MICROTURBINE BASED DISTRIBUTED GENERATOR IN SMART GRID APPLICATION

A.K.SAHA  
Jadavpur University  
-India

akshay_ksaha@yahoo.com

S.P.CHOWDHURY  
University of Cape Town  
- South Africa

sp.chowdhury@uct.ac.za

S.CHOWDHURY  
University of Cape Town  
- South Africa

sunetra69@yahoo.com

P.A.CROSLEY  
University of Manchester  
- UK

p.crossley@manchester.ac.uk

C.T.GAUNT  
University of Cape Town  
- South Africa

c.t.gaunt@uct.ac.za

ABSTRACT

This paper presents modeling and simulation of microturbine (MT) models to analyze its load following performance as distributed energy resource (DER) with general as well as critical priority loads. Two different models MT were considered for performance analysis. The first model consists of speed governor, acceleration control, and temperature control blocks while the other is GAST model of MT. The system comprises of a synchronous generator and a MT coupled to it. Simulations are carried out in islanded and grid-connected mode of the system to observe its behavior when supplying customer’s variable loads. The load following characteristics is observed and validated for this MT-synchronous generator model in Matlab-Simulink environment with power system block sets. This is applicable with combined heat power (CHP) generators both with general fuel as well as bio-fuels. The use of bio-fuels is very much promising for generating green power preventing green house gas emissions for fighting against global warming. But it may take some time to be in the market place for its commercial use.

INTRODUCTION

DERs have received significant attention as a means to improve the performance of the electrical power system, provide low cost energy, and increase overall energy efficiency [1]. DERs are constituted by a variety of small, modular distributed generation (DG) technologies that can be combined with energy management and storage systems. DER devices enable renewable energies utilization and more efficient utilization of waste heat in combined heat and power (CHP) applications and lowering emissions. [2]. Recent technology improvements in various types of DERs, including MTs fuel cells, mini-hydro, battery storage, and so on, have created the opportunity for large-scale integration of DERs into distribution systems. Such on-site supply may be the most practical approach to address increasing power demand and power quality requirements, given the current electric utility restructuring as well as public environmental policy [3].

MTs are small and simple-cycle gas turbines. The outputs of the MTs range typically from around 25 to 300 KW. They are part of a general evolution of in gas turbine technology. Techniques incorporated into the larger machines, to improve the performance, can be typically found in MTs as well. These include recuperation, low NOx emission technologies and the use of advanced materials, such as ceramic for the hot section parts [4][5]. Unlike traditional backup generators, MTs are designed to operate for extended periods of time and require little maintenance. They can supply a customer’s base-load requirements or can be used for standby, peak shaving and cogeneration applications. In additions, the current generation MTs has the following specifications [6][7]:

- Relatively small in size, compared to other distributed resources.
- High efficiency, fuel-to-electricity conversion can reach 25%-30%. However, if the waste recovery is used, combined heat and electric power could achieve energy efficiency levels greater than 80%.
- Environmental superiority, NOx emissions lower than 7 parts per million for natural gas machines in practical operating ranges.
- Durable, designed for 11,000 hours of operation between major overhauls and a service life of at least 45,000 hours.
- Economical, system costs lower than $500 per KW, costs of electricity that are competitive with alternative including grid-connected power for market applications.
- Fuel flexibility, capable of using alternative/optional fuels including natural gas, diesel, ethanol, landfill gas and other bio-mass derived liquids and gases.

There are essentially two types of MTs. One is high speed single shaft unit with a compressor and turbine mounted on the same shaft as an electrical synchronous machine. In this case, the turbine mainly ranges from 50,000 r.p.m. to 120,000 r.p.m. The other type of MT is split-shaft designed which uses a power turbine rotating at 3,000 r.p.m. and a conventional generator connected via a gear box [4][5].

Ref. [8] reported the development of a single stage axial flow MT for power generation. Nichols, D.K. et al. discussed the MT technology, its facilities and relevant test results [9]. Guda, S.R. demonstrated the development of a MT model and its operation with a permanent magnet synchronous generator [10]. Suter, M. reported an active filter for MT [11]. Adaptive control of fuel cell and MT is well described in ref. [12]. Gaonkar, D.N. et al. demonstrated the development of a MT model from the dynamics of each part which is suitable for studying various operational aspects of the same [13]. Ho, J.C. et al. presented the performance of a MT system for cogeneration application [14]. Ref. [15] proposed a control system for dispersed generators based on PI control and which was verified control simulations. A control system was developed for generated power control using generator data.
using double-loop configuration, controlling, respectively, the generated power and electric energy. Next, the proposed load-following control was verified. There are several issues related to the operation and integration of a MT to a distribution system and in particular its load following characteristics is of great importance. In this paper, the operating performance of a MT and its load following characteristics are validated and presented as it has been simulated in islanded and grid-connected mode via a distribution system.

MICROTURBINE MODELS

The designs of MTs are composed of the following parts [4][5]:
(a) Turbine: There are two kinds of turbines, high speed single shaft turbines and split shaft turbines. All are small gas turbines.
(b) Alternator: 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 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 gearbox.
(c) 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 voltage. In the split shaft design, the power inverters are not required.
(d) Recuperator: The recuperator is a heat exchanger which transfers heat from the exhaust gas to the discharge air before it enters the combustor to reduce the amount of fuel required to raise the discharge air temperature to that required by the turbine.

Control and communication: Control and communication systems include full control of the turbine, power inverter and start-up electronics as well as instrumentation, signal conditioning, data logging, diagnostics, and user control communications.

Two different models of MT are simulated and their load following characteristics is observed which are described in section 2.1 and 2.2 respectively.

MT Model-1

This model comprises of speed governor, acceleration control and temperature control blocks as illustrated in Figure (1). It is assumed that the MT is operating under normal operating conditions which neglect its fast dynamics (e.g. start-up, shut-down, internal faults and loss of power). Speed control operates on the speed error formed between a reference speed and MT-generator rotor speed. It is the primary means of the control for the MT under part load conditions. Speed control is usually modeled by using a lead-lag transfer function or by a PID controller [16][17]. Lead-lag transfer function has been used in this work to represent the speed controller. The governor controls are with parameters gain, X, Y, and Z which can be adjusted so that the governor can act with droop or as isochronous governor. Acceleration control is primarily used for during turbine start-up to limit the rate of 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 while modeling the MT. The output of the speed governor goes to a low value select to produce a value for \( V_{ce} \), the fuel demand signal. The other signal in to the low value select is from temperature controller. The per unit value for \( V_{ce} \) corresponds directly to the per unit value of the mechanical power on turbine based in steady state.

The fuel flow controls are shown as function of \( V_{ce} \), in a series of blocks including the valve position and flow dynamics. The value of \( V_{ce} \) 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 delays 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 temperature measured by a thermocouple. The output from the thermocouple is compared with a 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 uninhibited governor/speed control. When the thermocouple output 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 output, the former value will pass through the low value select to limit the output and the unit will run on temperature control [13]. As the temperature control comes in to action, it reduces the fuel input to the combustor which in turn reduces the exhaust temperature. Now, the difference is positive and the temperature control output increases. When the temperature control output becomes more than that of the governor, speed governor output passes through the low values select. The unit again operates on speed governor control.

MT Model-2

The MT model-2 considered is based on the following assumptions:
(a) The recuperator is not included in this model as it is mainly used to raise the efficiency of the system.
(b) The temperature control and acceleration control have no impact on the normal operating conditions; therefore, they can be omitted in the turbine model.
(c) The micro turbine does not use any governor, so, the model is not included in the model [4][5].

For load following analysis purposes a simplified block diagram for the MT can be represented as shown in Figure (2). The real power control variable \( P_m \) is then applied to the
In control system of the MT, \( P_{\text{dem}} \) is the demanded power, \( P_{\text{ref}} \) is the reference power, \( P_{\text{in}} \) is the power control variable to be applied to the input of the MT. \( K_p \) is the proportional gain and \( K_i \) is the integral gain of the proportional-integral controller. The real power control is described as conventional PI-control function as illustrated in Figure (3). For turbine model GAST model as shown in Figure (4) is simple, follows typical guidelines and most commonly used dynamic models of gas turbines [4][5].

**MODEL DESCRIPTION & PARAMETERS**

The synchronous machine used in the simulations is based on Matlab-SimPower system block set. The parameters related to the machine are given in Table2. The distribution network is of 11 KV rating and modeled by a simple R-L equivalent source of short circuit level 500 KVA with a load of 5 KW. It has a wye-delta connected transformer with voltage ratio of 11 KV/440 V. Other related parameters of the distribution system are shown in Table3. Simulations of MT-generator system were carried out in Matlab-Simulink environment with the system configuration as shown in Figure (5). The MT can supply its own loads without being connected with the distribution system. The Distribution system is also capable of supplying its own loads separately. The MT-generator system can be connected/disconnected to distribution system by closing/opening a circuit breaker.

**Table1-Microturbine parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power, ( P_{\text{rate}} )</td>
<td>150 KW</td>
</tr>
<tr>
<td>Real power reference, ( P_{\text{ref}} )</td>
<td>1.0</td>
</tr>
<tr>
<td>Proportional gain, ( K_p )</td>
<td>0.1</td>
</tr>
<tr>
<td>Integral gain, ( K_i )</td>
<td>1.0</td>
</tr>
<tr>
<td>Damping of turbine, ( D_{\text{tur}} )</td>
<td>0.03</td>
</tr>
<tr>
<td>Fuel system lag time constant 1, ( T_1 )</td>
<td>10.0 s</td>
</tr>
<tr>
<td>Fuel system lag time constant 2, ( T_2 )</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Load limit time constant, ( T_3 )</td>
<td>3.0 s</td>
</tr>
<tr>
<td>Maximum value position, ( V_{\text{max}} )</td>
<td>1.2</td>
</tr>
<tr>
<td>Minimum value position, ( V_{\text{min}} )</td>
<td>-0.1</td>
</tr>
<tr>
<td>Temperature control loop gain, ( K_{\text{T}} )</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Table2-Synchronous generator parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power, ( P_{\text{rate}} )</td>
<td>150 KW</td>
</tr>
<tr>
<td>Rated voltage, ( V_{\text{rat}} )</td>
<td>440 V</td>
</tr>
<tr>
<td>Frequency, ( f )</td>
<td>60 Hz</td>
</tr>
<tr>
<td>No. of poles, ( P )</td>
<td>2</td>
</tr>
<tr>
<td>Damping factor, ( K_D )</td>
<td>60 p.u.</td>
</tr>
<tr>
<td>Inertia constant, ( H )</td>
<td>0.822 s</td>
</tr>
<tr>
<td>Internal resistance, ( R )</td>
<td>0.02 p.u.</td>
</tr>
<tr>
<td>Internal reactance, ( X )</td>
<td>0.3 p.u.</td>
</tr>
</tbody>
</table>

**Table3-Distribution system parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-ph source base voltage</td>
<td>11 KV</td>
</tr>
<tr>
<td>3-ph source S.C. level</td>
<td>500 KVA</td>
</tr>
<tr>
<td>3-ph source X/R ratio</td>
<td>6</td>
</tr>
<tr>
<td>Dist. trans. nominal power</td>
<td>200 KVA</td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hz</td>
</tr>
</tbody>
</table>
The parameters of model-1 are adopted from [13][17] and the parameters used for simulations of model-2 are based on [5]. The MT parameters for model-2 are illustrated in Table 1.

SIMULATIONS AND RESULTS

The simulations of MT models have been performed in Matlab-Simulink environment and those are presented as follows:

Model-1

The MT-generator is initially running at no load up to 5 seconds. At t=5 seconds, a load of 30 KW was applied to it and at t=25 seconds another load of 90 KW was connected to the system. The simulation time is 50 seconds. Figure (6) shows the changes in loads on the generator which were connected to it. The output torque of the turbine is represented by Figure (7). It shows that the turbine torque closely follows the generator within a very short period of time. The fuel demand is illustrated in Figure (8). It is observed that the fuel flow at no load is 0.23 p.u. and it increases accordingly as the load on the generator increases.

Model-2

Islanded mode:

(i) In this simulation, the MT is initially running with a load of 30 KW applied to the generator bus up to t=150 seconds. After that, another load of 90 KW has been applied at t=150 seconds.

(ii) In the next simulation, a speed control has been incorporated with the MT-generator system to maintain the speed constant at 1 p.u. The MT-generator system is running initially at no load. At time t=50 seconds a load of 0.2 p.u. is applied and at t=200 seconds another load of 0.6 p.u. is applied. The mechanical power output of the MT is
shown in Figure (11) which displays that the MT follows the input power demand but with some time lag.

![Figure 11: MT output to generator](image1)

The electrical power measured at the generator output is illustrated in Figure 12 to show that the electrical load is initially zero, 0.2 p.u. from t=50 seconds to t=200 seconds and 0.8 p.u. from t=200 seconds to t=350 seconds.

![Figure 12: Generator output](image2)

The MT-generator speed is represented in Figure (13) which shows that the speed drops at the instant the load demand increases but it reaches 1 p.u. and maintained at that level as desired at steady-state.

![Figure 13: MT-generator speed](image3)

**Grid-connected mode:**

In this simulation, the MT-generator system has been connected to and then disconnected from a distribution system. The MT-generator system and distribution both are running initially at no load and at time t=5 seconds, 0.2 p.u. load is applied to MT-generator system and a load of 160 KW is connected to the distribution system. The MT-generator and the distribution system are running with their own load separately. At time t=125 seconds another load of 0.6 p.u. is applied to MT-generator system. At time t=250 seconds, the MT-generator system is interconnected with the distribution system and at time t=375 seconds the MT-generator is disconnected from the distribution system. The total simulation time is 500 seconds. The mechanical power output of the MT and the electrical power output of the generator are represented in Figure (14) and Figure (15) respectively.

![Figure 14: MT mechanical power output](image4)

![Figure 15: Generator electrical power output](image5)

The responses of the MT and generator to the input power demand are similar to those observed in the previous simulations. The variation of MT-generator speed is illustrated in Figure (16) which is also similar to that obtained with speed control in islanded mode. Figure (17) shows the variation of distribution system power which demonstrates that it is at zero up to 5 seconds; after that it maintains 160 KW up to 250 seconds. It shares a load of about 12 KW from the other system which is also evident from the electrical power output of the generator. The shared load is again transferred to MT-generator system as it is disconnected at t=375 seconds.
CONCLUSIONS

Simulations of MT models are performed for its operation both in islanded mode and grid-connected mode. Its load following performance as distributed energy resource with priority loads has been tested and validated. The load following characteristics observed from the simulation studies carried out in Matlab-Simulink environment are analyzed and presented in this paper. It has been observed that the MT can be used both in islanded and grid-connected mode as a distributed energy resource to supply customer load demands as and when required. Since MTs are mainly used for CHP systems with very high energy efficiency, its use is highly appealing with regard to distributed generators using both with general fuels and biofuels.

REFERENCES