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Simulation & Analysis of Performance of DER in Smart Grid Using Micro-Turbine

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Abstract:

Decentralized Generation (DG) is expected to play a vital role in the future of electric power system. The power electronics interfaced micro-turbine generation systems are currently attracting lot of attention to meet different needs both at end consumers and the distribution utility levels. Dynamic modeling of the micro-turbine is a challenging process because manufacturers do not readily provide model data, if any exist at all. In this paper a proposed micro-turbine DG dynamic model is developed in Matlab-Simulink and implemented using a test system built with SimpowerSystem block set. The proposed model is interfaced with the electrical system using a simplified Voltage Source Inverter (VSI) model. This model supports power system applications as long as harmonics are not the main concern.

For many techno-economical reasons, the amount of DG systems is expected to increase rapidly, especially for rural electrification. Therefore, this paper investigates the autonomous operation of micro-turbine DG system with a Voltage- frequency (V-f) control strategy. Test and validation results of the proposed dynamic simulation model and the proposed inverter controller are presented. Analysis of results shows that the proposed micro-turbine DG model has the advantage of generalized structure so that it can be used for performance testing of different micro-turbine commercial types, and it could be used for simulation and study of different DG applications by establishing proper interfacing and controllers.

Index Terms :

Decentralized Generation (DG), Micro-turbine Model, Voltage Source Inverter (VSI) Model, PID speed Controller, V-f control.

1.INTRODUCTION:

Decentralized Generation (DG) systems are small generating plants serving a customer on-site or providing support to a distribution network [1]. Micro-turbines are offering one of the best distributed power production options. Because of their small size, relatively low capital costs, expected low operations and maintenance costs, and automatic electronic control, micro-turbines are expected to capture a significant share of the DG market. In addition, micro-turbines offer an efficient and clean solution [2, 3]. In the last decade, most of the research efforts were focused on the modeling of steady state characteristics of DG units [4]. This means that they are not realistic models, because they do not capture the dynamic nature of the real power system. More accurate and realistic dynamic models could help in solving real power grid problems.For many technical and economical purposes, the amount of DG systems is expected to increase rapidly, especially for electrification of remote communities. More accurate models of DGs will help in reducing the cost of studies of integrating DGs in Egyptian distribution network.

Dynamic Modeling of DGs is a challenging process because the manufacturers do not readily provide model data, if any exist at all [5]. The literature on the micro-turbine as a DG unit is scarce [6]. A short review of most of the literature is presented here. A dynamic model for combustion gas turbine has been discussed in [7-10]. In 1983, a mathematical combustion gas turbine model was developed by Rowen to represent the gas turbine dynamics [7]. Since 1993, a working group proposed an extension of this work, including speed, temperature, acceleration and fuel controls [8-9]. However these research efforts deals with heavy-duty combustion turbine used as a conventional central generation system directly connected to the main grid. A nonlinear model of the micro-turbine is proposed and tested using NETOMAC software [11].

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The model was based on the Nern's non-linear long term model of a gas turbo-generator set [12]. Modeling of micro-turbine was reported in [13] and [14] where the authors developed a model of the grid connected micro-turbine converter. In [15], a linear model of the micro-turbine was adopted and compared to a first order transfer function. The dynamic behavior of the grid connected split shaft micro-turbine is discussed in [16] where the authors were interested in analyzing thermodynamics and electromechanical stability of microturbines. It can be concluded that an accurate model of the power electronic interfaced micro-turbine generation system is required to design and test different control strategies adopted for off-grid and grid connected applications, as well as analyzing different dynamic stability aspects. In this project work, a dynamic model of micro-turbine DG is proposed based on utility experience test data and a simplified mathematical description of heavy duty gas turbine, and scaled down to distribution system applications. A simplified model is proposed for the Voltage Source Inverter (VSI) power electronics interface of the DG system. The proposed VSI model is based on energy conversion principle to simplify the test and validation of the proposed computer model. Thereafter, the proposed model is tested for autonomous or stand-alone operation with the design of a proper V-f controller. All the proposed modules are built using Matlab- Simulink and SimpowerSystem block set.

2. SINGLE SHAFT MICRO-TURBINE:

Micro-turbine used in this study is considered to be small combustion turbine, with installed capacity of 25 to 500 kW and very high rotation speeds (between 50.000 and 120.000 rpm) [17-18]. This research paper is focused on the single shaft type. A Single Shaft micro-turbine has a single rotatingshaft, with the generator, air compressor, and turbine mountedon air bearings. The shaft operates at high speed without anylubrication. The power plant is an air-cooled, two polepermanent magnet generator. The shaft turns between 50,000and 120,000 revolutions per minute [11]. The generatorprovides a high frequency ac voltage source (angularfrequencies up to 10,000 rad/sec) [3]. Because the turbines runat high speeds, the ac generator is a high frequency generatorthat cannot be coupled directly to the ac grid. An intermediatedc link is used, a dc capacitor fed from the diode rectifier [19].

3. MICROTURBINE GENERATION SYSTEM MODELING AND CONTROL:

Gas turbine performance is characterized by utilizing real field test data from utility experience, by capturing the main dynamics of the heavy duty gas turbine over a wide range of operating conditions [20]. In this research paper authors used this approach in combination with the simplified mathematical representation of heavy duty gas turbines presented in [7]. The rated power of the model is scaled down to needs required for rural electrification. The method used to model the micro-turbine DG system is based on dividing the whole system to three modules as shown in Fig.1:

• Module 1: The micro-turbine mechanical and fuel systems.

• Module 2: The permanent magnet synchronous generator and the ac/dc rectifier

• Module 3: The dc/ac voltage source inverter (VSI), and the PWM controller.

The following sections present detailed description and modeling of each part.

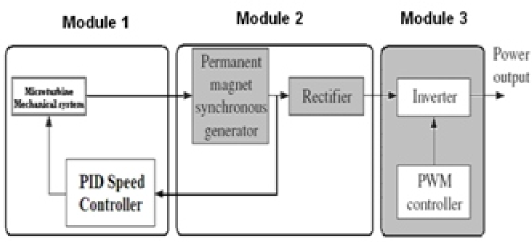

Fig. 1 Proposed Micro-turbine Generation System Model

A. Module 1: microturbine Mechanical and Fuel Systems:
Module Description:

Micro-turbines operate based on the thermodynamic cycle known as the Brayton cycle [17].

1) Mathematical and control function:

turbine speed controller signal (VCE). The valve positioner can be represented by the following transfer function [7]:

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$$VP = \frac{a}{bS+C} \quad (1)$$

Where a, b, and c are the valve positioner constants. The fuel system is presented by the following transfer function:

$$FS = \frac{1}{T_f S+1} \quad (2)$$

Where TF: is the fuel control time constant in seconds. The fuel combustion process in the combustor is presented by the following transfer function:

$$CB = e^{-E_{CR}} \quad (3)$$

Where ECR: is the combustion reaction time delay in seconds. The transfer function representing the hot computation gas expansion is expressed as follow:

$$CD = \frac{1}{T_{CD}+1} \quad (4)$$

Where TCD is: the discharge volume time constant in seconds. The produced mechanical torque driving the electric generator is presented by the following equation [7]:

$$T_{M=1.3(CD-0.23)+0.5(1-N)} \quad (5)$$

Where N is: the per unit rotor speed. For purposes of micro-turbine temperature control, the turbine temperature is calculated as follow:

$$T_{X=T_R-700(1-e^{-SE}rd)+550(1-N)} \quad (6)$$

Where ETD is: the turbine exhaust delay in seconds. Despite huge advances in the field of control systems engineering, Proportional Integral Derivative (PID) controller is still the most common control algorithm for industrial applications used today, therefore it is applied in this paper for the micro-turbine speed control. The tri-function controller model described in this work has the following control functions [8]:

1. Woodward PID Speed control acting under partial load conditions,

2. Temperature control acting as an upper output power limit, and

3. Acceleration control to prevent over speed.

The output of these control function blocks are the inputs to a least value gate (LVG), whose output is the lowest of the three inputs and results in the least amount of fuel to the compressor-turbine. The temperature is transferred through the radiation shield to the thermocouple. The radiation shield is presented by the following transfer function [7]:

$$RS = 0.8 + \frac{2}{15S+1} \quad (7)$$

And the thermocouple transfer function is given as:

$$TC = \frac{1}{2.5+1} \quad (8)$$

The turbine temperature is compared to the desired reference value and controlled by a temperature Proportional Integral (PI) controller with the transfer function.

$$T_{control} = \frac{3.3S+1}{T_T+S} \quad (9)$$

B. Module 2 :

The Permanent Magnet Synchronous Generator (PMSG) and the AC/DC The model of the generator is a two-pole permanent magnet synchronous machine (PMSM) with a non-salient rotor . The model is derived based on the generalized theory of electrical machines . In the proposed model, both electrical and mechanical parts of the machine are presented by a second-order state-space model. The flux established by the permanent magnet in the stator is assumed to be sinusoidal, which implies that electromotive forces are sinusoidal waves. The Electro-mechanical equations of the (PMSG) are described as follows in the synchronous rotor reference frame (d-q frame) .

1) Mechanical Equations:

$$\frac{dw_r}{dt} = \frac{l}{j}(T_e - Fw_r - T_{m)}$$
(10)

$$\frac{d\theta}{dw} = w_r$$
(11)

Where,
w_r: Angular velocity of the rotor.
λ: Flux induced by the PMSG in the stator windings.
p: Number of pole pairs.
T_e:Combined viscous friction of rotor and load.
θ: Rotor angular position.
T_m: Shaft mechanical torque.

4. PERMANENT MAGNET SYNCHRONOU MACHINE (PMSM):

Microturbine produces electrical power via a high-speed generator directly driven by he turbo-compressor shaft.

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Small gas turbines benefit in particular when the gearbox that reduces the shaft speed to the speed of conventional electrical machines is eliminated, as is the case with the single-shaft designs considered here. The result is a more efficient, compact and reliable machine and the shaft speed is normally above 30,000 rev/min and may exceed 100,000 rev/min. 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 machine (PMSM) with non- salient rotor.

High energy permanent magnets and high yield-strength materials like neodymium-iron-boron (NdBFe) or Samarium-cobalt magnets have proved very suitable for high-speed electrical machines in the following sections the equivalent circuit of a permanent magnet synchronous machine (PMSM) is presented along with a brief description of its construction, operation and the permanent magnet materials.

In a permanent magnet synchronous machine, the dc field winding of the rotor is replaced by a permanent magnet. The advantages are elimination of filed copper loss, higher power density, lower rotor inertia, and more robust construction of the rotor. The drawbacks are loss of flexibility of field flux control and possible demagnetization. The machine has higher efficiency than an induction machine, but generally its cost is higher.

A. Structure of the Permanent Magnet Machine:

The cross-sectional layout of a surface mounted permanent magnet motor is shown in Fig.5.2.

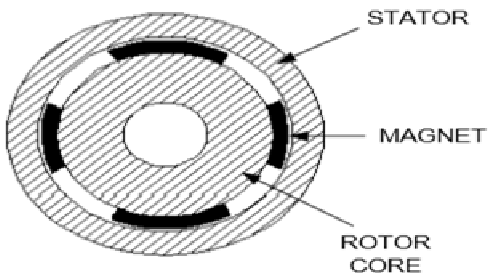

Fig.-2 Structure of the permanent magnet synchronous machine [3]

The stator carries a three-phase winding, which produces a near sinusoidal distribution of magneto motive force based on the value of the stator current. The magnets are mounted on the surface of the motor core. They have the same role as the field winding in a synchronous machine except their magnetic field is constant and there is no control on it .

B.Classification of Faults in PMSM:

Replacing rotor field windings and pole structure with permanent magnets makes the motor as brushless motors. Permanent Magnet Synchronous Machines (PMSM) can be designed with any even number poles. Greater the number of poles produces greater torque for the same level of current [1]. Surface Mounted PMSM and Interior PMSM are two types of PMSMs. In SPMSM magnets are mounted on the rotor, air gap is large hence armature reaction is negligible. Whereas in IPMSM, magnets are buried inside the rotor, rotor is robust and air gap is uniform hence suitable for high speed operation. Most frequently occurring faults in PMSM can be classified as:

- Faults related to electrical structure
- Faults related to mechanical structure

The important applications of permanent magnet synchronous machine are in the wind and microturbine based distributed generation systems. One of the major advantage of PMSM is the possibility of super high speed operation leading to a very small unit as the size of the machine decreases almost in directly proportion to the increase in speed. The mathematical model of a PMSM is similar to that of the wound rotor synchronous machine. The following assumptions are made in the modelling. Saturation is neglected although it can be taken into account by parameter changes.The induced EMF is sinusoidal. Start upinverter Eddy currents and hysteresis losses are negligible. There are no field current dynamics. Arrangements for MTG system. There is no cage on the rotor. With the above assumptions the stator dq-axis voltage equations of the PMSM in the rotor reference frame are given by

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + w_r L_d i_d + w_r \gamma_m$$

$$T_e = 1.5P(\gamma_m i_q + (L_d - L_q) i_q i_d)$$

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

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T_e is the electromagnetic torque, B is combined viscous friction of rotor and load, ω_r is the rotor speed, and J is the moment of inertia, B_r is rotor angular position and Tm is shaft mechanical torque. This is the standard current dynamics model (for control purposes) of a PMSM where, the stator resistance is denoted by R" the d-axis and q-axis inductances are L_d and L_q respectively, A_m is the flux linkage due to the permanent magnets, V_dand V_q are dq- axis voltages, ω_r is the rotor speed, i_dand i_q are the dq-axis current components. The d and q- axis equivalent circuit of PMSM is shown in Fig.

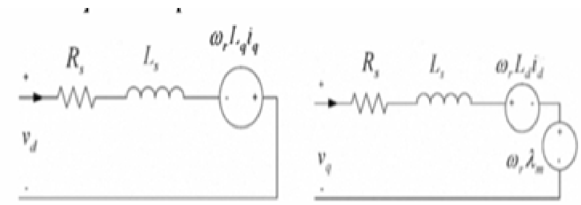

Fig.-3:dq-axis equivalent circuit model of the PMSM (a) d-axis(b) q-axis

Rectifier:- The rectifier circuit is used to convert the high frequency ac output of the PMSG terminals into dc power. The rectified direct current is fed into an inverter that interfaces with the ac electric power system. The model of the 3 phase rectifier bridge is obtained from SimpowerSystem block set.

C. Module 3: The dc/ac voltage source inverter (VSI), and the PWM controller.

C.1: VOLTAGE SOURCE INVERTER(VSI)

Inthis chapter the application of a Voltage Source Inverter (VSI) as a new controller unit is investigated. The dynamic and steady-state behaviour of the conniver will be considered. Furthermore. The overdo control range is sided and verified, and the rating of the controller components is discussed.VSI drives work with both induction and synchronous motors, some CSI drives also work with induction and synchronous motors, but LCI drives are limited to only synchronous motors.Single-phase VSIs cover low-range power applications and three-phase VSIs cover the medium- to high-power applications. The main purpose of these topologies is to provide a three-phase voltage source, where the amplitude, phase, and frequency of the voltages should always be controllable.

Although most of the applications require sinusoidal voltage waveforms (e.g., ASDs, UPSs, FACTS, var compensators), arbitrary voltages are also required in some emerging applications (e.g., active filters, voltage compensators). The standard three-phase VSI topology is shown in Fig. and the eight valid switch states are given in Table 14.3. As in single-phase VSIs, the switches of any leg of the inverter (S1 and S4, S3 and S6, orS5 and S2) cannot be switched on simultaneously because this would result in a short circuit across the dc link voltage supply. Similarly, in order to avoid undefined states in the VSI, and thus undefined ac output line voltages, the switches of any leg of the inverter cannot be switched off simultaneously as this will result in voltages that will depend upon the respective line current polarity. Of the eight valid states, two of them (7 and 8 in Table 14.3) produce zero ac line voltages. In this case, the ac line currents freewheel through either the upper or lower components.

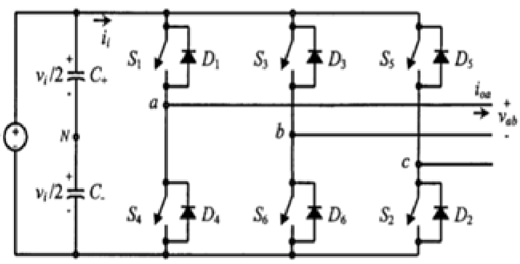

Fig.4 Voltage source Inverter

The remaining states (1 to 6 in Table 14.3) produce non-zero ac output voltages. In order to generate a given voltage wave- form, the inverter moves from one state to another. Thus the resulting ac output line voltages consist of discrete values of voltages that are v_i, 0, and -v_i for the topology shown in Fig. The selection of the states in order to generate the given waveform is done by the modulating technique that should ensure the use of only the valid states.

C.2: Operating properties:

The primaryobjective of the VSI-based controller is to introduce a semiconductor controlled device which is capable of emulating the characteristics of the excitation capacitors and injecting adequate reactive power into the induction generator and the load. The secondary objective is the regulation of the real power. Theproposed controller employees a DCside resistor such that the unwanted real power will be consumed in this resistor.

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As a consequence, the induction generator will always observe a constant real power demand. This VSI-based controller canreplace the earlier reported impedance controller and eliminates the need for excitation capacitor. Due to the nature of the VSI-based controller, a wider control rangethat cm accommodate various control operations of the overdo system is achievable. Thecontroller is capable of delivering or receiving real and reactive power. This control should beperformed in such a waythat the real and reactive power components cm be controlled independently. Moreover, the VSI-based controller should beable to respond rapidly to the control commands, and drive the operating point of the system to the desired one.

C.3: PWM (Pulse Width Modulation):

Pulse-width modulation (PWM) is a technique used to encode a message into a pulsing signal. It is a type of modulation. Although this modulation technique can be used to encode information for transmission, its main use is to allow the control of the power supplied to electrical devices, especially to inertial loads such as motors. In addition, PWM is one of the two principal algorithms used in photovoltaic solar battery chargers,the other being MPPT.

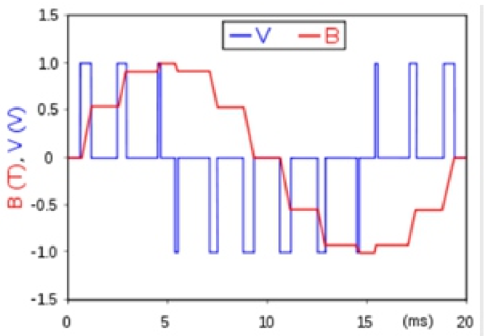

Fig-5 PWM Wave

The average value of voltage (and current) fed to the load is controlled by turning the switch between supply and load on and off at a fast rate. The longer the switch is on compared to the off periods, the higher the total power supplied to the load. The PWM switching frequency has to be much higher than what would affect the load (the device that uses the power), which is to say that the resultant waveform perceived by the load must be as smooth as possible.

Typically switching has to be done several times a minute in an electric stove, 120 Hz in a lamp dimmer, from few kilohertz (kHz) to tens of kHz for a motor drive and well into the tens or hundreds of kHz in audio amplifiers and computer power supplies.

The term duty cycle describes the proportion of 'on' time to the regular interval or 'period' of time; a low duty cycle corresponds to low power, because the power is off for most of the time. Duty cycle is expressed in percent, 100% being fully on.

The main advantage of PWM is that power loss in the switching devices is very low. When a switch is off there is practically no current, and when it is on and power is being transferred to the load, there is almost no voltage drop across the switch. Power loss, being the product of voltage and current, is thus in both cases close to zero. PWM also works well with digital controls, which, because of their on/off nature, can easily set the needed duty cycle.PWM has also been used in certain communication systems where its duty cycle has been used to convey information over a communications channel.(wikipidiya).

Types:

Three types of pulse-width modulation (PWM) are possible:

1.The pulse center may be fixed in the center of the time window and both edges of the pulse moved to compress or expand the width.

2.The lead edge can be held at the lead edge of the window and the tail edge modulated.

3.The tail edge can be fixed and the lead edge modulated.

5. MICROTURBINE MODELING AND ITS SUB BLOCK SIMULATION:

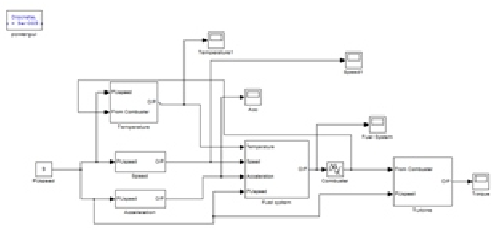

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Fig 6:Matlabsimulink of Micro-turbine and its sub-system.

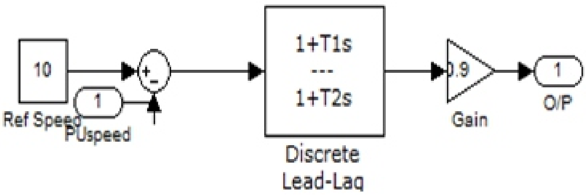


Fig 7:Matlabsimulink of Speed.

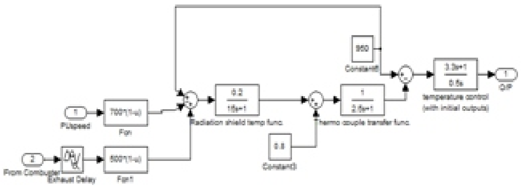


Fig 6.3 Matlab Simulink of Temperature

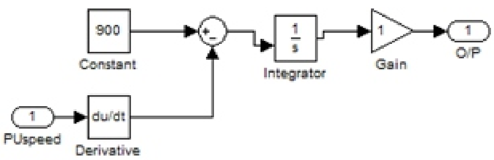


Fig 6.4 Matlab Simulink of Acceleration system

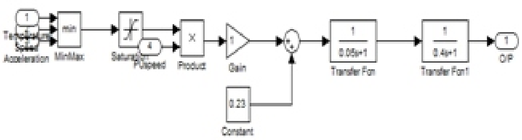


Fig 6.5 Matlab Simulink of Fuel system

5.1 Waveform of microturbine system.

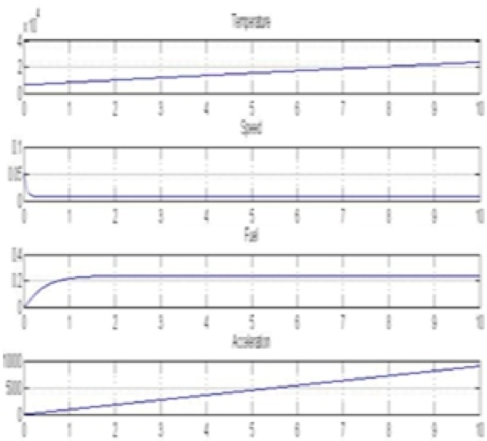
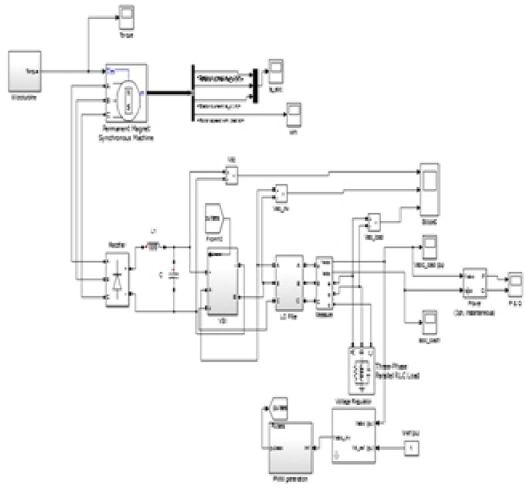


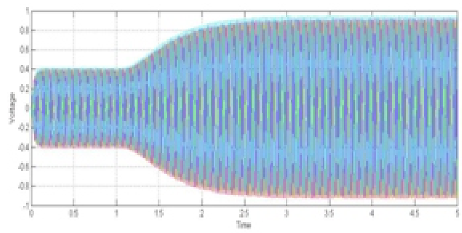
Fig 6.6 Matlab Simulink of microturbine system.

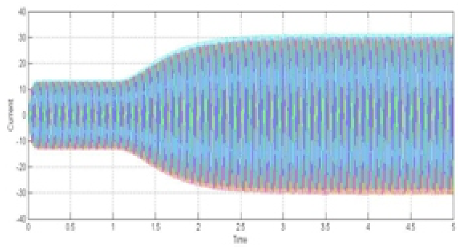
5.2Model of Micro-turbine with PMSM,VSI AND PWM.



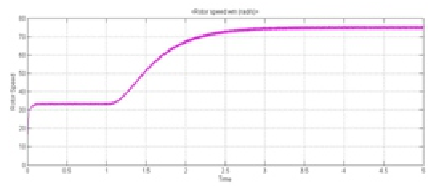
6.RESULTS:

6.1 Voltage VsTime ,CurrentVs Time

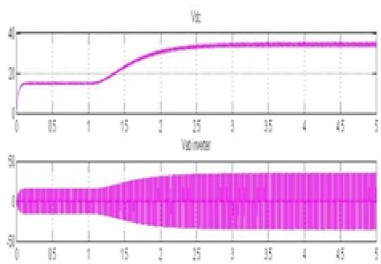




6.2 Rotor Speed



6.3 LC Filter waveform



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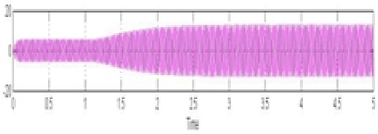

CONCLUSIONS:

This paper presents dynamic modeling micro-turbine DG system suitable for power studies. The micro-turbine Matlab-Simulink D as one block during a case study simulation variations. Test and validation of the propos DG model with the PID speed control, and controller, show that it works properly ac required mode and operation characteristics turbine PID controller allows constant speed f levels, within the generation capacity. The Voltage applied to autonomous operation proved to simple; and guarantees robust stability system load levels. The proposed model has the generalized structure which could be used for types of micro-turbines, and designing various strategies. to verify that the variations. This is segments of Pdc e. d increase.where variations in s at the ac and dc e accuracy of the of turbine is shows the results. controller loop is formed between a the micro-turbine its rated speed of ol g and control of system dynamic DG model is used ation with load micro-turbine the inverter V-f cording to the s. The proposed for different load f control method o be structurally m under different e advantage of testing different DG control.

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