

Simulation Of Microturbine Generation System For Unbalance Grid Power Supply

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ABSTRACT

Micro turbine generation is currently attracting lot of attention to meet users need in the distributed generation market due to the deregulation of electric power utilities, advancement in technology, environmental concerns This paper presents modeling and simulation of microturbine (MT) to analyze its load following performance as distributed energy resource (DER) with general as well as critical priority loads. This paper also presents the modeling and simulation of a microturbine generation (MTG) system, the nonrenewable source of energy suitable for isolated as well as grid-connected operation. The system comprises of a permanent magnet synchronous generator driven by a microturbine. A brief description of the overall system is given and mathematical models for the microturbine and permanent magnet synchronous generator are presented. In the last section of this paper, the developed models are simulated in MATLAB/Simulink. The simulated microturbine model is of single shaft type with control systems capable of regulating its output power. Simulation results are presented for the developed model of the MTG system under different load conditions.

Keywords:- Acceleration control, fuel system, compressor-turbine, machine, microturbine generation system (MTG), temperature control, permanent magnet synchronous generator

1.INTRODUCTION

Microturbines are small gas turbines which burn gaseous or liquid fuels to create high energy gas stream that turns an electrical generator. There is a growing interest in the application of MTGs as they can start quickly and are especially useful for on-peak power supply for grid support. Other applications include remote power and combined heat and power (CHP) systems by utilizing the heat contained in the exhaust gases to supply thermal energy needs in a building or industrial process. 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 120,000r.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. Various applications such as peak shaving, co-generation, remote power and base load power will make its use worldwide. Dynamic model of MTG system have been suggested in SIMULINK based dynamic model for microturbine system for distributed generation system. This paper presents the modeling and simulation of a microturbine generation (MTG) system, the non renewable source of energy suitable for isolated as well as grid-connected operation. The system comprises of a permanent magnet synchronous generator driven by a microturbine. A brief description of the overall system is given and mathematical models for the microturbine and permanent magnet synchronous generator are presented. In the last section of this paper, the developed models are simulated in MATLAB/Simulink. The simulated microturbine model is of single shaft type with control systems capable of regulating its output power. Simulation results are presented for the developed model of the MTG system under different load conditions.

2.Microturbine Generation (MTG) System

Microturbine is small gas turbines which burn gaseous or liquid fuels to create high energy gas stream that turns an electrical generator. There is a growing interest in the application of MTGs as they can start quickly and are especially useful for on-peak power supply for grid support. Other applications include remote power and combined heat and power (CHP) systems by utilizing the heat contained in the exhaust gases to supply thermal energy needs in a building or industrial process. Generally MTG systems range from 30 to 400 kilowatts, while conventional gas turbines range from 500 kW to more

than 300 MW. Microturbine are capable of burning 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%, where as 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, microturbine 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. Microturbine emissions can be up to eight times lower than diesel generators, and currently available ones produce less than 50% of the NOx emissions of a state of the art natural gas lean-burn engine. 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. 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.

3. Basic Phenomenon and Parts of a MTG System

The basic phenomenon of a microturbine generation system are: compressor, turbine, recuperator, high-speed generator and power electronics interfacing. In the following paragraphs a brief description of each component is given, followed by a detailed modeling of microturbine and high-speed generator. Figure 1 shows the schematic diagram of a single-shaft microturbine based generation system.

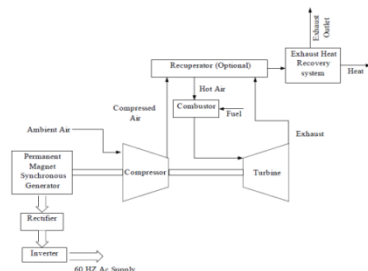


Fig 1 Microturbine based CHP system (Single-Shaft Design).

Microturbines, like large gas turbines, operate based on the thermodynamic cycle known as the Brayton cycle. In this cycle, the inlet air is compressed in a radial (or centrifugal) compressor. The compressed air is mixed with fuel in the combustor and burned. The hot combustion gas is then expanded in the turbine section, producing rotating mechanical power to drive the compressor and the electric generator, mounted on the same shaft (single-shaft design). In a typical microturbine air to gas heat exchanger called recuperator is added to increase the overall efficiency. The recuperator uses the heat energy available in the turbine's hot exhaust gas to preheat the compressed air before the compressed air goes into the combustion chamber thereby reducing the fuel needed during the combustion process. The high-speed generator of the single shaft design usually employs a permanent magnet synchronous generator (PMSG), and requires that the high frequency AC output in the order of kHz be converted to 60 Hz (or 50 Hz) for general use. This power conditioning involves rectifying the high frequency AC to DC and then inverting the DC to 60 Hz (or 50 Hz) AC. Power electronic interfacing is a critical component in the single-shaft design and is generally designed to handle transient and voltage spikes. The model presented in this paper concentrates on the slow dynamics of the MTG system, suitable for power management of MTG combined with other types of distributed generation (DG) systems. It is reasonable, while modeling the microturbine for the above purpose, to assume that the system is operating under normal operating conditions by neglecting fast dynamics of the microturbine (e.g., start-up, shutdown, internal faults and loss of power). Also, since the electromechanical behavior of the MTG system is of main interest the recuperator is not included in the model as it only serves to increase the turbine efficiency.

Physical Representation of a Microturbine

There exists a large literature on the modelling of gas turbines, with varying level of complexity depending on the intended application. The concept of gas turbine system presented in this section is based on the paper presented by Rowen. He proposed a single-shaft design, generator driven gas turbine model which includes speed control, temperature control and fuel system. This model was successfully adopted by the several authors for gas turbine simulations as well as for microturbine simulations with smaller

time constants.

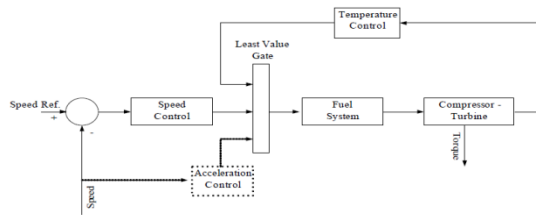


Fig2.Block diagram of a micro turbine.

The three control method of the micro turbine are: speed control acting under part load conditions, temperature control acting as an upper output power limit, and acceleration control to prevent over speeding. The output of these control method blocks are all inputs to a least value gate (LVG), whose output is the lowest of the three inputs and results in the least amount of fuel to the compressor-turbine as shown in Fig2.This figure shows the per-unit representation of a micro turbine, along with its control systems. Each subsystem of the micro turbine is discussed in the next sections.

3. Speed and Acceleration Control

The speed control operates on the speed error formed between a reference (one per-unit) speed and the MTG system rotor speed. It is the primary means of control for the microturbine under part load conditions. Speed control is usually modeled by using a lead-lag transfer function or by a PID controller. In this paper a lead lag transfer function has been used to represent the speed controller, as shown in Figure.3. In this figure K is the controller gain, T₁ (T₂) is the governor lead (lag) time constant, and Z is a constant representing the governor mode (droop or isochronous). A droop governor is a straight proportional speed controller in which the output is proportional to the speed error. An isochronous speed controller is a proportional-plus-reset speed controller in which the rate of change of the output is proportional to the speed error. Acceleration control is used primarily during turbine start-up 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, which is the case in this study.

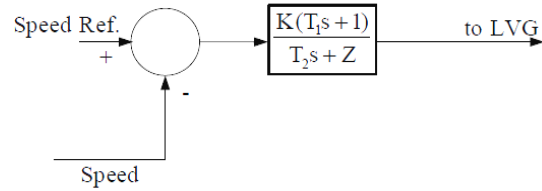


Fig.3Speed controller for the micro turbine

Fuel System

The fuel system consists of the fuel valve and actuator. The fuel flow out from the fuel system results from the inertia of the fuel system actuator and of the valve positioner, whose equations are given below.

The valve positioner transfer function is:

$$E_l = \frac{K_v}{T_v s + c} F_d \tag{1}$$

and the fuel system actuator transfer function is:

$$W_f = \frac{K_f}{T_f s + c} E_l \tag{2}$$

In Esq. (1) and (.2), k_v and k_f is the valve positioner (fuel system actuator) gain, T_v , T_f are the valve positioner and fuel system actuator time constants, c is a constant, F_d and E_l are the input and outputs of the valve positioner and ω_f is the fuel demand signal in p.u. The output of the LVG, V_{ce} , 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 V_{ce} , corresponds directly to the per-unit value of the mechanical power on turbine at steady-state. The fuel flow control as a function of V_{ce} , is shown in Figure4.

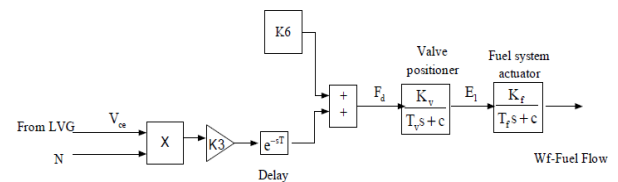


Fig4Block diagram of the fuel system

The value of V_{ce} , is scaled by the gain K3 ($K3= (1- K6)$), then delayed and offset by the minimum

amount of fuel flow K_6 to ensure continuous combustion process in the combustion chamber. K_6 is essentially the minimum amount of fuel flow at no-load, rated speed.

4. Temperature-control

Temperature control is the normal means of limiting the gas turbine output power at a predetermined firing temperature, independent of variation in ambient temperature or fuel characteristics. The fuel burned in the combustor results in turbine torque and in exhaust gas temperature. The exhaust temperature is measured using a series of thermocouples incorporating radiation shields as shown in the block diagram of the temperature controller Figure .5. In Figure5, T_t is the temperature controller integration rate and T_3 , T_4 are time constants associated with the radiation shield and thermocouple, respectively. K_4 and K_5 are constants associated with radiation shield and T_5 is the time constant associated with temperature controller. The output from the thermocouple is compared with a reference temperature, which is normally higher than the thermocouple output. This forces the output of the temperature control to stay on the maximum limit permitting the dominance of speed control through the LVG (Figure.2). When the thermocouple output exceeds the reference temperature, the difference becomes negative, and the temperature control output starts decreasing. When this signal (Figure .2) becomes lower than the speed controller output, the former value will pass through the LVG to limit the turbine’s output, and the turbine operates on temperature control. The input to the temperature controller is the exhaust temperature T_x and the output is the temperature control signal to the LVG.

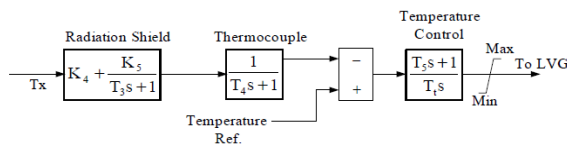


Fig5 Temperature controllers.

5.Compressor-Turbine

The compressor turbine is the heart of the microturbine and is essentially a linear, non dynamic device (with the exception of the rotor time constant). There is a small transport delay T_{CR} , associated with the combustion reaction time, a time lag T_{CD} , associated

with the compressor discharge volume and a transport delay T_{TD} , for transport of gas from the combustion system through the turbine. The block diagram of the compressor-turbine package is shown in Figure 6. In this figure both the torque and the exhaust temperature characteristics of the single-shaft gas turbine are essentially linear with respect to fuel flow and turbine speed and are given by the following equations:

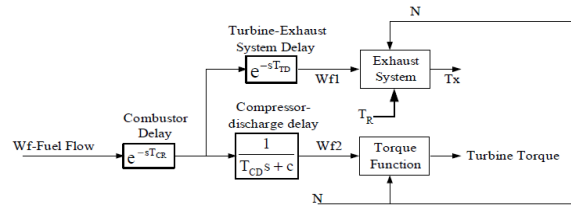


Fig6.Compressor-Turbine package of a micro turbine

$$\text{Torque} = K_{HHV} (W_{f2}-0.23)+0.5(1-N) \text{ (Nm)} \quad (3)$$

$$\text{Exhaust Temp.} T_x = T_R-700(1-W_{f1}) +550(1-N) \text{ (}^\circ\text{F)} \quad (4)$$

Where K_{HHV} is a coefficient which depends on the enthalpy or higher heating value of the gas stream in the combustion chamber and T_R is the reference temperature. The K_{HHV} and the constant 0.23 in the torque expression cater for the typical power/fuel rate characteristic, which rises linearly from zero power at 23% fuel rate to the rated output at 100% fuel rate. The input to this subsystem is the p.u. fuel demand signal W_f and outputs are the p.u. turbine torque and exhaust temperature ($^\circ\text{F}$).

6. Permanent Magnet Materials

The property of a permanent magnet and the selection of the proper materials are very important in the design of a permanent magnet synchronous machine (PMSM). A good permanent magnet should produce a high magnetic field with a low mass, and should be stable against the influences which would demagnetize it. The desirable properties of such magnets are typically stated in terms of the remanence and coercivity of the materials, and are quoted in Tesla, the basic unit for magnetic field B.

Iron, nickel, cobalt and some of the rare earth metals exhibit a unique magnetic behavior which is called ferromagnetism. Ferro magnets tend to stay magnetized to some extent after being subjected to an external magnetic field. The fraction of the saturation magnetization retained (remanence) when the driving field is removed is an important factor for the selection of the permanent magnets. All

ferromagnetic materials have a maximum temperature known as Curie temperature, where the ferromagnetic property disappears. Consequently, the range of temperatures plays an important role in the operation of a PMSM.

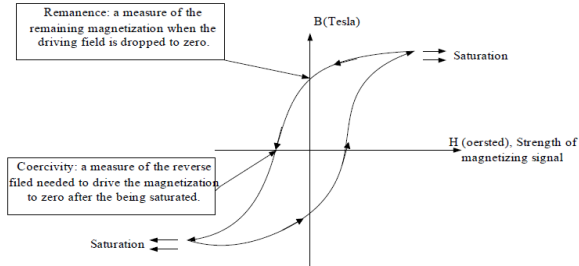


Fig 7 Hysteresis loop in the form of magnetization B and magnetic field strength H.

Operating Region of a PMSM;-

Figure 8 shows the demagnetization segment of the B-H curve where the permanent magnet is usually designed to operate.

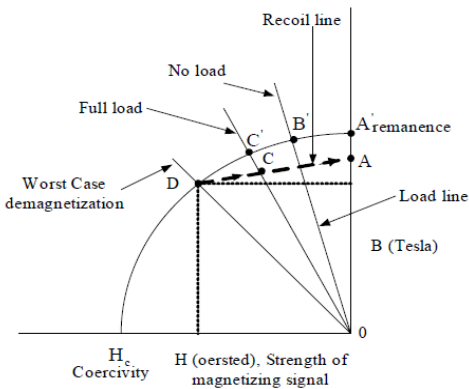


Fig8 Permanent magnet machine operating points on B-H curve.

The maximum flux density B_r corresponding to A will be available initially (no air gap). When the magnet is installed in the machine, the air gap will have some demagnetization effect and the operating point B' will correspond to the no-load line as shown in Figure.8. When current flows in the stator winding, the magnetic axis (direct axis) armature reaction effect can have further demagnetization effect, which will reduce the air gap flux density further. A load line representing worst-case demagnetization (may be due to starting, transient or machine fault condition) is also shown in Figure.8. Once the operating point reaches the D and the

demagnetization effect is removed, the magnet will recover along the recoil line (DA). Subsequently, the stable operating point will be determined by the intersection of the load line and IPM as well as SPM.

7.Simulinkmodel

The basic components of a MTG system are the Compressor, combustor, turbine, recuperator and high. The model adopted for the generator is a 2-pole Permanent magnet Synchronous Machine (PMSM) with a non salient rotor. The machine output power is 30 kW and its terminal line to line voltage is 480V. 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 (dqframe) are used to implement PMSM.

Electrical equations:

$$\frac{d}{dt} i_d = \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} p \omega_r i_q \quad (5)$$

$$\frac{d}{dt} i_q = \frac{1}{L_q} v_q - \frac{R}{L_d} i_d + \frac{L_d}{L_q} p \omega_r i_q - \frac{\lambda p \omega_r}{L_q} \quad (6)$$

$$T_e = 1.5p(\lambda i_q + (L_d - L_q)i_d i_q) \quad (7)$$

Mechanical equations:

$$\frac{d}{dt} \omega_r = \frac{1}{J} (T_e - F \omega_r - T_M) \quad (8)$$

$$\frac{d}{dt} \theta = \omega_r \quad (9)$$

Where, i_q, i_d : q and d axis current

J : Combined inertia of rotor and load

L_q, L_d : q and d inductances

p :Number of pole pairs

R: Resistance of the stator windings

T_e : Electromagnetic torque

T_M : Shaft mechanical torque

v_q, v_d :q and d axis voltages

θ :Rotor angular position

λ :Flux induced by the permanent magnets in the stator windings

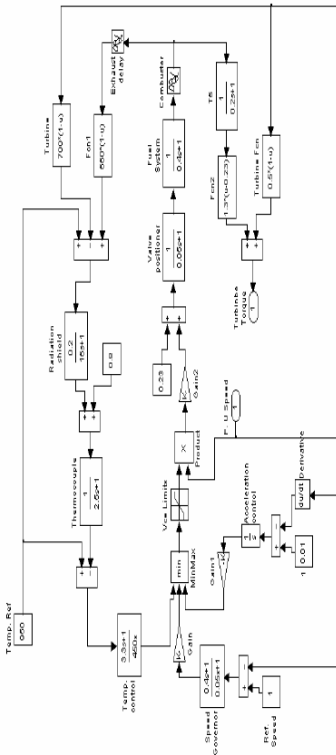
ω_r : Angular velocity of the rotor

F: Combined viscous friction of rotor and load

Fig9 SIMULINK model of the Micro-Turbine

8.MTG system operation in Generating Mode

At t=0.4 sec, the sign of the PMSM input torque is changed to operate it in generating mode. At t=0.4 sec, the reference speed and i_d current are set to the in order to generate the power . The time required to bring the output power value equal to reference power is about at 0.78 sec. So, the DC source will removed from the system at t=0.8 sec. After that, the MTG system will supply the power to the load



continuously. During the operation, the DC link voltage must be maintained constant by the line side converter. Otherwise, the PMSM fails to generate the power Figure 6

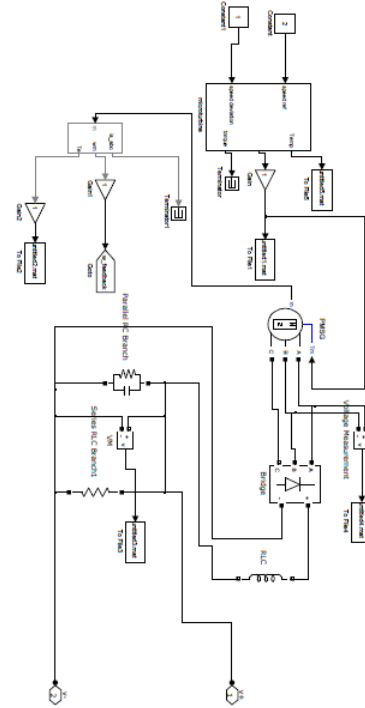


Fig10.Simulink model of Microturbine Generation System

Parameters are obtained form and adopted for this simulation. All time functions are in seconds.

Microturbine ratings: 400 kW, 70000 rpm.

Speed controller parameters (Figure3):

$$K=25, T_1=0.4, T_2=1.0, Z=3.$$

Fuel system parameters (Figure 4):

$$K_v=1, T_v =0.05, c=1, K_3=0.77, K_6=0.23, K_f=1, T=0, T_f=0.04.$$

Compressor-turbine combination parameters (Figure 6)

$$T_{CR}=0.01, T_{TD}=0.04, T_{CD}=0.2, K_{HHV}=1.2.$$

Temperature controller parameters (Figure5):

$$K_4=0.8, K_5=0.2, T_3=15, T_4=2.5, T_5=3.3, T_1=450 \text{ }^\circ\text{F}, T_R=950 \text{ }^\circ\text{F}.$$

Parameters used for the PMSG simulation.

$$R_s=12.5\text{m Ohms}, L_d=L_q=165\text{e-6 Henrys}, \Psi_f=0.2388 \text{ wb}, P=4, J=0.011 \text{ kg m}^2.$$

Speed reference was kept constant at 1 p.u. for all

simulations. All values are referred to a base power rating of 1 MVA. The response of the developed MTG system is given in the following simulation results: Initially the system is operating at no-load. At $t=10$ seconds a load of 200kW is applied on the MTG system, and at $t=15$ seconds, the load is increased to 400 kW. Figure11 shows the output power of the MTG system, responding to the above load variations. Figure 12 shows the fuel consumed by the microturbine for the applied load conditions. The fuel demand is equal to 23% (0.23 p.u.) until the load is applied on the system at $t=10$ seconds, increasing the amount of fuel required to keep the combustion process alive. Note that the fuel demand signal is 0.62 p.u. at 200 kW load and increasing to 1 p.u. at full load (400kW).

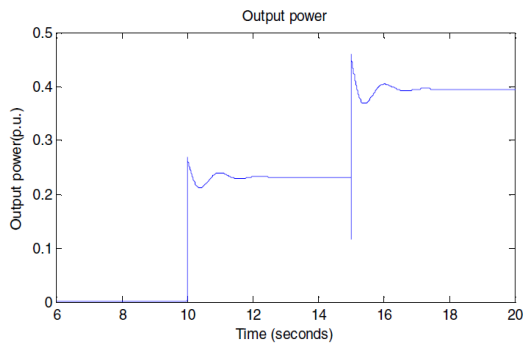


Fig11 Power output from the MTG system.

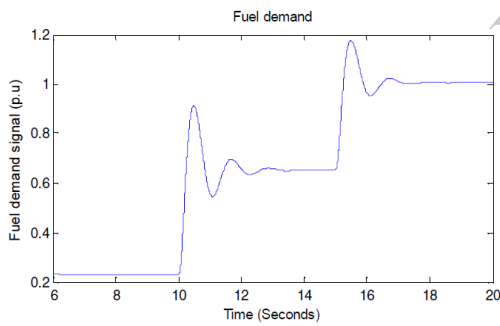


Fig12 Fuel demand signal of the microturbine.

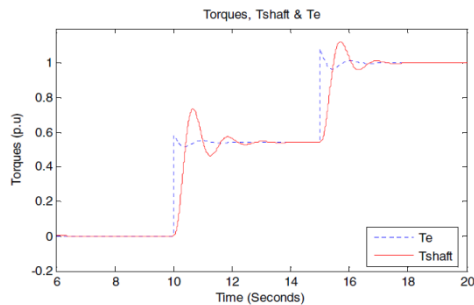


Fig13 Variation of shaft torque and electric torque generated.

Figure13 shows the shaft torque (T_{shaft}) produced by the microturbine, which drives the PMSG, and the electromagnetic torque (T_e) generated by the PMSG. The generator torque is approximately same as the shaft torque produced by microturbine at steady state. At no-load the electromagnetic torque is equal to zero; it increases to about 50% of its base value at 200kW and to 1 p.u. at full load.

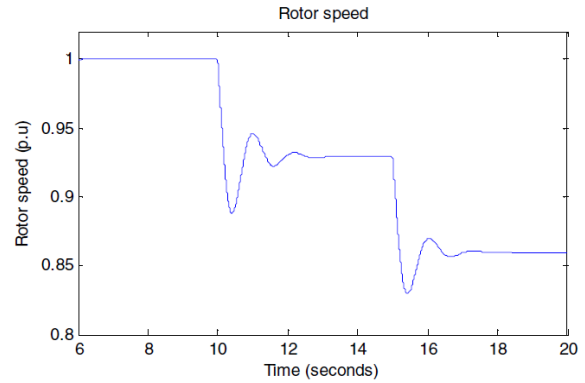


Fig14 Rotor speed variations with load.

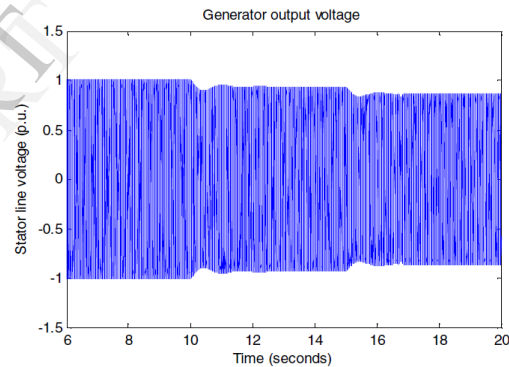


Fig15 Voltage across the stator terminals of PMSG.

Figures14 and 15 shows the rotor speed and output voltage of the PMSG. When the MTG is operating at no-load, the speed of the rotor is equal to 1 p.u. and the stator line voltage of the PMSG reaches no-load steady-state value of 1.p.u. (1p.u.= 6000 volts peak, Figure15. When the PMSG is loaded at $t=10$ seconds, the voltage decreases from no-load value to 0.94 p.u. and the frequency of the voltage waveform decreases from 2.33 kHz to 2.17 kHz. At $t=15$ seconds, as the load is increased again, the rotor speed Figure.14 and the stator voltage decrease further to 0.86 p.u. and 0.865 p.u., respectively.

Conclusion

The modeling of a single-shaft microturbine

generation system suitable for power management in DG applications is presented in this chapter. The model is good for both, power only and CHP applications. Detailed mathematical modeling of the control systems of the microturbine is given and simulation of the developed MTG system model is carried out. A MATLAB/Simulink model of the proposed MTG system was implemented in the SimPowerSystems block set. Different load conditions are applied on the MTG system. The simulation results show that the developed model of the MTG system has the ability to meet the power requirements of the load, within MTG's rating.

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