# DYNAMIC MODEL OF A GAS MICROTURBINE FOR DISTRIBUTED GENERATION IN SIMPOWERSYSTEMS OF MATLAB/SIMULINK

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***Abstract* – This paper discusses the modeling and the dynamic performance of a gas microturbine used as a distributed generator (DG). The model is valid for transient studies and includes a speed control, a temperature control and an acceleration or fuel control. The microturbine system consists of a gas microturbine engine, a permanent magnet synchronous generator (PMSG), a three-phase rectifier bridge and a three-phase voltage source inverter (VSI) for connecting to the electric distribution grid. The detailed modeling approach is accomplished by using SimPowersSystems of MATLAB/Simulink. Steady-state and transient performance analysis are carried out for validating the methodology applied and components used.**

***Keywords* – Distributed generation, Dynamic modeling, Gas microturbine, MATLAB/Simulink, Simulation.**

## I. INTRODUCTION

In the last decade, distributed generation (DG) has become an attractive method for power generation, as much for the user as for the electric power grid. The inherent benefits of these small-scale generators come from the application of new technologies. Among the numerous benefits for the user stand out: the increase in the dependability and quality of the power, reduction of the number of interruptions, efficient use of energy, decrease of cost of the energy (e.g. cost in peak hours), easiness of adaptation to the installation location conditions and decrease of polluting emissions. Among the numerous benefits for the electric system stand out: reduction of losses in transmission and distribution, power supply in remote areas, release of power system reserve capacity, more efficient control of power reactive and voltage regulation, decrease of required investment, reduction of failure index and increase in the power quality.

Among various DG sources, gas microturbine generation systems are obtaining special attention from electric power providers. Microturbines are small and simple-cycle gas turbines with outputs ranging from around 25 to 300 kW. They are one part of a general evolution in gas microturbine technology.

Modeling of combustion microturbines based on linear models has shown to be appropriate only in certain cases. This situation has imposed the need of developing new techniques for the analysis and design of gas microturbines aiming at considering non-linear effects. Consequently, the microturbine modeling has received special attention in the last years with researches devoted to the identification and analysis of non-linear systems. With this aim, complex and nonlinear models in continuous time have been found.

The modeling and simulation of microturbine systems presented in most papers are mainly based on the combustion turbine model proposed by Hannett [1]. Al-Hinai and Feliachi proposed in [2] a microturbine dynamic model to be used as distributed generator. The development of a dynamic model of a microturbine system coupled to a load was described in [3].

In this paper, the modeling and the dynamic performance of a gas microturbine used as a distributed generator is proposed. The model is valid for transient studies and includes a speed control, a temperature control and an acceleration or fuel control. The microturbine system consists of a gas microturbine engine, a permanent magnet synchronous generator (PMSG), a three-phase uncontrolled rectifier bridge and a three-phase three-level voltage source inverter for connecting to the electric distribution grid. The detailed modeling approach is accomplished by using SimPowersSystems of MATLAB/Simulink. Steady-state and transient performance analysis are carried out for validating the methodology applied and components used.

## II. MODELING OF A GAS MICROTURBINE SYSTEM

A gas microturbine system, as shown in Figure 1, is made up of a gas combustion microturbine engine integrated with a synchronous generator that produces electrical power operating at high speeds, normally in the range of 50.000 to 120.000 rpm. The high-frequency electrical power (in the order of 10.000s of Hz) is converted to DC voltage and then inverted back to low frequency (50-60 Hz) AC voltage by an inverter. A step-up transformer can be used for connecting the system to the electric distribution grid when required.

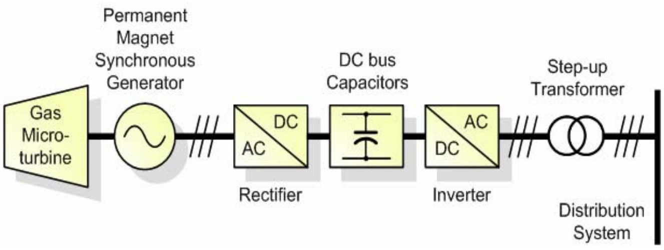


Fig. 1. General scheme of the microturbine global system

The proposed model of the microturbine system is based on the following assumptions:

- The microturbine engine is similar to a conventional gas combustion turbine, but smaller in size and spinning at higher speeds.
- The microturbine system shares a single rotating shaft including the microturbine engine and the synchronous generator.
- Brushless permanent magnet generators are used in order generate AC power.
- A power conditioning system (PCS) is employed for connecting the microturbine to the utility grid.

The modeling of the microturbine system consists mainly of four parts; the gas microturbine engine, the permanent magnet synchronous generator, the three-phase rectifier bridge and the three-phase power inverter.

### *A. Gas Microturbine Engine*

Analogous to a typical combustion gas turbine, the microturbine engine mainly involves an air compression section, a burner or combustion chamber for ignition of input fuel (i.e. gas), a recuperator of thermal energy from exhaust gasses for improving overall electrical efficiency, and a power microturbine driving a load, as depicted in Figure 2. The load is composed of a synchronous generator [4].

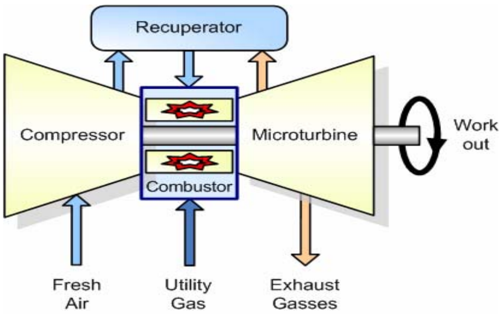


Fig. 2. Simplified scheme of a gas microturbine engine

Based on the above considerations, in this work de gas microturbine engine dynamics is modeled as a conventional gas turbine, as discussed in [1, 4, 5]. The model includes a speed control, a temperature control and a fuel control.

The detailed dynamic modeling of the microturbine engine is carried out by using SimPowersSystems of MATLAB/Simulink [6, 7]. The microturbine engine general model including control system algorithms is presented in Figure 3. Temperature of reference (Tref), angular speed of reference (Wref) and electromagnetic pair (Te) are used as inputs in the full model.

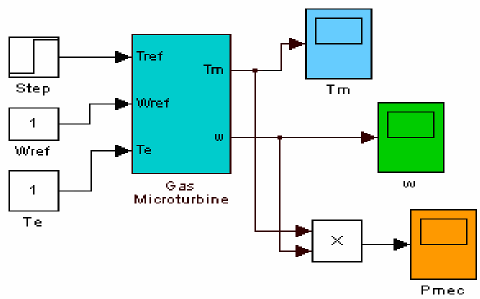


Fig. 3. General model of the gas microturbine engine implemented in MATLAB/Simulink.

The internal structure of the microturbine general model is shown in Figure 4. It consists basically of three blocks: the gas microturbine itself and the control system consisting of a speed control or governor and the temperature and fuel (gas) injection control (also known as acceleration control).

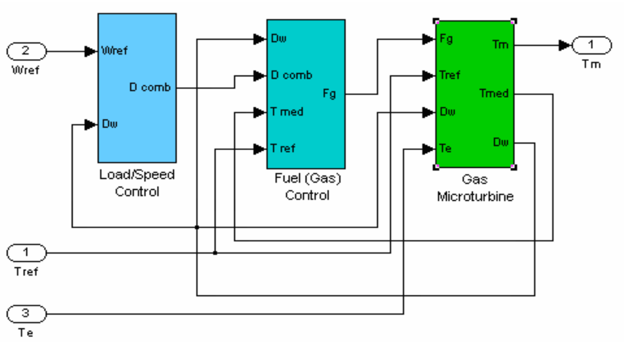


Fig. 4. Microturbine internal structure

#### *1) Speed/Load Control*

The diagram of the speed/load control implemented in MATLAB/Simulink is portrayed in Figure 5. The signals for the speed governor are compared with the reference speed value and then incorporated into a proportional-integral (PI) controller block previously being limited the maximum and minimum values of the signal. The PI controller includes a droop feedback in order to allow either droop or isochronous operation of the microturbine system, acting as a result as a first-order lag-compensator.

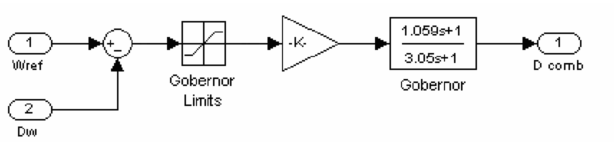


Fig. 5. Speed/load control implemented in MATLAB/Simulink.

#### *2) Fuel control or gas injection*

The fuel control scheme (or gas injection control) is shown in Figure 6. The input signals consist of the fuel demand signal Dcomb from the speed control, the measured exhaust temperature Tmed from the gas microturbine and the speed deviations Dw which is compared to the speed reference. The output signal of the model is the fuel flow Fg.

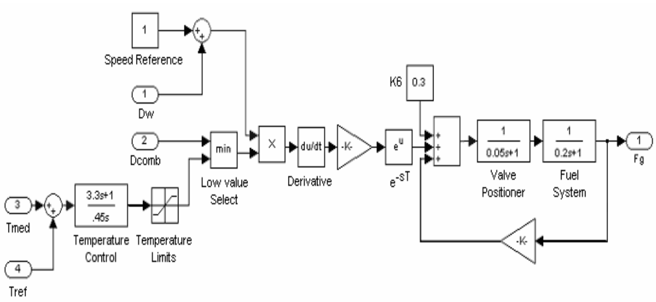


Fig. 6. Fuel (Gas injection) control system

The measured exhaust temperature Tmed is compared to Tref so that the error acts on the temperature controller. Normally Tmed is lesser than Tref causing the temperature controller to be at its maximum limit. In case Tmed exceeds Tref, then the controller will fall off the limit and goes to the point where its output takes over as the demand signal for fuel through the "low value select" block [2]. This signal corresponds to the mechanical power in steady-state and is offset after being scaled by K6, which represents the fuel flow at no load. The output of the fuel systems is directly the fuel flow Fg.

*3) Gas Microturbine*

The gas microturbine block diagram is depicted in Figure 7. The fuel flow Fg is burned in the combustor. The input signals to the gas microturbine are the fuel flow signal Fg from the prior gas injection control, the speed deviation Dw, the electromagnetic torque Te and the reference temperature Tref. The output signals are: the mechanical torque Tm, the measured exhaust temperature Tmed and the speed deviation Dw. Tmed is then feedbacked to the required inputs of other blocks [2].

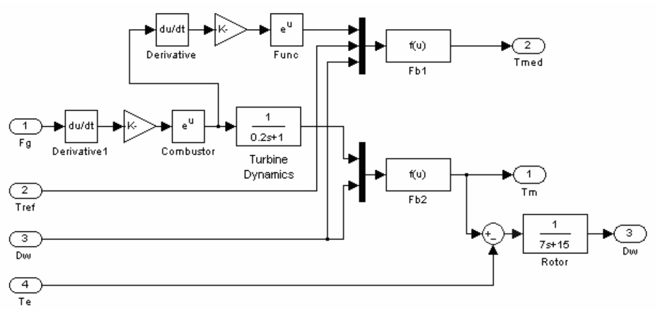


Fig. 7. Gas microturbine

*B. Permanent Magnet Synchronous Generator*

Electric power is generated by using a brushless permanent magnet synchronous generator which is coupled to the microturbine axis, as depicted in Figure 1. Essentially, a PMSG is similar in configuration to a conventional synchronous alternator with the electrical excitation system replaced by permanents magnets [2]. The benefits of using permanents magnets include the elimination of the brush/slip ring system. The output frequency of the AC voltage of the PMSG for microturbines is very high, up to 10 kHz. The generator also acts as a starting motor that allows the microturbine to start and to put the unit into operation.

The equations describing the PMSG dynamic behavior in the rotor reference frame *(dq* frame*)* are stated below. The electrical and mechanical parts of the machine are both represented by a second-order state-space model.

Electrical system equations:

The electrical system makes use of a sinusoidal model, which assumes that the flux established by the permanent magnets in the stator is sinusoidal, implying sinusoidal electromotive forces.

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

$$\frac{d}{dt} i_q = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q + \frac{L_d}{L_q} \omega_r i_d - \frac{\lambda \omega_d}{L_q} \qquad (2)$$

$$T_e = \frac{3}{2} p \left[ \phi_m i_q + (L_d - L_q) i_d i_q \right]. \qquad (3)$$

where:

$L_q$, $L_d$ - *q* and *d* axis inductances
$R$ - Resistance of the stator windings
$i_q$, $i_d$ - *q* and *d* axis currents
$v_q$, $v_d$ - *q* and *d* axis voltages
$\omega_r$ - Angular velocity of the rotor
$\lambda$ - Amplitude of the flux induced by the permanent magnets of the rotor in the stator phases
$p$ - Number of pole pairs
$T_e$ - Electromagnetic torque

Mechanical system equations:

$$\frac{d}{dt} \omega_r = \frac{1}{J} \left( T_e - F\, \omega_r - T_m \right) \qquad (4)$$

$$\frac{d\theta}{dt} = \omega_r \qquad (5)$$

where:

$J$ - Combined inertia of rotor and load
$F$ - Combined viscous friction of rotor and load
$\theta$ - Rotor angular position
$T_m$ - Shaft mechanical torque

*C. Power Conditioning System*

The power conditioning system (PCS) of the microturbine system is employed as interface between the high frequency PMSG (various kHz) and the low frequency (50-60 Hz) utility distribution grid. This power electronic device consists mainly of two distinctive blocks, i.e. an uncontrolled three-phase diode-rectifier bridge, and a voltage source inverter including the dc bus capacitors, as shown in Figure 8.

*1) Three-phase Diode-rectifier Bridge*

Since microturbine rotates at high speeds, the AC power generated from the PMSG is at high-frequency. This feature demands using an AC-AC frequency converter. The first stage of this device is carried out by an uncontrolled three-phase diode-rectifier bridge which is simple, robust and cheap. Furthermore it does not require a control circuit. The output terminals of the rectifier are linked to a DC-bus, which is also shared with a three-phase power inverter [8].

*2) Three-phase Power Inverter*

The conversion of DC power from the rectifier to AC power suitable for being connected to the utility grid is performed by a power inverter. The proposed inverter corresponds to a DC-to-AC voltage source inverter (VSI) using Insulated Gate Bipolar Transistors (IGBTs) [9]. In the distribution voltage level, the switching device is generally the IGBT due to its lower switching losses and reduced size. In addition, the power rating of power devices is relatively low. As a result, the output voltage control of the VSI can be achieved through pulse width modulation (PWM) by using high-power fast-switched IGBTs.

The VSI structure is designed to make use of a three-level pole structure, also called neutral point clamped (NPC), instead of a standard two-level six-pulse inverter structure This three-level inverter topology generates a more sinusoidal output voltage waveform than conventional structures without increasing the switching frequency. In this way, the harmonic performance of the inverter is improved,

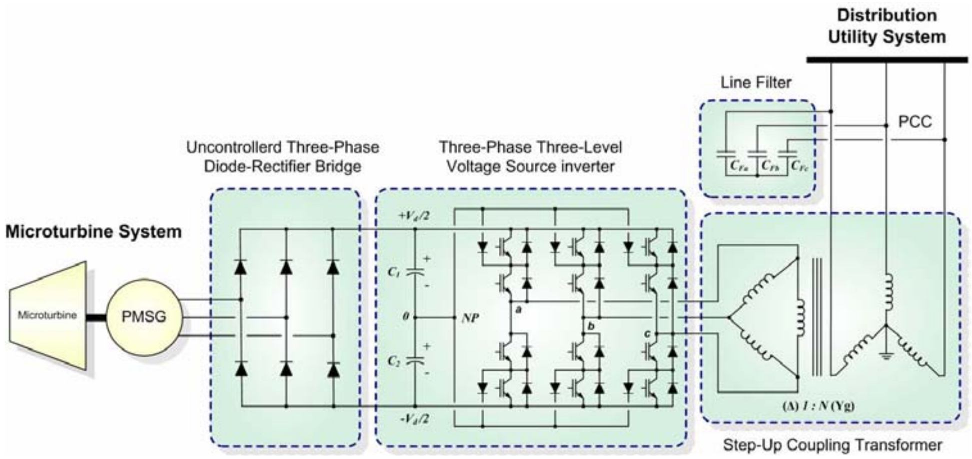


Fig. 8. Detailed model of proposed power conditioning system for microturbine for distributed generation

also obtaining better efficiency and reliability respect to the conventional two-level inverter.

A pair of capacitors is used as energy storage device to interface both, the rectifier bridge and the power inverter. The connection of the inverter to the distribution utility system can be carried out through a coupling step-up transformer in order to meet the voltage level requirements when necessary.

*3) Control of the microturbine PCS*

Figure 9 illustrates the simplified control scheme of the microturbine power conditioning system. The main purpose of this controller is to transfer the active power generated by the microturbine into the utility grid. This objective is fulfilled by regulating the DC bus voltage $V_d$ at a constant value via a proportional-integral (PI) controller, yielding a direct current reference $i_{dr}$ to the VSI. This is achieved by forcing a small active power exchange with the electric grid for compensating the transformer winding and VSI IGBTs losses while exchanging AC power with the utility grid. A reactive power generation of the VSI is possible through a reference value of $i_{qr}$, which should set at 0 when not required. It is to be noted that a simplified stated-space model of the VSI in the *dq* frame, which is detailed in depth in [9], is employed for generating the control pulses for the VSI IGBTs.

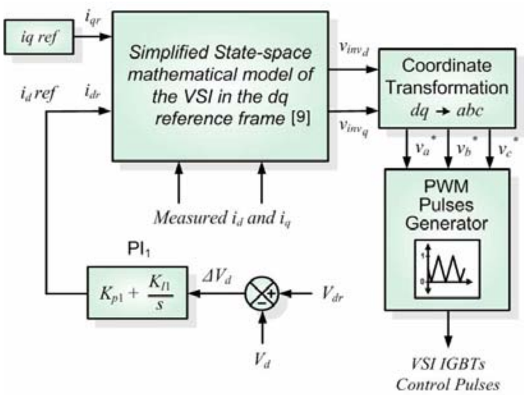


Fig. 9. Control of the microturbine PCS

## III. MODEL IMPLEMENTATION AND SIMULATION

In order to validate the proposed models and control schemes, a test system consisting of a microturbine system connected to a distribution utility grid is simulated by using SimPowersSystems of MATLAB/Simulink, as shown in Figure 10. Under this scenario, the 3 kV/5 MVA distribution utility is modeled as an infinite bus. The supply voltages and currents are balanced and in steady state.

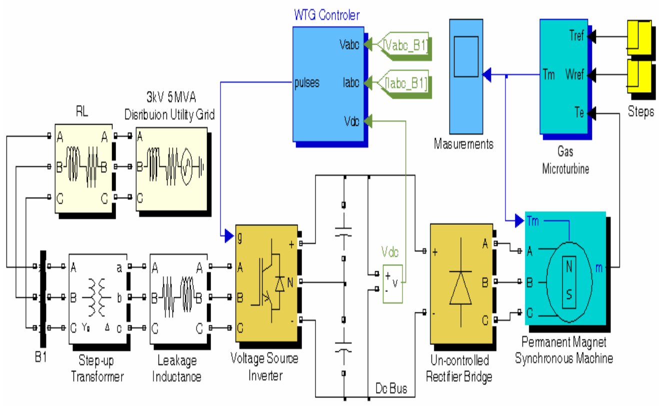


Fig. 10. Simulink implementation of the Microturbine system connected to the Distribution Grid

Digital simulations were carried out in discrete time with a fixed-step size of 25 µs as described in the following. The microturbine system was tested by imposing different disturbances, including a step change in: a) electromagnetic torque or load Te, b) reference angular speed Wref and c) reference temperature Tref.

*1) Step increase in the electromagnetic torque Te*

In this first case, a 1 % increase in the electromagnetic torque is applied at t=3 s. The simulation results for the mechanical torque, the rotor speed and the mechanical power are shown in Figure 11. As can be observed, the microturbine ramps up at about 2 s in order to balance the power variations occurred after applying the disturbance. It is to be noted the fast dynamic response of the entire high-speed microturbine system.

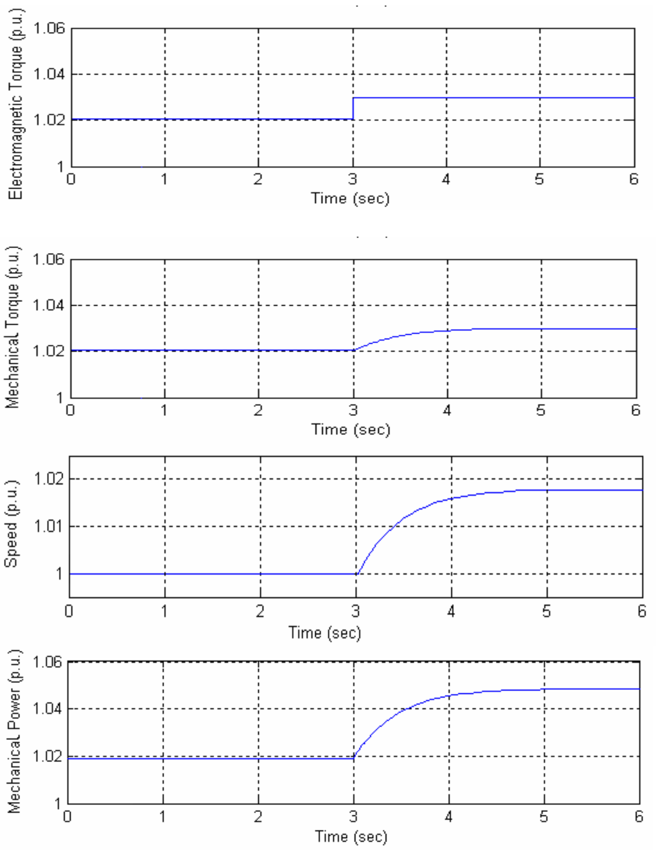


Fig. 11. Simulation results for a step increase in the electromagnetic torque Te

*2) Step increase in the reference angular speed Wref*

A 3 % increase in the reference angular speed is applied at t=3 s. The simulation results for the mechanical torque and the mechanical power are shown in Figure 12. As can be examined, the microturbine ramps up at about 1 s in order to increase the mechanical torque and thus the power for reaching the new reference speed. As can be seen, the dynamic response of the microturbine system is faster than the previous case, which applies a disturbance in the electromagnetic torque. This feature of higher sensibility to the disturbance is dependent of its point of entry. In the case of Wref deviation, the perturbation is directly applied to the microturbine model while in the prior disturbance case, Te is indirectly applied via the rotor dynamics which has a damping effect over the disturbance. In this way, the microturbine system is more robust to speed reference variations.

*3) Step increase in the reference temperature Tref*

In this case, a 3 % increase in the reference temperature is applied at t=3 s (base temperature, 1000ºC). The simulation results for the mechanical torque, the rotor speed and the mechanical power are shown in Figure 13. As can be noted, the reference temperature deviation is small enough as to produce a noticeable effect over all variables shown, contrary to the disturbances of both previously presented cases. Much larger variations in the reference temperature are expected to influence the performance of the gas microturbine engine and thus both the electrical power/torque output and efficiency of the machine. In this way, the microturbine system is robust enough to reference temperature variations because of the action of the temperature control.

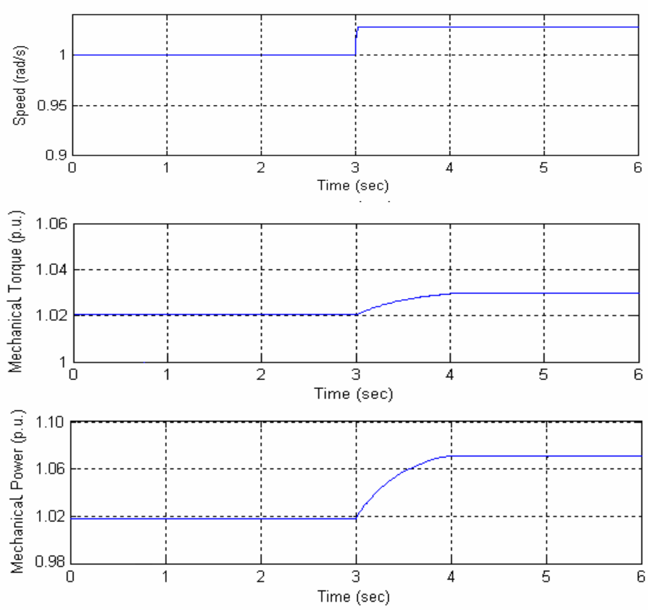


Fig. 12. Simulation results for a step increase in the reference angular speed Wref

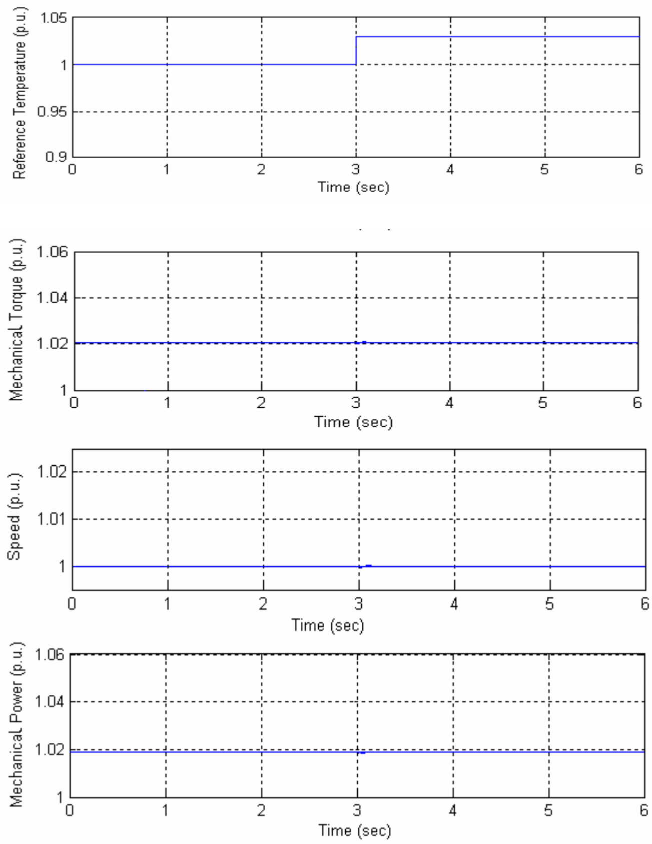


Fig. 13. Variation of outputs due to perturbation in Tref

Finally, Figure 14 depicts major electrical variables of the microturbine system connected to the distribution system for a load dispatch of about 1.2 kW. As can be observed, the permanent magnet synchronous generator output RMS voltage is about 180 V and the rated frequency reaches almost 760 Hz. In the same way, the PMSG output RMS current is around 7 A at the same rated frequency. The voltage at the DC bus of the three-level VSI, i.e. the rectified and filtered DC voltage from the PMSG AC output voltage, is effectively controlled by the inverter in order to be kept constant at a rated value of 200 V. In the output AC side of the microturbine global system, also called point of common coupling (PCC) to the electric distribution grid, the voltage reaches about 3 kV RMS via the step-up transformer (base voltage used, 5.3 kV) and the frequency is converted to 50 Hz by the three-phase inverter.

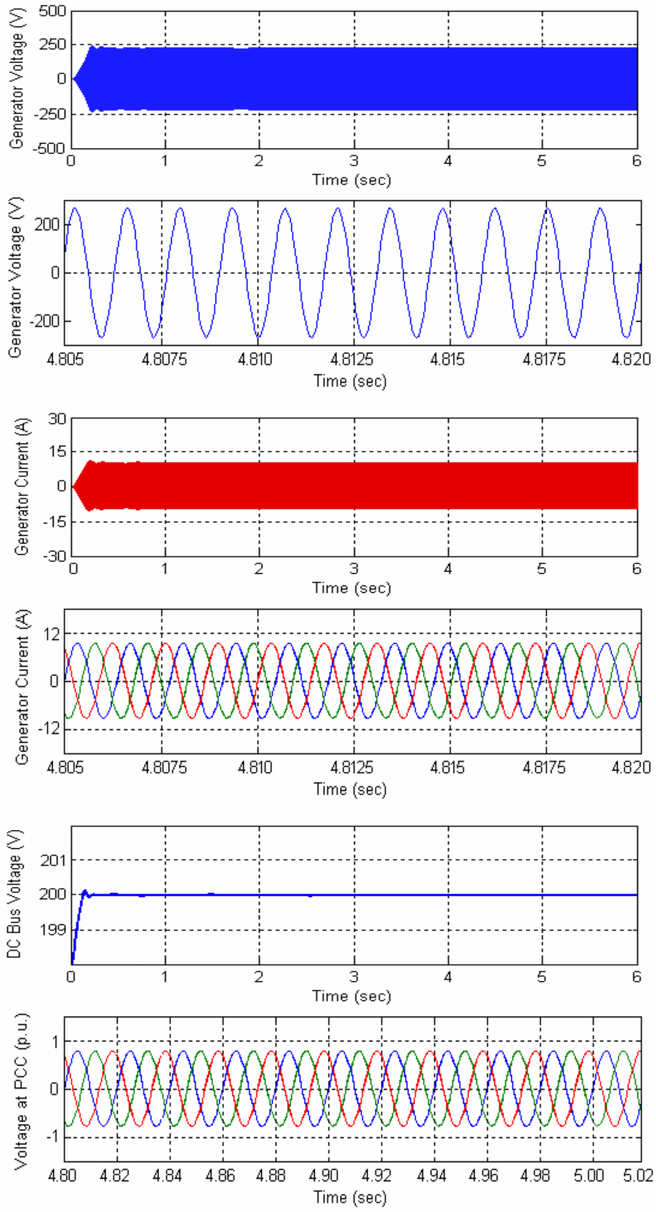


Fig. 14. Ac and DC voltages and currents

## IV. CONCLUSION

In this paper, a detailed model of a gas microturbine system for distributed generation is proposed. The model is developed by using MATLAB/Simulink. Dynamics of each part comprising the gas microturbine system, i.e. the gas microturbine engine, the PMSG, the three-phase diode bridge and the three-phase three-level VSI, are built by employing predefined models of SimPowerSystems and basic Simulink components. Simulation results permit concluding that the model proposed is adequate for both, steady-state and transient performance studies under different operating conditions. It can be used for analyzing the impact of incorporating combustion microturbines as distributed generators.

## ACKNOWLEDGEMENT

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