Modeling and Performance Analysis of Microturbine Generation System in Grid Connected/Islanding Operation

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Abstract- Distributed generation (DG) has drawn a great attention in distribution network due to reduction in transmission loss, load sharing property and improving the power quality. Among the different source of DG, the microturbine generation (MTG) system has a good record of improving the system stability, reliability and power quality. This paper presents modeling and performance analysis of MTG system in grid connected and islanding modes of operation. The model developed in this work includes the individual components of prime mover like, compressor, heat exchanger, burner and turbine. The model of MTG system consists of microturbine, permanent magnet synchronous machine (PMSM) and power electronics interfacing circuit for generation and conversation from AC/DC/AC respectively. The MTG system uses a DC link voltage to control the microturbine output power by fuel and air flow control methodology. The DC link power is delivered to the load through a voltage source inverter (VSI) with pulse width modulation (PWM) technique. The model of MTG system has been implemented using Matlab/Simulink environment and its simulation result shows the load following performance of MTG system for various loads.

Keywords- Distributed generation, Microturbine, Permanent Magnet Synchronous Machine, Power Interfacing Circuit.

1. Introduction

Distributed generation (DG) refers to a small scale generation, mainly between 1kW and 50MW electrical power generators that produce electricity at a site close to the customer or they tied to an electric distribution system. DG enables the rural electrification, industry to reduce the traditional cost of service by skillfully integrated system. In addition to that, DG enables the utilities to expand their service to include providing a base load power, thermal energy and value added energy services [1]. The small scale DG system based on microturbine technology are gaining popularity among the power industries and utilities in the last few years due to their several advantages as reported in[2]. The MTG system can generate a power in the range of 25kW to 500kW and can be operated in stand alone, mobile, remote or interconnected with fuel utility applications. The MTG system generated power can be used in the wide range of applications. Some of the application are base load power, peak power saving, combined heat and power etc. The MTG system is a new and fast growing technology and becoming a business and likely to become a dominate source of DG in the future power supply network. Thus, the dynamic modeling and system planning interconnected operation and management are essential. Hence to ensure safe operation and security of system MTG system must be seriously taken into consideration. There are several models and simulation of a MTG system in grid connected as well as isolated modes of operation has been reported in [3-10]. The modeling and simulation of MTG system for isolated and grid connected operation has been reported in [3]. In this, The MTG system uses a PMSM and power electronics interface for generation and delivering the power to load respectively. Also, the microturbine uses a reference speed and shaft speed to control the MTG system output power. The modeling of existence microturbine and advanced controls for both grid connected and isolated mode of operating has been developed in [4]. The model developed in [4] uses an active rectifier to control the DC link voltage. In this, active reactive power (PQ) control inverter for grid connected operation and voltage, frequency (V/F) control for isolated operation.

The development and simulation of microturbine model to analyze the load following performance with general as well as critical priority for the load is performed in [5]. In this, the two models of microturbine are considered, one is to operating under normal condition (neglecting fast dynamic) and other is based on standard GAST model. The model developed in [5] uses a synchronous generator (SG) and field excitation control to maintain the constant voltage. The detailed models of the components and control forming the thermo mechanical and electrical subsystems of microturbine power plant are reported in [6]. The model developed in [6] includes different control loops are developed for various control system. The model of MTG system in grid connected and islanding operation has been reported in [7]. In this, the model uses a DC link voltage to control MTG system output power. The dynamic model of MTG system in grid connected and islanding operation has been given in [8]. In this, the MTG system takes power from the grid to start the MTG system, and bring to ignition speed. Once the MTG system reaches to ignition speed it supplies the power back to grid using a bidirectional power flow control has been reported in [8]. The MTG system used to assist the transient stability in connected to the grid via two paths control of mechanical power and terminal voltage using static var compensator (SVC) and genetic algorithm are given in [9]. In this, two microturbine generations are connected to the grid and uncontrolled system simulation results shows unstable system where MTG oscillates between generation and motoring modes. The mathematical model which includes microturbine, PMSM, a three phase bridge rectifier, boost converter and inverter are developed using PSCAD/EMTDC in [10, 11]. The model developed in [10], is suitable for transient study and analysis for islanded mode of the microgrid as well as grid connected operation. In [11], the designed MTG system with control system is capable of regulating its output power in grid connected mode. Also, the designed MTG system is suitable for isolated operation and power electronics controller is used to maintain the constant output voltage at prescribed limit.

In this paper, the modeling and performance analysis of MTG system in grid connected and isolated mode of operation has been studied. The developed model uses a DC link voltage to control the MTG system output power. This DC link controlled MTG system can maintains a constant DC voltage which acts as an infinite source for the inverter operation. The model developed for this study has been implemented in Matlab/Simulink environment and simulation result shows the load following performance MTG system.

2. Microturbine Generation(MTG) System

The MTG system includes microturbine as a prime mover, generator and power electronics interfacing circuit to deliver power to the load. Figure.1 shows the schematic of MTG system in grid connected operation.

2.1. Microturbine

Microturbines are the evolution of gas turbine technology with small in size, low inertia and high speed of rotation. The power generation capacity of microturbine varies between 25 to 300kW and the rotational speed varies between 50,000 and 90,000 rpm with air foil bearings and interfaced to load through power electronics. Basically there are two types of microturbine, one is a high speed single shaft design with the compressor and turbine are mounted on the same shaft usually a permanent magnet synchronous machine is used to generate the electrical power. The generator generates a power at high frequency between 1.5 kHz to 4 kHz. The high frequency voltage is rectified and then inverted back to 60Hz power using a suitable power electronics circuit. Another is split shaft design that uses a power turbine rotation between 3600 rpm and conventional generator (usually induction generator or synchronous generator) connected via a gearbox. The power electronics interface in not required for this design. The turbine will be controlled by the gear transmission along with acceleration control, fuel flow control and temperature control [3, 8].

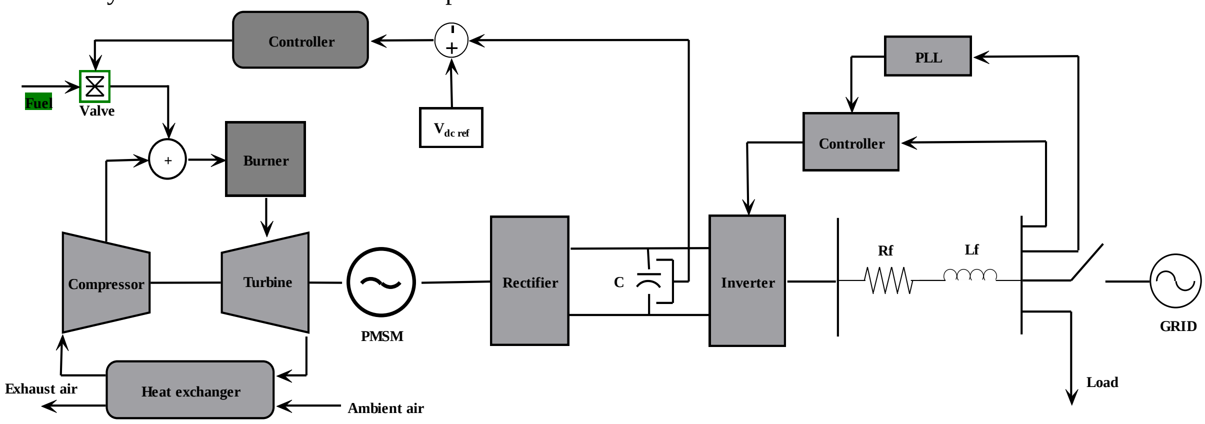


Fig. 1. Microturbine generation (MTG) system

The model developed for this sturdy consist of each component of microturbine connected to their inputs and output to MTG system connected to isolated and grid connected mode.

The mechanical power required driving the compressor for air pressurize[12] can be calculated with mathematical equation,

$$P_c = \frac{1}{\eta_{th,c}} m'_c\, C_p \left[PR_c^{\left(\frac{\gamma-1}{\gamma}\right)} - 1 \right] T_{in\_c} \tag{1}$$

Where, T_{in_c} is the input temperature (K),

PR_c is the pressure ratio of compressor,

m'_c is the mass flow rate of compressor(g/s).

γ is the specific heat ratio of air,

$\eta_{th,c}$ is the thermal efficiency of compressor

C_p is the specific heat ratio of air ($KJ/kg,K$)

m'_c mass flow of compressor(g/s).

The combustion chamber is normally involves heat production and increasing the air pressure by burning a fuel. The combustor used in this work burns the (un-used) waste fuel of SOFC with addition of fresh fuel to increase the pressure further. The energy balance equation of combustion process can be written as first order equation where the last term is the heat transfer to the ambient [12].

$$\frac{dT_b}{dT} = \frac{1}{C_b m_b}\left(\sum N_r \left(h^o{}_f + h(T) - h^o\right)_r - \sum N_p \left(h^o{}_f + h(T) h^o\right)_p - A_x h_x (T_b - T_{amb}) \right) \tag{2}$$

Where, N_r is a molar flow rate of reactant,

N_p is the molar flow rate of the output of product, $h^o(T)$ is the sensible enthalpy which is a function of temperature of function and can be defined experimentally. The mechanical power produced by the turbine can be calculated using the equation [12].

$$P_t = \left\{ \eta_t \left[1 - PR_t^{\left(\frac{\gamma-1}{\gamma}\right)} \right] T_b \sum \left(N_p C_p (T_b) m_p \right) \right\} \tag{3}$$

Where, T_b is the turbine temperature (K), PR_t is the turbine pressure ratio of turbine, C_p is the specific heat of produced in the burner which is a function of temperature ($KJ/kg.K$), m_p is the mass flow rate of the product(g/s).

The shaft mechanical power is the difference of the power required to drive compressor and turbine power. The equivalent shaft mechanical power is converted to torque to drive the PMSM are expressed as,

$$P_{mt} = P_t - P_c \tag{4}$$

$$T_{mt} = \frac{P_{mt}}{\omega} \quad \text{.......(5)}$$

Where, P_c is compressor mechanical power (W),

P_t is generated mechanical power of turbine (W),

P_{mt} is the mechanical power of microturbine (W),

T_{mt} is the mechanical torque of microturbine (Nm),

ω is the speed of microturbine(rad/s).

2.2. Permanent Magnet Synchronous Machine

The microturbine generates electrical power via a high speed PMSG, directly driven by the turbine rotor shaft. In this work, the model adopted for the generator is a 2 pole permanent magnet synchronous generator (PMSG) with non-salient rotor. At 1.6 kHz (61,000 rpm), the rated output power generated by the machine is 60kW and its terminal line to line voltage is 550V. The equivalent circuit of PMSM without considering the iron loss is shown in Figure 2. The model assumes that the flux established by the permanent magnet in the stator is sinusoidal, which implies that electromotive forces are sinusoidal. The following equation expresses in the rotor reference frame (dq frame) are used to implement PMSM [13].

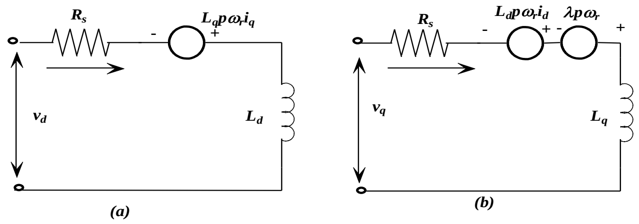


Fig. 2. d q-axis equivalent circuit of PMSM

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - L_q p\omega_r i_q \tag{6}$$

$$v_q = R_s i_q + L_q \frac{di_d}{dt} + L_d p\omega_r i_d + \lambda p\omega_r \tag{7}$$

$$T_e = \frac{3}{2} p\left[\lambda i_q + \left(L_d - L_q\right) i_d i_q\right] \tag{8}$$

Where, L_q, L_d are the q and d axis inductance (H),

R_s is a stator resistance (Ω),
i_q, i_d are q and d axis current(A),
v_d *and* v_q are d and q axis voltage(V),
p *is* the number of poles,
T_e is electromagnetic torque (Nm),
λ is the flux linkage of PM reference to stator(wb).

Table 1. PMSM Parameter

Parameters	Values
Rated output power	60kW
Rated voltage	550Vrms
Rated current	63Amps
Rated speed	61,000rpm
Number of poles	2
Stator resistance	0.0201ohm
Ld and Lq Inductance	258.2μH
Stator flux linkage	0.077685Wb
Rotor	0.848595e-3kg/m^2

3. MTG System Control

The control system plays an important role for the reliable operation MTG system under all circumstances, it must be able to respond and function properly for any change in the external system. In the developed model of MTG system there are two possible controllers. One is fuel flow controller and another is air flow controller for the microturbine. When the demand power changes, it will changes the microturbine output power by controlling the fuel and air flow. As the DC link voltage changes, it will change the fuel and air flow correspondingly. Because of this reason, DC link voltage is used to control the fuel and air flow, the control system used for MTG system is shown in Figure 3. The control system implemented in Matlab/Simulink can maintain the constant DC link voltage by fuel and air flow control for the burner of microturbine [7].

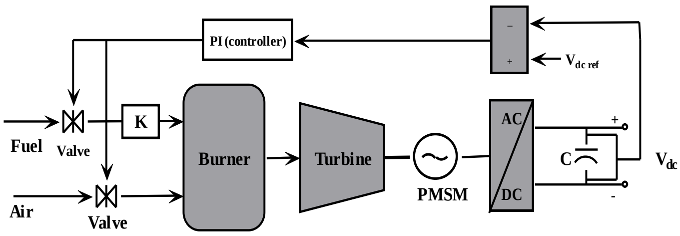


Fig. 3. Block diagram of MTG system controller

4. Power Electronics Interface

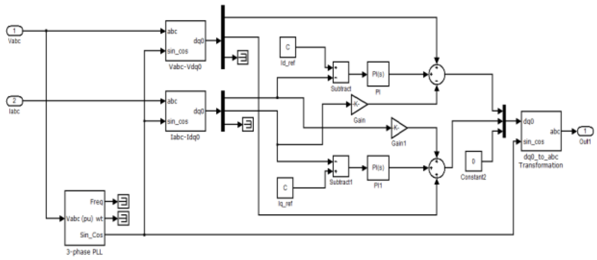
The power electronics interfacing is a critical component for the single shaft MTG system and its design represents significant challenge, specially in matching MTG system output power to utility power. There are different configurations available to interface the MTG system output power connected to utility. One possible is to use a three phase diode rectifier and voltage source invert with filter. This type of conversion requires a separate start-up arrangement for the microturbine. The configuration used for this work is assumed to be brought to rated speed(start-up and shut-down arrangement are not considered) for the isolated mode of operation and bidirectional power converter has been used for the grid connected mode of operation [8].

5. Grid Connected Mode

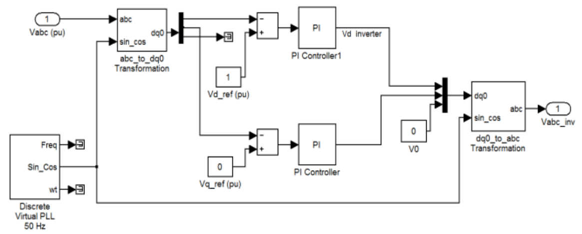
The control structure for grid connected MTG system implemented in Matlab/Simulink is shown in Figure 4(a). The grid side converter operates as a controlled power source and standard PI controller are used to regulate the grid current in the *dq* synchronous frame in the inner control loops. The converter does not take an account to maintain DC link voltage constant by regulating i_d and i_q. The i_d represents the active power component injected current into the grid and i_q is reactive component. In this work i_d and i_q reference values are given and they will fallowed by the actual values by the hybrid DG system. In order to obtain only a transfer of active power only a transfer of active power, the i_q current reference is set to zero. The decoupling terms are used to obtain independent control of i_d and i_q. A PLL is used to synchronize the converter with the grid frequency. The philosophy of the PLL is that, the difference between the grid phase and inverter phase angel can be reduced to zero using PI controller and locking the line side inverter phase to grid [8].

6. Isolated mode

For the isolated mode of operation of MTG system, the power conditioning unit consists of a three phase diode rectifier and a voltage source inverter (VSI) with LC filter are used. The control system for a voltage source inverter implemented using Matlab/simulink is shown in Figure 4 (b). A 1.66 kHz, voltage source feeds a 60Hz, 50kW load through an AC/DC/AC converter. The high frequency AC power is first rectified by six pulse diode bridge rectifier and filtered. A DC link voltage is given to an IGBT two level inverter generating 60Hz. The IGBT inverter uses Pulse Width Modulation (PWM) with 2kHz carrier frequency. The voltage is regulated at 1p .u. (480 V_{rms}) by a PI voltage regulator using *abc* to *dq* and *dq* to *abc* transformation. The conventional converter regulates the output voltage by a vector containing the three modulation signals used by the PWM generator to generate six IGBT pulses [8]. In this work the output voltage is regulated by the MTG system.



(a)

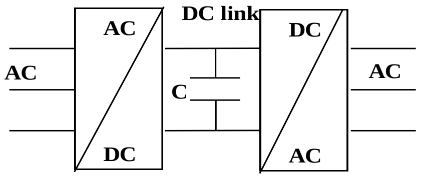


(b)

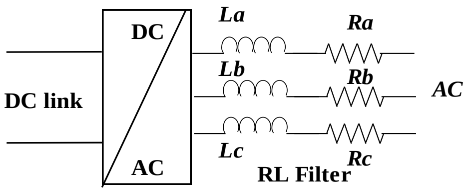
Fig. 4. (a). Line side converter control, grid connected, (b). Converter control, isolated mode

7. DC link capacitor

A DC link capacitor is used to maintain the constant DC voltage due to sudden load change. The sudden dip in DC link voltage may trip the inverter operation. The calculation for size of the DC link capacitor for active filter is based on controlling the voltage change of DC link as shown in Figure .5 (a). It is assumed that, the active filter is providing compensation at the fundamental line frequency for displacement factor correction, then capacitor is charged and discharged twice per line cycle and the charging and discharging time are even. Based on changing and discharging balance [14], the following equation is used to determine the capacitance value for DC link capacitor.



(a)



(b)

Fig. 5 (a). DC link capacitor, (b). RL filter

$$C_d = \frac{I_{f,rms}\Delta t}{\Delta V_d} = \frac{I_{f,rms}}{4f\Delta V_d} \tag{9}$$

Where, $I_{f,rms}$ the filter *rms* current(*A*), *f* is the fundamental frequency(*Hz*), V_d is the DC link voltage (*V*).

The relation between the DC link voltage and load voltage can be calculated using the equation,

$$V_{dc} = \sqrt{2/3} \times 2 \times V_{Load} \tag{10}$$

Where, V_{dc} is the DC link voltage (*V*).

V_{Load} is the load voltage (*V*).

8. Filter

Normally LC filter are used for inverter power supply in a grid connected mode, however it has some unique requirement that an LC filter may not sufficient. The purpose of the inductor filter is to filter the switching component out of the currents of the inverter/active filter [14] as shown in Figure 5 (b). The inductor filter size is designed to limit the ripple current at switching frequency, and DC link voltage for line to line output voltage can be calculated by,

$$Lf = \frac{V_{dc} - V_{ab_{pk}}}{f_s \times \Delta i} \tag{11}$$

Where, V_{dc} is the DC link voltage (*V*)

V_{ab_pk} is the peak voltage value(*V*)

Δi is the rate of change of current (*A*)

Fs is the switching frequency (*Hz*)

9. Simulation Results

The model of microturbine used in this work has been implemented using Matlab/Simulink as shown in Figure 6. This developed model of microturbine is used for a MTG system is shown in Figure 7. The microturbine includes compressor, heat exchanger, burner and turbines which are mechanical components used a prime mover of generator. The distribution network is considered as three phase balance sinusoidal voltage source with 480Vrms and 60Hz. The resistive load of 50kW is considered for the isolated mode study. It is assumed that, the turbine is brought to a rated speed and running at steady state (ex, start up and shunt down of MTG system is ignored). The performance of the developed model is studied in both grid connected and isolated operation.

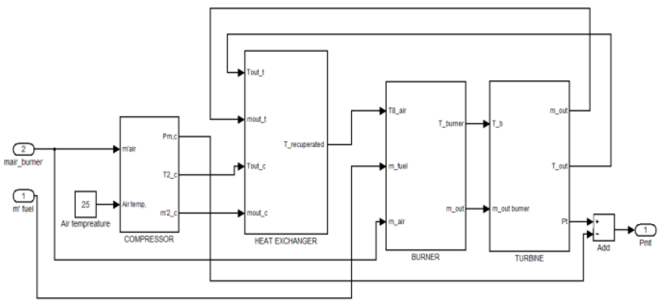


Fig. 6. Matlab/Simulink model of microturbine

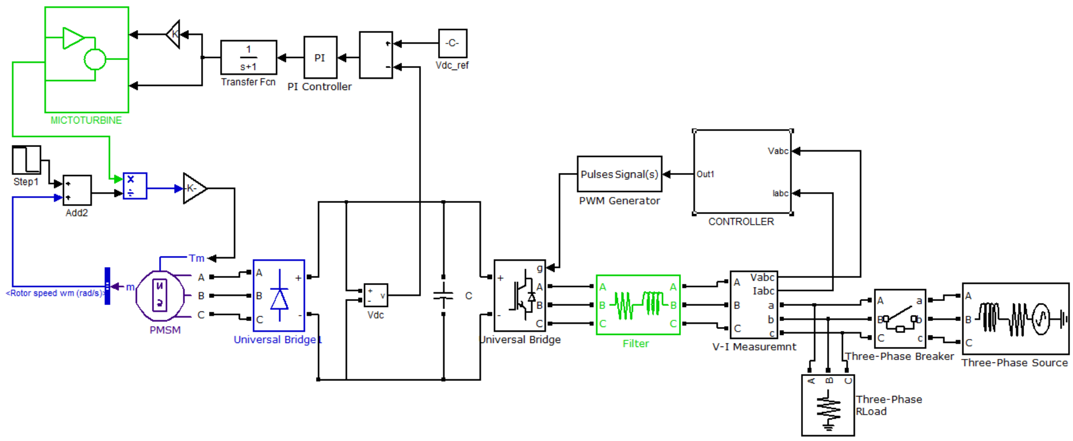


Fig. 7. Matlab/Simulink model of MTG system in connected grid/Islanding

10. Grid Connected Mode

During the grid connected mode the MTG system is sharing the load power is ascertained by the I_d and I_q values. The variation of DC link voltage and current are shown in Figure 8. From the Figure 8. It is observed that, the DC link voltage remains constant even if the current varies. The variable power is shared by MTG system by controlling fuel and air flow to the burner. Thus, the variation of power and additional power supplied by the MTG system is shown in Figure 9. The active and reactive powers are the most important parameters of the DG system for load sharing and power flow.

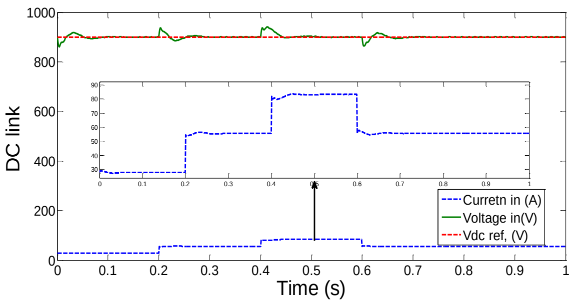


Fig. 8. DC link voltage and current

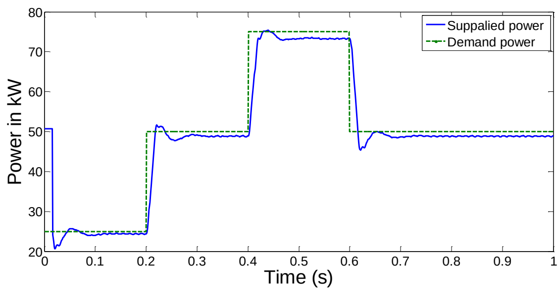


Fig. 9. Demand and turbine power

The model of MTG system uses a PMSM, hence the system is made to supply only the active power, not to supply the reactive power. Thus, the variation of active and reactive power is shown in Figure 10. The d and q axis currents variation I_d and I_q are shown in Figure(s)11 and 12 respectively. From the Figure(s)11 and 12 it is obtained that the actual I_d current follows the reference I_d and actual I_q current follows the I_q reference current. The instantaneous value of load voltage and current are shown in Figure(s) 13 and 14 respectively.

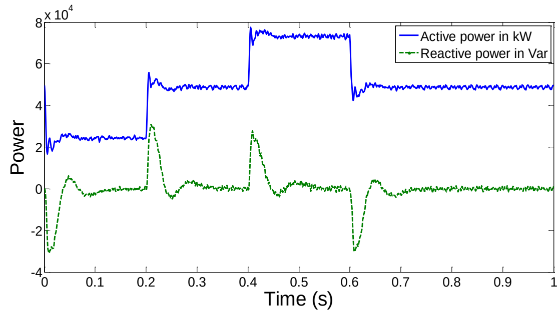


Fig. 10. Active and reactive power

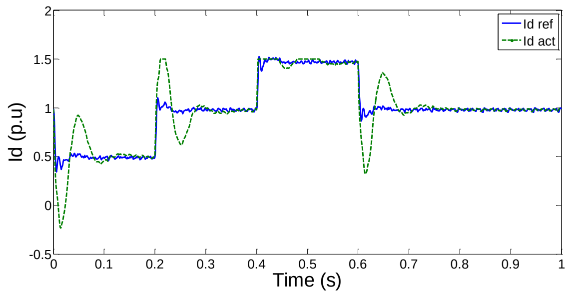


Fig. 11. Id current

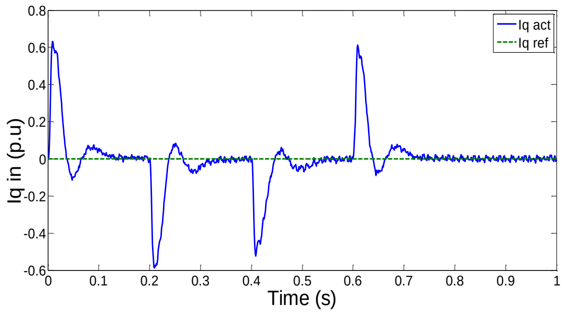


Fig. 12. Iq current

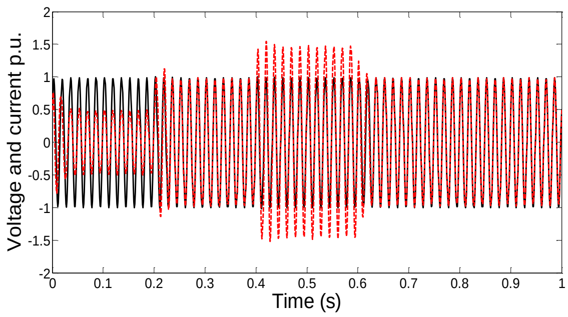


Fig. 13. Load voltage and current

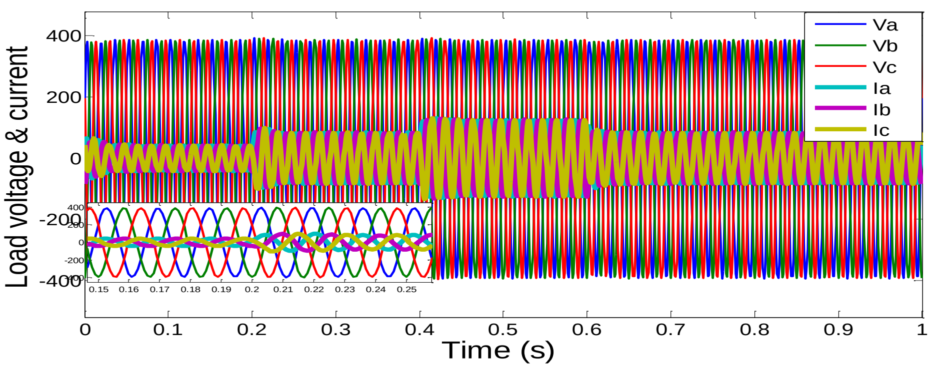


Fig. 14. Load voltage & current

Isolated mode: The load following performance of MTG system for an isolated mode of operation is predicted on the basis of torque and fuel flows to the microturbine shown in Figure15. and 16. respectively. It is observed from the Figure15. and 16. that, turbine, compressor, mechanical powers and fuel flow are increases with increase in the load. For this study, the load variation is made in steps of 10kW with respect to time. It can also be observed that, the power and fuel demand are decrease with decrease in load. Thus the developed model of MTG system is capable of following the load variation with the system ratings. Since the developed model of MTG system uses a DC link voltage to control the microturbine output power. The transient and steady state formation are observed during the load change in DC link voltage is shown in Figure17.

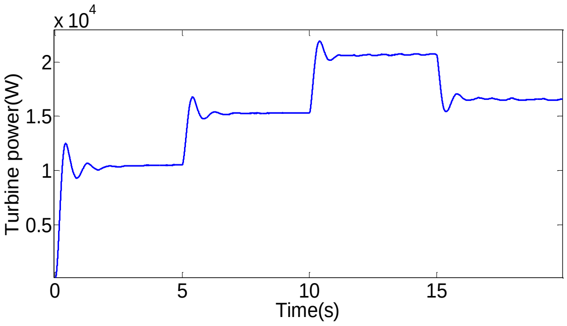


Fig. 15. Turbine power

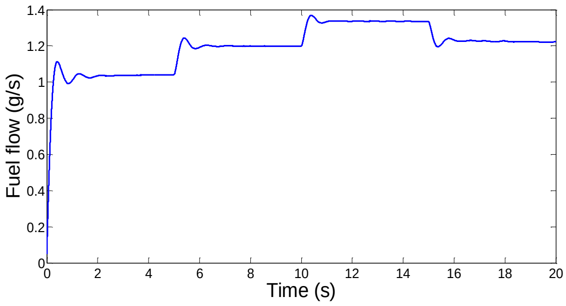


Fig. 16. Fuel demand

The mechanical torque required to drive the generator varies with load, the turbine speed and torque, thus the turbine torque and speed variation of PMSM for a different load is shown in Figure(s).18 and 19 respectively. It is also observed from the reported Figure(s) 18 and 19 that, there is formation of transients when load changes and settles to steady state after two seconds. The microturbine operating temperature will also vary due to the variable flow of fuel. Thus the variation of turbine operating temperature for a different load is shown in Figure 20. The instantaneous value of load voltage and current are shown in Figure 21. and 22. respectively. From Figure(s) 21. and 22. it is observed that, the terminal voltage remains constant due to the speed variation of PMSM and current vary with respect to load.

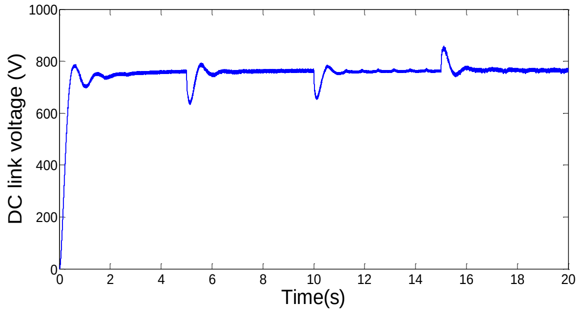


Fig. 17. DC link voltage

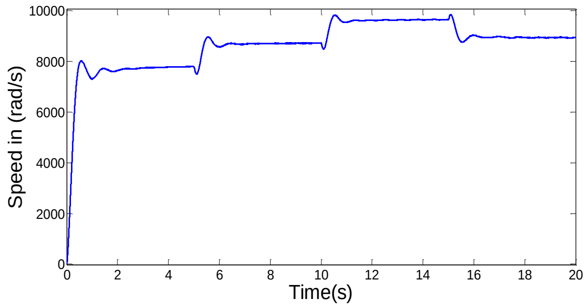


Fig.18. Turbine speed

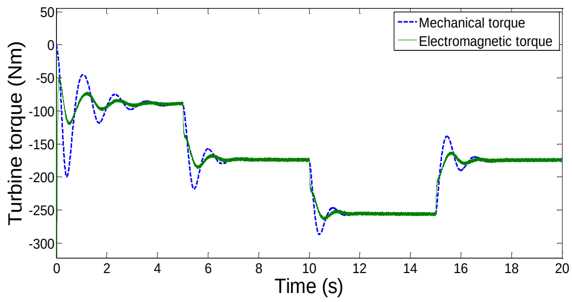


Fig. 19. Turbine torque

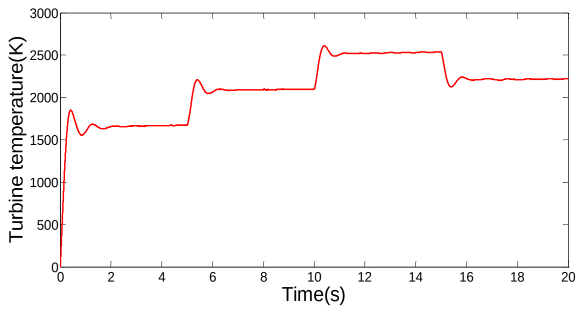


Fig. 20. Turbine temperature

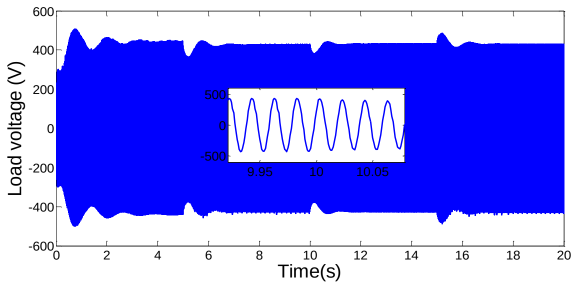


Fig. 21. Load voltage

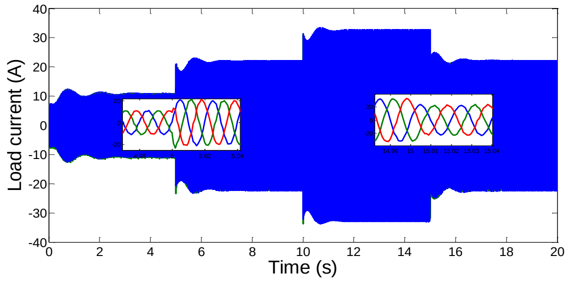


Fig. 22. Load current

11. Conclusion

The modeling and performance analysis of MTG system in grid connected and islanding modes of operation has been studied using Matlab/Simulink environment. The MTG system uses a DC link voltage to control the microturbine output power for a different load. Thus, the use of DC link voltage controller for the MTG system, the load voltage can be maintained constant even if load current is varies. From the simulation studies it is conclude that, the MTG system could follow the load and vary there is variation of fuel flow, power and temperature of system as per the load. The developed model can be used for the study and performance and analysis of electrical phenomena that occurs in connected to the grid and isolated mode of operation. This work initiates the integration of MTG system to the distribution network as it is mainly contributes to a clean, reliable and cost effective for the future DG systems.

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