Modeling and Control of Micro-Turbine Based Distributed Generation System

Ashwani Kumar, K. S. Sandhu, S. P. Jain, P. Sharath Kumar

***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. In this paper modeling of micro-turbine distributed generation system has been implemented and a new converter controller for a simulation of dynamic model of a micro-turbine generation system (MTG) has been proposed. The converter controllers are built on the dq synchronous frame. The converter controller models are implemented in the MATLAB / SIMULINK using SIMPOWER Systems library. The performance of the implemented MTG model is studied with an isolated load considering RL, LCL filter without and with reactive power injection into the system.

***Keywords*— Converter Controller, Distributed Generation, Filter, Micro-turbine, Permanent Magnet Synchronous Machine.

I. Introduction

With the deregulation of electric power utilities, advancement in technology, and environmental concerns, optimal distributed generation (DG) will be a focus to the electric utilities to cater the growing need of electric power [1]. Distributed generator is generally connected directly to grid or can operate independently. They are considered to be less than 5MW in capacity. DG can be based on renewable technologies such as wind turbine, photovoltaic or nonrenewable technologies such as micro-turbine and fuel cell. Distributed generation using micro-turbine generator (MTG) is a practical solution because of its environment-friendliness and high energy efficiency. Various applications such as peak shaving, co-generation, remote power and base load power will make its use world wide. Dynamic model of MTG system have been suggested in [2-8]. SIMULINK based dynamic model for micro-turbine system for distributed generation system has been proposed in [2-5]. A dynamic model of combustion gas turbine has been proposed in [6].

In MTG system, PMSM does not start as a generator. So, the PMSM start as a motor and it drives the micro-turbine. When the micro-turbine gets the ignition speed, then the PMSM runs as a generator. The configuration of MTG system is a three phase diode rectifier, a voltage source inverter (VSI) via DC link and with a filter. It requires a separate start up inverter during stating [4]. This paper describes a new configuration of MTG system. In this new configuration, the MTG system eliminates the start up inverter and uses back to back voltage source converter in the place of diode rectifier. The converter controllers are built on the *dq* synchronous frame. The converter controller models are implemented in the MATLAB / SIMULINK using SIMPOWER Systems library. The performance of the implemented MTG model with new converter control has been studied with an isolated load. The impact of RL and LCL filter without and with reactive power injection has also been studied on the load end side voltage and current waveforms.

II. Main Components of MTG System

The basic components of a MTG system are the compressor, combustor, turbine, recuperator and high frequency generator with power electronics interfacing [2].

A. Micro-Turbine

The simplified single shaft gas turbine including all its control systems which is implemented in MATLAB / SIMULINK is shown in fig. 1 [5, 6]. The model consists of speed governor, acceleration control blocks, fuel system control, and temperature control and turbine dynamics.

B. Permanent Magnet Synchronous Machine (PMSM)

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 (dq frame) are used to implement PMSM [7, 8].

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Electrical equations:

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

$$\frac{d}{dt} i_q = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q - \frac{L_d}{L_q} p\omega_r i_d - \frac{\lambda p \omega_r}{L_q} \tag{2}$$

$$Te = 1.5p\,(\lambda i_q + (L_d - L_q)\, i_d i_q) \tag{3}$$

Mechanical equations:

$$\frac{d}{dt} \omega_r = \frac{1}{J}(T_e - F\omega_r - T_M) \tag{4}$$

$$\frac{d}{dt} \theta = \omega_r \tag{5}$$

where,

F :Combined viscous friction of rotor and load

i_q, i_d :q and d axis currents

J :Combined inertia of rotor and load

L_q, L_d :q and d axis 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

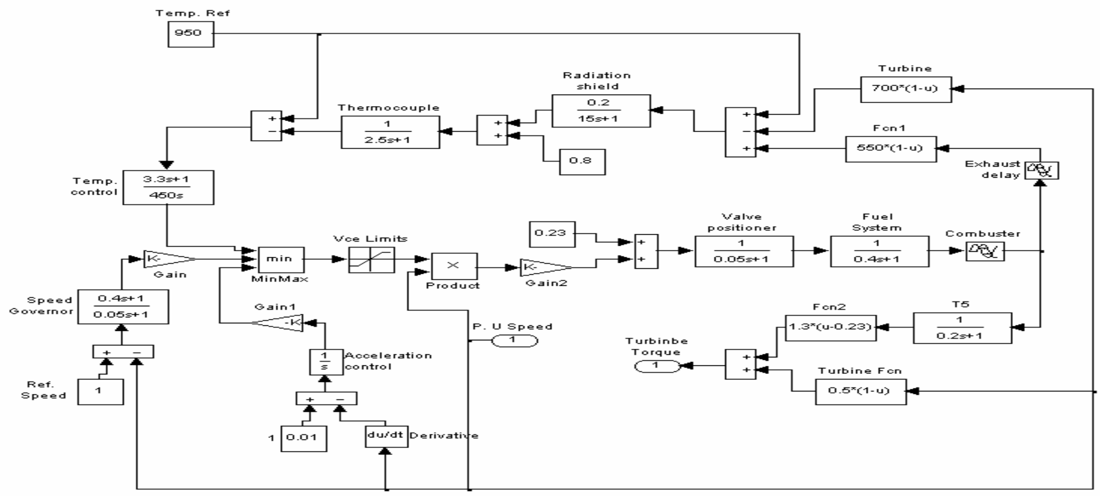

Fig. 1 SIMULINK model of the Micro-Turbine

C. LCL Filter

The primary function of the AC filter is to filter out the high frequency components caused by the inverter switching operation. However, the filter also affects the low order harmonic performance of the system. The LCL-filter aims to reduce the high order harmonics at grid side (load side). In fact the current harmonics generated by the rectifier or inverter can cause saturation of the inductors or filter resonance. So, the inductors should be correctly designed considering the current ripple and the filter should be damped to avoid resonance. The transfer function of the LCL filter designed by the output voltage to the input current is given as follows:

$$G^{\alpha\beta}(s) = \frac{\frac{1}{L_1 + L_2 C}}{s\left(s^2 + \frac{L_1 + L_2}{L_1 L_2 C}\right)} \tag{6}$$

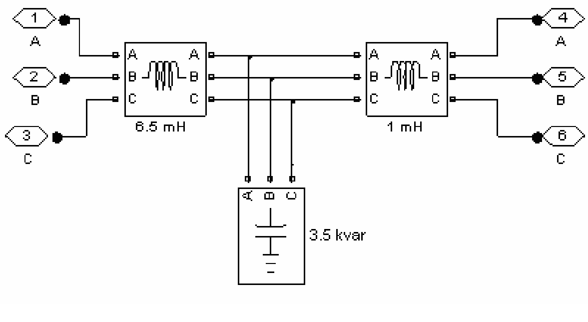

Fig. 2 LCL Filter

The series resistance of the inductors is neglected for simplicity. Using the above equation and considering resonance frequency and low ripple current, inductors values are determined. In addition the capacitor value is rated with the accepted reactive power level of the system for LCL filters [9]. The design of LCL filter is shown in fig. 2. The three-phase active LCL filter, capacitive load injected the reactive power into the system as well as do harmonics attenuation. The values for LCL filter configuration with inverter side inductance (L1) and line side (L2) are 6.5mH and 1mH and capacitive load value considered is 3.5kVar.

III CONVERTER CONTROLLERS

The converter is IGBT / Diode based 3-phase circuit. It is available in the MATLAB /SIMULINK SIMPOWER systems library. The converter controlling is a critical component in the single shaft micro-turbine design and represents significant design challenges, specifically in matching turbine output to the required load. The configuration used in this paper, this topology allows bi-directional power flow between the PMSM to DC source and Load, and hence no separate start up arrangement is required. During the starting of PMSM, acts as motor and draws power from external source to bring the turbine to ignition speed. In this period the machine side converter acts as inverter. Once the micro-turbine gets the ignition speed, the PMSM will be run as a generator. In this period the machine side converter acts as rectifier.

A. Machine Side Converter Controller

Usually, the vector control strategy is formulated in the synchronously rotating *dq* reference frame. It is known that the transformation of the synchronous machine equations from a, b, c phase variables to the *dq* variables, forces all sinusoidally varying variables in the, b, c frame to become constant in the *dq* frame. This concept facilitates the control tasks [10]. Two loop control structure, using inner and outer loops in *dq* synchronous reference frame has been used. The inner current loop also assures fast current response within the drive system. The drive is fed in such a way that the *q*-axis current provides the desired torque [10, 11]. Figure 3 shows the implemented model of the machine side converter controller in MATLAB /SIMULINK using SIMPOWER Systems library. It is the high efficiency drive control system for the MTG system. The reference speed ω_{ref} is pre calculated according to the turbine output power and set to the optimum speed [11]. Based on the speed error the commanded *q*-axis reference current i_{qref} is determined through the speed controller. In this system the following PI controller is employed as the speed controller.

$$i_{qref} = K_{p\omega}e_{\omega} + K_{I\omega}\int e_{\omega}dt \quad (7)$$

Where, $K_{p\omega}$ and $K_{I\omega}$ are the proportional and integral gains of the speed controller respectively. e_{ω} is the error between the reference speed and the measured speed. Based on the current errors, the *d-q* axis reference voltages are determined by the PI controllers as given below:

$$V_d = K_{pi}e_d + K_{Ii}\int e_d dt - \omega_r L_q i_q \quad (8)$$

$$V_q = K_{pi}e_q + K_{Ii}\int e_q dt + \omega_r(L_d i_d + \lambda_m) \quad (9)$$

Where,
K_{pi} and K_{Ii} are the proportional and integral gains of the controller respectively. $e_d = i_{dref} - i_d$ is the *d*-axis current error and $e_q = i_{qref} - i_q$ is the *q*-axis current error. The commanded *dq* – axis voltages (V_d, V_q) are transformed into a, b, c quantities (V_a, V_b, V_c) and given to PWM generator to generate the gate pulse for machine side converter.

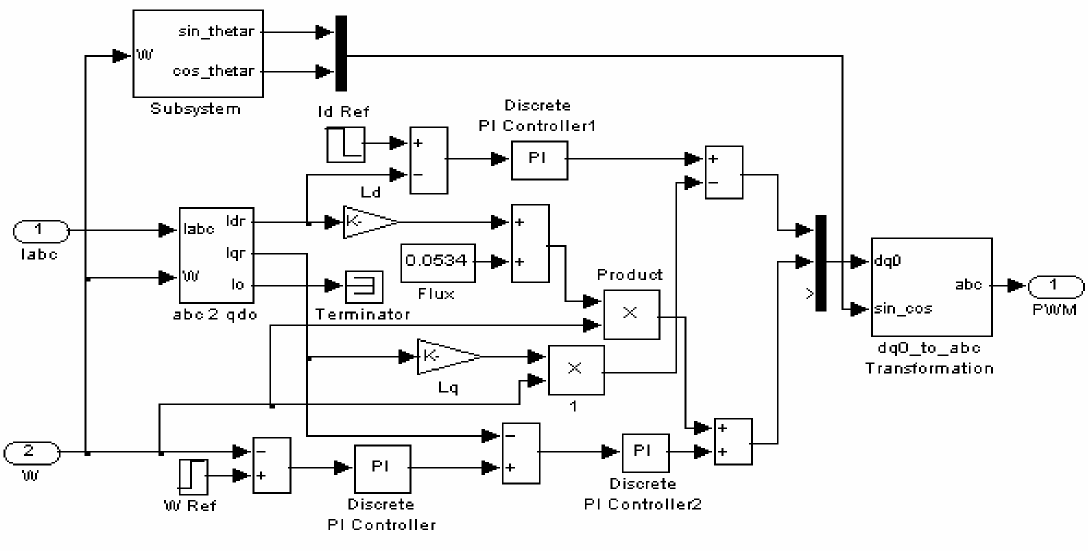

Fig. 3 Machine side converter controller in SIMULINK

B. Line Side Converter Control

The objective of the Line side converter is to keep the DC link voltage constant, regardless of the magnitude and direction of the rotor power. A vector control approach is used with the reference frame oriented along the line voltage vector position. This enables independent control of the voltage and frequency between the load and line side converter. The PWM converter is current regulated, where the direct axis current component is used to regulate the DC link voltage and q-axis current component is used to regulate the reactive power [12].
Using the Park's transformation, the voltage equations can be transformed to the *dq* reference frame.

$$V_d = L_f\,(di_d / dt) + R_f i_d - \omega L_f i_q \qquad (10)$$
$$V_q = L_f\,(di_q / dt) + R_f i_q + \omega L_f i_d \qquad (11)$$

The last two terms in both equations causes coupling of the two equations, which makes it difficult to control both currents independently. The last terms can be considered as a disturbance on the controller [10, 13]. Figure 4 shows the current controllers on *dq* synchronous frame in line side converter controller [10]. Figure 5 shows the implemented model of the line side converter controller in MATLAB / SIMULINK using SIMPOWER Systems library.
The Line side converter operates as a controlled power source. The standard PI – controllers are used to regulate the line currents in the *dq* synchronous frame in the inner control loops and the DC voltage in the outer loop.

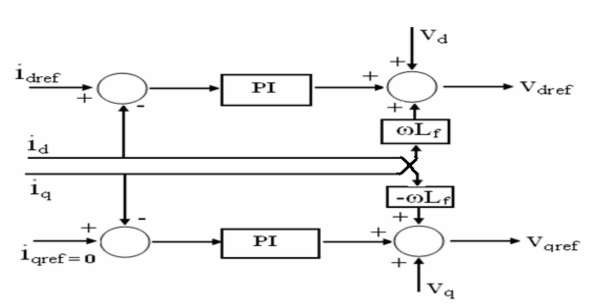

Fig. 4 Control block diagram of *dq* current controllers of line side converter

It is observed that a PI controller regulates the DC bus voltage by imposing an i_d current component. i_d represents the active component of the injected current into the Line, and i_q is its reactive component. In order to obtain only a transfer of active power, the i_q current reference is set to zero. The decoupling terms are used to have independent control of i_d and i_q. A phase locked loop (PLL) is used to synchronize the converter with the line. The philosophy of the PLL is that the difference between line phase angle and the inverter phase angle can be reduced to zero using PI controller [10, 14]. For the DC Link voltage regulation, the following assumptions have been considered [15]:

- The line voltage amplitude is constant, if it is connected to grid.
- The displacement between the line voltage and current is zero.
- The q-axis component of the injected current is zero.
- The harmonics due to switching and the losses in the inductor resistance and converters are neglected.

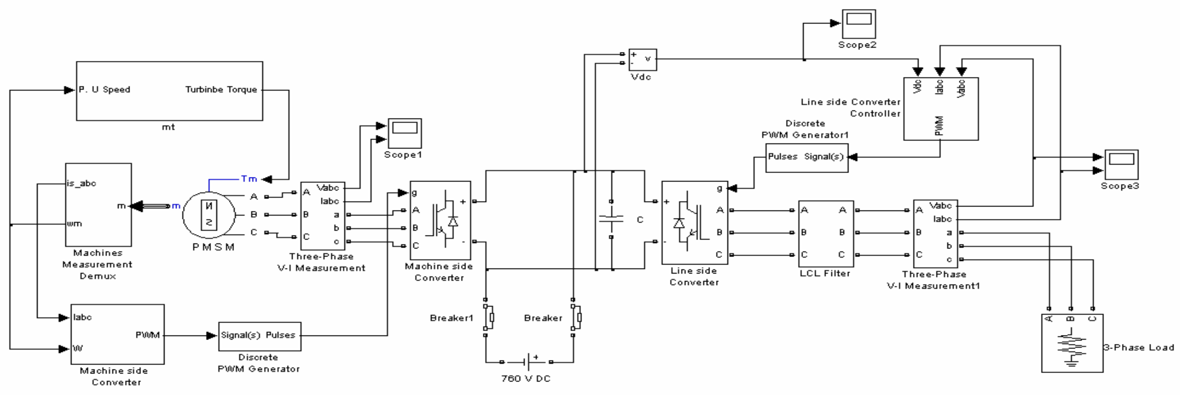

Fig. 5 Line side Converter controller in SIMULINK

IV CASE STUDY OF MTG SYSTEM

The performance evaluation of Micro Turbine Generation (MTG) system under motoring and generating mode operating conditions has been determined, when it is connected to an isolated load.

A. MTG system Start-up (Motoring mode of PMSM)

The operation of PMSM in generating or motoring mode is decided by the sign of the input mechanical torque. During start-up the PMSM operates as a motor to bring the turbine speed of 30,000 rpm. In this case, power flows from the DC source to MTG system. The Micro-turbine reaches the set value of speed in 0.4 sec. To ensure the operating condition, the pre-calculated reference speed and direct current component (i_d) are set to 3142 radian /sec and -5.36A respectively [11, 16]. The speed regulator provides the reference value for the i_q current component. In this mode of operation of MTG system, the machine side converter acts as inverter.

B. 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 pre-calculated values of 5849 radian /sec and -15.89A in order to generate the power [16]. 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 [3, 14]. Figure 6 shows the developed model of the MTG system with external DC source in MATLAB / SIMULINK using SIMPOWER Systems library and data for different components is given in Appendix-I.

C. MTG system Voltage and Current wave forms with RL and LCL Filter

The PMSM voltage and current waveform obtained with RL filter are shown in fig. 7. Load end side voltage and current waveforms with RL filter are shown in fig. 8. It is observed that load end side voltage and current waveforms are not sinusoidal. The PMSM voltage and current waveform obtained with LCL filter are shown in fig. 9. Fig. 11 shows the effect of reactive power injection on voltage and current waveform with LCL filter. The waveforms are found to be almost sinusoidal. DC link voltages obtained with RL and LCL filter with reactive power injection are shown in figs. 12 and 13. With RL filter, DC link voltage is not constant as obtained with LCL filter. In this model, machine side and line side converter controllers are very important as machine side controller maintains the PMSM voltage level and the micro-turbine ignition speed level. If ignition speed is not maintained, the PMSM will be shutdown. The line side converter is maintaining the constant DC voltage level and the load side voltage level. From figures 7 to 11, it is observed that the machine side and the line side converter controllers are working properly. So, the micro-turbine maintains the ignition speed and the PMSM runs as a generator. The MTG system delivering the rated active power to the load continuously and the load side voltage and current waveforms are sinusoidal. Figure 13 shows the constant DC link voltage waveform with LCL filter which inject the reactive power into the system. It has no disturbances throughout the operation period.

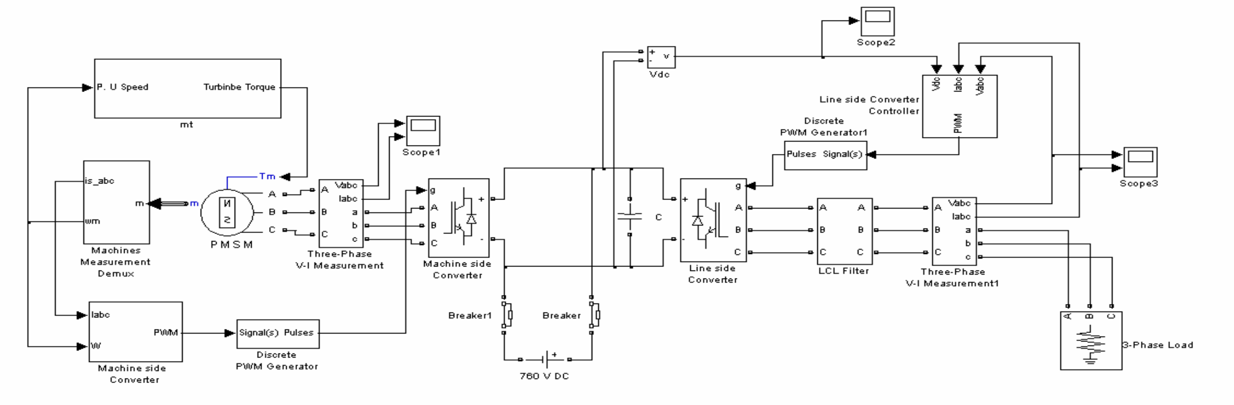

Fig. 6 Model of the MTG system in Simulink

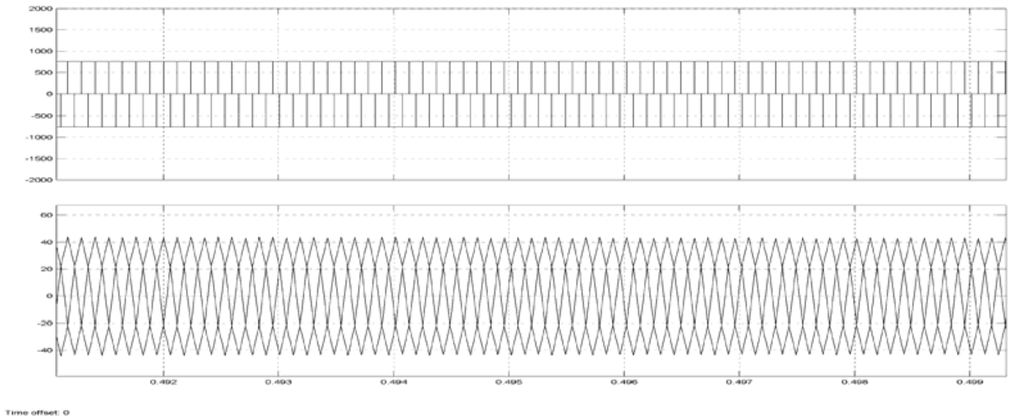

Fig. 7 PMSM voltage and current wave forms with RL filter

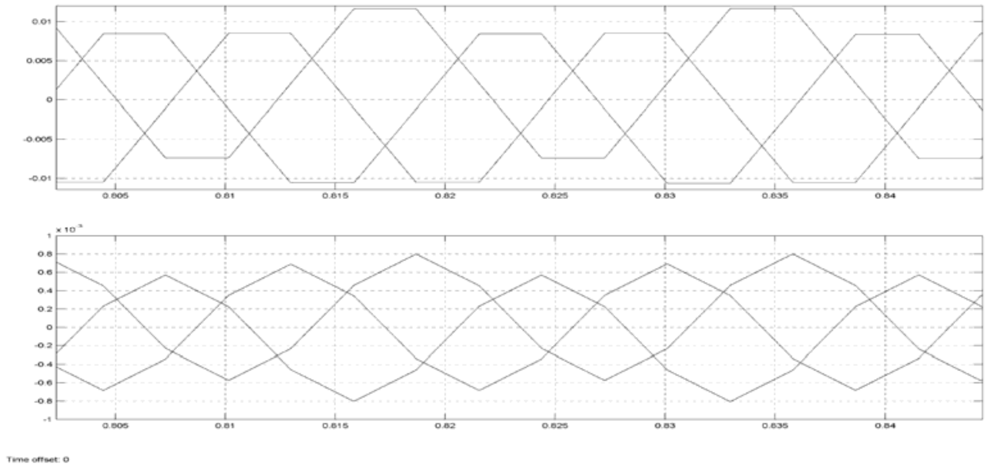

Fig. 8 Load end side voltage and current wave forms with RL filter

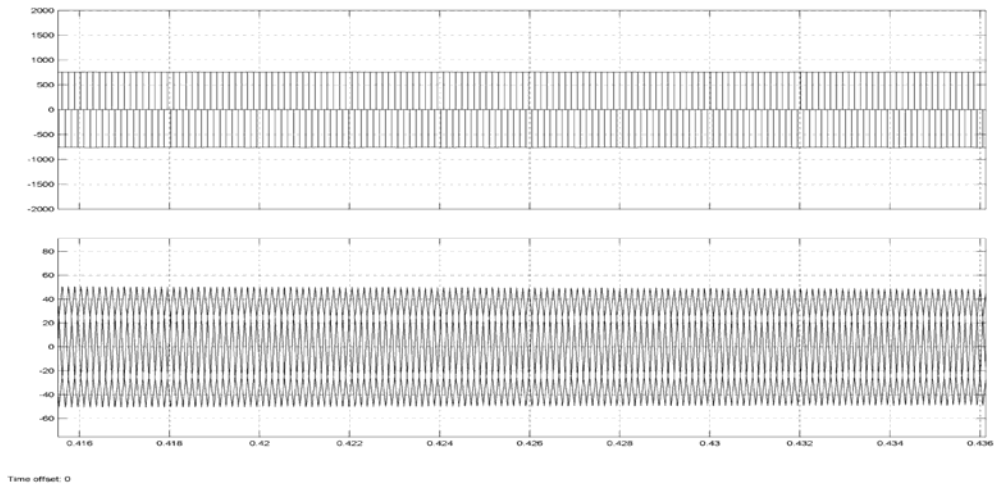

Fig. 9 PMSM voltage and current wave forms with LCL Filter

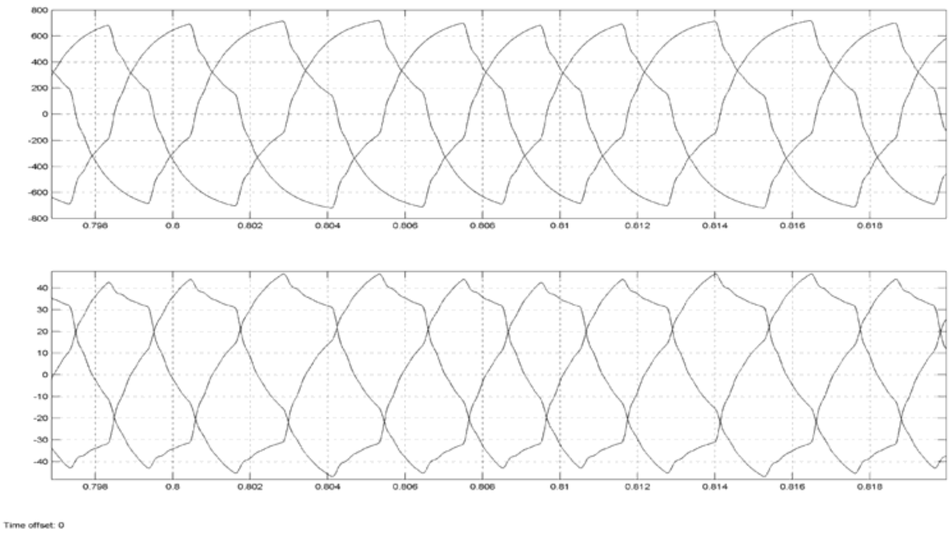

Fig. 10 Load end side voltage and current wave forms with LCL filter with no reactive power injection

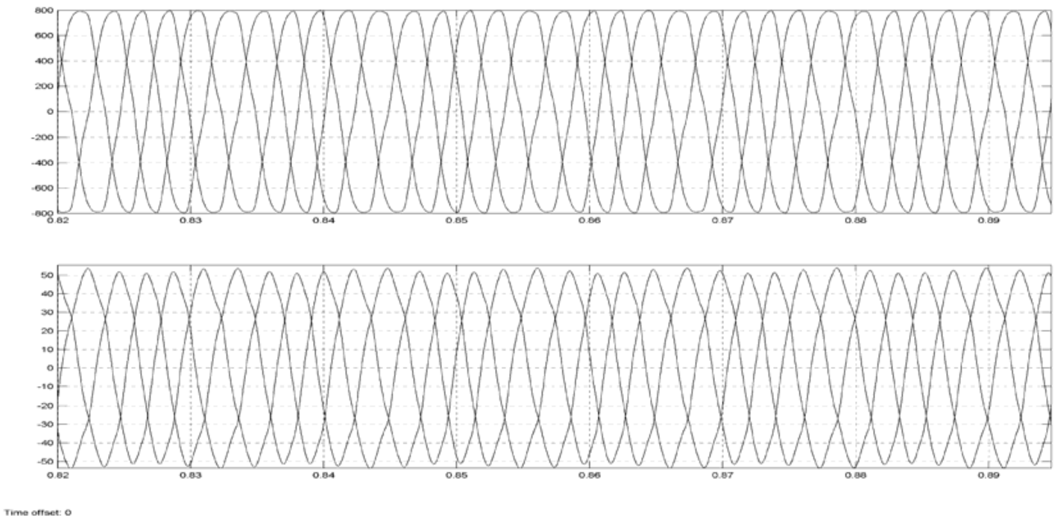

Fig. 11 Load end side voltage and current wave forms with LCL filter with reactive power injection

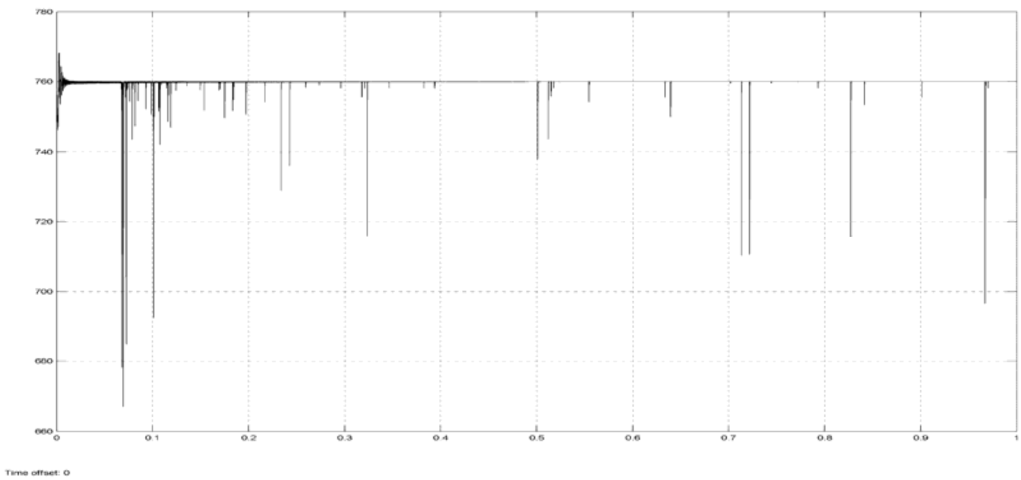

Fig. 12 DC link voltage with RL filter

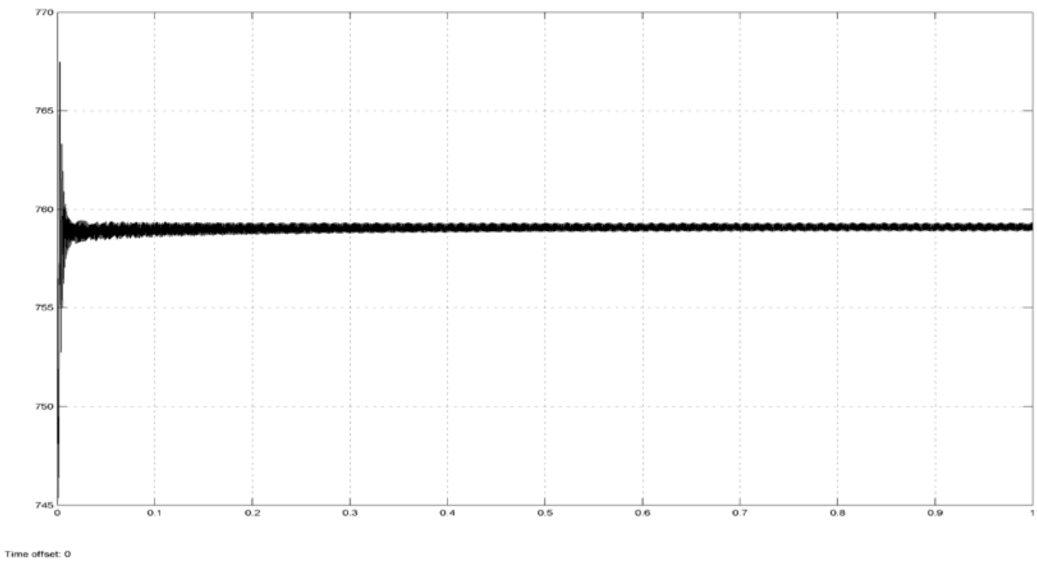

Fig. 13 DC link voltage with LCL filter with reactive power injected into the system

V. CONCLUSIONS

A detailed simulation model of the MTG system is implemented in MATLAB / SIMULINK using SIMPOWER Systems library and new converter controller schemes have been proposed. Case study has been obtained with RL and LCL filters without and with reactive power injection into the system. With the machine side converter controller, the micro-turbine maintains the ignition speed and with the line side converter controller, constant DC link voltage has been obtained without any disturbance. The LCL filter supplies the reactive power to the system, as well as reduce the high order harmonics at the load end side and sinusoidal waveforms are obtained at the load end side.

APPENDIX-I

PI controller parameters: $K_{p\omega} = 5$, $K_{pq} = 2$, $K_{pd} = 1.35$
Machine side converter: $K_{i\omega} = 19.275$, $K_{iq} = 740$, $K_{id} = 500$
Line side converter::$K_{pDC} = 0.015$, $K_{pq} = 2.5$, $K_{pd} = 2.5$
$K_{iDC} = 1$, $K_{iq} = 500$, $K_{id} = 500$
PI controller sampling time: 100µsec
PWM switching frequency: Line side converter = 20000Hz
Machine side converter = 8000Hz

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