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Study of Microturbine Generator System using MATLAB

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Abstract : Microturbine generator systems are considered as distributed energy resources which are interfaced with the electric power distribution system. They are most suitable for small to medium-sized commercial and industrial loads. The microturbine provides input mechanical energy for the generator system, which is converted by the generator to electrical energy. Microturbines are a relatively new distributed generation technology being used for stationary energy generation applications. Because of their small size, relatively low capital costs, expected low operations and maintenance costs, and automatic electronic control, microturbines are expected to capture a significant share of the distributed generation market. In addition, microturbines offer an efficient and clean solution to direct mechanical drive markets such as compression and air-conditioning. MTG's are small, high speed power plants that usually include the turbine, compressor, generator and power electronics to deliver the power to the grid. Microturbines can be used for stand-by power, power quality and reliability, peak shaving, and cogeneration applications.

IndexTerms **- Micro turbine, harmonics, development, manufacturing, distributed generation.**

I. INTRODUCTION

Microturbine generator systems are considered as distributed energy resources which are interfaced with the electric power distribution system. They are most suitable for small to medium-sized commercial and industrial loads. The microturbine provides input mechanical energy for the generator system, which is converted by the generator to electrical energy. The generator nominal frequency is usually in the range of 1.4-4 kHz. This frequency is converted to the supply frequency of 50 Hz by a converter. The electrical energy, passing through the transformer, is delivered to the distribution system and the local load. A mathematical model of a microturbine generator system includes electromechanical sub-system, power electronic converter, filters, interface transformer, local load, distribution system, turbine-generator control and converter control. The prefix micro is commonly known to imply "small". Where the word "turbine", is defined as "a device that converts the flow of a fluid (air, steam, water, or hot gases) into mechanical motion for generating electricity". It should follow then that a Microturbine is simply a small device that converts fluid flow into mechanical motion for electric generation processes. Micro turbines can be defined as follows "Microturbines are small electricity generators that burn gaseous and liquid fuels to create high-speed rotation that turns an electrical generator with size ranges available from 30 to 400 kilowatts (kW)". Micro turbines are a relatively new distributed generation technology being used for stationary energy generation applications. They are a type of combustion turbine that produces both heat and electricity on a relatively small scale. Microturbines offer several potential advantages compared to other technologies for small-scale power generation, including: a small number of moving parts, compact size, lightweight, greater efficiency, lower emissions, lower electricity costs, and opportunities to utilize waste fuels. Waste heat recovery can also be used with these systems to achieve efficiencies greater than 80%. Because of their small size, relatively low capital costs, expected low operations and maintenance costs, and automatic electronic control, microturbines are expected to capture a significant share of the distributed generation market. In addition, microturbines offer an efficient and clean solution to direct mechanical drive markets such as compression and air-conditioning.

II. CLASSIFICATION OF MICROTURBINE

2.1 Un recuperated MTG:

In a simple cycle or un recuperated systems the compressed air is mixed with fuel and burned under constant pressure conditions. The resulting hot gas is allowed to expand through a turbine to perform work. Simple cycle MTGs have lower efficiency at around 15%, but also lower capital costs, higher reliability and more heat available for co-generation applications than recuperated units.

2.2 Recuperated MTG:

Recuperated units use a thin sheet-metal heat exchanger that recovers some of the heat from an exhaust stream (1,200ºF) and transfers it to the incoming air stream, boosting the temperature of the air stream (around 300ºF) supplied to the combustor. Further exhaust heat recovery can be used in a co-generation configuration. The fuel-energy to electrical conversion efficiencies are in the range of 20 to 30%. In addition, recuperated units can produce 30 to 40% fuel savings from preheating. Depending on the micro turbine operating parameters, recuperators can more than double machine efficiency.

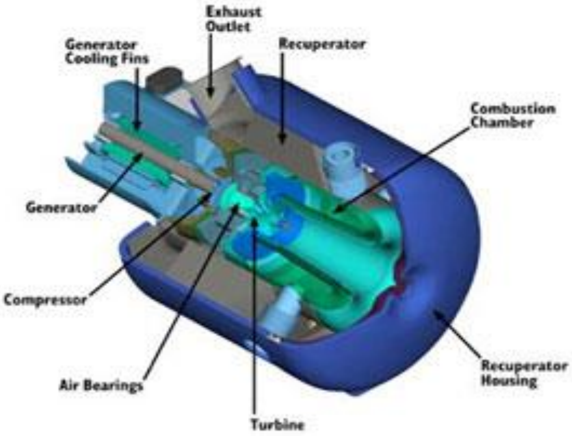

Fig.1. Recuperated Micro turbine

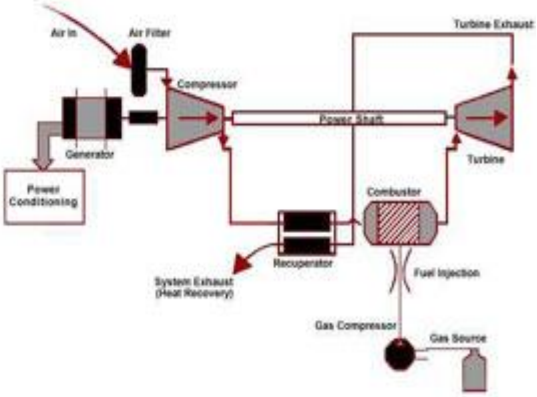

Fig.2. Recuperated Micro turbine System

III. TECHNICAL BACKGROUND

MTG's are small, high speed power plants that usually include the turbine, compressor, generator and power electronics to deliver the power to the grid. These small power plants typically operate on natural gas. Future units may have the potential to use lower energy fuels such as gas produced from landfill or digester gas. The generic MTG can be divided into three primary subsystems:

- **Mechanical**: including turbine, generator, compressor and recuperator.
- **Electrical**: including main control software, inverter and power firmware.
- **Fuel**: including fuel delivery and combustion chamber.

MTGs have a high-speed gas turbine engine driving an integral electrical generator that produces 20-100 kW power while operating at a high speed, generally in the range of 50,000-120,000 rpm. Electric power is produced in the 10,000s of Hz, converted to high voltage DC, and then inverted back to 60 Hz, 480 VAC by an inverter. Most of MTG engine designs typically have one or several power producing sections, which include the turbine, compressor, and generator on a single shaft. During engine operation, engine air is drawn into the unit and passes through the recuperator where temperature is increased by hot exhaust gas. The air flows into the combustor where it is mixed with fuel, ignited and burned. The igniter is used only during start up, and then the flame is self-sustaining. The combusted gas passes through the turbine nozzle and turbine wheel, converting thermal energy of the hot expanding gases to rotating mechanical energy of the turbine. The turbine drives the compressor and generator. The gas exhausting from the turbine is directed back through the recuperator, and then out the stack.

IV. CHARACTERISTICS OF MICRO TURBINES

Some of the primary characteristics for micro turbines include:

- **Distributed generation** — stand-alone, on- site applications remote from power grids.
- **Quality power and reliability**—reduced frequency variations, voltage transients, surges, dips, or other disruptions.
- **Stand-by power** — used in the event of an outage, as a back-up to the electric grid
- **Peak shaving**—the use of micro turbines during times when electric use and demand charges are high.
- **Boost power**—boost localized generation capacity and on more remote grids.
- **Low-cost energy**—the use of micro turbines as base load or primary power that is less expensive to produce locally than it is to purchase from the electric utility.
- **Combined heat and power (cogeneration)**—increases the efficiency of on-site power generation by using the waste heat for existing thermal process.

V. TYPICAL MICROTURBINE CONSTRUCTION

Microturbines are a simple form of gas turbine, usually featuring a radial compressor and turbine rotors and often using just one stage of each. They typically recover exhaust energy to preheat compressed inlet air, thereby increasing electrical efficiency compared with a simple-cycle machine. The air-to-air heat exchanger is termed a "recuperator," and the entire system is typically called a recuperated cycle.

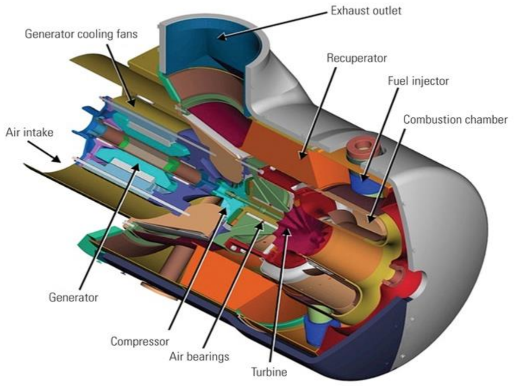

Fig.3. Cutaway View of a Capstone C65 Turbo generator

Figure 3 shows a cutaway view of a Capstone 65-kW micro turbine illustrating how these major components are arranged in a commercial product. The assembly is often called a "turbo generator," as it includes all the micro turbine components plus the generator. The single shaft of turbine, compressor, and generator rotates at high speed—96,000 rpm in the case of the Capstone C65 turbo generator. Generator output is therefore high-frequency AC, which must be conditioned using power electronics to provide a useable 50 or 60 Hertz electrical output. This cutaway view of a Capstone C65 turbo generator illustrates the arrangement of all the gas turbine components, including the generator. Ambient air is compressed in the compressor, fuel is burned in the combustor to raise the temperature of the compressed air, and the high-pressure hot gases expand through the radial turbine to produce shaft power for the generator. The recuperator recovers heat from the hot gases to heat the compressed air before entering the combustor to reduce the amount of fuel consumed, thereby increasing the thermal efficiency of the turbo generator system.

VI. WORKING OF A MICROTURBINE

Microturbines are small combustion turbines approximately the size of a refrigerator with outputs of 25 kW to 500 kW. They evolved from automotive and truck turbochargers, auxiliary power units (APUs) for airplanes, and small jet engines. Most microturbines are comprised of a compressor, combustor, turbine, alternator, recuperator (a device that captures waste heat to improve the efficiency of the compressor stage), and generator. The figure below illustrates how a microturbine works.

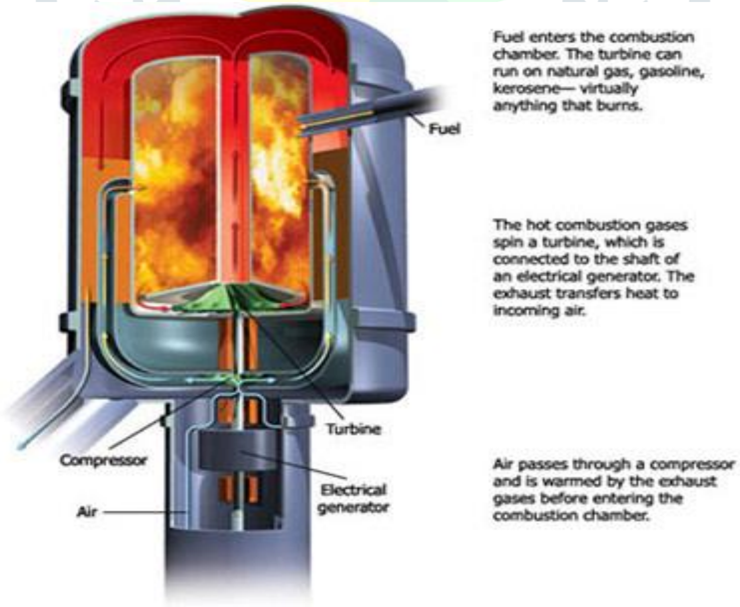

Fig.4. Working of A Microturbine

VII. MICROTURBINE SYSTEM COMPONENTS

In a microturbine, a radial flow (centrifugal) compressor compresses the inlet air that is then preheated in the recuperator using heat from the turbine exhaust. Next, the heated air from the recuperator mixes with fuel in the combustor and hot combustion gas expands through the expansion and power turbines. The expansion turbine turns the compressor and, in single shaft models, turns the generator as well. Two-shaft models use the compressor drive turbine's exhaust to power a second turbine that drives the generator. Finally, the recuperator uses the exhaust of the power turbine to preheat the air from the compressor. Single-shaft models generally operate at speeds over 60,000 revolutions per minute (rpm) and generate electrical power of high frequency, and of variable frequency. This power is rectified to direct current (DC) and then inverted to 50 or 60 hertz (Hz) for commercial use.

7.1. Turbo Compressor:

The basic components of a microturbine are the compressor, turbine generator, and recuperator. The heart of the microturbine is the compressor-turbine package, which is commonly mounted on a single shaft along with the electric generator. Two bearings support the single shaft. The single moving part of the one-shaft design has the potential for reducing maintenance needs and enhancing overall reliability. In microturbines, the turbocompressor shaft generally turns at high rotational speed, about 96,000 rpm in the case of a 30 kW machine and about 80,000 rpm in a 75 kW machine. One 45 kW model on the market turns at 116,000 rpm. There is no single rotational speed power size rule, as the specific turbine and compressor design characteristics strongly influence the physical size of components and consequently rotational speed. For a specific aerodynamic design, as the power rating decreases, the shaft speed increases, hence the high shaft speed of the small microturbines. Recuperators are heat exchangers that use the hot turbine exhaust gas (typically around 1,200ºF) to preheat the compressed air (typically around 300ºF) going into the combustor, thereby reducing the fuel needed to heat the compressed air to turbine inlet temperature. Depending on microturbine operating parameters, recuperators can more than double machine efficiency. The controllers of the gas turbine implements three major control loops: start up, speed and temperature. For the purpose of these modelling tests, the speed control, receives the most attention. The reason for this is that during start up, the unit is not on-line, and in temperature control mode, the governor will not respond to system frequency changes. The primary valve demand control signal is selected by a low value select gate from the outputs of these control loops.

7.2. Generator:

The microturbine produces electrical power via a high speed generator turning on the single turbo-compressor shaft. The high-speed generator of the single-shaft design employs a permanent magnet (typically Samarium- Cobalt) alternator, and requires that the high frequency AC output (about 1,600 Hz for a 30 kW machine) be converted to 50 or 60 Hz for general use. This power conditioning involves rectifying the high frequency AC to DC, and then inverting the DC to 50 or 60 Hz AC. Power conversion comes with an efficiency penalty (approximately five percent).

7.3. Power Conditioning Unit:

Single-shaft microturbines feature digital power controllers to convert the high frequency AC power produced by the generator into usable electricity. The high frequency AC is rectified to DC, inverted back to 60 or 50 Hz AC, and then filtered to reduce harmonic distortion. This is a critical component in the single-shaft microturbine design and represents significant design challenges, specifically in matching turbine output to the required load. To allow for transients and voltage spikes, power electronics designs are generally able to handle seven times the nominal voltage. Most microturbine power electronics are generating three phase electricity.

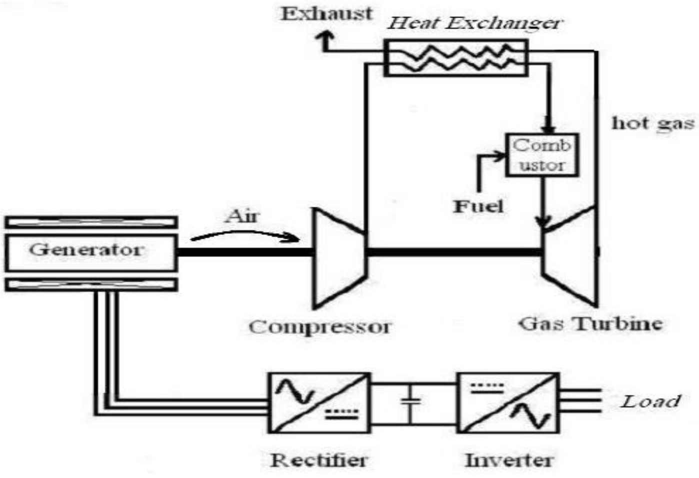

Fig.5. Microturbine Generation System

VIII. MICROTURBINE GENERATION SYSTEM

Microturbine unit (MTU) is well suitable for a different distributed generation application, because the MTU is flexible in connection method, can be stacked in parallel to serve larger loads, can provide reliable power and has low-emissions profile. The potential applications of the MTU configuration include peak shaving, premium power, remote power, and grid support. In locations where power from the local grid is unavailable or extremely expensive to install, or the customer is far from the distribution system the MTU can be a competitive option. In this case, MTU is operated in off-grid mode. In the growing distribution system, the MTU can be a grid support. In this case, MTU is in on grid mode. Accurate modelling is necessary to study MT units operation and impact on distribution system. A microturbine based DG system can generate electric power in the range of 25 to 500 kW. They are designed so that 2 to 20 units can easily be stacked in parallel, to generate multiple of rated power.

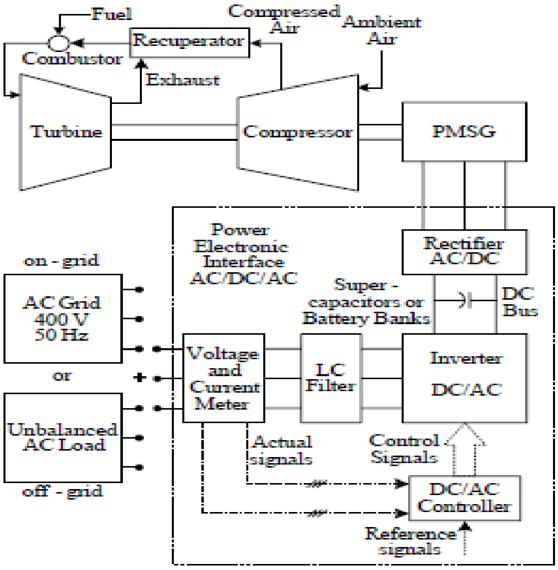

Fig.6. Schematic Diagram of Microturbine Unit

The MTU components are: single-shaft turbine with its control system, high speed permanent magnet generator, power electronic interfacing (rectifier and voltage source inverter) and control system for power electronic interface. The DC bus, shown in Fig. 1, is assumed to be lossless. Microturbine operates in the thermodynamic cycle, known as the Brayton cycle. The produced rotating mechanical power in the turbine turns both compressor and generator. The high speed generator of the single shaft design is a permanent magnet synchronous generator (PMSG). This generator requires that the high frequency (about 1.6 kHz) AC output be rectified to DC for use in the DC grid, inverted back to 50 (or 60) Hz AC for use in the AC grid. Power electronic interface in the single shaft microturbine is a critical component. Microturbine is generally equipped with controls that allow the unit to be operated either in parallel with, or independent of the grid.

IX. MICROTURBINE SYSTEM MODELLING

The model describes the dynamics of this device when used as distributed generation source. The model is suitable for transient simulation and analysis and the final model can be used in a distribution network to study the effect of microturbine system on the distribution network stability and the effect of network transients on the microturbine stability. In order to model a microturbine system, four major parts are considered: high speed gas turbine, high speed permanent magnet generator, power conditioning unit which itself consist of a rectifier and an inverter and the final part is load connected to microturbine terminal. The model is consisting of the dynamics of each part and their interconnections.

Here's a simplified example of how to model a microturbine system using MATLAB. This example focuses on a basic steady-state model:

```
% Parameters
efficiency_turbine = 0.8; % Turbine efficiency
efficiency_generator = 0.9; % Generator efficiency
fuel_heat_value = 45e6; % Heat value of the fuel (J/kg)
air_density = 1.2; % Air density (kg/m^3)
ambient_temperature = 298; % Ambient temperature (K)
compressor_efficiency = 0.85; % Compressor efficiency
turbine_inlet_temperature = 1200; % Turbine inlet temperature (K)
turbine_inlet_pressure = 1.0e5; % Turbine inlet pressure (Pa)
fuel_flow_rate = 0.01; % Fuel flow rate (kg/s)

% Calculate air mass flow rate
air_mass_flow_rate = fuel_flow_rate * fuel_heat_value / (efficiency_turbine *
turbine_inlet_temperature - ambient_temperature);

% Calculate compressor power
compressor_power = air_mass_flow_rate * (turbine_inlet_temperature -
ambient_temperature) / (compressor_efficiency * efficiency_generator);

% Calculate turbine power
turbine_power = fuel_flow_rate * fuel_heat_value * efficiency_turbine;

% Calculate net power output
net_power_output = turbine_power * efficiency_generator - compressor_power;
```

```
% Display results
fprintf('Compressor Power: %.2f kW\n', compressor_power / 1000);
fprintf('Turbine Power: %.2f kW\n', turbine_power / 1000);
fprintf('Net Power Output: %.2f kW\n', net_power_output / 1000);
```

This MATLAB code calculates the compressor power, turbine power, and net power output of a microturbine system based on given parameters.

Below is an example of a basic dynamic model of a microturbine system using MATLAB's Simulink. This model includes a simplified representation of the turbine, compressor, generator, and control system.

```
% Define parameters
R = 287; % Gas constant for air (J/kg*K)
cp = 1005; % Specific heat capacity of air at constant pressure (J/kg*K)
ambient_temp = 298; % Ambient temperature (K)
ambient_pressure = 1.013e5; % Ambient pressure (Pa)
turbine_efficiency = 0.8; % Turbine efficiency
compressor_efficiency = 0.85; % Compressor efficiency
generator_efficiency = 0.9; % Generator efficiency
fuel_heat_value = 45e6; % Heat value of fuel (J/kg)
fuel_flow_rate = 0.01; % Fuel flow rate (kg/s)

% Define simulation time
t_end = 100; % Simulation time (s)

% Simulate the dynamic model
sim('microturbine_system');

% Plot results
figure;
subplot(3,1,1);
plot(time, turbine_speed);
xlabel('Time (s)');
ylabel('Turbine Speed (rpm)');
title('Turbine Speed vs Time');

subplot(3,1,2);
plot(time, compressor_speed);
xlabel('Time (s)');
ylabel('Compressor Speed (rpm)');
title('Compressor Speed vs Time');

subplot(3,1,3);
plot(time, generator_power);
xlabel('Time (s)');
ylabel('Generator Power (W)');
title('Generator Power vs Time');
```

And the Simulink model (`microturbine_system.slx`):

In this Simulink model:

- The "Turbine Model" block represents the turbine dynamics.
- The "Compressor Model" block represents the compressor dynamics.
- The "Generator Model" block represents the generator dynamics.
- The "Control System" block adjusts the fuel flow rate based on the desired power output.

9.1. Gas Turbine Model

According to the thermal process in gas turbine system different models are presented for prediction of gas turbine systems behavior. A model for gas turbine which is suitable for dynamic analysis is employed. Also three control loops have been considered and the systems modeled including these three control systems.

A-1) Speed Control

The governor controls can be modified to droop or isochronous governor by adjusting the given parameters W,X,Y and Z.

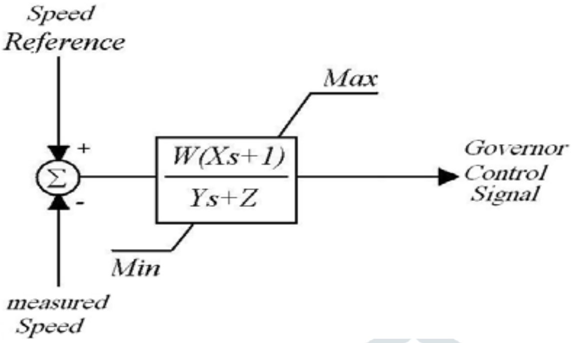

Fig.7. Speed Control Block Diagram

The speed governor control block diagram shows, the activation signal for speed governor is the comparison of reference per unit signal and the measured speed signal from the synchronous PM machine block.

A-2) Temperature Control

Another control loop that is considered is a temperature control system. The measured exhaust temperature TE is compared with the reference value TR and the error act the temperature controller. Normally, the signal resulted from comparison of the reference signal and thermocouple signal is positive, which makes temperature on the maximum limit, permitting an uninhibited governor or speed control. When the thermocouple output exceeds the reference temperature, the output would be negative and it starts lowering the temperature control.

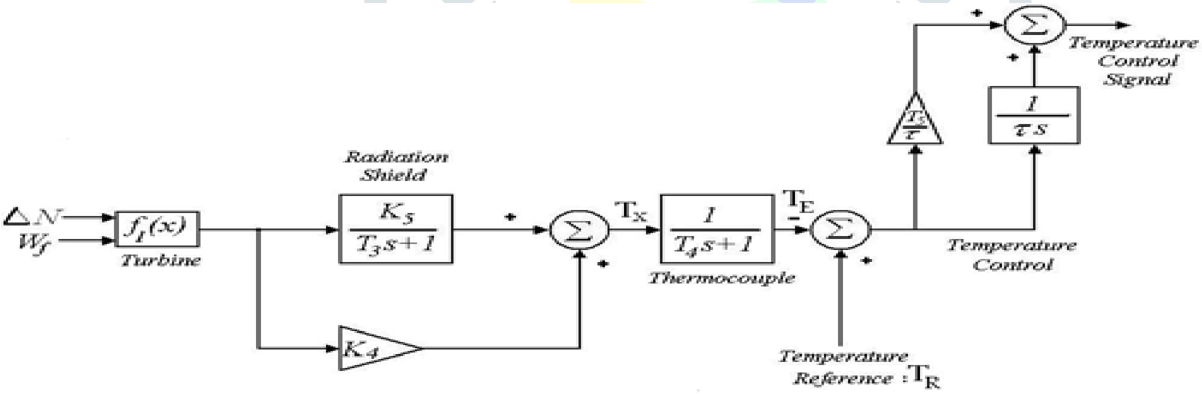

Fig.8. Temperature Control Block Diagram

A-3) Fuel Control

The input signals to the fuel control are the fuel demand signal from speed control, the temperature control signal from the gas turbine and the acceleration control signal. The output signal is the fuel flow WF. The output of three control systems are go through a low value select block that the lowest input of this block wins and act as an output. According to this signal the demand signal for fuel, Vce is generated. This per unit value, Vce correspond directly to the per unit value of mechanical power on turbine base in the steady state. The Vce signal goes through, scaled by a gain K3. This signal is again offset by K6, which is the fuel flow at a no load, rated speed condition. The fuel flow is burned in the combustor.

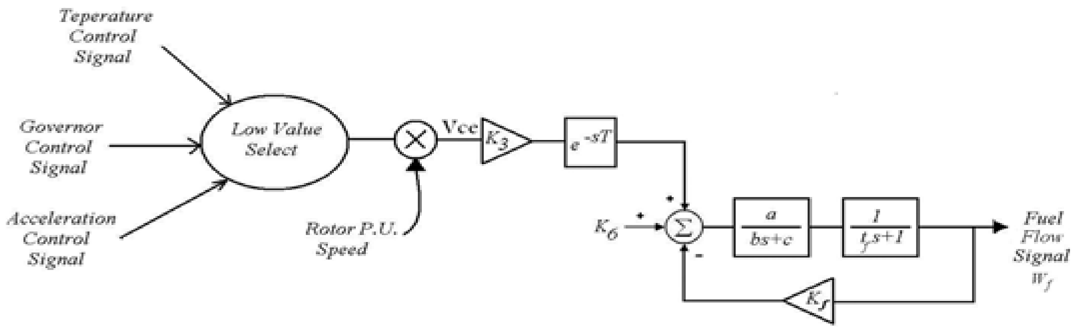

Fig.9. Fuel Control Block Diagram

9.2. Permanent Magnet Generator

The electric power is generated in a high speed permanent magnet synchronous generator, which is integrated with the micro turbine. These generators are used as means to generate AC power in variable speed wind/micro turbines and flywheel type electromechanical energy conversion systems. Permanent magnets have supplied excitation in alternator application for many years. Essentially, a PM synchronous alternator is similar in configuration to a conventional synchronous alternator with the electrical excitation system replaced by permanent magnets. There are several benefits of this arrangement, including the elimination of the brush/slip ring systems. The rotor is suspended by one bearing on each side of the permanent magnet rotor and there are no additional bearings on the turbine shaft, The output frequency of the generator is high – up to 2,4 kHz. The generator also acts as an electric starter for the gas turbine to bring the CHP unit into operation.

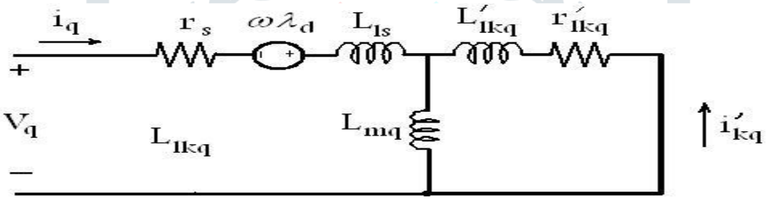

Fig.10. q-axis Circuit

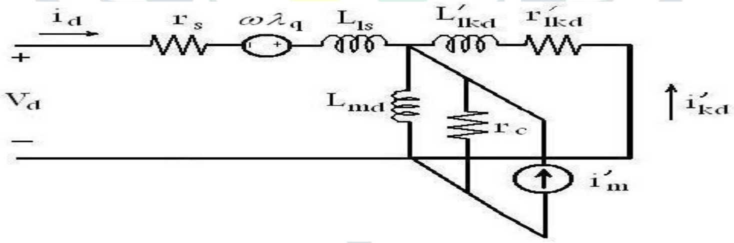

Fig.11. d-axis Circuit

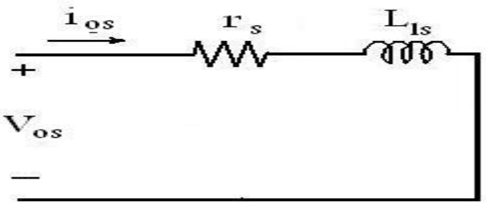

Fig.12. Zero Sequence Circuit

In this circuit the damper cage winding is appeared but no field winding can be obtained because of replacement of magnets in rotor. For modeling purpose the permanent magnet inductance L_{rc}, that is associated with its recoil slope, can be lumped with the common d-axis mutual inductance denoted still by L_{md}. The current, i_m , is the equivalent magnetizing current of the permanent magnets, referred to the stator side. According to this circuit the mutual flux linkages in terms of the total flux linkages of the windings are:

$$\psi_{mq} = x_{MQ} \left(\frac{\psi_q}{x_{ls}} + \frac{\psi'_{kq}}{x'_{lkq}} \right) \qquad (1)$$

$$\psi_{md} = x_{MD} \left(\frac{\psi_d}{x_{ls}} + \frac{\psi'_{kd}}{x'_{lkd}} + i'_m \right) \qquad (2)$$

where

$$\frac{1}{x_{MQ}} = \frac{1}{x_{mq}} + \frac{1}{x'_{lkq}} + \frac{1}{x_{ls}} \qquad (3)$$

$$\frac{1}{x_{MD}} = \frac{1}{x_{md}} + \frac{1}{x'_{lkd}} + \frac{1}{x_{ls}} \qquad (4)$$

9.3. Power Conditioning Unit

This unit consists of a three-phase diode rectifier and a DC-AC power inverter. 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. Different methods may be employed in order to model and simulate the diode rectifier but here a model is employed that is used to represent diode rectifier as part of electric power conditioning unit. In this method the modeling process is done with the help of three Heaviside functions. These Heaviside functions determine if the diode is conducting or in blocking state. The functions g_k (k=1,2,3) are defined as shown in figure 13 in this figure i_k is ac line currents.

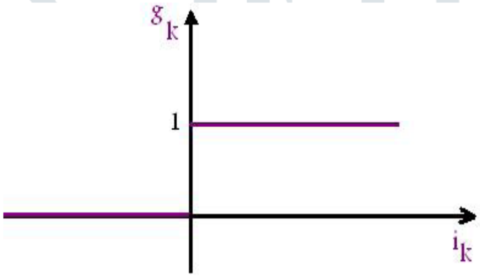

Fig.13. Definition of g_k Function

X. MACHINE PERFORMANCE TEST CRITERIA

10.1. Endurance

For the test program, MTGs will be operated for as long as practicable at nominal load. Daily operating parameters: fuel flow, ambient air pressure, temperature and humidity, energy (kWh), operating temperatures and pressures will be recorded. Critical MTG parameters will be recorded with the intent of correlating degradation with factors other than wear and tear.

10.2. Transient Response

MTGs should be able to respond adequately to load changes. Units that are not capable of isolated bus operation will operate in parallel with the system grid. Changes in system load will be picked up by the grid and not by MTG units. Load changes on these MTG units will be accomplished by manually setting load using the control system.

10.3. Harmonic Distortion

The power output will be measured with a BMI or equivalent recorder, which will measure total harmonic distortion (THD). The BMI will also be used to determine the power factor of the fully loaded unit during the endurance test.

10.4. Noise Measurement

Ambient noise levels will be measured using a handheld noise meter. Each unit will be operated independently to acquire the noise measurements during operations.

10.5 Emissions Measurement

For each MTG type tested, one certified test will be conducted to determine compliance with South Coast Air Quality Management District Rule 2005 for NO_x emissions. Additionally, periodic measurements with available handheld equipment would be made to determine trends and any condition of degradation that may occur with operating hours.

10.6. Peak Load Gross and Net

Peak load gross and net measurements will be taken with a BMI meter or equivalent recorder that measures power. For units without compressors, or compressors that are externally powered, the net output must be determined by subtracting the external power requirements to sustain MTG operation. Results of this test will yield performance characteristics such as efficiency, heat rate, fuel consumption and operating hours.

XI. CONCLUSION

Microturbines can operate continuously or on-demand and be either grid connected or stand alone. They can run individually or multi-packed and with a variety of fuels: Diesel, Propane, Kerosene, Flare Gas, Biogas, Low- or High-Pressure Natural Gas, among others. Other applications can be combined heat and power (CHP) and micro grid. Microturbines are targeted to telecommunication companies, retail services, financial services, financial services, office buildings, restaurants and other commercial services. Microturbines also operate in resource recovery operations like oil and gas production fields. “Reliable operation is important since these locations may be remote from the grid, and even when served by the grid, may experience costly downtime when electric service is lost due to weather, fire or animals.”

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