are presented. The model is potentially useful in studying the DG applications of MTG systems.

2. Model Description

2.1 Microturbine model

The MT components are:
A gasturbine with a heat recuperator
A high speed electric generator
A Back-to-back voltage source converter
A Machine-side and grid side converter control

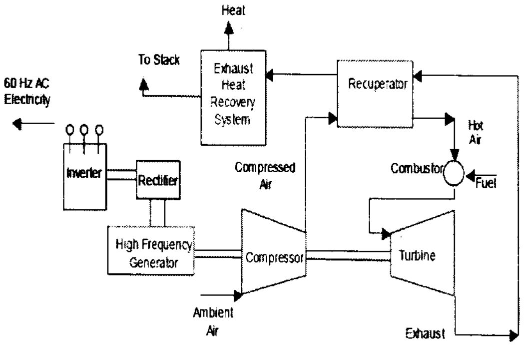

Fig. 1. Microturbine generation system(MTG)

There are essentially two types of MT design. One is a high-speed single shaft design with compressor and MT mounted on the same shaft as the permanent magnet synchronous generator. The generator generates a very high frequency three phase signal ranging from 1,500 to 4,000[Hz]. The high frequency voltage is first rectified and then inverted to a normal 50 or 60[Hz] voltage. Another is a split shaft design that uses a power turbine rotating at 3,600[rpm] and a conventional generator (usually induction generator) connected via a gearbox. The power electronics interfacing is not needed in this design. Along with the MT there will be control systems including speed and acceleration control, fuel flow control, and temperature control. A MT can generate power in the range of 25[kW] to 500[kW]. Fig. 1 shows the basic components of MTG.

The simplified single shaft gas turbine including its control systems which is implemented in Simulink of the Matlab is shown in Fig. 2. The model consists of fuel control, turbine dynamics and speed governor blocks. The electromechanical behavior is of main interest in this work. The speed control operates on the speed error formed between a reference (one per-unit) speed and MTG system rotor speed. It is the primary means of control for the MT under part load conditions [12]. Speed control is usually modeled by using a lead-lag transfer function or by a PID controller [13]. In this study, a lead-lag transfer function has been used to represent the speed controller. The governor controls are shown in the speed governor block in the Fig. 2 with parameters gain, X, Y, and Z which can be adjusted so that the governor can act with droop or as isochronous governor. In this paper, the isochronous governor with Z parameter in zero is chosen. It is a proportional-plus-reset speed controller in which the rate of change of the output is proportional to the speed error. The isochronous governor parameters X and Y are 0.4 and 0.05, respectively. Acceleration control is used primarily during MT startup to limit the rate of the rotor acceleration prior to reaching operating speed. If the operating speed of the system is close to its rated speed, the acceleration control could be eliminated in the modeling. The output of the governor goes a low value select to produce a value for Vce, the fuel demand signal. The other signal into the low value select is from the temperature controller. The per-unit value for Vce, corresponds directly to the per unit value of mechanical power on turbine base in steady state. The fuel system consists of the fuel valve and actuator. The fuel flow from the fuel system results from the inertia of the fuel system actuator and of the valve positioned. The fuel flow controls as function of Vce, are shown in a serious of blocks including the value position and flow dynamics. The output of the LVG, Vce in the Fig. 2, represents the least amount of fuel needed for that particular operating point and is an input to the fuel system. Another input to the fuel system is the per unit turbine speed N (limited by the acceleration control). The per-unit value for Vec corresponds directly to the per-unit value of the mechanical power from the turbine in steady state. The value of Vce, is scaled by the gain value of 0.77 and offset by value represented by which is the fuel flow at no load, rated speed condition. The time delay preceding the fuel flow controls represents delay in the governor control using digital logic in place of analog devices. The fuel flow, burned in the combustor results in turbine torque and in exhaust gas compressor measured by a thermocouple. The temperature control is a hard limit at the temperature set-point. The output from the thermocouple is compared with the reference value. Normally the reference value is higher than the thermocouple output and this forces the output from the temperature control to stay on the maximum limit permitting free governor/speed control. When thermocouple temperature exceeds the reference temperature, the difference becomes negative and it starts lowering the temperature control output. When the temperature control output becomes lower than the governor, the former value will pass through the low value select to limit the output, and the unit will operate on temperature control.

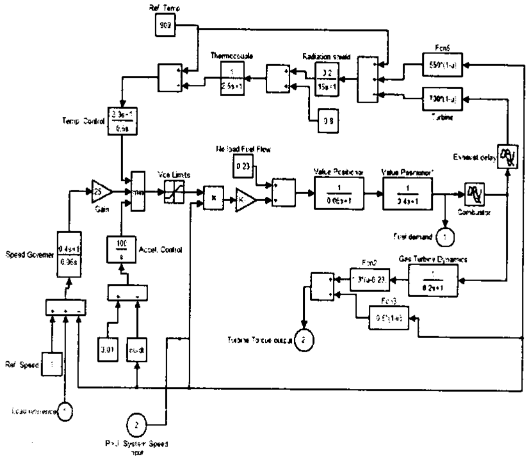

Fig. 2. Simulink model of the microturbine

2.2 Permanent magnet synchronous machine (PMSM)

The model for the generator is a 2 poles permanent magnet synchronous machine (PMSM) with nonsalient rotor [14]. At 1,600[Hz] (96,000 [rpm]), machine output power is 30[kW] and its terminal line-to-line voltage is 480[V]. The electrical and mechanical parts of the machine are each represented by second order state-space model. The model assumes that the flux established by the permanent magnet in the stator is sinusoidal, which implies that electromotive force. The following equations expressed in the rotor reference frame (dq frame) used to implement PMSM.

Electrical equations:

$$\frac{d}{dt}i_d = \frac{1}{L_d}v_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}p\omega_r i_q$$

$$\frac{d}{dt}i_q = \frac{1}{L_q}v_q - \frac{R}{L_q}i_q + \frac{L_d}{L_q}p\omega_r i_d - \frac{\lambda p\omega_r}{L_q}$$

$$T_e = 1.5p(\lambda i_q + (L_d - L_q)i_d i_q)$$

Mechanical equations:

$$\frac{d}{dt}\omega_r = \frac{1}{J}(T_e - f\omega_r - T_M)$$

$$\frac{d\theta}{dt} = \omega_r$$

Where,

L_q, L_d : q and d axis inductance

R : Resistance of the stator winding

i_d, i_q : 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 winding

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

2.3 Frequency changer

The frequency changer consists of two back-to-back active converters. This topology allows bi-directional flow of the active power. The frequency changer i_d used to launch the MT, and also to adjust the phase between current and voltage on both utility and grid side. Synchronization of the grid-side converter is carried out by a phase lock loop (PLL). Both converter use PWM modulation techniques.

2.4 Grid

A state space model is presented for all the subsystems: control loop, output filter and coupling inductor. The is represented by a balanced three-phase source, 480 volts line to line(RMS), 60[Hz] frequency, having grid parameters of per phase impedance of 0.4 ohms resistance and 2mH inductance.

Load parameters are 25[kW] power rating having line-to line voltage 480[V] and frequency 60[Hz].

3. Regulation and Control

3.1 Control structure

The power conditioning system is a critical component in the single shaft MT design and represents significant design challenges. It is can be observed that the most generalized and versatile form of power electronics topology for the MT application is the back-to-back rectifier/inverter connection which provides the improved power flow control as well as increased efficiency. The grid side converter regulates the DC bus voltage while the machine-side converter controls the PMSM speed and Displacement factor. This control structure decouples effectively the two converter control scheme. Depending on the status of the MTG system two different control strategies for the line side converter have been considered: P-Q control strategy with DC-link voltage control is used for grid-connected mode of operation and V-f (voltage-frequency) control for standalone or islanding operation mode.

3.2 Machine-side converter control

The machine-side converter in generating mode operates as a power source with controlled current. This converter controls generator speed and phase between current and voltage at the output of PSME [15]. A PI controller that supplies an i_{qref} current component reference to the second PI controller regulates the MT speed. The i_{dref} current component is precalculated and regulated by a third PI regulator to insure a unity displacement factor. It is known that the MT speed reference ω_{ref} is also percalculated so that the turbine operates with optimal efficiency. Fig. 3 shows high efficiency drive control system for the MTG. Based on the speed error the commanded q axis magnetizing current i_{qref} is determined through the speed controller. The command d axis current i_{dref} predetermined and set to the optimum magnetizing current value. Based on the current errors, the commanded dq-axes voltages are determined through the current controller. In this system, the following PI controllers with decoupling terms are utilized for the current controllers. The commanded dq-axes voltages (v_d, v_q) are transformed into the abc quantities(v_a ,v_b, v_c) and given to PWM generator to generate the gate pulse.

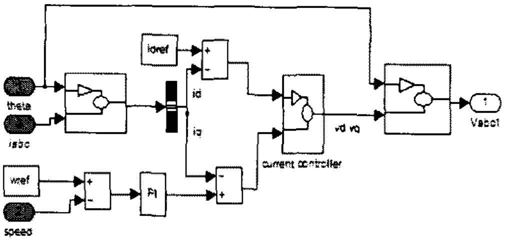

Fig. 3. Machine side converter control.

3.3 Line-side converter control

The MTG system line side converter can operate both in grid connected control mode and stand alone control mode.

Grid-Connected Mode: The control structure for grid-connected mode is shown in Fig. 4. The grid-side converter operates as a controlled power source. The standard PI controllers are used to regulate the grid currents in the dq synchronous frame in the inner control loops and dc voltage in the outer loop. A PLL is used to synchronize the converter with the grid. The philosophy of the PLL is that the difference between grid phase angle and the inverter phase angle can be reduce to zero using PI controller. It is seen that a PI controller regulate the DC bus voltage by imposing an i_d current component. i_d represents the active component of the injected current in the grid and i_q is its reactive power. In order to obtain only a transfer of active power, the i_q current reference is set to zero. The decoupling terms are used to have independent control of i_d and i_q.

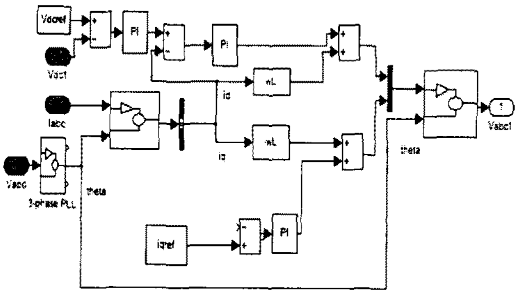

Fig. 4. Line side converter control for grid connected mode

Islanding Operation Mode: The control structure for islanding control mode is depicted in Fig. 5. It must regulate the voltage value at the reference bar and frequency of the whole grid. The output controller will control the output voltage with a minimal influence from the shape of the load current or load transient.

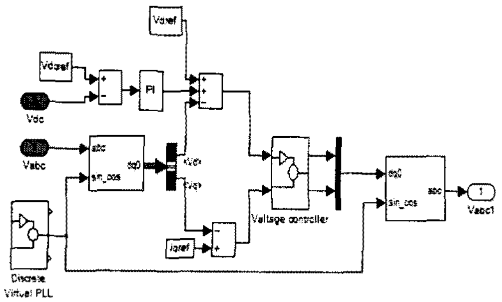

Fig. 5. Line side converter control for islanding mode

A standard PI controller operating in the synchronously rotating coordinate system where

v_q is kept to zero is used. The load voltage is regulated at 480[V] rms by a PI voltage regulator using *abc* to *dq* to abc transformations. The output of the voltage regulator is a vector containing the three modulating signals used by the PWM generator to generate the gate pulses.

4. Simulation and Results

The simulation of the MTG system model is performed using SimPowerSystem library. It concludes Grid-connected /islanding mode as shown in Fig. 6. The distribution network to which MTG system is connected, is represented by balanced 3 phase source. The performance of the model is studied for different values of reference output power. Table 1 contains the parameters used for the simulation.

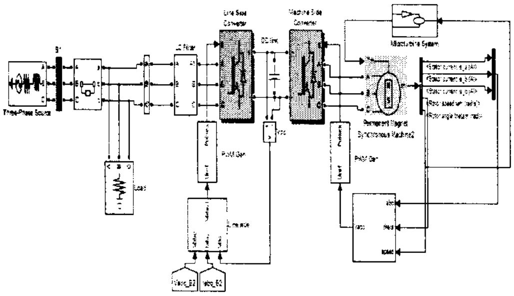

Fig. 6. SimPowerSystems implementation of MTG system

4.1 start up : PMSM functioning as a motor

This section presents dynamic responses of the simulated model with an output reference power set at 14[kW]. During start up, the PMSM operates as a motor to bring the turbine at a speed of 30,000[rpm]. In this case, power flows from grid to MTG system. Fig. 8 shows that the MT reaches the set value of speed in 0.35[s]. At this speed MTG system draws fundamental current of 14. 43[A] resulting absorptive power of 5.2[kW] as shown in Fig. 9. To ensure this operating condition at a unity displacement factor, the percalculated reference speed and direct current component i_d are set 3,142[rad/s] and -5.36[A], respectively. The speed regulator provides the reference for the I_q current component. Fig. 7 shows that the DC bus voltage regulated at 760[V] when the machine is operating in grid-connected mode.

Table 1. Grid connected microturbine simulation parameters

Permanent magnet synchronous machine(PMSM)	480[V], I=36[A], f=1,600[Hz]
Number of poles	P=2
Direct and quadrature inductances	$L_d = L_q = 6.875 \times 10^{-4}$
Stator resistance	R_s = 0.25[Ω]
Flux induced by the permanent magnet	Φ_m =0.0534[wb]
DC bus capacitor	C= 5000[μF]
PI controller sampling period	100[μs]
Speed governor parameters	Gain(K)= 25, X=0.4, Y= 0.05, Z=1
Load parameters	25[kW], 480[V], 60[Hz]

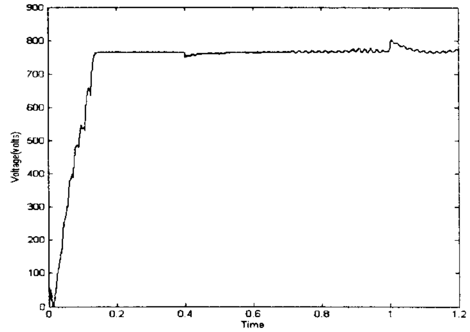

Fig. 7. DC bus voltage

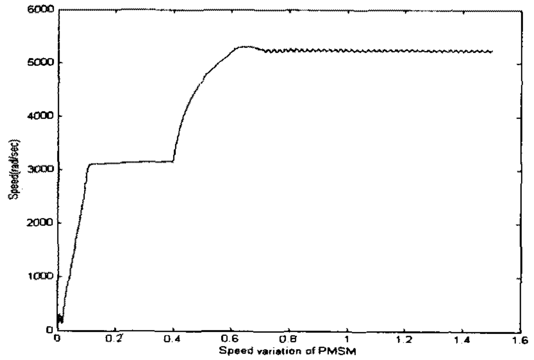

Fig. 8. Speed variation of PMSM

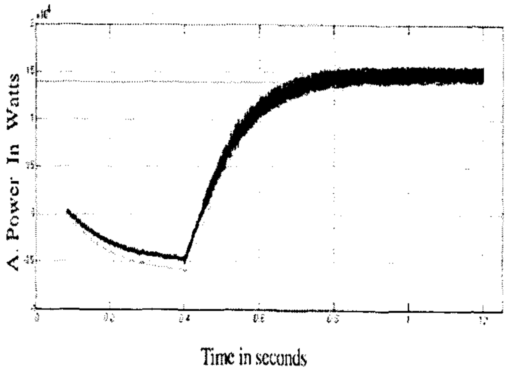

Fig. 9. Variation of active power starting/ generating PMSM-side(14[kW])

4.2 Generating

When motor is switched to the generating mode as shown in Fig. 8, the power flows from MTG system to the grid. To ensure this operating condition at a unity displacement factor, the reference speed is set at 5849rad/s and the reference for the direct current i_{dref} is set at -15.89 A. This reference speed corresponds to output power of 14[kW] and at this speed, the generator line to line voltage is 330[V], the frequency is 931[Hz]. The q axis reference current i_{qref} is therefore imposed by the speed controller. Fig. 10 shows the line current of the PMSM when operating in generating mode, supplying 14[kW] to the grid. Fig.11 shows the reactive component of current injected into the grid for zero reference value of i_q. The terminal voltage at the load is shown in Fig. 12.

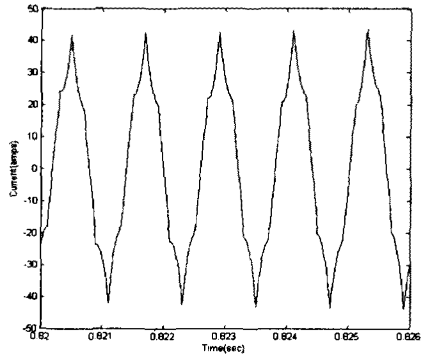

Fig. 10. Line current of PMSM in generating mode at 14[kW]

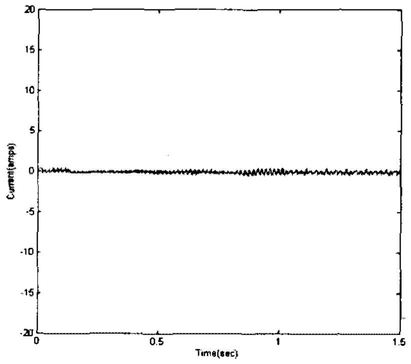

Fig. 11. Current iq injected the grid

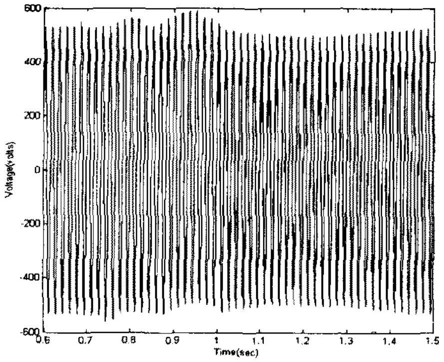

Fig. 12. Voltage across the load terminal

Islanding Operation mode : At t=1[s] the interface circuit breaker between MTG system and grid is open and the voltage-frequency (V-f)control scheme for island operation is applied. Fig. 13 shows the line current variations of MTG system both during grid connected and islanding operations. A the time of switching from grid connected to islanding operation there is a dip in dc link voltage as shown in Fig. 7.

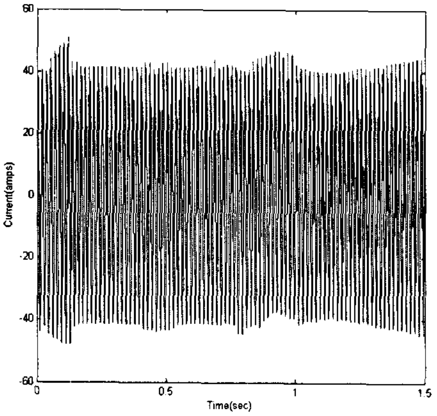

Fig. 13. Line current variation of the load

5. Conclusions

The single-shaft microturbine generation system has been successfully modeled by using MATLAB's SimPowerSystems library. A MT system and related controls has been analyzed into detail in order to explore the possibility for the small generator to efficiently operate both in grid connected mode and in islanding operation. The simulated model and the results obtained for various operation conditions permit to predict the MT performance of the grid-connected and island operation mode. The simulated results demonstrate that the established model provides a useful tool suitable to study and to perform accurate analysis of most electrical phenomenon that occurs when a MT is connected to the grid or is operating islanding mode. The intentional islanding helps in providing high reliability for the customer. These results can be utilized directly to implementation of building cooling, heat and power (BCHP) system. The future work will be to focus on the switching operation and protection from grid connected to stand-alone and vice versa.

Acknowledgment

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Biography

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