Modelling and Simulation of Microturbine Generation System for Grid Connected/Islanding Operation

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Abstract— **in recent years, global attention to distributed generation is more than before and in between a variety of distributed generators, micro-turbines as one of the best and most reliable sources, have a significant contribution in this regard. This paper presents a dynamic modeling of a micro-turbine with a new passive filter design. Proposed structure consists of a permanent magnet synchronous generator (PMSG), an AC/DC rectifier, a boost converter, a DC/AC inverter and a removal ripple circuit (RRC). Using the boost converter with RRC filter is new and efficient method for micro turbine operations.**

Simulation studies have been carried out in MATLAB/Simulink under isolated and grid-connected simultaneously. Results show that the structure has fast dynamic and desired performance.

Keywords-Microturbine; boost converter; RRC filter; distributed generation;

I. Introduction

The interest in distributed generation (DG) is increasing due to technical, economical, reliability and environmental merits. There are a variety of methods to produce energy such as solar energy, wind energy and fuel cells and diesel generators. Micro-turbine (MT) is a small and simple gas turbine that produces power in range of 25 to 500 kW. Generally, its advantages are compact size, reliable and low initial cost, maintenance inexpensively, simple control, low environmental pollution, less moving parts and it can be operate with different fuels like Natural gas, Hydrogen, Diesel, Propane, etc. The efficiency of MT is about 20-30% and with heat recovery and use as combined heat and power (CHP) it can be Improve about 80%. The potential applications of the MT configuration include peak shaving, premium power, remote power, and grid support. These are mainly two types of micro-turbine generation system design, single-shaft models and split-shaft models. In the single-shaft design all component of MT including compressor, turbine and permanent magnet generator mounted on a same single-shaft. The PMSG creates high frequency AC voltage in the range of 1.5-4 kHz and it requires a power electronic interface for converting high frequency to utility frequency.

Fig. 1 shows a single-shaft MT model in two operating modes: grid connected and islanding. Micro-turbines system includes a turbine, compressor, recuperator and a permanent magnet generator. Compressed air combined with the fuel in the combustion chamber and burns under high pressure and passing through the turbine causing mechanical power and rotating PMSG.

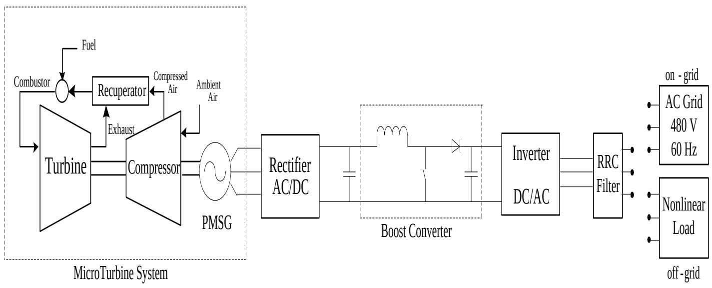


Fig. 1. Micro-turbine generation system

One way to convert high PMSG frequency to desired frequency is using AC/DC/AC structure. In this way, at first AC voltage converted to DC voltage and then with a boost converter, it goes into a higher voltage level and fluctuations reduce. Output DC voltage of the boost converter changed to 50Hz or 60Hz through inverter but for better output power and reduces ripple and harmonics, an appropriate filter is needed and RRC is a good choice.

Recently micro turbines efficient operation is one of challenges and various methods have been proposed. In [1] and [2] the basic principle of MTGs as a distributed resource are presented. In [3] a complete mathematical model of PMSG and a single-shaft micro-turbine in isolated mode under MATLAB/Simulink is proposed. The evaluation of MT electromagnetic transients in grid-connected mode is done in [4]. Dynamic model of a MT system and control strategies for grid connected and islanding operation has been introduced in [5]. In [6] the model of MTG system as micro grid under PSCAD/EMTDC is presented and the SPWM control strategy for power electronic interface is done. In [7] thermo mechanical system with different control loop like a controller for limiting temperature and a controller for start-up is introduced. A distribution system embedded with a micro-turbine plant and an integrated fuel cell power plant is used for load-following and economic value is done in [8].

In this paper, modeling of a single-shaft MT with AC/DC/AC structure is proposed. This structure with boost converter and RRC as new filter topology caused sending desired power to the load and output voltage has low harmonic and ripple. For comprehensive analysis, MT is grid-connected and feed a nonlinear load simultaneously and all simulation carried out in MATLAB/Simulink. In section 2 a dynamic model of micro-turbine and control strategy for grid-connected and islanding operation is proposed and then in section 3 simulation results under load changing is presented.

II. Model Description

A. Modeling of a Microturbine

A dynamic model of single-shaft micro-turbine in MATLAB/Simulink is illustrated in Fig. 2. This model consists of acceleration control, speed governor, temperature control, fuel control and turbine dynamic blocks [5]. In this modeling, suppose that system operate in normal condition without fast dynamics.

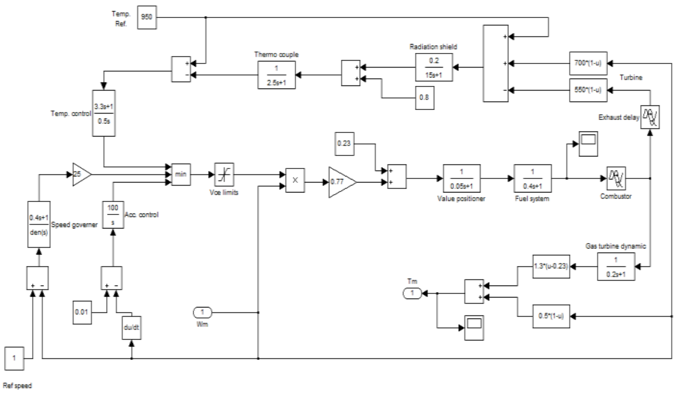


Fig. 2. Matlab/Simulink model of microturbine

Speed controller operates based on speed error between reference and MTG rotor speed. A lead-lag transfer function or a PID controller can be used for modeling of speed governor and in this paper a lead-lag transfer function has been proposed. Acceleration control is used for start-up time of micro-turbine and when reference speed is near to rated speed it can be ignored. Governor output and acceleration control with temperature controller output goes to a MIN block and this block selects the least value signal. The output of MIN block is scaled by gain value of 0.77 and offset with 0.23 that represented the fuel flow at no load condition. The time delay preceding the fuel flow controls represents delays in the governor control. Finally fuel burn in combustor and lead to turbine for mechanical torque generation. The temperature of output gas is measured by a thermocouple and compared with a reference value (950). In normal condition, reference is higher than thermocouple output and caused maximum value for temperature control. If thermocouple output exceed reference, negative value caused system operate for decreasing temperature.

B. Permanent Magnet Synchronous generator (PMSG)

For producing electric power MT need a synchronous generator like PMSG. The structure of high speed PSMG is presented in [11]. In this paper, PMSG is a 2 poles and non-salient that produce 500v at 100000 RPM. In this model assumes that flux in stator is sinusoidal and caused sinusoidal electromotive forces. Following equations in dq0 reference frame illustrate PMSG structure.

Electrical equations:

$$\frac{di_d}{dt} = \frac{v_d}{L_d} - \frac{Ri_d}{L_d} + \frac{L_q}{L_d} p\omega_r i_q$$

$$\frac{di_q}{dt} = \frac{v_q}{L_q} - \frac{Ri_q}{L_q} - \frac{L_d}{L_q} p\omega_r i_d - \frac{\lambda p \omega_r}{L_q}$$

$$T_e = \frac{3}{2} p(\lambda i_q + (L_d - L_q) i_q i_d)$$

Where
L_q, L_d :q and d axis inductances
R : Stator winding resistance
i_q, i_d : q and d axis currents
v_q, v_d : q and d axis voltages
ω_r : Angular velocity of rotor
λ : Flux linkage
P : Number of pole
Te : Electromagnetic torque

Mechanical equations:

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

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

Where
j : Combined inertia of rotor and load
F : Combined viscous friction of rotor and load
T_m : Shaft mechanical torque
Θ : Rotor angular position

C. Boost converter

In this paper a boost converter is used in DC bus for stabilize fluctuated output voltage which comes from PMSG [9]. Fig. 3 represented Boost converter and control strategy diagram.

In boost converter, output voltage is more than input voltage and to increase further, there is need to increase the duty cycle (D).

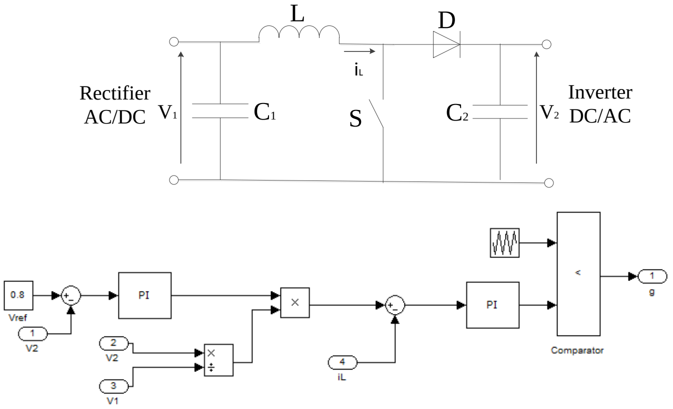


Fig. 3. Schematic of boost converter and control

D. inverter controller circuits

Generally, micro-turbines can operate grid-connected mode (on-grid) or isolated mode (off-grid). In this paper, MT simultaneously feeding a nonlinear load like a 6 pulse diode rectifier and is also connected to the distribution network and each mode has special control circuit.

1) *Isolated inverter*

For islanding operation mode V-f control strategy is used. That's mean, voltage magnitude and frequency are controllable parameters. Fig. 4 shows schematic of inverter control in off-grid mode.

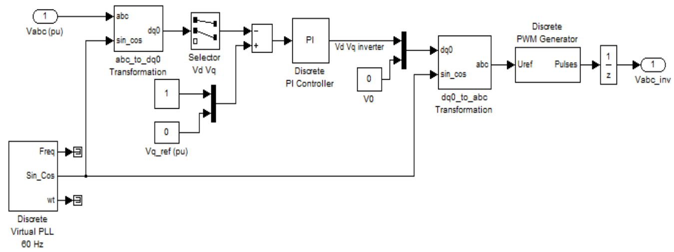


Fig. 4. Inverter control for isolated mode

At first voltage applied to dq0 reference frame and then compared with a reference value. Finally, passing through PI controller, converted to desired pulse for inverter And it is seen that the voltage and frequency are under control here.

2) *grid-connected inverter*

For grid-connected operation mode P-Q control strategy is used. In this case, delivering desired active and reactive power to load is important and any deficit can be compensating by grid. On-grid control diagram is represented in Fig. 5.

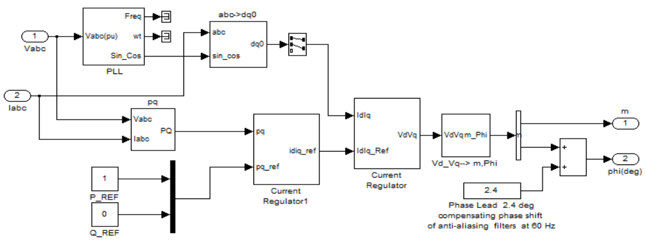


Fig. 5. Inverter control for grid-connected mode

At first, grid side measured voltage and current converted to active and reactive power and then this values compared with references and by passing through PI controller, reference currents are generated. On the other side, dq currents are produced by frequency of voltage and with compared and pass through PI controller, finally desired pulse for inverter is generated.

E. Removal Ripple Circuit (RRC)

For deliver optimum power, inverter needs output filter to reduce harmonics and ripple. In this paper, a new topology RRC filter is used instead of conventional LC or LCL filter. RRC have a lot advantage like: No need to additional switches, No need to additional drive and control circuit and have simple structure. Fig. 6(a) shows RRC structure.

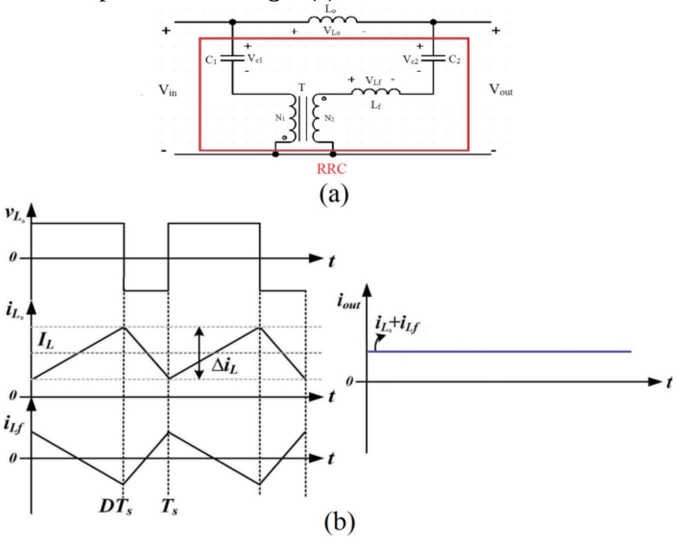


Fig. 6. Proposed filter: (a) RRC structure (b) key waveforms for eliminating ripples

This filter works based on reflected ripples that are automatically induced therefore, eliminate output current ripple and enhance power quality for loads. RRC Key waveforms for eliminating output ripple are shown in Fig. 6(b). The RRC parameters are chosen as following and these values are based on [12]:

L_0 = 9mH, L_f=800 µH, C_0=1.5 µF, $C_{1,2}$=150 µF

III. Simulation Results

For analysis mentioned structure, simulation is carried out in MATLAB/Simulink software. In this model, micro-turbine systems simultaneously feeding a nonlinear load and is also connected to the grid. Fig. 7 shows MT system and subsystems.

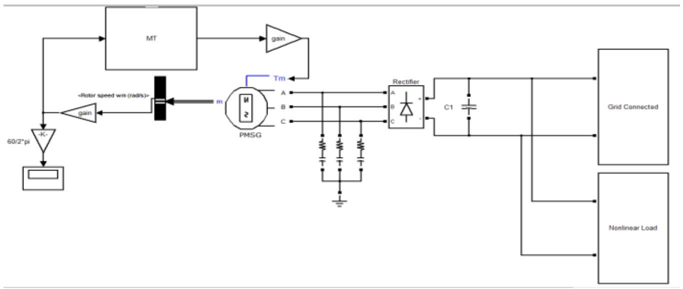


Fig. 7. Micro-turbine generation system in MATLAB/Simulink

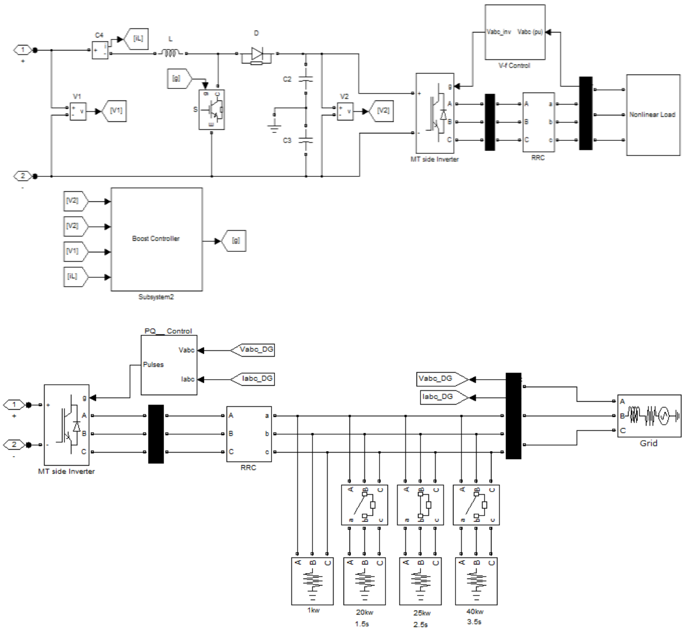


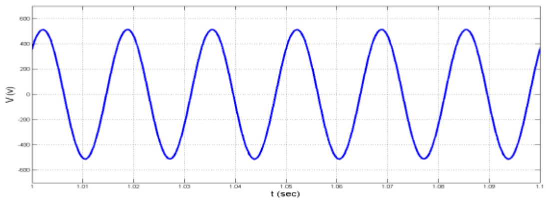
Fig. 8. MTG subsystems: (a) isolated subsystem (b) grid-connected subsystem

Nonlinear load is connected to MT through a boost converter. The aim of this study is to evaluate dynamic behavior of MT and effective operation of RRC filter and the boost converter. The grid is a 480v and 60Hz and nonlinear load is a 3 leg diode Rectifier with a RL load equal to 500+j100 VA. In grid-connected subsystem the scenario is as following:

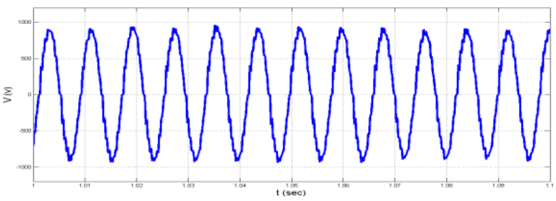
According to mention above, P-Q control is applied. A 1kw load is parallel connected permanently. At t=0 s a 25kw load applied to system and at t=1.5 s another load with 20kw value added to system until at t=2.5 s the first load is disconnected. Finally, a 40kw load at t=3.5 s is applied to system.

In isolated mode, inverter controller is a V-f control and nonlinear load is connected to MT through a boost converter and RRC filter.

Fig. 8 shows load voltage for two operation mode.



(a)

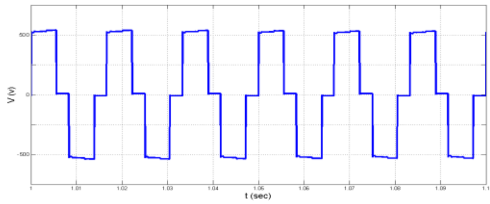


(b)

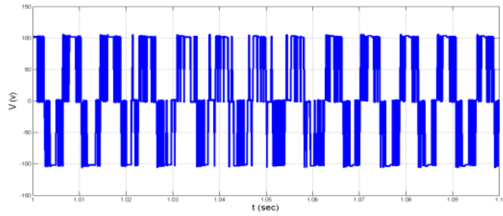
Fig. 9. Output load voltages: (a) grid-connected mode (b) isolated mode

Fig. 9(a) represented load voltage in detail. The 480 v is sinusoidal and sending to load with lowest harmonics. Fig. 9(b) illustrates nonlinear load voltage that is close to sinusoidal waveform due to the use of RRC filter.

Inverter output voltage is represent in Fig. 10.



(a)



(b)

Fig. 10. Inverter output voltages: (a) grid-connected mode (b) isolated mode

Fig. 11 shows DC link voltage and there is a slight drop in voltage due to increase in load but DC link voltage remains around 500V.

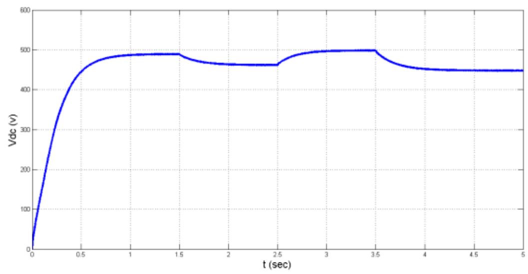


Fig. 11. Voltage at DC side

Fig. 12 shows Changes in transmitted power to the load due to change in load. It is seen that when load is increase, output power is increase too and a good dynamic behavior is occurs.

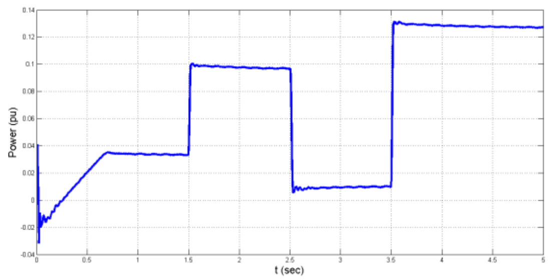


Fig. 12. Output power of the MTG

A rotor speed change is represented in Fig. 13. With changing in load, a rapid change is occurring in MT but speed is around 90,000 RPM without significant drop.

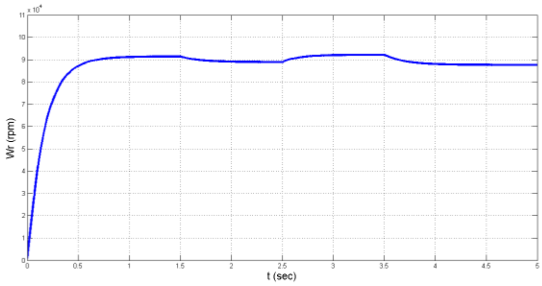


Fig. 13. Speed of the MTG

Fig. 14 shows MT output current that is close to sinusoidal waveform and it represents PMSG has good performance. Inverter output currents are close to sinusoidal too with low harmonics and ripple.

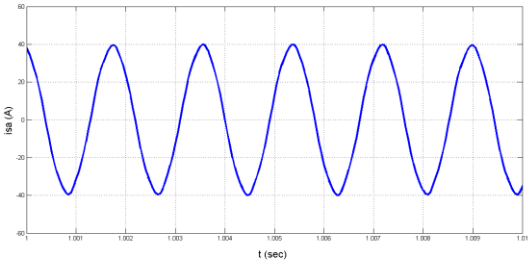


Fig. 14. Output current of the MTG

IV. CONCLUSION

This paper presented a dynamic modeling of a single-shaft micro-turbine in MATLAB/Simulink. Micro-turbine generation structure is based on AC/DC/AC that at first high frequency output voltage of PMSG converted to DC voltage through rectifier and then converted to 60Hz (50Hz) voltage through an inverter. In this study, MT operates in grid-connected mode and isolated mode simultaneously. In isolated subsystem there is a nonlinear load and in grid-connected subsystem there is a changeable load. To have the desired output voltage without ripple and harmonics, an appropriate filter is needed and a new topology filter that name is RRC is used. Results show desired RRC performance as output filter as well as boost converter for Stabilizing and output voltages are close to sinusoidal waveform. Mentioned structure doesn't have negative effect on system dynamic performance and there are proportional changes in power and speed with load.

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