MODELING OF DISTRIBUTED GENERATION SYSTEMS

A DISSERTATION
Submitted in partial fulfillment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
ELECTRICAL ENGINEERING
(With Specialization in Power Systems Engineering)

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CANDIDATE'S DECLARATION

I hereby declare that the work presented in this dissertation entitled **"Modeling of Distributed Generation Systems"** submitted in partial fulfillment of the requirements for the award of the degree of Master of Technology with specialization in Power System Engineering in the Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out from July 2005 to June 2006 under the guidance of **Dr. R.N.Patel,** lecturer, Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee.

I have not submitted the matter embodied in this report for the award of any other degree or diploma.

Date: 30 June 2006
Place: Roorkee

(K.SURESH KUMAR)

CERTIFICATE

This is to certify that the above statement made by the candidate is true to the best of my knowledge and belief.

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ABSTRACT

Consumers want an economical and uninterrupted electric power. It is crucial to the industrial consumers and wholesalers who have to pay the penalty for a blackout, if power is disconnected for any reason. Recently, distributed generation (DG) has become an attractive method of providing electricity to consumers and retailers. In addition, from the viewpoint of economic feasibility, the costs of installing the generators and producing the electricity can be comparatively inexpensive using the DG method. Furthermore, electrical or thermal efficiency can also be improved if the utilities use co-generation or a combined heat cycle.

In this thesis, dynamic models of small turbine generators [i.e. a Microturbine (combustion turbine), a Diesel engine], are used for analysis of their performance. Also, the detailed permanent magnet synchronous machine model is developed. Study of self-excited induction generator, salient-pole synchronous machine and the excitation system are obtained for the standard simulation. The simulation will be performed with an isolated load system. The machines are connected with a local load in order to develop the terminal voltage.

The goal of this thesis is to evaluate the performance microturbine and diesel engine energy systems through computer simulation studies. The primary focus of this study is the development of dynamic models for a standalone microturbine generation system and a diesel engine generation system. The system models developed is suitable in distributed generation studies.

A dynamic model for the microturbine generation system is achieved by integrating models of a microturbine and an electric generator driven by it. The model illustrates the dynamics of the microturbine and its control systems. A set of mathematical equations are used to model a permanent magnet synchronous machine acting as the electric generator of the microturbine generation system and study of self-excited asynchronous (induction) generator with microturbine generation system. The developed system is capable of simulating the dynamics of the microturbine generation system, demonstrating its ability to meet load requirements.

The dynamic model of the microturbine generation system is integrated using power electronics interfacing and model of diesel engine generation system are simulated in MATLAB/Simulink. Simulation results indicate the suitability of the developed model to study the dynamic behavior of the generation systems under different load conditions.

Keywords: Distributed generation, Microturbine, Diesel engine.

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CHAPTER-1

INTRODUCTION TO DISTRIBUTED GENERATION SYSTEMS

MOTIVATION:

The term "distributed generation" (DG) is defined as method of small power generation technologies, typically below 10-12MW of electrical output. Which can be sited at or near the load that they serve. Distributed generation systems will play a role in supporting available capacity to meet peak power demands, provide critical customer loads with emergency standby power, improve user power quality, and provide low cost total energy in CHP applications. According to the latter definition, DG may include any generation integrated into distribution system, commercial and residential back-up generation, stand-alone onsite generators and generators installed by the utility for voltage support or other reliability purposes.

The key success factor for Distributed generation systems in a competitive situation can be best described as "providing the customer with the lowest coast solution to meet his particular needs." i.e. "POWER FOR ALL". As shown in the figure 1.1

1.1 Present Power Production Situation :

Since the beginning of the twentieth century, the backbone of the electric power industry structure has been large utilities operating within well-defined geographical territories and within local market monopolies under the scrutiny of various regulatory bodies. Traditionally, these utilities own the generation, transmission, and distribution facilities within their assigned service territories; they finance the construction of these facilities and then incorporate the related capital costs in their rate structure which is subsequently approved by the relevant regulatory bodies. The technologies deployed and the siting of the new facilities is generally also subject to regulatory approval. [1][2][3]

The three major types of power plants have been constructed primarily:

- Hydro, either run-of-the-river facilities or various types of dams.
- Thermal, using either coal , oil, or gas
- Nuclear.

As we look into the future, other generation Technologies only had an incidental impact. All the three technologies mentioned above have their own sets of problems associated with them:

Given their friendly environmental impact, hydropower plants are most often the preferred generation technology wherever and whenever feasible. However, the identification of feasible new sites in highly industrialized countries is becoming increasingly difficult. In Highly developed countries, where the cost attractive traditional hydro facility sites have been almost entirely built, some power plants could be, and are, reconfigured to become pumped-storage facilities. On the other hand, while hydro electric power production is saturating within industrialized countries, it represents very significant development opportunities in several developing regions of the world. While hydro power plants do not create any pollution related to their daily operation, they do bring significant environmental and often common disorder when they are constructed.

Even though several pollution-abatement technologies are being successfully implemented, often at significant capital and operational costs, fossil fuel thermal power plants bring operating pollution problems that are becoming increasingly difficult to ignore. The emergence of a broad array of "green power" marketing initiatives provides yet another indication of the growing Concern regarding air pollution. While some parts of the world have significant coal reserves, a growing concern is the depletion of the world's increasingly scarce oil and gas reserves for the purpose of electricity production. Future generations will most probably need our remaining carbon resources to fulfill materials production requirements as opposed to as a raw energy source. [1][4]

Environmental concerns consent that nuclear power plants be located far away from population centers. These siting issues, as well as the need to share these large power production facilities within a official market structure, have required the construction of large, complex, and capital-Intensive electric power transmission networks. [1][4] These transmission networks have become an increasing source of concern as their sustained development becomes a problem from a right-of-way point of view and as their economic operation comes in midpoint under a deregulated electric utility industry. Ecological and environmental protection concerns, as well as political pressure, also often consent that new transmission facilities are constructed underground, which even further compounds the issue by imposing often unbearable construction cost impediment.

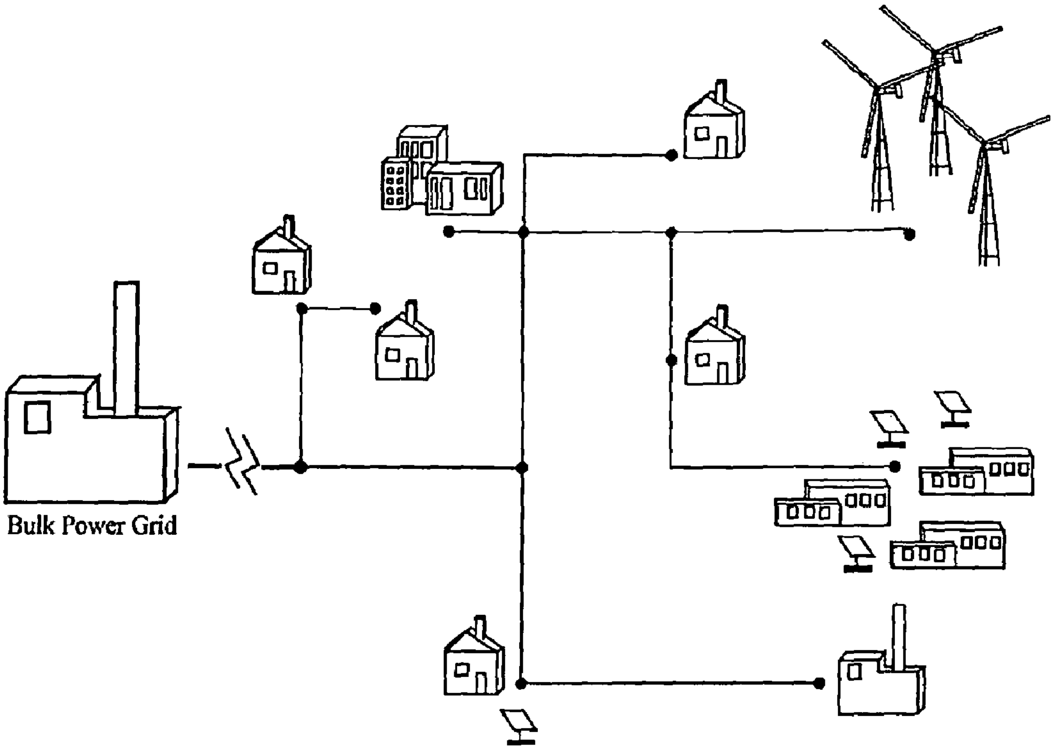


Figure 1.1 Future structure of the Distribution System with multiple Distributed Generators

1.2 Why Distributed Generation:

The purpose of distribution generation is to provide a source of active electric power. According to this definition, distributed generation does not need to be able to provide reactive power. DG is the best answer to energy supply shortfalls because the traditional electricity grid will never be able to satisfy today's needs for quantity or quality of power.

- First, the grid cannot be expanded fast enough to keep up with demand Even if more centralized generators are constructed; their output will be trapped inside insufficient transmission networks.
- Secondly, the traditional grid is susceptible to damage from falling trees, wildlife, and other interruptions that last any where from a few seconds to several hours.

1.3 Benefits of utilizing Distributed generation systems:

In many applications, DG technology can provide valuable benefits for both the consumers and the electric-distribution systems [5]. The small size and the modularity of DG encourage their utilization in a broad range of applications the downstream location of DG units in distributed systems reduces energy losses and allows utilities to postpone upgrades to transmission and distribution facilities.

The benefits of utilizing DG can be summarized as follows:

- improving availability and reliability of utility system
- voltage support and improved power quality
- reduction of the transmitted power and, as a result, the transmission and distribution expenditures are postponed or avoided
- power-loss reduction
- possibility of cogeneration applications
- emission reduction

1.4 Application of DG units :

DG can be used for different applications due to their small size, modularity and location in power systems. The main applications of DG units include the following fields [6]:

- generating the base-load power, as in the case of variable-energy DG sources
- providing additional reserve power at peak-load intervals
- providing emergency or back-up power to increase the stability and reliability of important loads
- supplying remote loads separated from the main-grid system
- supporting the voltage and reliability by providing power services to the grid
- Cooling and heating purposes

It is also possible to use DG to cover the load demand most of the time. In this case, DG has to be connected to a local grid for back-up power. Another possibility is to use energy storage devices to ensure the continuity of supplying the load.

1.5 Distributed Generation Technologies:

Distributed generation is any small-scale electrical power generation technology

That provides electrical power at or near the load site; it is either interconnected to the distributed system, directly to the customer's facilities or both.

There are number of technologies for DG, such as [1] [13]:

- Microturbines
- The internal combustion engine (Diesel Engine)
- Biomass
- Combined heat power (CHP)
- Wind Turbines
- Photovoltaic
- Fuel cells
- Small hydro and etc.,

1.5.1 Microturbines:

MTs are small high-speed gas turbines that produce power in the range of 25 to 500kW. They operate on the same principles of conventional gas turbines depending on Brayton (constant pressure) cycle. Small gas turbines are firstly developed by Allison in the 1960s, where the first application was to supply a radar set and engagement control station of U.S. Army Patriot Missile system [7].

Construction of Microturbines: The construction of the MT unit is shown in Fig1.2.

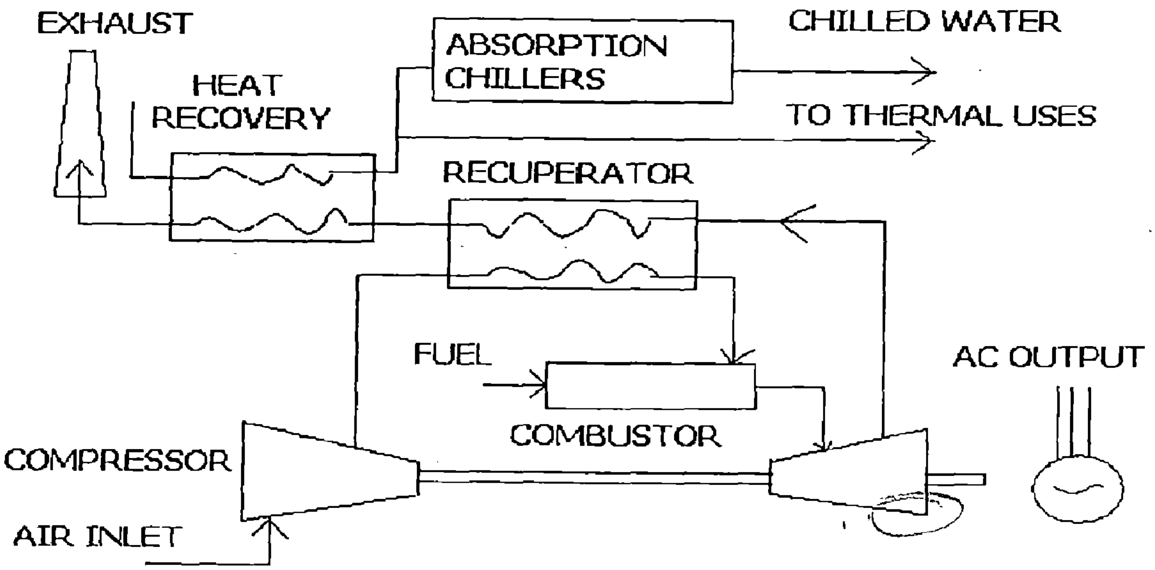


Figure 1.2. Construction of the microturbine unit

The main components include an air compressor, a combustor, a recuperator, a turbine and a generator. Filtered air at atmospheric pressure and temperature is pressurized in the compressor before entering the combustor. A controlled amount of injected fuel is mixed with the compressed air in the combustor and the mixture is ignited. The combustion products at high temperature and pressure flow and expand over the turbine blades to produce mechanical energy. Most constructions of MTs depend on a single shaft designed to rotate at high speeds in the range of 3000 to 120000rpm [8]. Hence, a high-speed Permanent Magnet Synchronous Generator "PMSG" is used to produce variable voltage AC power at high angular frequencies up to 10000rad/s. A part of the extracted horsepower in the turbine is used for driving the air compressor. The recuperator is used to improve the overall efficiency of the system by transferring the waste heat from the exhaust gas to the combustion air stream. The high frequency of the generated power can be reduced using cycloconverters or rectifier –inverter systems.

Advantages of microturbines :

The newly developed MTs have the following advantages [7]:

- low installation and infrastructure requirements
- low maintenance costs
- smaller and lighter than other engines with the same capacity
- reliable and durable due to the simplicity of the structure
- fuel flexibility since they can run on a variety of fuels including natural gas, diesel, ethanol, propane and gasoline
- high efficiency, with fuel energy-to-electricity conversion reaching 25%-30%
- possibility of cogeneration by using the waste heat recovery, which could achieve overall energy efficiency levels reaching 75%
- environmental superiority of MTs operating on natural gas

Applications of micro-turbines:

The availability of small, low cost, high efficient MTs is well suited for the following applications [7]:

- firm power for isolated communities, small commercial buildings and light industry

- peak shaving for utility-system in order to decrease the required incremental cost to serve additional loads
- standby and emergency power for more reliable operation of the utility and with important loads
- uninterruptible power supply (UPS) since they provide low initial cost, low maintenance requirements and high reliability

1.5.2 The Internal Combustion Engine:

The most important mechanism of the DG systems around the world has been the internal combustion engine because for urgent situations when the central power generation is not supplying at that time the diesel engine are used mostly at offices, institutes, house hold purpose. Through the diesel engine is efficient, starts up relatively quickly, it is not environmental friendly and has high O&M costs. Consequently its use in the development world is limited. In India, the diesel engine is used very widely on account of the immediate need for power, especially in rural areas, without much concern either for long term economies or for environment [1]. Operating experience with diesel and Otto cycle units is extensive. The cost units are the least of any DG technology, but maintenance costs are among the greatest.

Internal combustion engines are also called reciprocating engines, these requires fuel, air, compression and a combustion source to function. IC generating sets come in wide in a wide range of commercially available sizes from KW to several MW. IC engines can produce electrical energy and at the same time produce useful thermal energy to be utilized in commercial / industrial applications. [8][13]

The key barrier to ICE usage includes the following:

1. Maintenance cost is highest among the DG technologies due to the large number of moving parts.
2. NO_X emissions as highest among the DG technologies.
3. Noise is low frequency and more difficult to control than for other technologies; adequate attenuation is possible.

Attractive ICE features include:

- Capital cost is lower of the DG approaches.
- Efficiency is higher
- Thermal or electrical cogeneration is possible in buildings.

- Modularity is excellent, nearly any building related load can be matched well (kW to MW range), part load efficiency is good.

1.5.3 Biomass:

Biomass refers to renewable energy resources derived from organic matter, such as forest residues, agricultural crops and wastes, wood, wood wastes that are capable of being converted to energy. The extraction of energy from biomass, biogas, and liquid bio-fuels. Biogas is obtained by an aerobically digesting organic material to produce the combustible gas methane. These are two common technologies, one of fermentation of human and animal waste in specially designed digesters, the other of capturing methane from municipal waste landfill sites. [1]

1.5.4 Combined Heat Power Technology:

CHP is one of the distributed generation source , that it use the fuel source in the form of heat , which is available and use from the reciprocating engines , Micro turbines , Fuel cells , combustion Turbines and etc,. Where CHP main source of fuel is heat, that it will use the exhaust heat of the mentioned DG technologies either directly or indirectly depending upon the requirements. Because of usage of fuel as heat there is no pollution or environmental effects. CHP can be modeled depending upon the source of the heat available. [8]

1.5.5 Wind turbines:

Wind turbines extract energy from moving air and enable an electrical generator to produce electricity. These comprise the rotor (blade), the electrical generator, a speed control system and tower. (i.e., kinetic energy to Electrical energy) these can be used in a distributed generator, a speed control system and tower. These can be used in a distributed generation in hybrid mode with solar or other technologies. Research on adaptation of wind turbines for remote and stand-alone applications is receiving increasingly greater attention and hybrid power systems using 1-50 kW wind turbines are being developed for generating electricity off the grid system. Wind turbines are also being used as grid connected distribution resources wind turbines are commercially available in variety of size and power ratings ranging from kW to over one MW. [11]

Wind turbines convert he kinetic energy into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water). The components of a typical wind energy conversion system include a wind turbine, generator, interconnection apparatus and control system, as shown in Figure. 1.3. [12] [13]

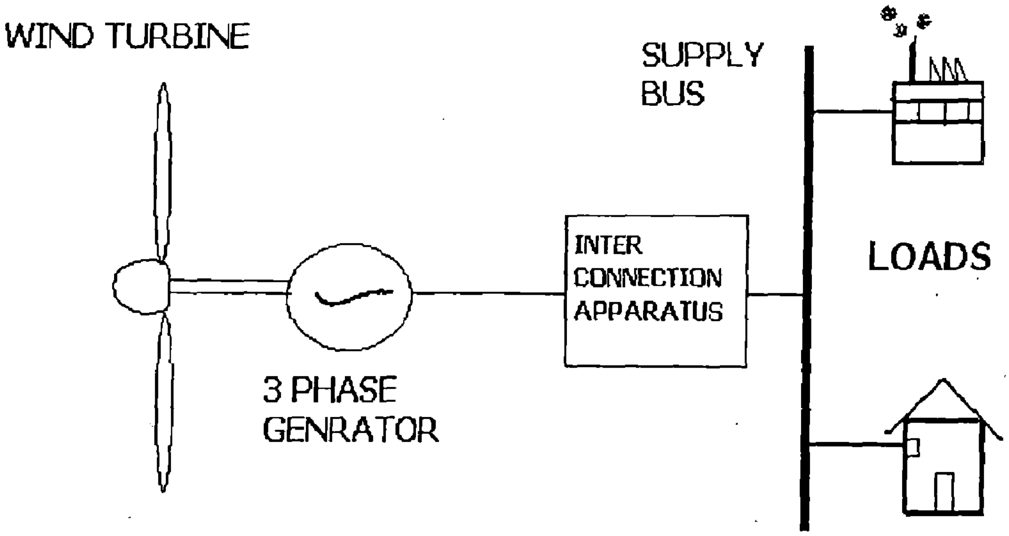


Figure 1.3 Structure of a typical energy conversion system

Wind turbines can be classified into the vertical axis type and the horizontal axis type most modern wind turbine uses a horizontal axis configuration with two or three blades, operating either down-wind or up-wind. A wind turbine can be designed for a constant speed or variable speed operation. Variable speed wind turbines can produce 8% to 15% more energy output as compared to their constant speed counterparts; however, they necessitate power electronic converter to provide a fixed frequency and fixed voltage power to their loads.

1.5.6 Photovoltaic:

Photovoltaic power cells are solid state semi conductor device that converts sunlight into direct current electrical power and the amount of power generated is directly related to the intensity of the light PV system are most commonly used for stand alone applications and are commercially available with capacities ranging between 1KW to 1MW. The systems are commonly used in India and can contribute a great deal for rural areas, especially remote and inaccessible areas. It can be of great help in grid connected applications where the quality of power provided by the grid is low.

Undertaken for cost reduction in SPV cells, modules, systems besides improvements in operational efficiency [1].

1.5.7 Fuel cells :

A fuel cell is an electrochemical energy conversion device that converts hydrogen and oxygen directly into usable electrical energy - with water and heat byproducts – without combustion. Fuel cell technologies are of different types, depending on their electrolyte.

Some of the different electrolyte types include

- phosphoric acid (PAFC)
- molten carbonate (MCFC)
- solid oxide (SOFC)
- proton exchange membrane (PEMFC)

PAFC and PEMFC are low temperature fuel cells and their operating temperature is 200°C and 90°C respectively. By contrast, SOFC and MCFC are high temperature fuel cells with operating T of 1000°C and 650°C resp. [8].[11]

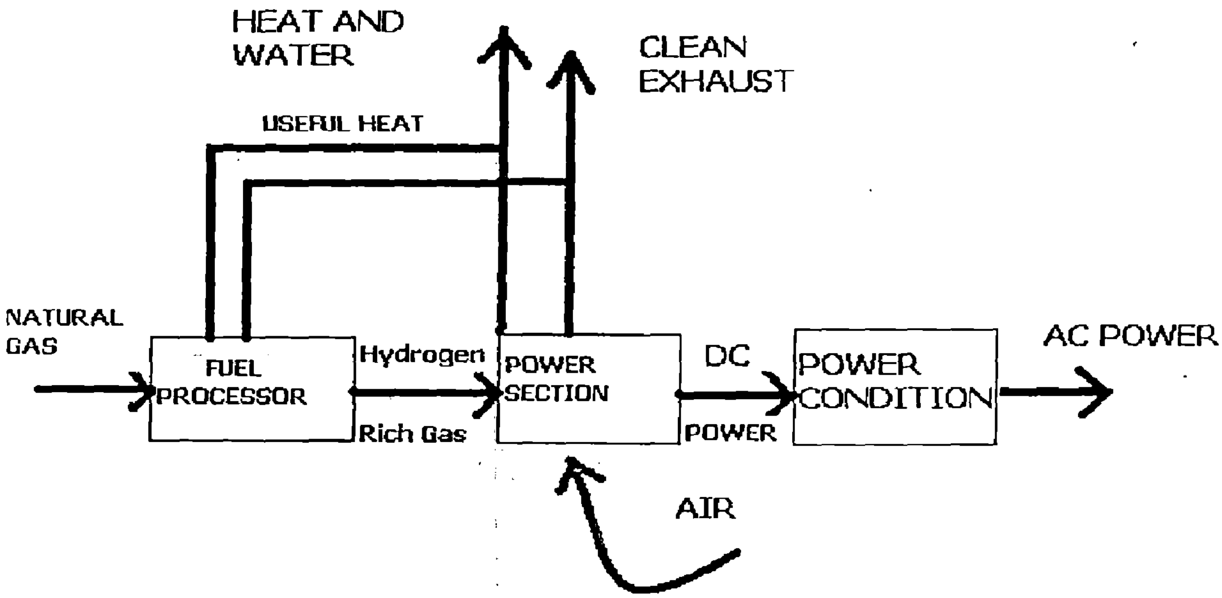


Figure 1.4 Schematic representation of fuel cell system

As shown in Figure 3.22, a fuel cell power plant is composed of three subsystems: a fuel-processing section, a power section and a power conditioning section. Heat recovery unit can be added to capture useful thermal energy from cooling water in the fuel processor and the power section. Currently, the 200kW PAFC – a product from UTC fuel cells – is the only commercial available fuel cells in the market. Other types of fuel cells are now in field test and demonstration. Since

PAFC operates at low temperature, i.e. 200°C, it cannot produce high-quality steam. It is more suitable to produce hot water in industrial or commercial applications.

1.5.8 Small Hydro Power (SHP) System :

Small Hydro Power Plants (SHP) are similar to any hydro power scheme whose upper limit of output ranges from 5 to 25 MW (in India).The layout of SHP depends on the basis of sources of water as:

1. Dam schemes
2. Run off river scheme
3. Canal scheme

Figure 1.5 presents the essential components of the small hydro power plant, [13]

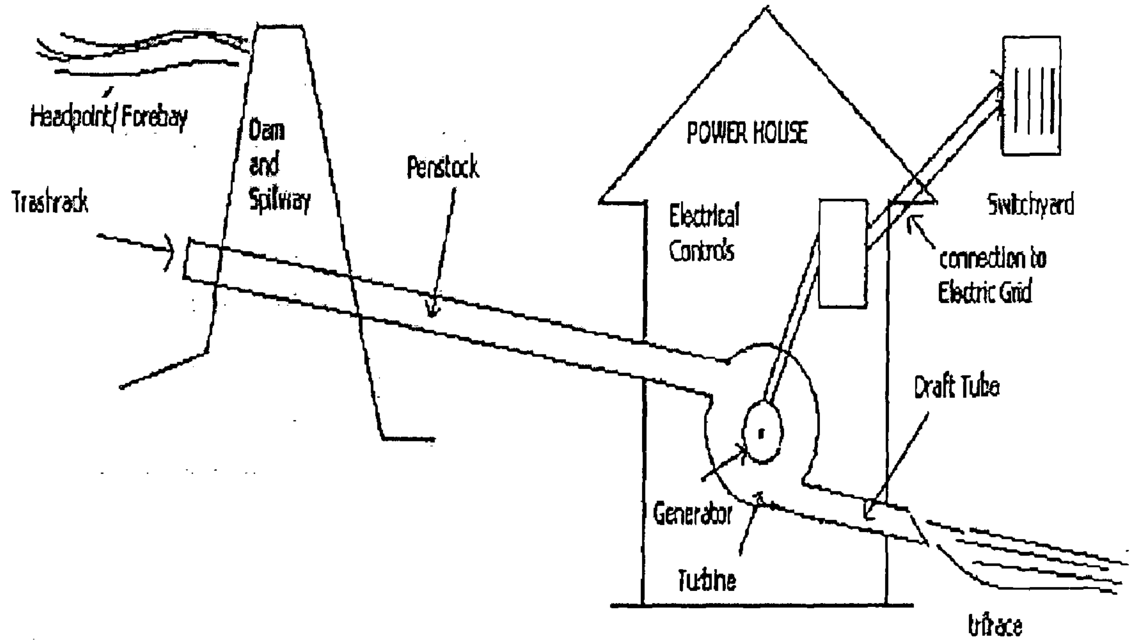


Figure 1.5 Small Hydro systems

The various elements of a Small hydroelectric power station :

1. **Penstock:** the water to the power house penstock, which conveys water under pressure, can be made of steel, iron, and fiberglass, plastic, concrete or wood.
2. **Power house:** contains most of the mechanical and electrical equipment. it is made of conventional building materials, generally at the minimum size position
3. **Tailrace:** carries the water from the turbine exists back to the mechanical and electrical ~~equipment.~~
4. **Generating plant and allied equipment:** consist of all mechanical and electrical equipment.

The primary electrical and mechanical components of a small hydro power plant are the turbine(s) and generator(s); there are two main categories of turbine depending on which two methods for extracting energy are used: impulse and reaction turbine. the type of turbine depends on water head available ;for low to medium head application , reaction type includes Francis and fixed or variable pitch (Kaplan) propeller are used ; high head application uses generally impulse turbines. There are two types of generators that can be used in small hydro power plants: asynchronous and synchronous machines. The asynchronous generator must normally be operated I conjunction with other generator or capacitors .synchronous generator can be operated in isolation and they are best suited for isolated diesel –grid and stand alone small hydro plants. Besides the two primary electrical and mechanical components , a small hydro plants includes : speed increaser between turbine and the generator , river by-pass gate and controls (if required), protection and control system , transformers , ventilation system, backup power supply , batteries , etc .[12][13]

Advantages of SHP: Under favorable circumstances, small hydro represents one of the cheapest methods of electricity generation. A small hydro plant is characterized by reliability and flexibility of operation, including fast start-up and shutdown in response to rapid demand changes .in any large electrical system, the small hydro technology becomes a valuable alternative for increasing overall economy, efficiency and reliability. The following gives some other advantages of SHP. [12] [1] [13]

1. Small hydro plants are a non –consumptive generator of electrical energy, utilizing a renewable resource, which is made continually available through the hydrologic cycle by the energy of the sun.
2. SHP is essentially non-polluting and releases no heat adverse environment impacts are negligible and for small installations, it may be totally eliminated.
3. SHP required some type of water control, up to and including full regulation of watershed discharge. Thus. They are an important element in multipurpose utilization of water resources and can reduce potential flood damage.
4. SHP is characterized by reliability and flexibility of operation, including fast start – up and shutdown in response to rapid change in demand. It thus becomes a valuable part of any large electrical system, increasing overall economy, efficiency, and reliability.

5. SHP has an excellent peak –power capability the input is low –cost hydraulic energy and the output is high value electrical energy with higher efficiency.
6. Technologies for SHP have a long life. Dams and control work will perform a century or more with little maintenance
7. In remote areas, small hydro can create economic opportunities for local residents by using local materials and labor. Compared to thermal facilities, the small hydro usually provides local employment in the construction of civil works.

Draw backs of SHP: Specific for a hydro plant is high investment cost and low operating cast. Beside the high capital cost, the primary drawback of hydroelectric is its environment effects hydroelectric sites create several problems as listed below Tree cleaning from the development of hydroelectric dam can result in soil corrosion and landslides, also causing a build-up of sediments that clog up streams.

1.6 Objectives of the dissertation :

In the previous sections, the DG (distributed generation) Technologies and the advantages of the DG were examined. It is clear that there are advantages and attraction in using the DG by understanding the benefits of using DG as an aspect of the economic test. Also, one needs to look at what the advantages for using DG are with respect to electrical power. The power quality of the DG using small turbines such as, Microturbine, a diesel engine will be examined.

Where the main objective of this thesis is to develop the selected distributed generation sources and integrate simulation model of various components of a generation system. Achieving this objective, involves performance evaluation of all the systems components of microturbine generation systems and diesel engine generation system and demonstrating its voltage and frequency management ability with the help of simulation results. The simulation model is suitable to study the DG technologies applications besides being able to simulate the behavior of the overall systems under different operating load conditions.

(Note: In this thesis considering the isolated load operations only)

1.7 Thesis Organization:

The remaining part of this thesis is organized in to five chapters.

Chapter 2 presents the literature review of the references

Chapter 3 presents modeling of the microturbine generation systems with detailed mathematical model of the microturbine with all aspects of controlled system, detail model and study of the permanent magnet synchronous generator (PMSG) and also presents the study of self-excited induction generators (SEIG), in order to maintain the system voltage and frequency of the PMSG a power electronics interface have been used in a simple approach.

Chapter 4 presents modeling of the diesel engine generation system with simple mathematical model and speed control aspects of the system. Study of the 3-phase salient-pole synchronous machine with an excitation system.

Chapter 5 presents Simulation results obtained in MATLAB/Simulink are given by the developed models [(Microturbine generation system with PMSG and SEIG), (Diesel Engine generation system with synchronous machine)] with different load conditions.

Chapter 6 gives the conclusion of this thesis and aspects worthy of future work. and references.

And not but least simulation models and parameters used in the models are given in the appendixes at the end of this thesis.

CHAPTER-2

LETERATURE REVIEW

Ramnarayn Patel et al. [1], analyses the advantages and techno-economic constraints associated with the distributed generation .and explains prominent DG Technologies of DG sources; this paper has been identified as the future shape of the power sector reforms and also as one of the alternatives for ensuring supply of power in rural areas. This paper also gives the key components of the future power sector have been identified and the possible technical and economic constraints are discussed along with the advantages and incentives in using DG as an alternative power mix for future.

Borbely and Kreider [2] elaborately discussed the distributed generation importance in the new millennium, in this book, a first step in understanding the many issues facing both home owners and businesses. This book describes the technologies being developed today-fuel cells, micro turbines, Stirling engines, photovoltaic and finally, the profound resource and air-quality implications of combined heat and power, an old idea also given new life by a suite of technical advances, are discussed.

Dugan et al. [4] described that new planning methods and computer tools are needed to help the planner better understand the true economic impact of each alternative. This paper also describes a methodology for performing distribution planning that also permits the incorporation of such diverse means of improving the capacity and reliability of the system as DG, distribution automation (DA), and demand-side management (DSM), also gives the analysis techniques tools , because of the added complexities associated with these analysis techniques , the planning process must incorporate appropriate screening tools to determine the depth of analysis needed for particular projects, thereby making more efficient use of already scarce planning resources.

Ramakumar and Chiradejia, [5] recorded the benefits of DG; this paper proposes a general approach and a set of indices to assess some of the technical benefits in a quantitative manner. The indices proposed are: 1) voltage profile improvement index; 2) line loss reduction index; 3) environmental impact reduction index; and 4) DG benefit index. Simulation results obtained using a simple 12-bus test system and a radial system are presented and discussed to illustrate the value and usefulness of the proposed approach.

Padiyar, [12] elaborately describes, the generator model is derived starting from the basic circuit equations and the use of park's transformation. The models of excitation system and the turbine governor system, the analysis of single machines connected to infinite bus and the study of transients by simulation is also presented in this book.

Robert Lasseter. [14] , gives Distributed resources (DR) include a variety of energy sources, such as micro-turbines, photovoltaic, fuel cells, and storage devices, with capacities in the 1 kW to 10 MW range. Deployment of DR on distribution networks could potentially increase their reliability and lower the cost of power delivery by placing energy sources nearer to the demand centers. By providing a way to by-pass conventional power delivery systems, DR could also offer additional supply flexibility.

Y. Zhu, K. Tomsovic, [17] elaborately discussed Utility restructuring, technology evolution, public environmental policy, and expanding power demand are providing the Opportunity for microturbines and fuel cells to become important energy resources. Deregulation has begun to allow for the provision of various ancillary services, such as load-following. In order to investigate the ancillary services ability of these units in distribution systems, new simulation tools are needed. This paper presents simplified slow dynamic models for microturbines and fuel cells. Their stand-alone dynamic performances are analyzed and evaluated. A distribution system embedded with a microturbine plant and an integrated fuel cell power plant is used as an example. The control strategy and load-following service in this distribution system are simulated. It is illustrated that microturbines and fuel cells are capable of providing load-following service, significantly enhancing their economic value

Shirou Suzaki, et al. [18], explains Large-scale blackouts due to a cascade trip of gas turbine generators have been reported. From the viewpoint of improving power system reliability, the behaviors of a gas turbine generating plant and a combined cycle plant during occurrence of a large disturbance in the power system should be clarified. a block diagram representing dynamic behaviors of a combined cycle plant, derived from process physical relationships, is described and a modeling method of a multi-shaft type combined cycle plant is proposed. Simulation methods of the combined cycle plant in an analog power system simulator are shown

Alan I.Sheldrake. [23], explored a combined cycle power plant, which combines a gas turbine and a steam turbine, can achieve high energy efficiency. Many combined cycle plants have been installed in the world. However, a large-scale blackout occurred in Malaysia in 1996. Combined cycle and gas turbine plants sequentially tripped out. The cause of this chain trip was thought to be a system frequency drop. Considering these backgrounds, it is important to study dynamic behavior of combined cycle plants. Several dynamic models of the combined cycle plant have been proposed. In our analysis, we use some of them and build a model for a single-shaft combined cycle plant. We execute numerical simulations to see how the combined cycle behaves when the system frequency drops.

Q. Zhang and P.L.So [27], analyses the presents a mathematical representation of a combined cycle plant that is suitable for use in power system stability studies. The model incorporates gas turbine, heat recovery steam generator and steam turbine and includes speed control, temperature control and inlet guide vane control. A PID controller is designed for the governor-gas turbine system to improve system dynamic performance. The proposed combined cycle plant model and its controls are tested on a simple two-area power system. The performance of the combined cycle plant is investigated following system disturbances.

Francisco Jurado and Jose Ramon Saenz. [28], explains the composition of natural gas may vary significantly, and load power varies randomly. Traditional control design approaches consider a fixed operating point in the hope that the resulting controller is robust enough to stabilize the system for different operating conditions. On the other hand, adaptive control incorporates the time-varying dynamical properties of the model and considers the disturbances acting at the fuel cell-microturbine hybrid power plant. It may be possible to identify the parameters of the adaptive controller. This scheme is called direct adaptive control, because we are going to obtain directly the required controller parameters through their estimation in an appropriately redefined plant model. An adaptive minimum variance controller is developed in this paper.

O. Fethi, L.-A. Dessaint and K. Al-Haddad. [31], “gives a simulation model of the electric part of a grid connected micro turbine (MT). The model contains a detailed representation of the main components of the electric system that are the permanent magnet synchronous machine and the static frequency changer. The micro turbine is controlled so that the energy is exchanged with unity displacement factor.

The simulation results obtained with the model using SimPowerSystems software were compared with experimental results obtained with a Capstone 30 kW micro turbine. Finally, the simulation model is used to analyze the micro turbine performance during steady state and transients such as grid voltage and phase unbalances and operation under grid polluted voltage

Afshin Majd Zarringhalam and Mehrdad Kazerani. [32], gives the commercial microturbine-based dispersed generation systems are composed of a high-speed permanent-magnet alternator and a diode rectifier-PWM inverter pair. In this paper, a dispersed generation scheme made up of a microturbine, an induction generator, and a diode rectifier-PWM inverter pair is introduced. A complete model for the self-excited squirrel-cage induction generator is developed and used to study the steady-state and transient behaviors of the overall system. The power delivered to the grid is controlled by an injected current control loop and the input/output power balance is maintained by regulating the dc bus voltage using a new method based on the torque control of microturbine. It is shown through analysis and Simulink simulation results that induction generator is a viable substitute for permanent magnet alternator in microturbine-based dispersed generation systems due to its low cost, low maintenance, rugged structure, and slack between rotor speed and terminal frequency, which isolates the transients of the grid from the generator system, when the dc-bus capacitor size is reduced.

Amer Al-Hinai, Karl Schoder and Ali Feliachi. [35], - Presents a split-shaft microtnrbine model using induction generators is used to assist transient stability of microturbines when connected to the grid as distributed generator. Microturbines can he controlled via two paths, control of the turbine's mechanical power and control of terminal voltage from induction generator using connected SVC at the generator's terminal PI controllers, for SVC and output turbine mechanical power are designed based on linearized model using genetic algorithms as optimization technique Model development and simulation are presented within the MATLAB/ Simulink (Power System Analysis Toolbox (PAT')) environment using various toolboxes.

W. I. Rowen. [36] elaborately explored the simplified mathematical representations of heavy-duty gas turbines that are suitable for use in dynamic power system studies and in dynamic analysis of connected equipment. The full range of heavy duty, single-shaft gas turbines is covered, as well as parallel and isolated operation and alterations to the model.

D. Canever et al. [55], gives the tendency in the industrialized countries to significantly improve the contribution of distributed generation in the existing electrical networks poses new technical and economical challenges to power system control and management. Coordination of distributed resources for the control of active power is addressed in this paper. The models of two typical distributed electrical sources - a photovoltaic array (PV) and a diesel driven generation plant (DPP) - are first individually derived and examined. Successively these models have been adapted in view of their reciprocal integration into an existing distribution network. A coordinated management of the two distributed sources is suggested in order to fully exploit the PV renewable energy from the sun. A suitable regulator is derived from secondary control structures typical of large electrical systems by using a power signal exchanged between the two sources. Other possible consequences of this approach are presented with reference to a competitive electric market.

Gerald claeys et al. [56], describes a new dynamic model of a turbo-charged Diesel generator. The purpose of this model is to study the impact of dispersed generation on distribution systems. The model is based on the mean torque method which presents the advantages to be simple and representative and to have a modular structure.

F. Bonanno et al. [57] explored the implementation in a continuous simulation language of the dynamic model of an Integrated Generation System (IGS) named "Combined Multiple Renewable Energy Sources System Simulator" (CMRESSS). The software package is a useful tool to evaluate the IGS electric transient behavior during the planning stage. Dynamic transients in normal and faulted conditions are simulated exploiting the main features of the package which are flexibility and Graphic User Interface (GUT) for easy handling of input data and events scheduling. Simulation results are discussed and validated to demonstrate the validity of the proposed approach. The results confirm the consistence of the simulation package and the benefits achievable in preliminary design by comparative analysis of different power plants

CHAPTER-3

MODELING OF MICROTURBINE GENERATION SYSTEMS

INTRODUCTION

In a renewable source of energy, there should be some storage facility or backup generation to maintain continuity of supply to the load when renewable source alone is not sufficient. The objective of this chapter is to present one such generating system which is capable of acting as backup generators.

This chapter presents the modeling and simulation of microturbine generation systems, the nonrenewable source of energy considered in this thesis, suitable for isolated as well as grid-connected operation. The system comprises of a permanent magnet synchronous and induction generators are driven by a microturbine. A brief description of the overall system is given and mathematical model for the microturbine; permanent magnet synchronous generator and self excited induction generator are presented.

Microturbine generation systems may offer one of the best short-term distributed power production options because of their simplicity and because no major technological breakthroughs are required for their deployment. Because of low emissions, smaller size, high efficiency (with recuperator) and faster response microturbine generation systems are gaining popularity in distributed power generation. Today's microturbine technology is the result of the development work, in small stationary, aero-derivative, light industrial, heavy industrial and automotive gas turbines, pursued by the automotive industry beginning in the 1950's as a result of which , modern microturbines are able to combine the reliability of on board commercial aircraft generators with the low cost of automotive turbochargers .[13]

Aero-type gas-turbine engines have been widely adopted as prime candidates for electrical power generation. The fully automatic start-up capability and the fast run-up characteristic of such engines have made them particularly suitable for peak-load lopping and standby power supply purposes. The gas turbines have let itself directly to the oil and gas industries, not only as an ideal candidate for electrical power generation, but also for gas compression and injection and crude oil pumping. Unlike steam-turbine or hydro-electric generators, gas–turbine generators are commonly connected to small net-works or even used in isolated operation such as in oil fields in desert areas and offshore installations.

Microturbine Generation system

Microturbines are small gas turbines which burn gaseous or liquid fuels to create high energy gas stream that turns an electrical generator. There is a growing interest in the application of microturbine generation systems as they can start quickly and are especially useful for on-peak power supply for grid support. Other applications include remote power and combined heat and power (CHP) systems by utilizing the heat contained in the exhaust gases to supply thermal energy needs in a building or industrial process[13][14]].

Generally MTG systems range from 30 to 400 kilowatts [15] [16] [2], while Conventional gas turbines range from 500 kW to more than 300 MW

Microturbines are capable of burring a number of fuels at high and low pressure levels. They generally have marginally lower electrical efficiencies than similarly sized reciprocating engine generators. Without a recuperator the overall efficiency of a microturbine is 15 to 17%, where as with an 85% effective recuperator the efficiency can be as high as 33 to 37% [2]. However, because of their design simplicity and relatively fewer moving parts, microturbines have the potential for simpler installation, higher reliability, reduced noise and vibration, lower maintenance requirements, lower emissions, continuous combustion and possibly lower capital costs compared to reciprocating engines [13], [15] Microturbines emissions can be up to eight times lower than diesel generators, and currently available ones produce less than 50% of the NOx emissions of a state of the art natural gas lean-burn engine .

3.1 Types of Microturbine systems:

There are basically two types of microturbine driving methods, known as 'single –shaft' and 'two (or twin) shaft' drives. In a single gas turbine, all the rotating elements share a common shaft. A single expansion turbine turns both the compressor and the generator. As a result they operate at high-speeds, some in excess of 100,000 rpm, and generate electrical power at high frequency (in the order of kHz). Two-shaft models on the other hand, uses a turbine to drive the compressor on one shaft and a power turbine on a separate shaft connected to a conventional generator via a gear box which generates AC power at 60 Hz or 50 Hz [17]. In a single-shaft design, since the generator provides a high frequency AC voltage source, a power electronic interface between the MTG system and the AC load is required. For a two-shaft design, on the other hand, there is no need for such interfacing. This thesis considers the modeling single-shaft type only.

In some gas turbines, the compressor turbine and the power turbine are an integral component. This tends to be the case with heavy- duty machines.

The basic arrangement is shown in Figure 3.1.

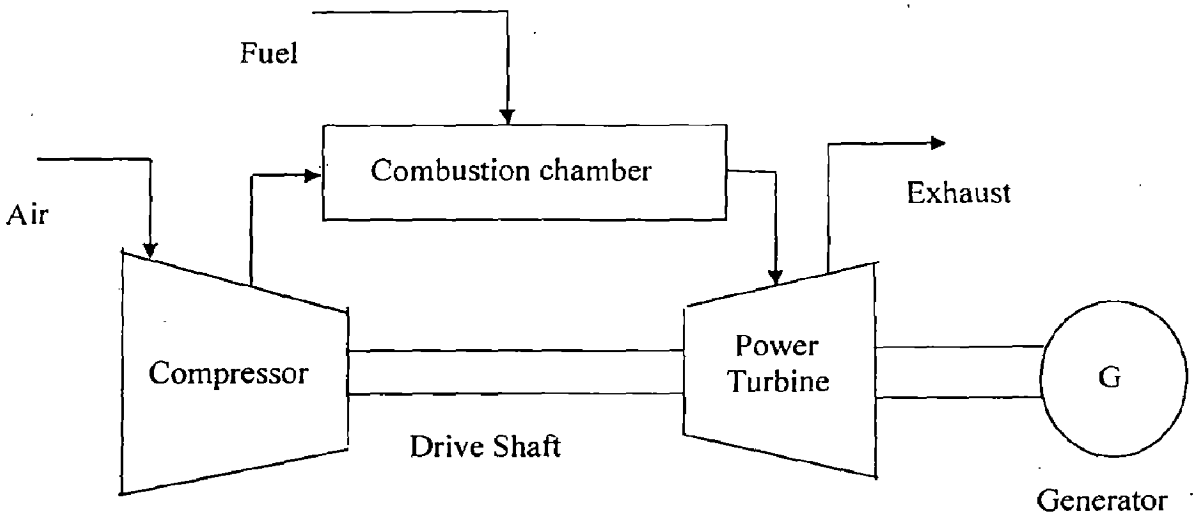


Figure 3.1 Single –shaft Microturbine

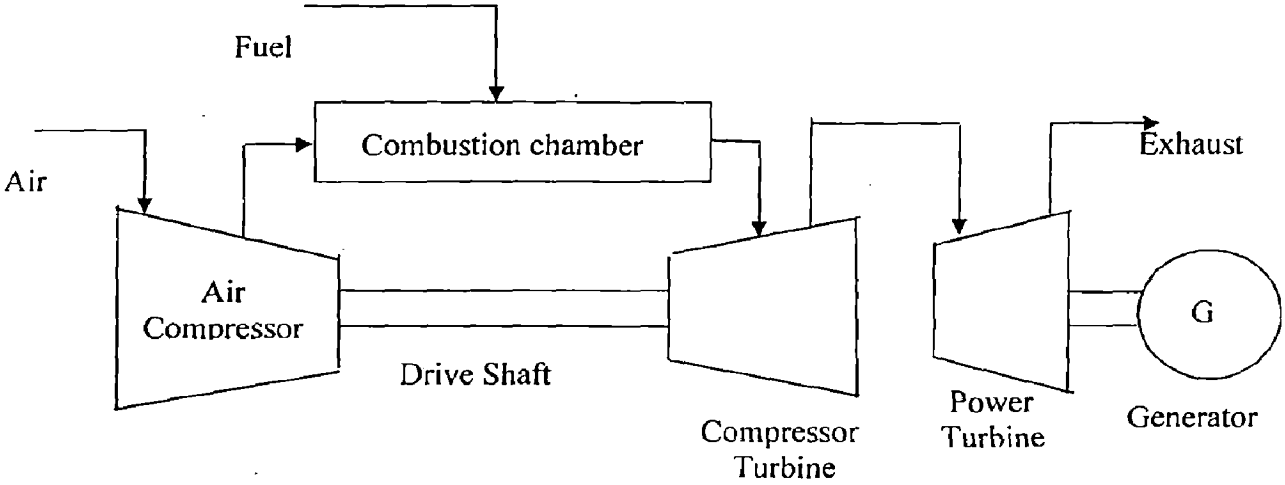


Figure 3.2 Two -shaft Microturbine

In a two-shaft microturbine the compressor is driven by a high pressure turbine called the compressor turbine, and the generator is driven separately by a low pressure turbine called the power turbine.

The basic arrangement is shown in Figure 3.2.

Two-shaft systems are generally those which use aero-derivative engines as 'microturbine generator', i.e. they produce hot, high velocity, high pressure gas which is directed into the power turbine. Some light industrial gas turbines have been for either type of drive. This is achieved by fitting a removable coupling shaft between the two turbines. Some points to consider with regard to the two types of driver are:-

- High speed of rotation tends to improve the compressor and turbine efficiency. Hence, with two separate shafts, the best thermodynamics performance from both turbines and the compressor is obtainable.
- Using aero-derivative machines means that a simple 'add on' power turbine can be fitted in the exhaust streams of the aero engine. The enables may manufacturers to design a simple power turbine and to use a particular aero engine.
- Two-shaft machines are often criticized as electrical generators because of their slower response to power demands in comparison with single-shaft machines. This can be a problem when a two-shaft machine may have to operate in synchronism with other single-shaft machines or steam turbine generators. Sometimes the slower response may affect the power system performance during the starting period of large motors. A power system computerized stability study should be carried out to investigate these type of problem.

Some of the recent aero engines could be called 'three-shaft' arrangements because within the microturbine generator there are two compressor turbines and two compressors. [18][19][20]

3.2 Fuel for Microturbines:

The fuels usually consumed in gas turbines are either in liquid or dry gas forms and, in most cases, are hydrocarbons. In special cases non-hydrocarbon fuels may be used, but the machines may then need to be specially modified to handle the combustion temperatures and the chemical composition of fuel and its combustion products. [21]

Microturbines internal components such as blades, vanes, combustors, seals and fuel gas valves are sensitive to corrosive components present in the fuel or its combustion products such as carbondioxide, sulphur, sodium or alkali contaminants.

The fuel can generally be divided into several classifications:-

- Low heating value gas.
- Natural gas.
- High heating valve gas.
- Distillate oils.
- Crude oils.
- Residual oil.

3.2.1 Heat Rate and Fuel Consumption:

The heat rate is the ratio of heat given up by the fuel, in terms of its lower calorific or heating value (LHV), to the power available at the gas turbine coupling to its generator. It has the SI units of $^{kJ}/_{kWh}$. [22]

The reduction in output power is typically 0.5 to 0.8 %/°C.

The fuel consumption can be calculated approximately from,

$$\text{Fuel consumption} = \frac{poweroutput \times Heatrate}{FuelLHV} \, m^3/_h \, (Kg/h)$$

3.3 ENERGY OBTAINED FROM A MICROTURBINE:

A microturbine functions as a heat engine using the thermodynamic Joule cycle, as explained in many textbooks, [18] [[22] [23]

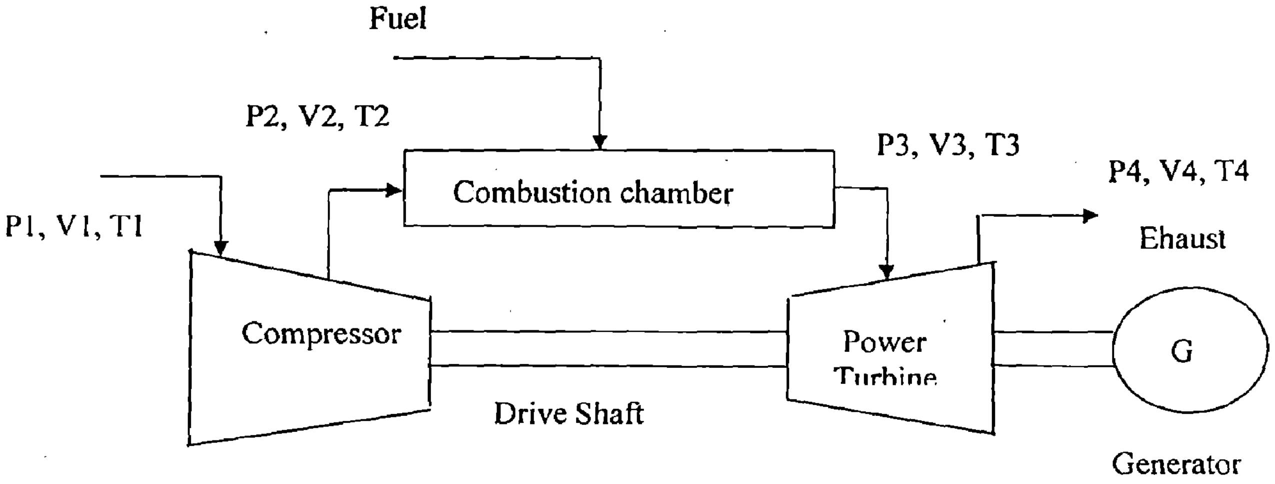


Figure 3.3 Microturbine thermodynamic cycle, a simple microturbine

Most microturbines used in the power generation use the 'simple-cycle' version of the Joule cycle. The main components of the gas turbine are shown in Figure 3.3.

The thermodynamic relation ships used to describe the operation of the microturbine are the pressure(P) versus volume (V) characteristic and the temperature (T) versus entropy(S).

Air is drawn into the compressor at atmospheric pressure P_1 (in practice slightly lower due to the inlet silencer, filter and ducting) and atmospheric temperatureT_1, and compressed adiabatically to a higher pressure P_2 to reduce its volume toV_2 and raise its temperature to T_2 .The adiabatic compression is given by the following equations; [22][23][24]

$$\frac{P_2V_2}{T_2} = \frac{P_1V_1}{T_1} = cons\tan t \qquad (1)$$

$$P_2V_2^{\gamma} = P_1V_1^{\gamma} = cons\tan t \qquad (2)$$

The work done in the compressor per kg of fluid U_c is,

$$U_c = \frac{\gamma}{\gamma - 1}(P_2V_2 - P_1V_1) \qquad (3)$$

The following standard relationships apply,

$$P_1V_1 = RT_1 \qquad (4)$$

$$P_2V_2 = RT_2 \qquad (5)$$

$$C_p - C_v = R \qquad (6)$$

$$\frac{C_p}{C_v} = r \qquad (7)$$

Where, C_p is the specific heat of the air at constant pressure, kcal/kg K $\cong$ 1.005

C_v is the specific heat of the air at constant volume, kcal/kg K $\cong$ 0.718

R is the particular gas constant for air , kJ/kg K $\cong$ 0.287

r is the ratio of specific heats $\cong$ 1.4

From (3) and (4),

$$\frac{\gamma}{\gamma - 1} = \frac{C_p}{R} \qquad (8)$$

Substitute (4, 5 and 8) into (1),

$$U_c = C_p(T_2 - T_1) \text{ kJ/kg} \qquad (9)$$

The air leaving the compressor at pressure P_2 passes of combustion chamber where its temperature is rated to T_3, at constant pressure.

The hot air –fuel mixture burns and the gaseous products of combustion pass into the turbine where the pressure falls to the atmospheric pressure $P_4 = P_1$ (in practice slightly higher due to the resistance or 'back pressure' of the exhaust silencer and ducting). The exhaust gas temperature is T_4 and lower than the combustion temperature T_3. (The ducting systems should be arranged so that the exhaust gas is discharged at a point far enough away from the inlet ducting entrance that no interaction occurs i.e. T_4 does not influence T_1.)

The turbine expansion process can be described by similar equations to (1) through (7), with T_3 replacing T_2 and T_4 replacing T_1. Hence the work done by the turbine (U_t) is,

$$U_t = C_p(T_3 - T_4) \text{ kJ/kg} \tag{10}$$

The heat supplied by the fuel is $C_p(T_3 - T_2)$

In a conventional gas turbine the turbine supplies power to drive its compressor and so the power available to drive a generator is the net power available from the turbine. Neglecting inefficiencies in the compressor and the turbine, the work done on the generator at the coupling of the gas turbine is U_{out},

$$U_{out} = U_t - U_c = C_p(T_3 - T_4 - T_2 + T_1) \text{ kJ/kg} \tag{11}$$

The ideal cycle efficiency η_i of the gas turbine is:

$$\eta_i = \frac{C_p(T_3 - T_4 - T_2 + T_1)}{C_p(T_3 - T_2)} = 1 - \left(\frac{T_4 - T_1}{T_3 - T_2}\right)$$

= 1-(Rejection temperature difference / Combustion temperature difference)

(12)

From (1), raise to the power γ ,

$$\left(\frac{P_2 V_2}{T_2}\right)^{\gamma} = \left(\frac{P_1 V_1}{T_1}\right)^{\gamma} \tag{13}$$

From here onwards the following substitutions will be used in order to keep the presentation of the equations in a simple format.

$$\beta = \frac{\gamma - 1}{\gamma}, \beta_c = \frac{\gamma_c - 1}{\gamma_c}, \beta_t = \frac{\gamma_t - 1}{\gamma_t}$$

$$\delta = \frac{1 - \gamma}{\gamma}, \delta_c = \frac{1 - \gamma_c}{\gamma_c}, \delta_t = \frac{1 - \gamma_t}{\gamma_t}$$

Where subscript 'c' refers to the compressor and't' to the turbine, the absence of a subscript means a general case.

Divide (2) by (13) to obtain an expression for the compressor,

$$\left(\frac{P_2}{P_1}\right)^{\delta} = \frac{T_1}{T_2} \tag{14}$$

Similarly for the turbine,

$$\left(\frac{P_3}{P_4}\right)^{\delta} = \frac{T_4}{T_3} \tag{15}$$

It is of interest to determine the work done on the generator in terms of the ambient temperature T_1 and the combustion temperature T_3.

From (14),

$$T_2 = T_1 \gamma_p^{\beta}$$

And from (15)

$$T_4 = T_3 \gamma_p^{\delta}$$

Therefore (11) becomes,

$$\begin{aligned} U_{out} &= C_p\left(T_3 - T_3\gamma_p^{\delta} - T_1\gamma_p^{\beta} + T_1\right) \\ &= C_p T_3\left(1 - \gamma_p^{\delta}\right) - C_p T_1\left(\gamma_p^{\beta} - 1\right) \end{aligned} \tag{16}$$

The ideal cycle efficiency η_i can also be expressed in terms of T_1 and T_3.

$$\eta_i = 1 - \left(\frac{T_3\gamma_p^{\delta} - T_1}{T_3 - T_1\gamma_p^{\beta}}\right) \tag{17}$$

The specific heat C_p is assumed to be constant and equal for both compression and expansion in practice these assumptions are not valid because the specific heat C_p is a function of temperature. The average temperature in the turbine is about twice that in the compressor. Also the products of combustion i.e. water vapour and corban dioxide, slightly increase the specific heat of air–gas mixture in the turbine.

3.3.1 Maximum Work Done on the Generator:

If the temperatures T_{2e} and T_{4e} are used in (11) to compensate for the efficiencies of the compressor and turbine, then it is possible to determine the maximum power output that can be obtained as a function of the pressure ratio γ_p.[25][22][24][18]

The revised turbine work turbine work done U_{te} is,

$$U_{te} = C_p(T_3 - T_4)\eta_t \text{ kJ/kg} \qquad (18)$$

The revised compressor work done U_{ce} is,

$$U_{ce} = C_p(T_2 - T_1)\frac{1}{\eta_c} \text{ kJ/kg} \qquad (19)$$

The revised heat input from the fuel U_{fe} is,

$$U_{fe} = C_p(T_3 - T_{2e}) \text{ kJ/kg} \qquad (20)$$

Where,

$$T_{2e} = T_1\left(\frac{\gamma_p{}^{\beta} - 1 + \eta_c}{\eta_c}\right)$$

In (14) and (15) the pressure ratios are theoretically equal, and in practice nearly equal, hence:

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} = \gamma_p{}^{\beta}$$

Where γ_p is the pressure ratio $\frac{P_2}{P_1} or \frac{P_3}{P_4}$

From the above equation,

$$T_4 = T_3\gamma_p{}^{\delta} \qquad (21)$$

And

$$T_2 = T_1\gamma_p{}^{\beta} \qquad (22)$$

Substituting for T_2, T_{2e} and T_4 gives the resulting output work done U_{oute} to be,

$$U_{oute} = U_{te} - U_{ce} = C_p\left(T_3 - T_3\gamma_p{}^{\delta}\right)\eta_t - C_p\left(\frac{T_1\gamma_p{}^{\beta} - T_1}{\eta_c}\right)$$

$$= C_p\left[T_3\left(1 - \gamma^{\delta}\right)\eta t - \frac{T_1}{\eta_c}\left(\gamma_p{}^{\beta} - 1\right)\right] \text{kJ/kg} \qquad (23)$$

To find the maximum value of U_{oute} differentiate U_{oute} with respect to γ_p and equate the result to zero. The optimum value of γ_p to give the maximum value of U_{oute} is,

$$\gamma_{p\max} = \left(\frac{T_1}{T_3 \eta_c \eta_t} \right)^d \tag{24}$$

Where

$$d = \frac{1}{2\delta}$$

Which when substituted in (23) gives the maximum work done $U_{oute\max}$.

3.4 Power Output From A microTurbine :

In the above section the performance of a microturbine was determined as the energy obtained at the output shaft coupling. The energy equations are based on a unit of mass flow, 1.0 kg/s, of the fluid passing through the gas turbine i.e. from the air intake to the exhaust aperture. [22][25]

The mass flow through the turbine is about 1% higher than that through the compressor because of the presence of the burnt fuel. Hence the mass flow rate (m) to produce the output power is,

m = output power to the generator / output energy per unit mass kg/s

$$= \frac{W_{out}}{U_{out}} \qquad (\text{kW kg/kj} \quad = \text{kg/s})$$

Therefore it is a simple matter to predetermine the required output power and divide this by the specific energy available to the generator. The result is then the mass flow rate.

3.4.1Mechanical and Electrical Power losses :

The power and specific energy available to driven the generator determined in the pervious sub-section are those at the output shaft of the microturbine. In most situations in the oil industry, where these machines seldom are rated above 40MW, a speed-reducing gearbox is placed between the turbine and the generator. The generators are usually 4-pole machines that operate at 1500 or 1800 rev/min. the power loss in a typical gearbox is about 1.5% of the rate output power. Let the gearbox efficiency be η_{gb} .[25][24][23][22]

The efficiency (η_{gen}) of electromechanical conversion in the generator can defined as,

η_{gen} = power output at the terminals / power input to the shaft coupling

Per unit (pu)

Most rotating electrical machines above about 500kW have efficiencies above 95%, which increase to about 98% for large machines in the hundreds of megawatts range. Their losses copper electrical losses.

In some situations, such as 'packaged' microturbine generators, all the necessary auxiliary electrical power consumers are supplied from the terminals of the generator through a transformer and small motor control center (or switchboard). These auxiliaries include lubricating oil pumps, fuel pumps, filter driven motors, cooling fans, purging air fans, local lighting, and sump heaters. Some of these operate continuously while others are intermittent. A rule-of-thumb estimate of the consumed power of these auxiliaries is between 1% and 5% of the rate power of the generator.

Care needs to be taken when referring to the efficiency of a microturbine generator set. The power system engineer is concerned with the power output from the terminals of the generator that is obtainable from the fuel consumed. Hence considering the practical efficiency η_{pa} of the microturbine, and the conversion efficiency through the gearbox η_{gen} . Hence the Overall Thermal Efficiency η_{pao} would be:-

$$\eta_{pao} = \eta_{pa} \times \eta_{g} \times \eta_{gen}$$

3.5 Starting Methods for MicroTurbines:

Microturbines are usually started by a DC motor or an air motor. Either system is available for most turbines up to about 20MW. Occasionally Ac motors are used. Beyond 20MW, when heavy industrial machines tend to be used, it becomes more practical to use air motors or even diesel engine starters. DC motors require a powerful battery system. The DC motor and battery systems. Air motors require air receivers and compressors. The compressors require AC motors or diesel engines. Air start and diesel start systems are more popular for onshore plants especially remote plants, e.g. in the desert. This is partly due to the fact that batteries tend to suffer from poor maintenance in hot, dry locations. Air systems require regular maintenance and much be kept fully charged in readiness for a quick start. Air system receivers can become very large if more than three successive starting attempts are required. More starts can probably be obtained by a battery system that occupies the same physical space. (Note:-in my model starting method is neglected) [22][15][16]

3.6 Speed Governing of Microturbines:

3.6.1 Open-loop Speed –Torque Characteristic:

The ungoverned or open-loop speed –torque characteristic of a gas turbine has a very steep negative slop and is unsuitable for regulating the power output of the generator. The open-loop characteristic is explicitly determined by the thermodynamic design of the gas turbine, together with the mechanical inertial and frictional characteristics of the rotating masses. Without closed-loop feedback control action the initial decline in speed inertia. Let T, ω and P be the torque, speed and shaft power respectively in per –unit terms. The expression relating these variables is,

$$P = T\omega \tag{25}$$

The open-loop speed-torque function may be expressed as,

$$\omega = f(T) \tag{26}$$

Which may be represented by a simple linear function,

$$\omega = \omega_o - kT \tag{27}$$

Where K is a positive number in the order of 1.0 pu equal to the open-loop slope, and ω_o is the shaft speed at no-load.

Assume that the turbine is designed to deliver unit torque at unit speed, therefore,

$$1.0 = \omega_o - k(1.0) = \omega_o - k \tag{28}$$

From which $\omega_o = 1 + K$ and so (27) becomes,

$$\omega = 1 + k - kT \qquad \text{Or}$$

$$T = \frac{1 + k - \omega}{k} \tag{29}$$

Or in the form of quadratic equation,

$$0 = \omega^2 - (1 + k)\omega + kP \tag{30}$$

The two roots of which are,

$$\omega_{1,2} = \frac{1+k}{2} \pm \left(\frac{(1+k)^2 - 4kp}{2} \right)^{\frac{1}{2}} \qquad (31)$$

The positive root applies to the stable operating region, whilst the negative root applies to the unstable region after stalling occurs.

For example at P=1.0 the torque corresponding to the positive root is T=0.667 pu, whilst that for the negative root is T=1.00pu. Hence the torque at full-load power is less than unity (due to the speed being higher than unity). [26][27][28][29]

3.6.2 Closed-loop Speed –Power Characteristic:

All prime-movers used for driving electrical generators are equipped with closed-loop speed governors. Their main purpose is to reduce the variation in shaft speed to a small amount over the full range of shaft power. Deviations in speed are measured and amplified. The amplified signal is used to operate the fuel value in such a manner as to reduce the deviation in speed. It may be assumed that a linear relationship exists between the amplified signal received at the value and the shaft power created by the fuel passed through the valve orifice. The fuel valve may be regarded as a regulating device for power available at the shaft. It may therefore be assumed that the output of the valve is the shaft power P, whilst its inputs are a reference power P_{ref} and the amplified speed error P_e.

Therefore,

$$P = P_{ref} - P_e \qquad (32)$$

Where

$$P_e = F(\omega_o - \omega) \qquad (33)$$

And ω_o is the nominal shaft speed, and F is the feedback gain.

Hence the closed –loop control system for steady state conditions may be described by the forward transfer function of (31), using the positive root, and the feedback transfer function of (33). In order to establish suitable relations between k and F it is necessary to consider small changes in the variables and by so doing linearise the equations using a two-term Taylor's series Transpose and square the positive root of (31).

$$\left(\omega - \frac{1+k}{2} \right)^2 = \frac{1}{4}\left((1+k)^2 - 4kP \right) \qquad (34)$$

Let ω be increased by $\Delta\omega$ as the power P is increased by ΔP.

Equation (34) becomes,

$$2\omega\Delta\omega - \Delta\omega(1+k) + \omega^2 - \omega(1+k) + \left(\frac{1+k}{4}\right)^2$$

$$= \left(\frac{1+k}{4}\right)^2 - kP - k\Delta P \tag{35}$$

Subtract the predisturbance state,

$$\frac{\Delta\omega}{\Delta \mathrm{P}} = \frac{-k}{4(2\omega - 1 - k)} \tag{36}$$

In (32) and (33) let ω be increased by $\Delta\omega$ and P by $\Delta \mathrm{P}$, and subtract the predisturbance state , Hence $\Delta \mathrm{P}_e = F\Delta\omega$

Or

$$\frac{\Delta\omega}{\Delta \mathrm{P}_e} = \frac{1}{F} \tag{37}$$

And

$$\Delta \mathrm{P} = \Delta \mathrm{P}_{ref} - \Delta \mathrm{P}_e \tag{38}$$

A change in the demand for shaft power $\Delta \mathrm{P}_d$ may be added to the summing point of $\Delta \mathrm{P}_{ref}$ and $\Delta \mathrm{P}_e$, and $\Delta \mathrm{P}_{ref}$ summed to be zero. Hence the overall closed-loop transfer function gain G_c at the speed ϖ is found to be,

$$G_c = \frac{\Delta\omega}{\Delta \mathrm{P}_d} = \frac{Forwardgain}{1 + (Forwardgain)(Feedbackgain)}$$

$$= \frac{\dfrac{-k}{4(2\omega - 1 - k)}}{1 - \dfrac{kF}{4(2\omega - 1 - k)}}$$

$$= \frac{k}{kF - 4(2\omega - 1 - k)} \tag{39}$$

For typical power system applications gain has the per-unit value of 0.04, and the operating shaft speed ω is within a small range centered on the rated speed .the rated speed corresponds to the nominal frequency of the power system. Hence the term $4(2\omega - 1 - k)$ may be neglected since k is typically in the range of 1.0 to 2.0.

The transfer function simplifies to become,

$$G_c = \frac{1}{F} \quad \text{Where F is typically 25 per unit} \tag{40}$$

The transfer function gain is also called the 'droop' characteristic of the gas turbine. [22][27][28][29]

3.6.3 Governing Systems for Microturbines:

The following discussions outline the important principles behind the governing of microturbines. In all power systems the requirement is that the steady state speed state speed deviation, and hence frequency , is kept small for incremental changes in power demand , even if theses power increments are quite large -20%, for example.[13][15][18]

There are two main methods used for speed governing gas turbines,

1. Droop governing.
2. Isochronous governing.

Droop governing required a steady state error in space to create the necessary feedback control of the fuel value.' Droop' means that a fall in shaft speed (and hence generator electrical frequency) will occur as load is increased. It is customary that a droop of about 4% should occur when 100% load is applied. Droop governing provides the simplest method of sharing load between a group of generators connected to the same power system.

In control theory terminology this action is called 'proportional control'. This method of governing is the one most commonly used in power systems because it provides a reasonably accurate load sharing capability between groups of generators.

Isochronous governing causes the steady state speed error to become zero, thereby producing a constant speed at the shaft and a constant frequency for the power system. Isochronous governing is also a from of 'integral control'. This method is best suited to a power system that is supplied by one generator. This type of power system has very limited application. However, there are situations where one isochronously governed generator can operate in parallel with one or more droop-governed generators. The droop-governed generators will each have a fixed amount of power assigned to them for the particular system frequency. This is achieved by adjusting their set points. As the demand on the whole system changes, positively or negatively, this isochronously governed generator will take up or reject these changes, and the steady state frequency will remain constant. This hybrid type of load sharing is seldom used in the oil industry.

Accurate power sharing and constant speed control can obtain by using a specially designed controller. This controller incorporates load measurement of each generator, measurement of common system frequency and a sub-system to reduce the power mismatches of each generator to zero. The controller regularly or even continuously trims the speed set points of each microturbine to maintain zero mismatches. A slowly operating integrator can be superimposed onto these set points to adjust them simultaneously so that the frequency is kept constant , this is a form of 'proportional integral'(Governor lead and lag compensating dynamics) controller.[30]

3.7 Basic Process and Components of a Microturbine Systems:

The basic components of a microturbine generation system are: compressor, turbine, recuperator, high-speed generator (permanent magnet synchronous Generator) and power electronics interfacing. In the following paragraphs a brief description of each component is given, followed by a detailed modeling of microturbine and high-speed generator. Figure 3.4 shows the schematic diagram of a single-shaft microturbine based generation system [14][31][32][33][34].

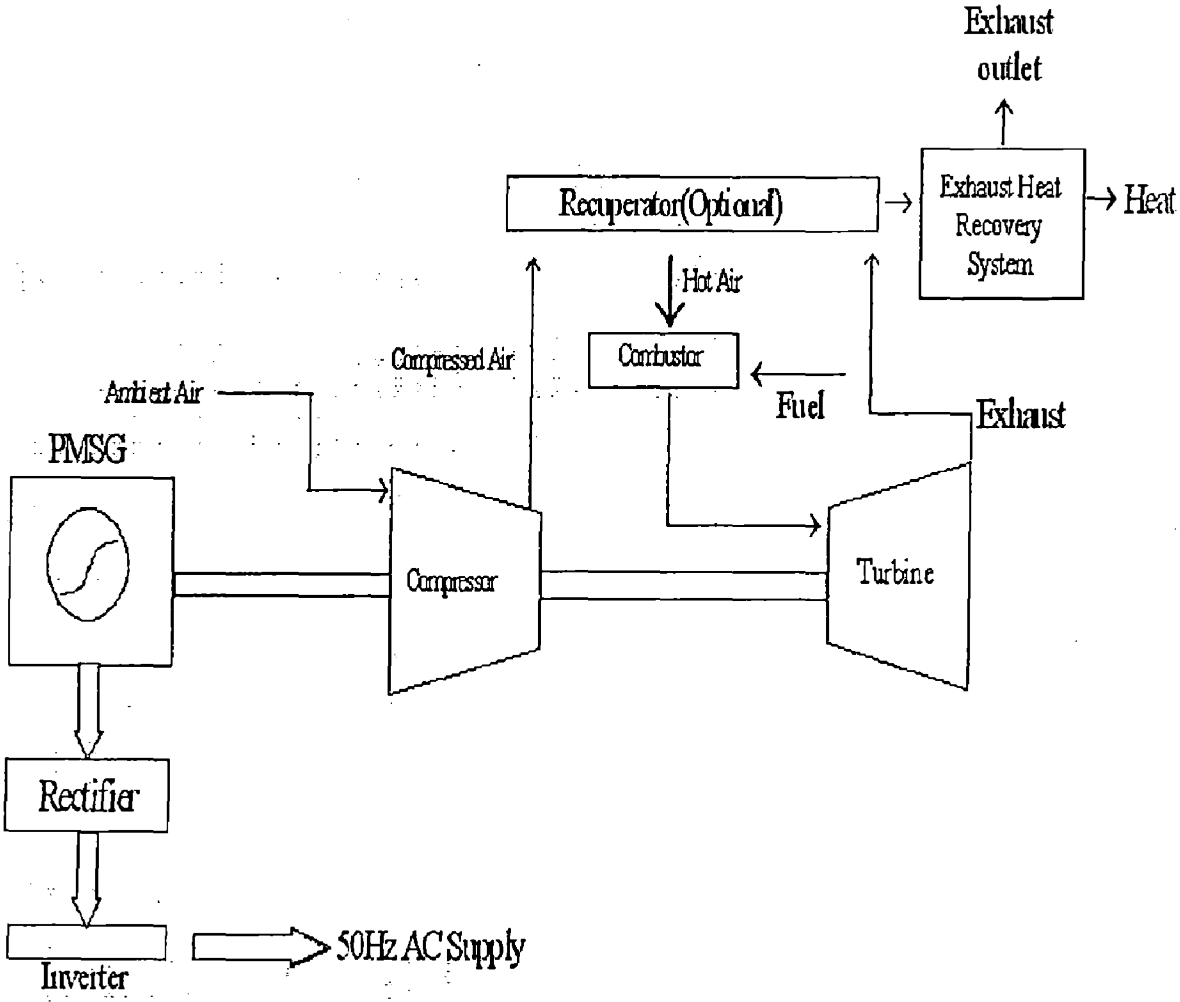


Figure 3.4 Microturbine based CHP system (Single –Shaft Design)

Microturbines, like large gas turbines, operate based on the thermodynamic cycle known as the Brayton cycle [33]. In this cycle, the inlet air is compressed in a radial (or centrifugal) compressor. The compressed air is mixed with fuel in the combustor and burned. The hot combustion gas is then expanded in the turbine section, producing rotating mechanical power to drive the compressor and the electric generator, mounted on the same shaft (single-shaft design). In a typical microturbine air to gas heat exchanger called recuperator is added to increase the overall efficiency. The recuperator uses the heat energy available in the turbine's hot exhaust gas to preheat the compressed air before the compressed air goes into the combustion chamber thereby reducing the fuel needed during the combustion process.

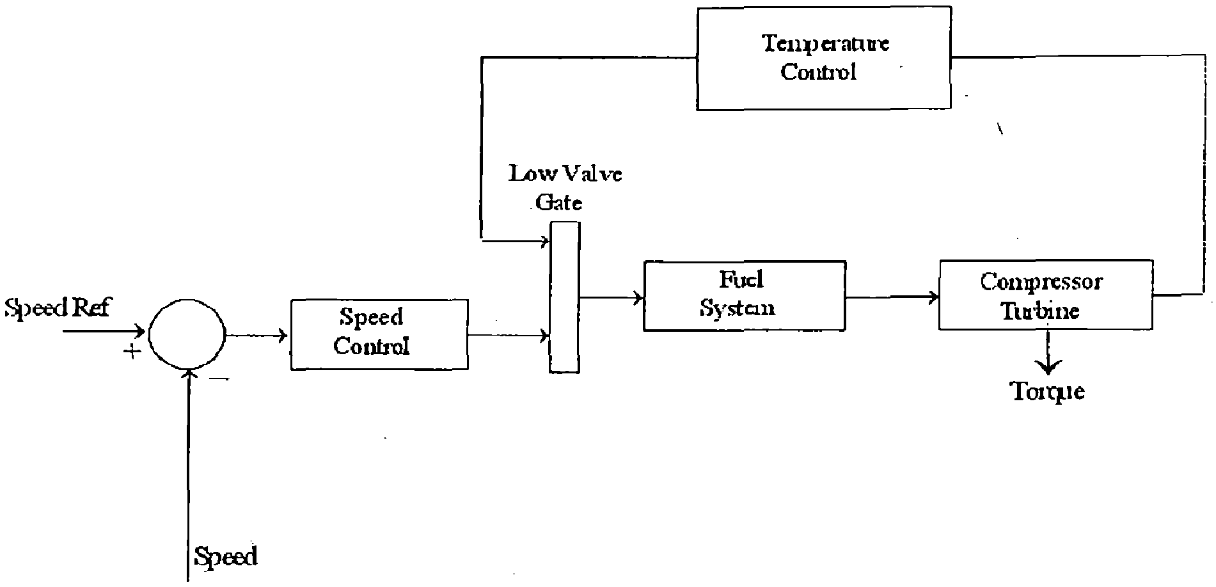
The high-speed generator of the single shaft design usually employs a permanent magnet synchronous generator (PMSG), and requires that the high frequency AC output in the order to be converted to 60 Hz (or 50 Hz) for general use. This power conditioning involves rectifying the high frequency AC to DC and then inverting the DC to 60 Hz (or 50 Hz) AC. Power electronic interfacing is a critical component in the single-shaft design and is generally designed to handle transient and voltage spikes [31][32][33][34]

The model presented in this thesis concentrates on the slow dynamics of the Microturbine generation systems, suitable for power management of MicroTurbine Generation combined with other types of distributed generation (DG) systems. It is reasonable, while modeling the microturbine for the above purpose, to assume that the system is operating under normal operating conditions by neglecting fast dynamics of the microturbine (e.g., start-up, shutdown, internal faults and loss of power). Also, since the electromechanical behavior of the Microturbine generation system is of main interest the recuperator is not included in the model as it only serves to increase the turbine efficiency [35][17].

3.7.1 Mathematical Representation of a Microturbine:

There exists a large literature on the Modeling of gas turbines, with varying level of complexity depending on the intended application. The three control functions of the microturbine are: speed control acting under part load conditions, temperature control acting as an upper output limit, and acceleration control to prevent over speeding. The output of these control function blocks are all 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 as shown in Figure 3.5 . This figure shows the per-unit representation of microturbine, along with its control systems. Each subsystem of microturbine is discussed in the following subsections. [33][36]

Figure 3.5 Block diagram of microturbine.



3.7.2 Speed and Accelaration Control:

The governor implements three major control loops: start-up, speed and temperature. For the purposes of these modeling tests, the speed control, which is active during partial load conditions, receives the most attention. The reason for this is That during start-up, the unit is not on-line, and in temperature control mode, the governor will not respond to system frequency changes.

The primary valve demand control signal is selected by a low value gate from the outputs of the three control loops. Lights on the control panel indicate the controlling mode.

The speed control operates on the speed error formed between a reference (one per-unit) speed and the Microturbine generation system rotor speed. It is the primary means of control for the microturbine under part load conditions. Speed control is usually modeled by using a lead-lag transfer function [36][30][28], or by a PID controller [29]. In this work a lead lag transfer function has been used to represent the speed controller, as shown in Figure 3.6 In this figure K is the controller gain, T_1 (T_2) is the governor lead (lag) time constant, and Z is a constant representing the governor mode (droop or isochronous). A droop governor is a straight proportional speed controller in which the output is proportional to the speed error. An isochronous speed controller is a proportional-plus-reset speed controller in which the rate of change of the output is proportional to the speed error.

Step input signals were introduced, and the speed measurement time constants, T_1 and T_2 were measured. The speed measurement circuit did not implement the expected single time constant (lag) response; instead, a lead-lag arrangement was found.

Lead -Lag controller, with typical gain values with in 10 to 50 (corresponding to 10% to 2% droop settings, respectively). It operates on the speed deviation formed between the reference speed of 1.0 p.u. and the actual speed.

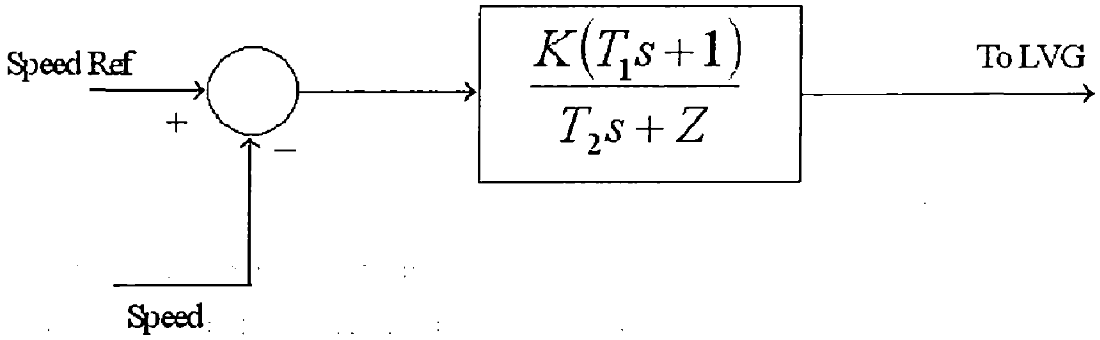


Figure 3.6 Speed controllers for the microturbine.

Acceleration control is used primarily during turbine startup to limit the rate of the rotor acceleration prior to reaching operating speed. If the operating speed of the system is close to its rated speed, the acceleration control could be eliminated in the modeling. Which is the case in this study. And also digital set point is not considering. Only considering the speed deviation of the generator with respective to the speed reference. [36][28][37]

3.7.3 Fuel System:

The fuel system consists of the fuel valve and actuator. The fuel flow out from the fuel system results from the inertia of the fuel system actuator and of the valve positioner [36], [38], whose equations are given below.

The valve positioner transfer function is:

$$E_1 = \frac{K_v}{T_v + c} F_d \qquad (41)$$

And the fuel system actuator transfer function is:

$$W_f = \frac{K_f}{T_f s + c} E_1 \qquad (42)$$

In (41) and (42), $K_v(K_f)$ is the valve positioner (fuel system actuator) gain, T_v, T_f are the valve positioner and fuel system actuator time constants, c is a constant, F_d and E_1 are the input and outputs of the valve positioner and W_f is the fuel demand signal in p.u.[39][40][41][42]

The output of the LVG, V_{ce} , represents the least amount of fuel need for that particular operating point and is an input to the fuel system. Another input to the fuel system is the per-unit turbine speed N (limited by the acceleration control). The per-unit value for V_{ce} corresponds directly to the per-unit value of the mechanical power on turbine at steady-state. The fuel flow control as a function of V_{ce} is shown in Figure 3.7.

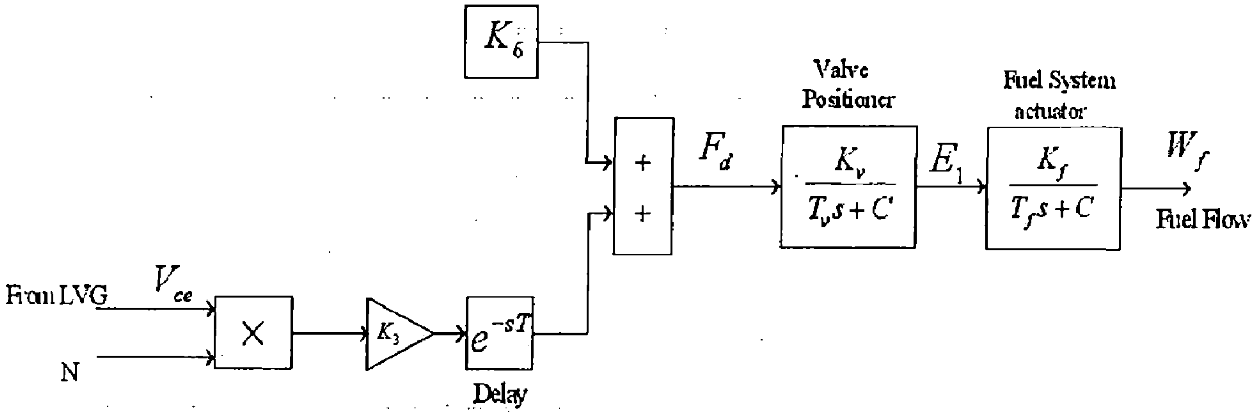


Figure 3.7 Block diagram of the fuel system.

The value of V_{ce} is scaled by the gain $K_3 (K_3 = (1 - K_6))$, then delayed and offset by the minimum amount of fuel flow K_6 to ensure continuous combustion process in the combustion chamber. K_6 is essentially the minimum amount of fuel flow at no-load, rated speed.

3.7.4 Compressor-Turbine:

The compressor-turbine is the heart of the microturbine and is essentially a linear, nondynamic device (with the exception of the rotor time constant) [36]. There is a small transport delay T_{CR}, associated with the combustion reaction time, a time lag T_{CD}, associated with the compressor discharge volume and a transport delay T_{TD} , for transport of gas from the combustion system through the turbine. The block diagram of the compressor-turbine package is shown in Figure 3.8. In this figure both the torque and the exhaust temperature characteristics of the single-shaft gas turbine are essentially linear with respect to fuel flow and turbine speed and are given by the following equations [33][36][43][44];

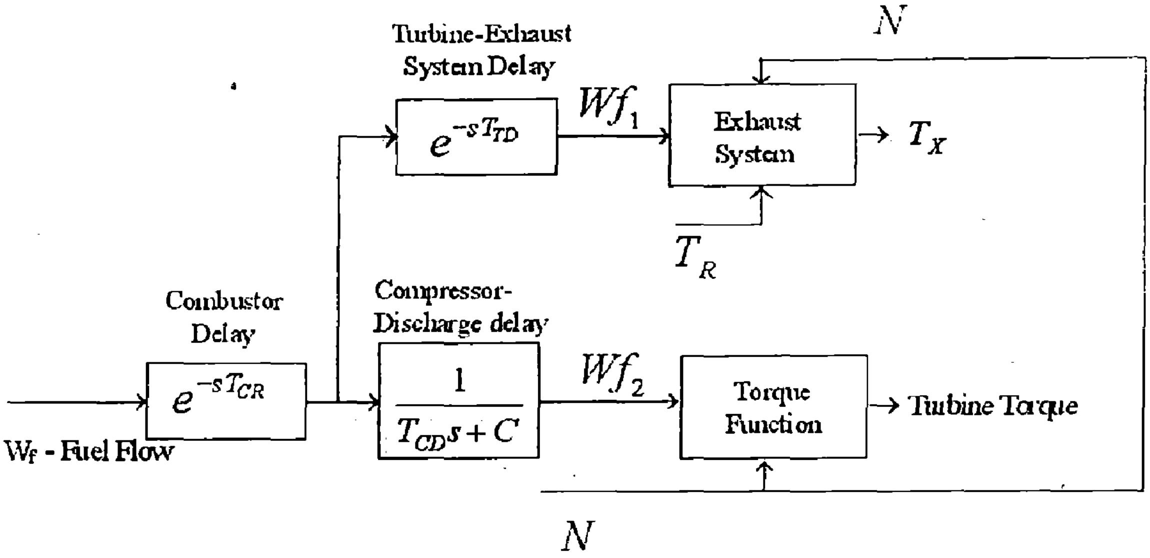


Figure 3.8 Compressor-Turbine Package of microturbine.

$$Torque = K_{HHV}\left(W_{f2} - 0.23\right) + 0.5\left(1 - N\right)\left(Nm\right) \tag{43}$$

$$Exhaust \quad Temp., T_X = T_R - 700\left(1 - W_{f1}\right) + 550\left(1 - N\right)\left({}^{o}F\right) \tag{44}$$

Where K_{HHV} is a coefficient which depends on the enthalpy or higher heating value of the gas stream in the combustion chamber and T_R is the reference temperature. The K_{HHV} and the constant 0.23 in torque expression cater for typical power/fuel rate characteristic, which rises linearly from zero power at 23% fuel rate to the rated output at 100% fuel rate.

The input to this subsystem is p.u.fuel demand signal W_f and outputs are the p.u turbine torque and exhaust temperature $\left({}^{o}F\right)$

3.7.5 Temperature Control:

Temperature control is the normal means of limiting the gas turbine output power at a predetermined firing temperature, independent of variation in ambient temperature or fuel characteristics. The fuel burned in the combustor results in turbine torque and in exhaust gas temperature. The exhaust temperature is measured using a series of thermocouples incorporating radiation shields as shown in the block diagram of the temperature controller (Figure 3.9). In Figure 3.9, T_t is the temperature controller integration rate and T_3, T_4 are time constants associated with the radiation shield and thermocouple, respectively. K_4 and K_5 are constants associated with radiation shield and T_5 is the time constant associated with temperature controller. The output from the thermocouple is compared with a reference temperature, which is normally higher than the thermocouple output. This forces the output of the temperature control to stay on the maximum limit permitting the dominance of speed control through the LVG (Figure 3.5). When the thermocouple output exceeds the reference temperature, the difference becomes negative, and the temperature control output starts decreasing. When this signal (Figure 3.5) becomes lower than the speed controller output, the former value will pass through the LVG to limit the turbine's output, and the turbine operates on temperature control. The input to the temperature controller is the exhaust temperature (T_x) and the output is the temperature control signal to the LVG [33] [36] [38] [40] [42] [43] [44].

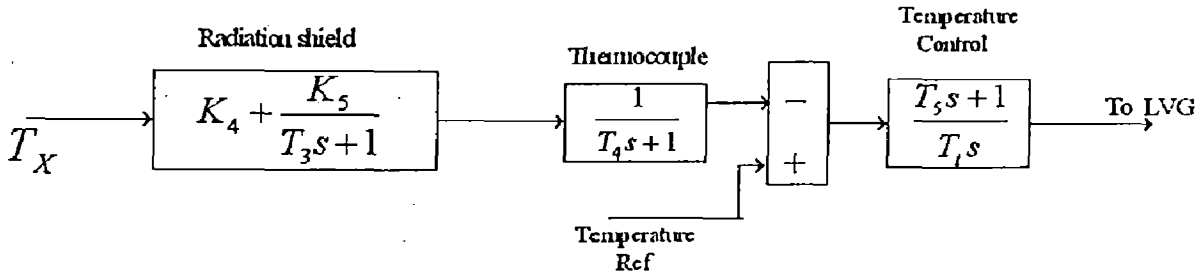


Figure 3.9 Temperature Controller.

3.8 Permanent Magnet Synchronous Generator (PMSG):

The Microturbine produces electrical power via a high-speed Generator directly because microturbine here used a single shaft turbine that is driven by the turbine-compressor shaft. As in the case of small gas turbines benefit in particular when the gearbox that reduces the shaft speed to the speed of conventional electrical machines is eliminated, as in the case with single-shaft design considered here. The result is a more efficient, compact and reliable machine and shaft speed is normally above 3000 rev /min and may exceed 90,000 rev/min. high energy permanent magnets [14][31][45][46][47]

In the following section the equivalent circuit of a permanent 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 [48] [45] [46]

Permanent Magnet Materials :

The property of a permanent magnet and the selection of the proper materials are very important in the design of a permanent magnet synchronous machine (PMSM). A good permanent magnet should produce a high magnetic field with a low mass, and should be stable against the influences which would demagnetize it. The desirable properties of such magnets are typically stated in terms of the *remanence* and *coercivity* of the materials, and are quoted in Tesla, the basic unit for magnetic field B.

Iron, nickel, cobalt and some of the rare earth metals exhibit a unique magnetic behavior which is called ferromagnetism. Ferromagnets tend to stay magnetized to some extent after being subjected to an external magnetic field. The fraction of the saturation magnetization retained (remanence) when the driving filed is removed is an important factor for the selection of the permanent magnets. All ferromagnetic materials have a maximum temperature known as *Curie temperature,* where the ferromagnetic property disappears. Consequently, the range of temperatures plays an important role in the operation of a PMSM [49].

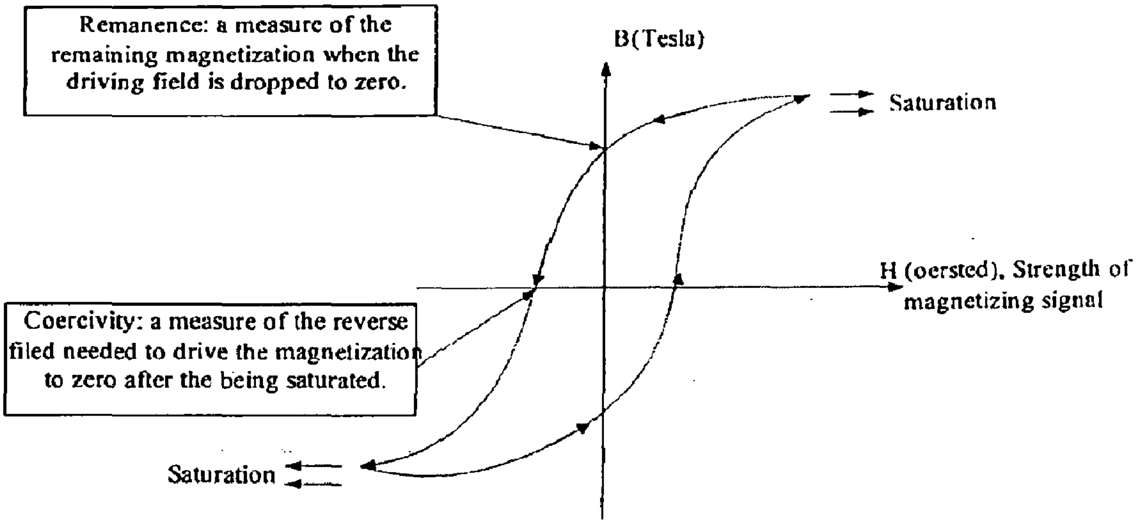


Figure 3.10 Hysteresis loop in the form of magnetization B and magnetic field strength H.

Operating Region of a PMSM:

Figure 3.11 shows the demagnetization segment of the B-H curve where the permanent magnet is usually designed to operate [48].

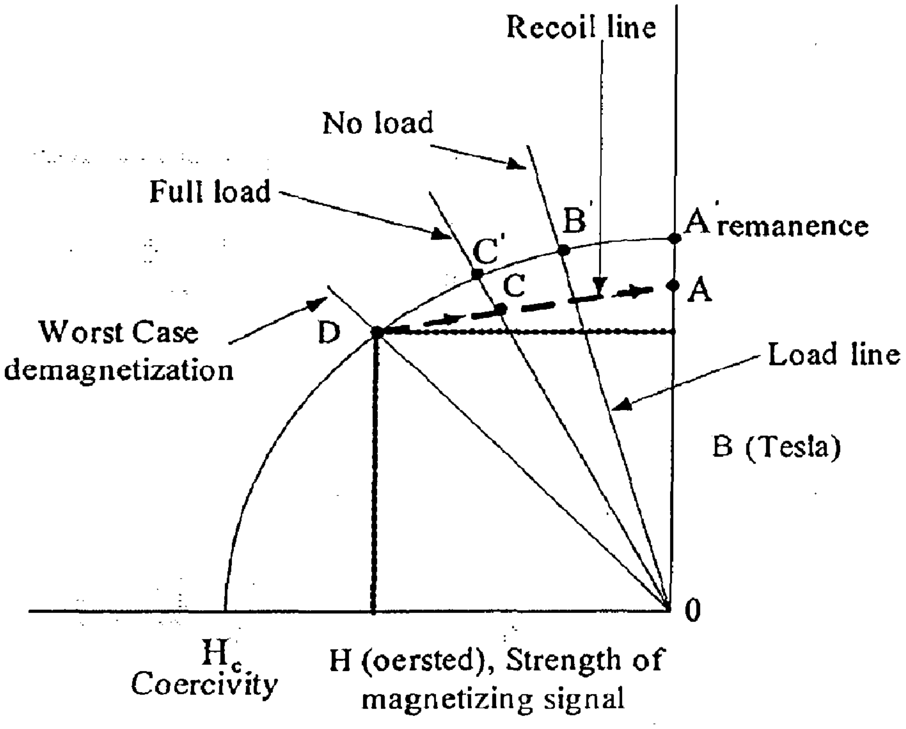


Figure 3.11 Permanent magnet machine operating points on B-H curve.

The maximum flux density Br corresponding to A' will be available initially (no airgap). When the magnet is installed in the machine, the air gap will have some demagnetization effect and the operating point B' will correspond to the no-load line as shown in Figure 3.11. When current flows in the stator winding, the magnetic axis (direct axis) armature reaction effect can have further demagnetization effect, which will reduce the air gap flux density further. A load line representing worst-case demagnetization (may be due to starting, transient or machine fault condition) is also shown in Figure 3.11. Once the operating point reaches the D and the demagnetization effect is removed, the magnet will recover along the recoil line (DA). Subsequently, the stable operating point will be determined by the intersection of the load line and the recoil line. The magnet is therefore permanently demagnetized at no-load operation, corresponding to the vertical distance between A' and A. If the permanent magnet material has a straight-line demagnetization curve, the recoil line will coincide with the demagnetization line irrespective of the worst case magnetization point (i.e., permanent demagnetization will be negligible). The characteristics for several possible permanent magnet materials are given in reference [48].

dq Axis Representation of a PMSM:

In a PMSM, the permanent magnets are glued on the rotor in surface sinusoidal magnet machine (SPM), and are mounted inside the rotor in case of an interior or buried magnet synchronous machine (IPM). The stator has three-phase sinusoidal winding, which creates a synchronously rotating air gap flux. If the machine is rotated by a prime mover, the stator windings generate balanced three-phase sinusoidal voltages. The *dq* axis representation of a permanent magnet synchronous machine (for a balanced system the *0*-axis quantities are equal to zero), where is shown in the Figure 3.12 [48],[50] In this figure the finite core loss is represented by the dotted damper windings.

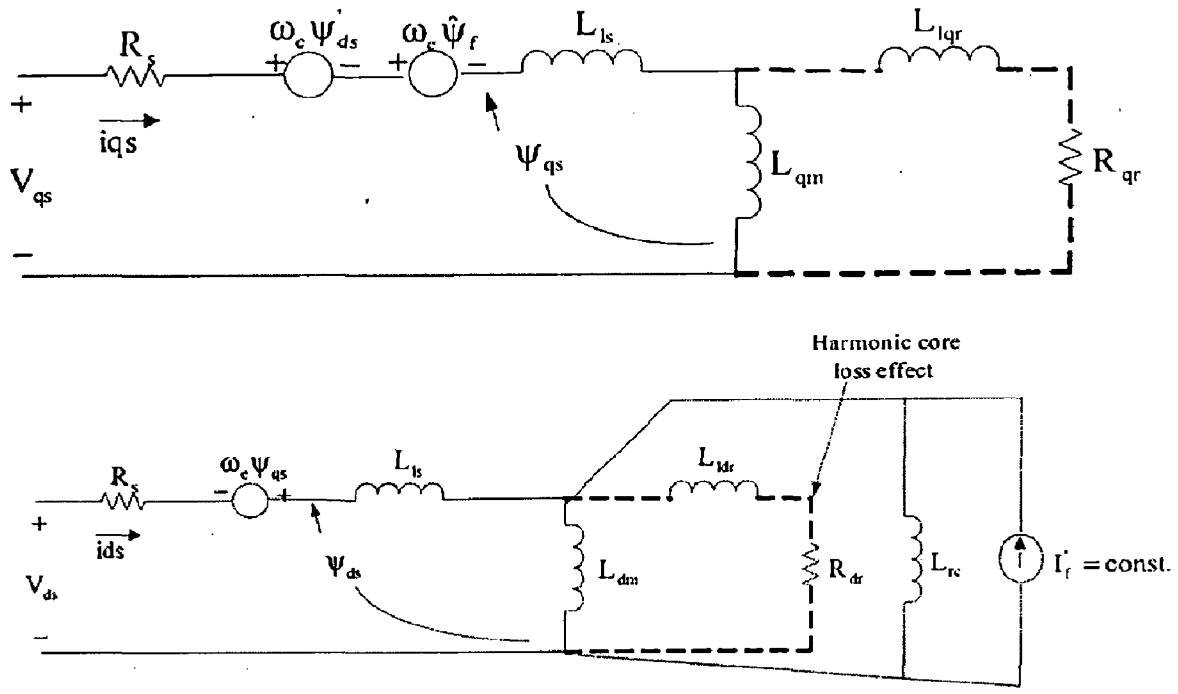


Figure 3.12 Synchronously rotating frame equivalent circuits of a PMSM

Ignoring core loss, the circuit equations can be written as (equations are valid for both IPM as well as SPM) (for SPM $L_{dm} = L_{qm}$) :

$$V_{qs} = R_s i_{qs} + \omega_e \psi'_{ds} + \omega_e \hat{\psi}_f + \frac{d\psi_{qs}}{dt} \qquad (45)$$

$$V_{ds} = R_s i_{ds} - \omega_e \psi_{qs} + \frac{d\psi_{ds}}{dt} \qquad (46)$$

Where the flux linkages are given by the following equations:

$$\hat{\psi}_f = L_{dm} I'_f \qquad (47)$$

$$\psi'_{ds} = i_{ds}\left(L_{ls} + L_{dm}\right) = i_{ds} L_{ds} \qquad (48)$$

$$\psi_{ds} = \hat{\psi}_f + \psi'_{ds} \qquad (49)$$

$$\psi_{qs} = i_{qs}\left(L_{ls} + L_{qm}\right) = i_{qs} L_{qs} \qquad (50)$$

The electromagnetic development in the machine air gap is given by:

$$T_e = \frac{3}{2} \times \frac{P}{2}\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \qquad (51)$$

Substituting (45)-(48) in (43), (44) and (49) and simplifying, we have

$$\frac{di_{qs}}{dt} = \frac{1}{L_{qs}}\left[V_{qs} - R_s i_{ds} - L_{ds}\omega_e i_{ds} - \hat{\psi}_f\right] \tag{52}$$

$$\frac{di_{ds}}{dt} = \frac{1}{L_{ds}}\left[V_{ds} - R_s i_{ds} + \omega_e L_{qs} i_{qs}\right] \tag{53}$$

$$T_e = \frac{3P}{4}\left[\hat{\psi}_f i_{qs} + \left(L_{ds} - L_{qs}\right) i_{qs} i_{ds}\right] \tag{54}$$

The rotor speed is obtained from the dynamics of the mechanical system as follows:

$$\frac{d\omega_r}{dt} = \frac{1}{J}\left(T_e - T_{shaft}\right) \tag{55}$$

Where $\omega_{e,}\omega_r$ are electrical and mechanical angular velocities of the rotor (rad/sec), $V_{qs}, V_{ds}\left(I_{qs} I_{ds}\right)$ are q and d axis voltage (current) components and L_{qs} and L_{ds} are q and d axis inductances of the stator respectively. L_{dm} is the common $d-axis$ mutual inductance of the stator lumped with the damper windings and the permanent magnet inductance L_{re} (associated with the recoil slope).

I_f is an equivalent field current of the permanent magnets and I'_f is its equivalent referred to the stator side,

$\psi_f\left(\psi_f = L_{dm} I'_f = consant\right)$ denotes flux linkage induced by the permanent magnets of the rotor in stator phases,

J is the inertia of the rotor (Kgm^2),

T_{shaft} is the shaft torque produced by the microturbine (Nm),

T_e is the electric torque generated by the PMSG (Nm), and

P is the number of poles .

Note that the signs for the generated torque T_e and shaft torque T_{shaft} are positive for motor operation and negative for generation operation. (Referred in Matlad documentation)

3.9 Self-Excited Induction Generators(SEIG):

The Self-Excited Induction Generators (SEIGs) are receiving increased attention from the utilities over the world to obtain the energy from renewable/non-conventional sources for remote and isolated areas. The main problem in the use of induction machine as a generator are related to the varying voltage and frequency, the loss of self excitation, the overloading of the machine, the transient over voltages due to the capacitance switching or the load loss. But, the robust construction of induction machine specially squirrel cage type rotor, offers maintenance free operation and the least cost of the generating system. This has motivated to facilitate the use of the induction generator in isolated mode with suitable low cost control which could ensure the reliable supply of good quality. Also, such system for power generation could be made efficient and cost effective to compete with the other conventional sources of energy. [32][35][51]

The squirrel cage induction generators have been preferred in comparison with the synchronous generators for small scale power generation due to their low cost, robust construction and ease of maintenance. The induction generators do not require separate dc exciter and its related equipment like field breaker, automatic voltage regulator etc. therefore, such generators need minimal maintenance. The cage induction generators can be driven at a run away speed relatively for a longer duration than the other type of generators (such as the synchronous or the dc generator) because of the absence of the field windings on the rotor and its cage construction. In case of the short circuit across the machine terminals, the sustained transients are not generated due to the absence of field. The other advantage of the cage induction generators such as the absence of the slip ring, the commutator brushes, the battery packs and the inverter are well known.

However, in spite of the several advantages, the conventional induction motor used as the induction generator has various disadvantages such as poor inherent voltage and frequency regulation and moderate efficiency. To overcome poor voltage regulation of SEIG a number of schemes have been proposed. The scheme based on switched capacitor [52] [53] finds limited application because it regulates the terminal voltage in discrete steps. In recent years, the inverter based reactive power sources have been used for regulating the AC output voltage profile of a SEIG under balanced three-phase loading conditions.

Advantages of self-excited induction generator

- Lower capital cost.
- Simple and rugged construction.
- Self-excited induction generator do not require any sophisticated control and can provide reliable and relatively inexpensive means to generate electricity for loads, where small frequency variation is allowed up to certain extent.

- A separate dc source is eliminated in case of a SEIG, which is necessary for excitation in case of a synchronous generator. Maintenance problem like brush maintenance is removed.
- Main feature is the automatic protection against external short circuit, which causes the excitation to collapse and consequently no current flow.
- The variable speed prime mover need not be governed.

SEIG can be operated in parallel with out any problem of synchronization i.e. they may operate at different speed and still share load

Disadvantages of self-excited induction generator:

- It has poor inherent frequency and voltage regulation.
- Its efficiency is comparatively less due to higher core and magnetizing current losses.
- More heating in rotor.
- The terminal voltage waveform is likely to be distorted because of the need to stabilize the excitation for saturated conditions.
- A high voltage is generated at the terminals if synchronous machine connected to induction generator through long transmission line is disconnected and the line capacitance excites the induction machine. This phenomenon is called as accidental self-excitation. But would be rare in actual practice since use is made to shorter lines.

The most sever disadvantage of SEIG is its inherently low lagging power factor

Methods to improve voltage and frequency regulations:

a) **Switched capacitor:** Regulates terminal voltage in discrete steps.

b) **Saturable core reactor:** The saturable core reactor in parallel to the fixed capacitors can maintain the terminal voltage constant. Absence of switching operation will provide smooth waveform of the terminal voltage of the induction generator. But it involves potentially large size and weight due to necessity of a large saturating inductor.

c) **Long shunt and short shunt compensation:** The terminal voltage can be improved by including an additional series capacitance to provide additional VAR with load. It gives better performance in terms of voltage regulation but the series capacitor causes the problem of sub synchronous resonance.

d) **Static VAR compensation:** The static VAR compensator consists of thyristor phase controlled reactor in parallel with thyristor switched capacitor and fixed excitation capacitor. It faces the problem of weight losses in the inductor.

e) **Current-controlled voltage source inverter:** Current-controlled voltage source inverter acts as a voltage regulator for maintaining constant terminal voltage.

f) **Electronic load controller/Induction generator controller:** Electronic load controller controls both voltage and frequency regulation.

Note:-For simulation of microturbine with Permanent Magnet Synchronous Generator and Induction generator, I have been used inbuilt machines from sim power system (MATLAB/Simulink).

3.10 Power Electronics Interface:

In order to realize a load system, the output voltage and frequency should be maintained at a predetermined level so that the load system can be achieved. This is made possible by employing power electronics interface which has the ability to control the system output variables such as voltage and frequency to keep or bring them to match their reference values after a disturbance. In microturbine system have their own dq transformed [50] power electronics interface and the control logic. The power electronics interface comprises of a rectifier and voltage source inverter. A pulse width modulation (PWM) controller was used to control the inverter in order to satisfy the voltage regulation as well as frequency control [54]. a brief description of the system is given in the following section.

The power electronics interface used has the ability to control the real and reactive power by the controlling the inverter output voltage and frequency [54]. This is realized by converting AC power output from the generator in to DC and then in to AC. A 3-phase uncontrolled rectifier made up of six bridge connected diodes has been used to rectify the generator output from AC to DC. A voltage source inverter (VSI) is then employed to convert the DC output from the rectifier to AC. control of voltage source inverter is achieved by means of control loop namely , voltage regulator loop .the overall system along with its control strategies is shown in Figure 3.14.

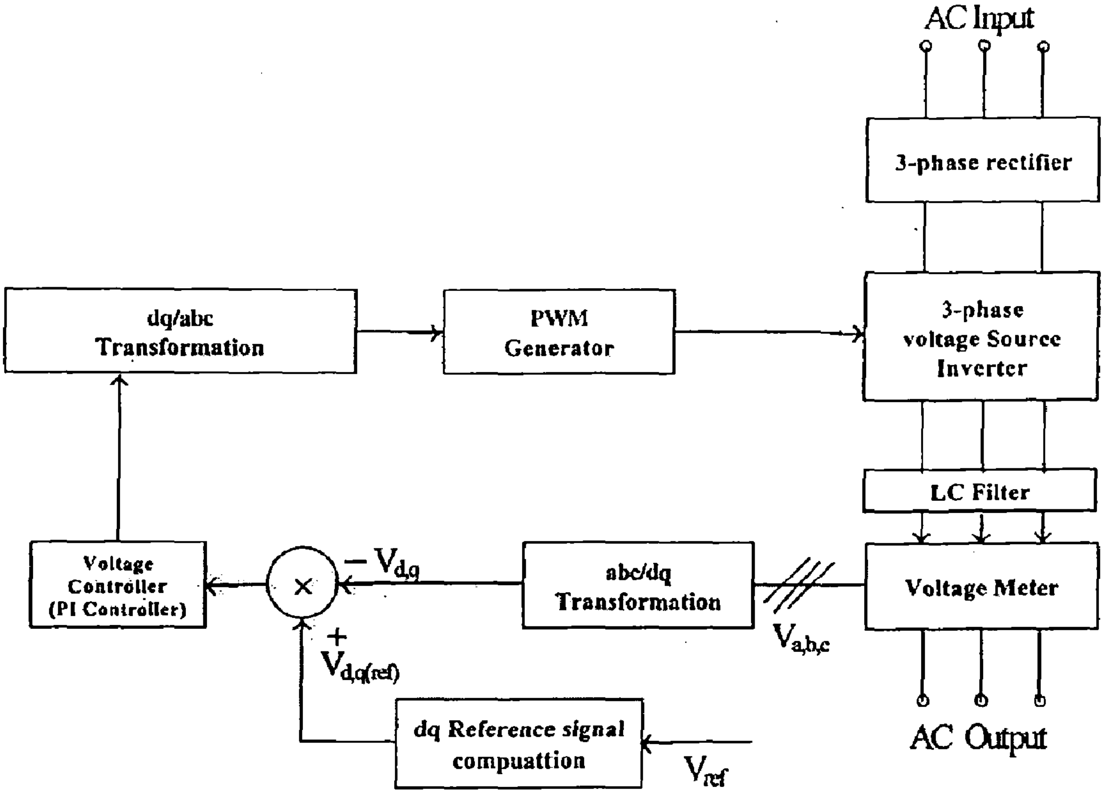


Figure 3.14. Block Diagram of the Power electronics interfacing.

The "abc/dq Transformation" block takes the time varying voltages (in abc coordinates) from the voltage measurement devices and converts them into dq (time-invariant) values. The voltage controller takes he error signals between the actual output in dq frame $\left(V_{d,q}\right)$ and the reference voltage $\left(V_{d,q(ref)}\right)$ and generates the voltage controller loop. The voltage controller produces the dq control signal, which is converted back to the control signals in abc coordinates through the "dq/abc Transformation" block. These control signal is used the gating pulse for the inverter to control its output voltage, using pulse-width modulation (PWM) generator. Actually my objective is to maintain the constant frequency (50 Hz) and constant voltage. [50][31]

For full bridge rectifier: Snubber resistance Rs (ohms) = 100, Snubber capacitance Cs (F) = 0.1e-6, L= 200e-6, C= 5000e-6.

For IGBT/Diode PWM IGBT Inverter: Snubber resistance Rs (ohms) = 5000, L=2mH, C= 3kvar, Sampling Time Ts = 2e-6.

Voltage regulator: PI controller: KP=0.4, Ki= 500.

PWM generator carrier frequency (Hz) = 2000.

CHAPTER-4

MODELING OF DIESEL ENGINE GENERATION SYSTEM

4.1 Dynamic model of Diesel Engine system:

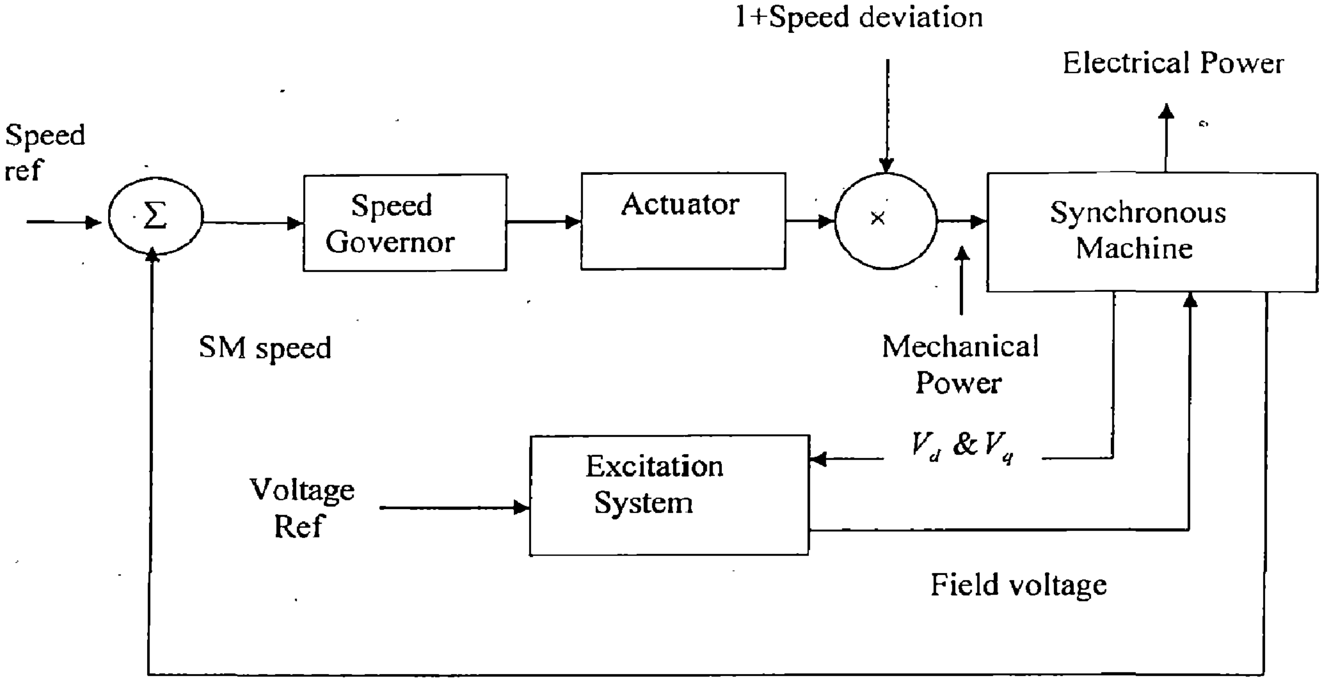


Figure 4.1 a Block Diagram for Diesel engine.

The overall block diagram of the diesel engine with governor, actuator and synchronous machine is shown in Fig. 4.1. The differences between the desired speed and the synchronous machine speed or engine speed produce the control signal, causing a change in the torque of the prime mover. The diesel engine then produces the torque, driving the synchronous machine generating the electrical power output. The diesel engine generates the torque and the mechanical power would be given in the following equation are: [55]

$$P_m = \omega \times T_e \tag{4.1}$$

Where P_m = Mechanical power (per unit)

ω_r = Rated speed (per unit)

T_e = Engine Torque (per unit)

Then the measured synchronous machine speed is fed back to compare with the reference signal to control the governor. The diesel engine model implemented by the MATLAB SIMULINK is shown in Fig. 4.2. [55][56][57]

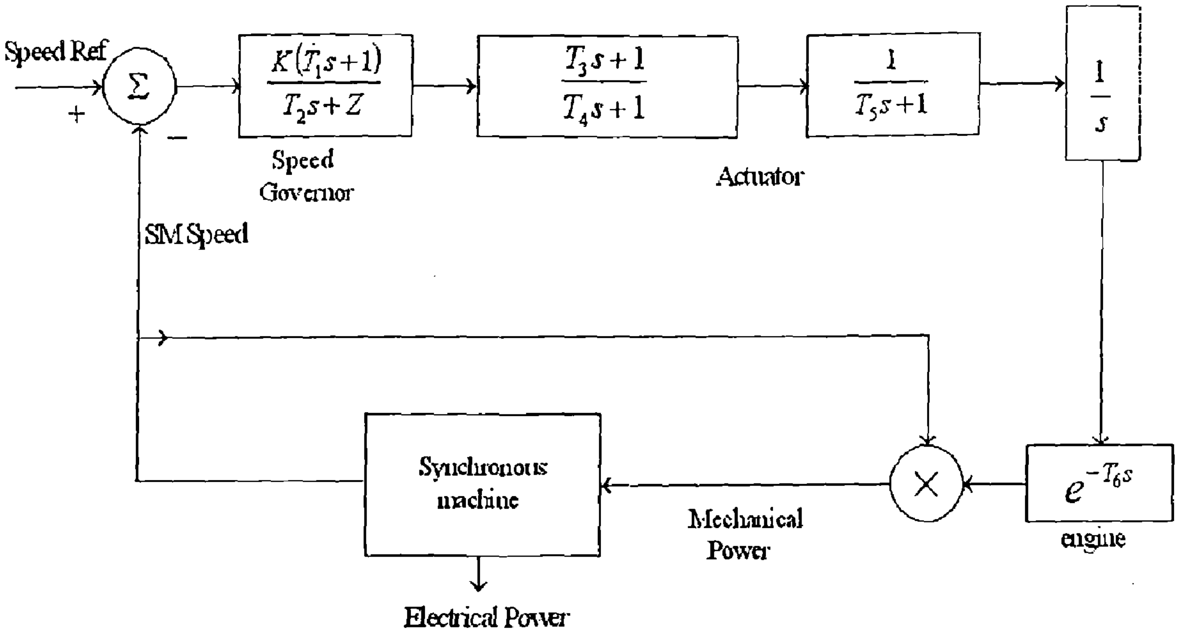


Figure 4.2 an implemented diesel engine dynamic model.

The speed deviation produced by comparing reference and synchronous speed generates the command signal in the speed governor (lead lag controller). The actuator is implemented by two block transfer functions, and finally the engine is represented by a simple time delay. Between the engine delay and the actuator, there is a possible limiter.

4.2 Excitation System Model:

The excitation systems can be classified as three of the main types from IEEE Std. 421.5-1992. [50] [12]

1. DC type excitation systems, which utilize a direct current generator with a

   Commutator as the source of excitation system power.
2. AC type excitation systems, which use an alternator and either stationary or rotating rectifiers to produce the direct current needed for the synchronous machine field.

3. ST type excitation systems. in which excitation power is supplied through transformers or auxiliary generator windings and rectifiers.

These detailed excitation system models are in IEEE Recommended Practice for Excitation System for Power System Stability Studies. Excitation system models can include a terminal voltage transducer and a local compensator, excitation control elements, an exciter, and, a power system stabilizer.

The exciter is transformed as the first order transfer function with an amplifier. In general, the K_A(Amplifier Gain) can be chosen to make the error as small as possible. On the other hand, K_A can be chosen as a large value, as long as the system is stable because if the amplifier gain were increased, the system would be unstable. The system can avoid this unstability by introducing the addition of the stabilization block of the excitation system with a first-order transfer function. An overall diagram for an excitation system with a simple synchronous machine model is shown in

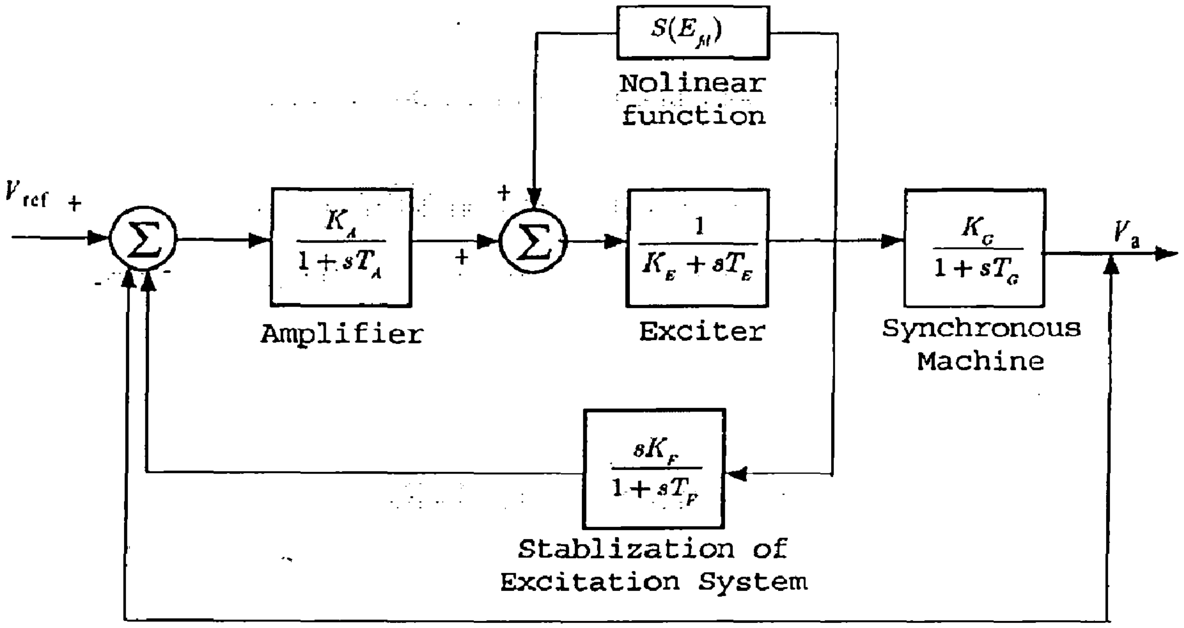


Figure. 4.3. [12]

Figure 4.3 an overall block diagram for a DC excitation system.

Also, the time constants and gain constants must be defined as follows

T_A = Time constant for an amplifier, typically from 0.01 to 10 sec

K_A = Gain constant for an amplifier, typically from 1 to 250

K_G = Gain constant for a synchronous machine

T_G = Time constant for a synchronous machine

K_F = Gain constant for a stabilization block

T_F = Time constant for a stabilization block

The implemented excitation system model using the MATLAB/ SIMULINK is shown in Figure 4.4. All the parameters for gain constants and time constants are given below for the entire simulation.

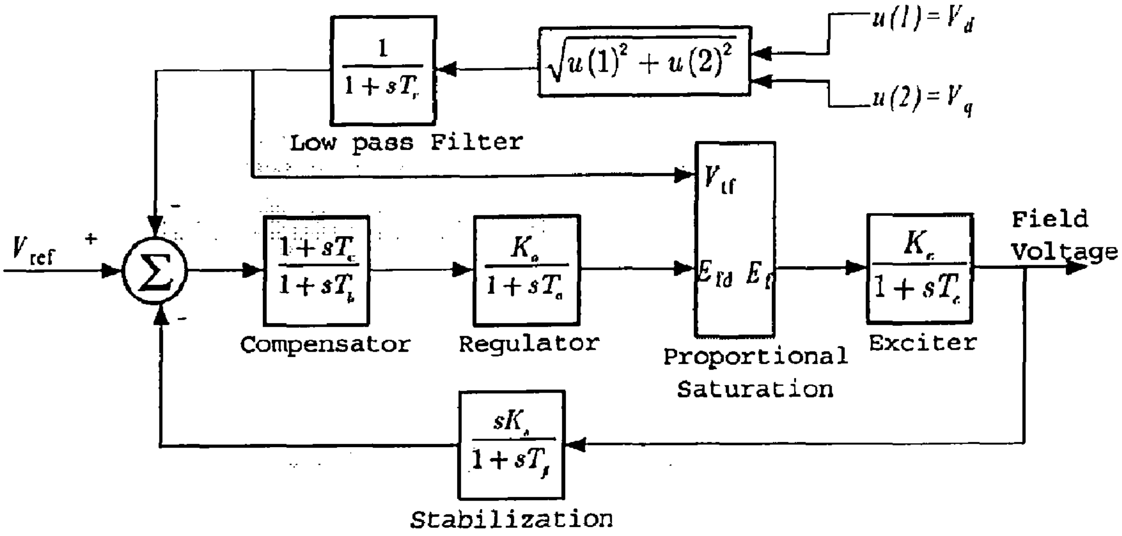


Figure 4.4 a block diagram of DC excitation system for implementing with MATLAB /SIMULINK. [50][12]

T_r = Time constant for a Low Pass Filter, 0.02

T_c = Time constant for Compensator, 0

T_b = Time constant for Compensator, 0

K_a = Gain for Regulator, 300

T_a = Time constant for a Regulator, 0.001

T_e = Time constant for an Exciter, 0

K_e = Gain for an Exciter, 0

K_f = Time constant for a Stabilization, 0.01

T_f = Time constant for a Stabilization, 0.1

This block diagram comes from the MATLAB POWER SYSTEM BLOCKSET example. The several new blocks that need to be explained are added (i.e., a positive sequence block, a low pass filter block, a lead and lag compensator block, and finally a proportional saturation block). The positive sequence and low pass filter produce the command signals from voltages coming from the synchronous machine d and q axis (Park's Transformation, later on explained). The proportional saturation block saturates the signals depending on E_{fd} and V_{tf} with a maximum or minimum value. The maximum and minimum values can be determined by an exciter system characteristic.

4.3 Synchronous machine:

The 3-phase salient-pole synchronous machine shown in Figure. 4.5 can predict the electrical and electromechanical behavior of most synchronous machine [58]. In general, the rotor of a synchronous machine has a field winding and one or more damper windings. Furthermore, all rotor windings have different electrical characteristics. In the model, there are one field winding, one damper winding on the d-axis, and two rotor damper windings on the q-axis. In the model, all of the rotor parameters are viewed from Stator.

In Figure 4.5 two-pole, 3-phase wye-connected salient-pole synchronous machine is shown. Since the rotor of a salient-pole synchronous machine is magnetically unsymmetrical, there is no advantage in utilizing a change of variables for rotor variables
the way there is for the induction machine.

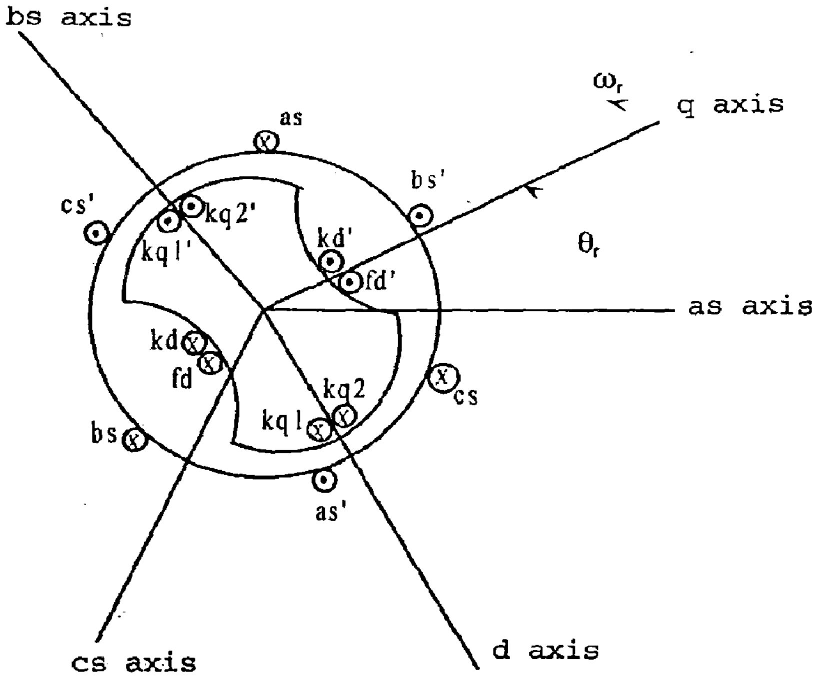


Figure 4.5 A two-pole, 3-phase, wye-connected salient-pole synchronous machine.

However, there is a benefit to utilizing a change of variables for the stator variables. In most cases, we can apply the rotor fixed reference frame for the stator variables, assuming that the stator windings are identical sinusoidal distributed windings. All rotor currents, voltages, resistances, and inductances are viewed from the stators.

Every subscript represents below:

r_s = A stator resistance

N_s = An equivalent turn

fd = The field windings

$k_d k_q$ = The damper windings

abc = Phase A, Phase B, Phase C for real

$qd0$ = Q, D, O axis

f = Currents, voltages, and flux linkages

s = A stator reference frame

$$p = \frac{d}{dt}$$

CHAPTER-5

RESULTS AND DISCUSSIONS

5.1 MicroTurbine Systems:

A mathematical model of the microturbine as explained in the chapter -3 sections is built in MATLAB/Simulink using SimPowerSystem block set. An inbuilt model of the permanent magnet synchronous machine in the SimPowerSystems block set, based on equations (52)-(55), is used to simulate the PMSG by applying negative torque to the model , Similar to the Induction Generator .All the parameters values used for the simulation are given in Tables-[I]. The block diagram of the simulated microturbine generation system is given in Figure 5.1, Appendix-[A1] followed by the simulation results for different operating conditions. [A2][A3]

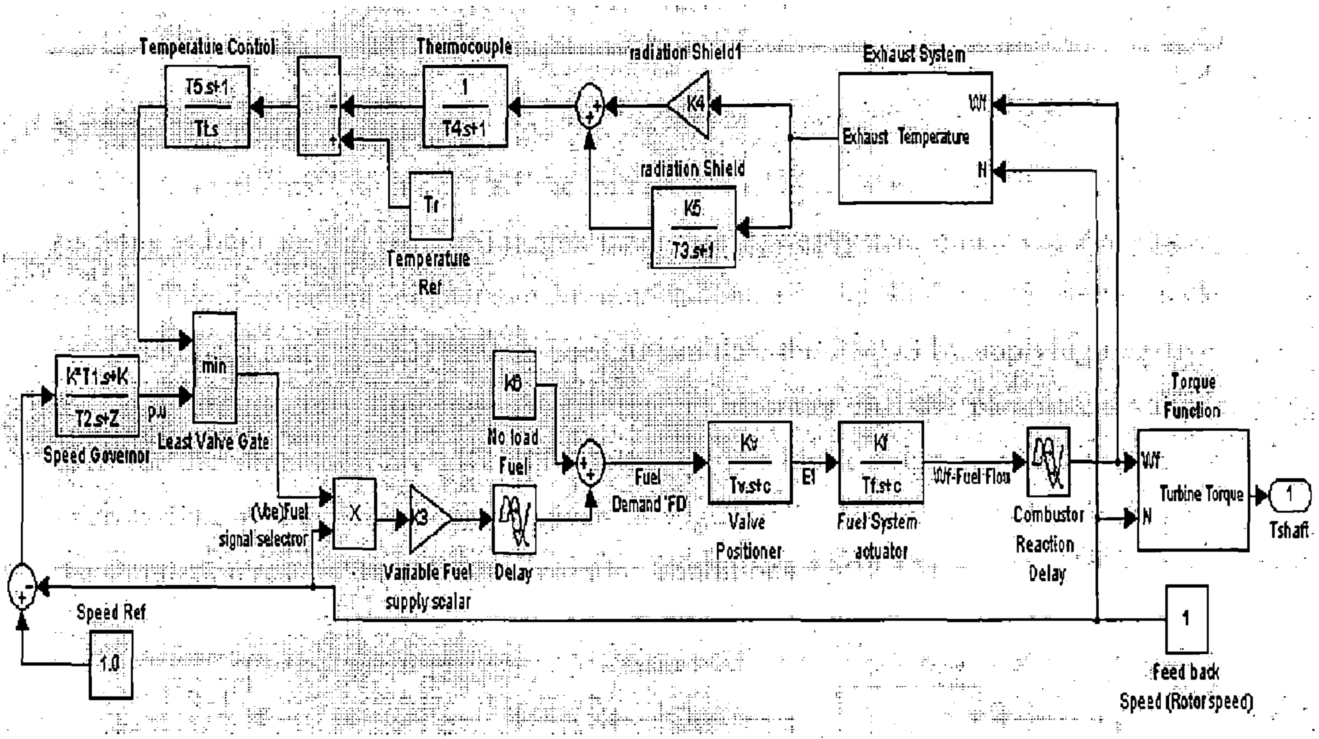


Figure 5.1 Block diagram of the simulated Microturbine System.

All time functions are in seconds.

Microturbine ratings: 35 kW (max), 3000 rpm.

Parameters used for the permanent magnet synchronous generator [50].

$R_s = 0.05$ Ohms, $L_d = L_q = 0.000635$ Henrys, $\psi_f = 0.192$ wb,

Friction factor =0.001889, Pairs of poles 'p' = 4.

Speed reference was kept constant at 1 p.u. for all simulations. The response of the developed Microturbine System is given in the following simulation Results:

5.2 **Section-I**: **Permanent Magnet Synchronous Machine**:

5.2.1 Case-1: At variable load:

Initially the system is operating at no-load. At t=10 seconds a load of 15kW is applied on the microturbine generation system and at t= 15 seconds, the load is increased to 34 kW. Figure 5.2 and 5.2.1 shows the fuel consumed by the microturbine for the applied load conditions.

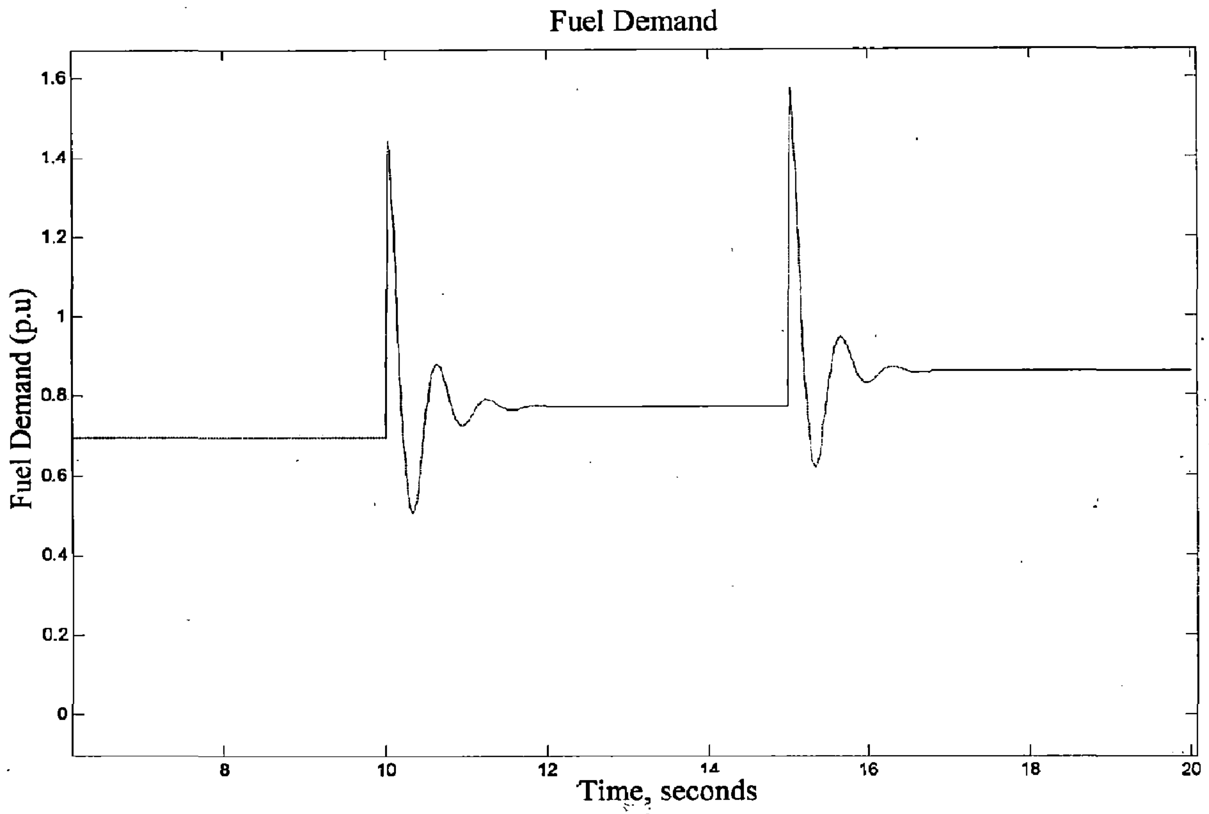


Figure 5.2 Fuel Demand Signal of the Microturbine

The fuel demand is equal to 23% (0.23 p.u) until the load is applied on the system at t=10seconds, increasing the amount of fuel required to keep the combustion process alive. Note that the fuel demand signal is 0.68 p.u at 15kW load and increasing to 0.85 at 34 kW.

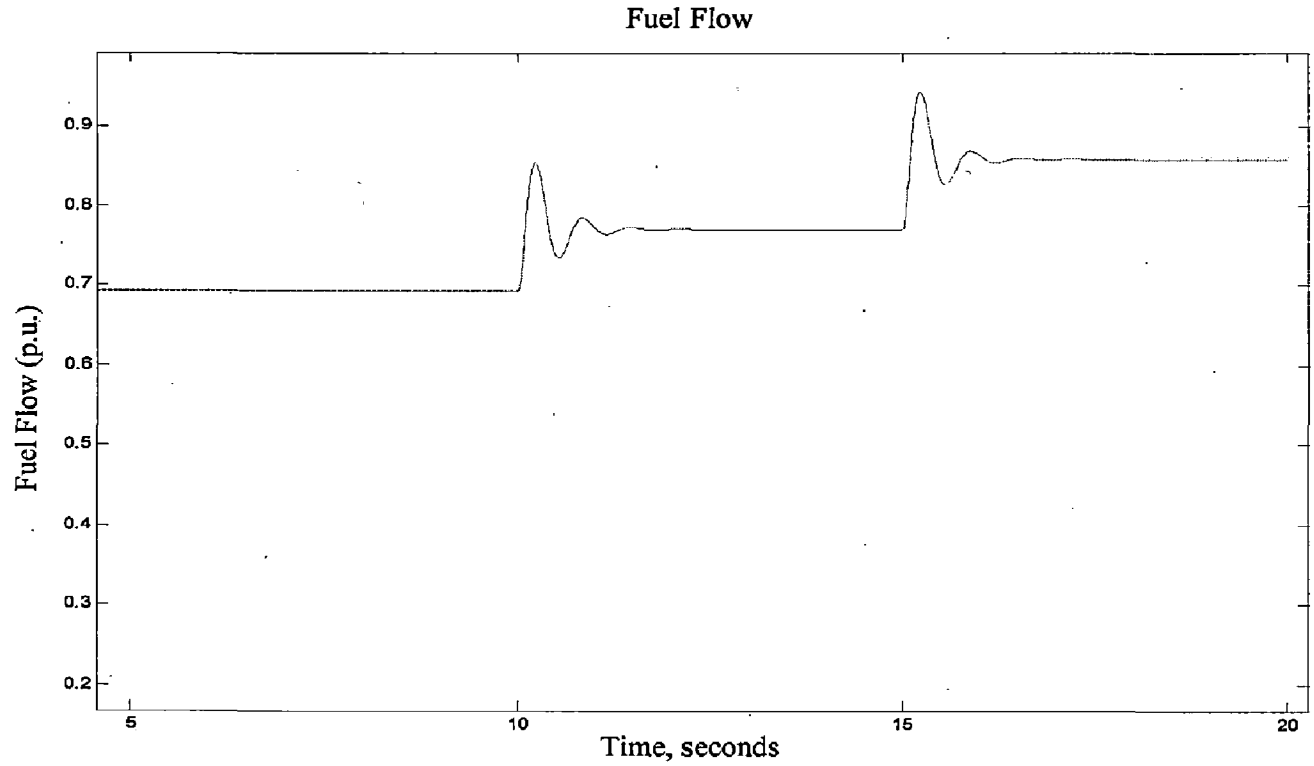


Figure 5.2.1 Fuel Flow Signal of the Microturbine

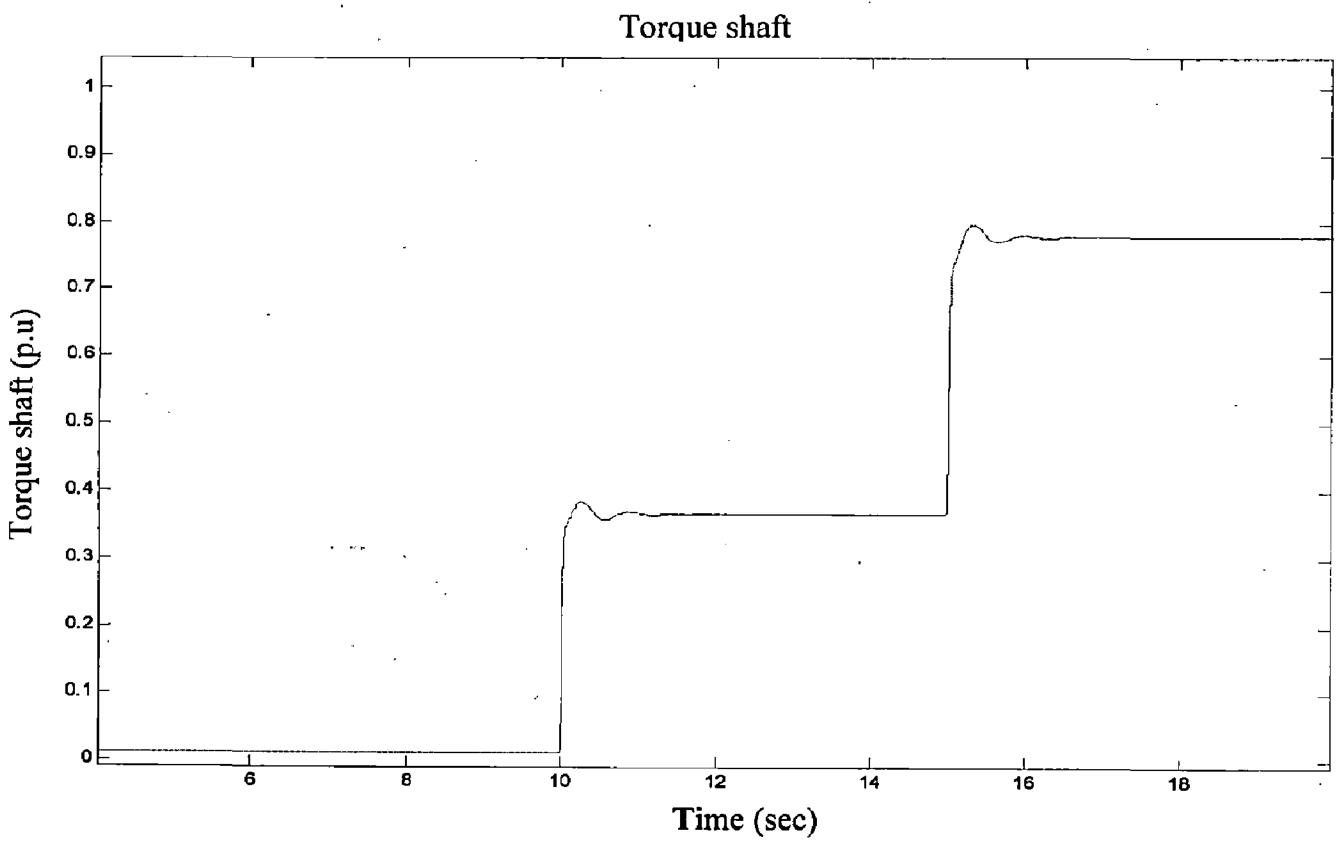


Figure 5.3 Variation of shaft Torque (Tshaft) of the Turbine

Figure 5.3 shows the shaft torque (Shaft) produce by the microturbine , which drives the PMSG, and figure 5.4 shows the electromagnetic torque (Te) generated by the PMSG . The generator torque is approximately same as the shaft torque produce by microturbine at steady-state. At no load the electromagnetic torque is equal to zero; it increase to about 40% of its base value at 15 kW and to 0.92 p.u at 34kW load.

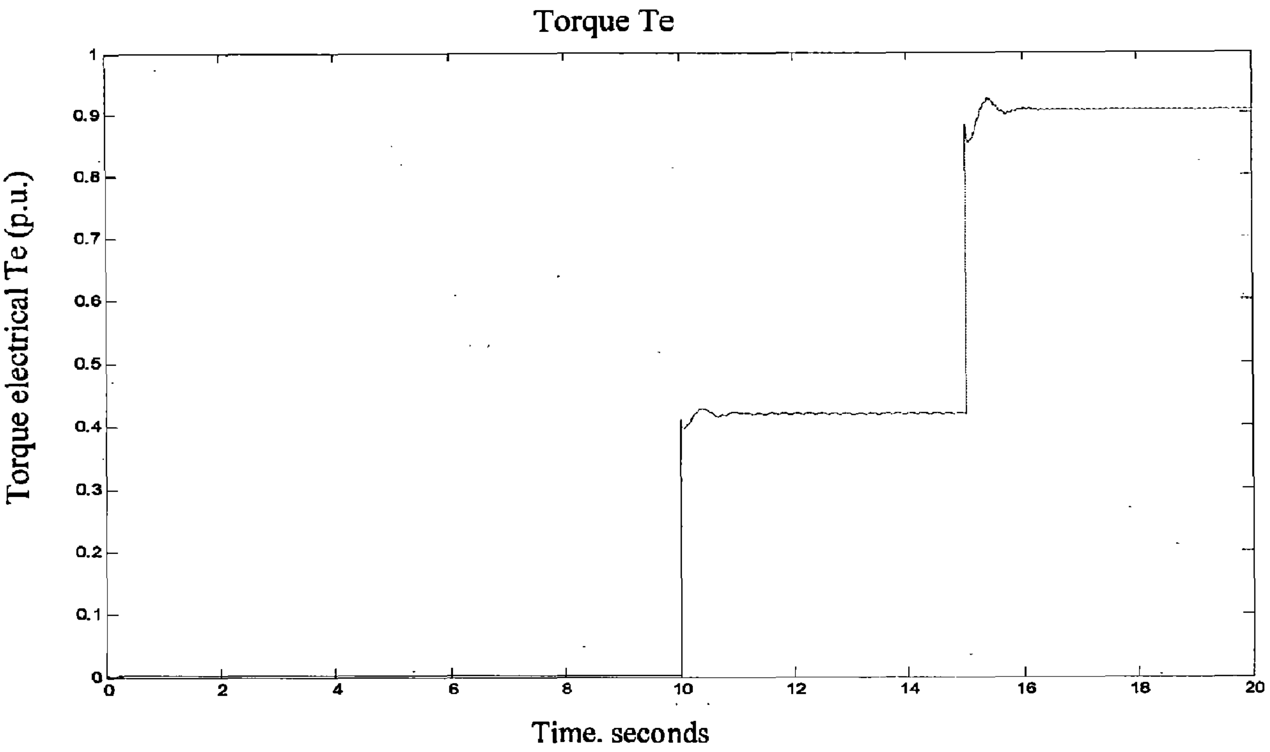


Figure 5.4 Variation of electric Torque generated

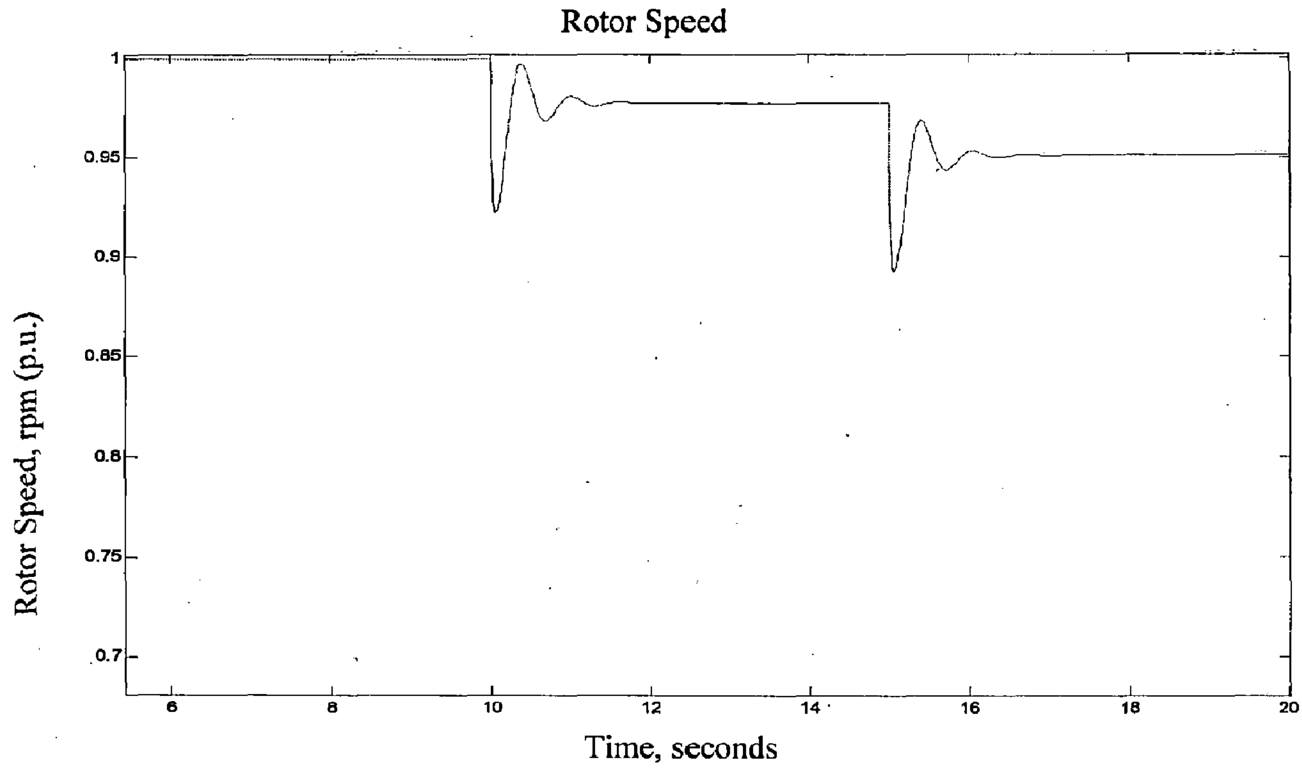


Figure 5.5 Rotor Speed variations with load

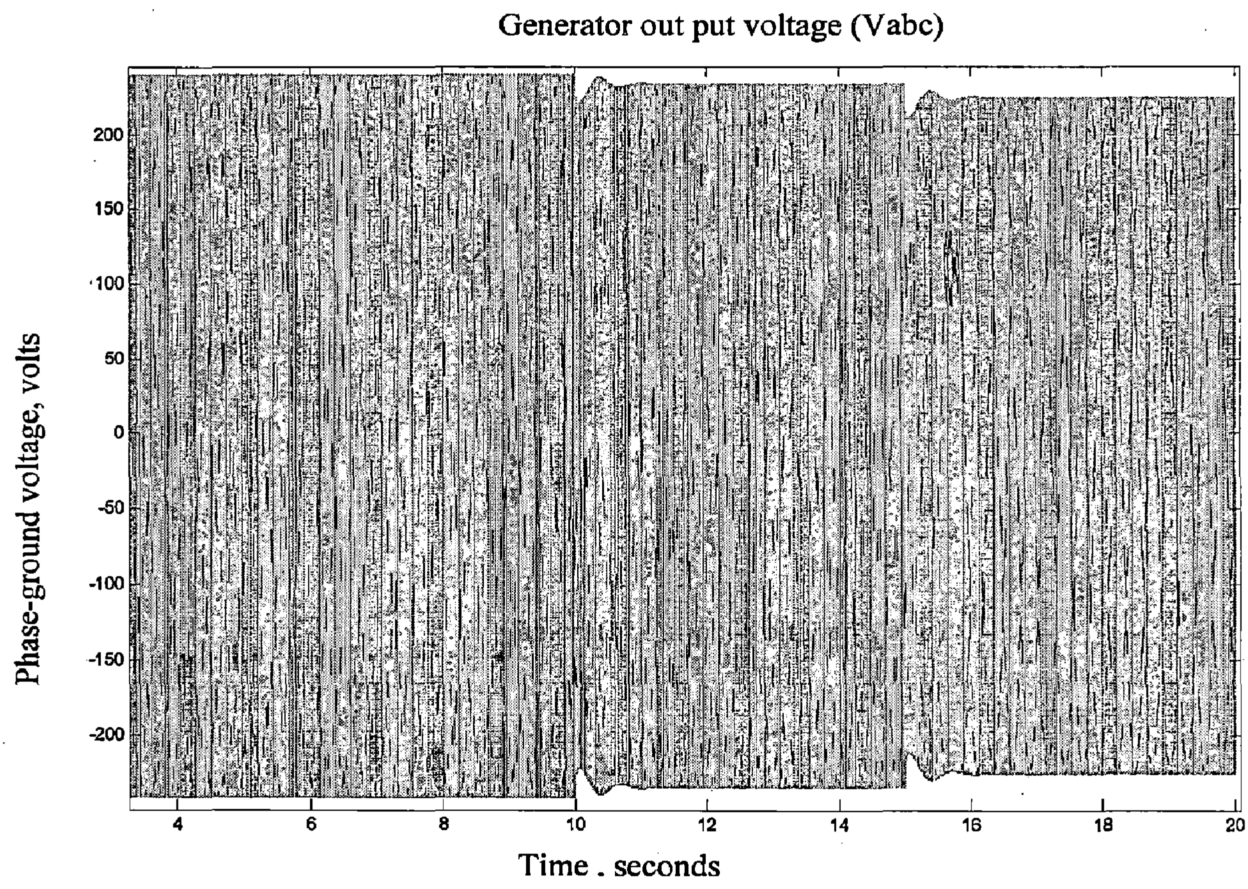


Figure 5.6 phase-ground voltage across the stator terminals of PMSG

Figure 5.5 and 5.6 shows the rotor speed and output voltage of the PMSG. When the microturbine generation system is operating at no-load, the speed of the rotor is equal to 1 p.u. and the stator phase to ground voltage of the PMSG reaches no-load steady–state (240 volts shown in Figure 5.6). When the PMSG is loaded at t = 10 seconds, the voltage decreases from no-load value. As the load is increased again, the rotor speed (Figure 5.5) and the stator stator voltage decrease further. as from rotor speed as the load increase from no-load to 15kW, the rotor speed decrease to 0.98 p.u. and time response taken is very less due to the speed governor controller (lead-lag controller) and further increase in load to 34kW , the rotor speed is decrease to 0.95p.u. As shown in the figure 5.5.

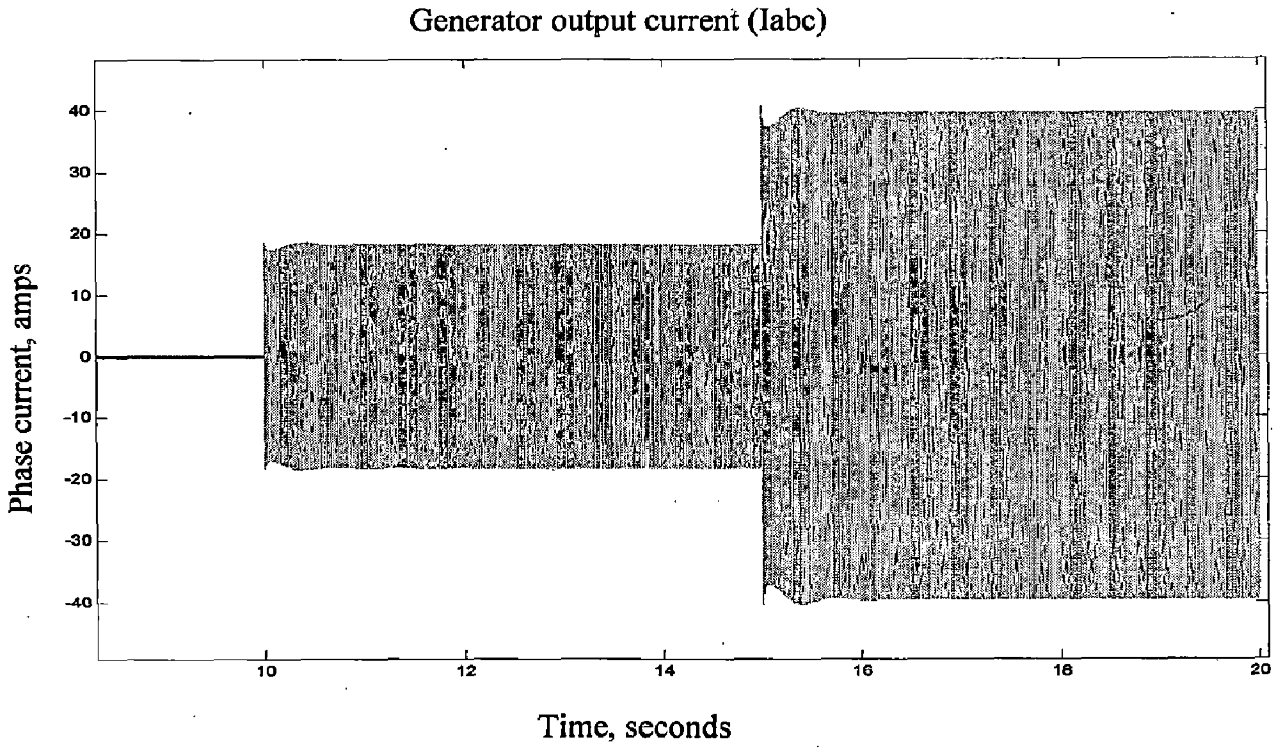


Figure 5.7 current across the stator terminals of PMSG

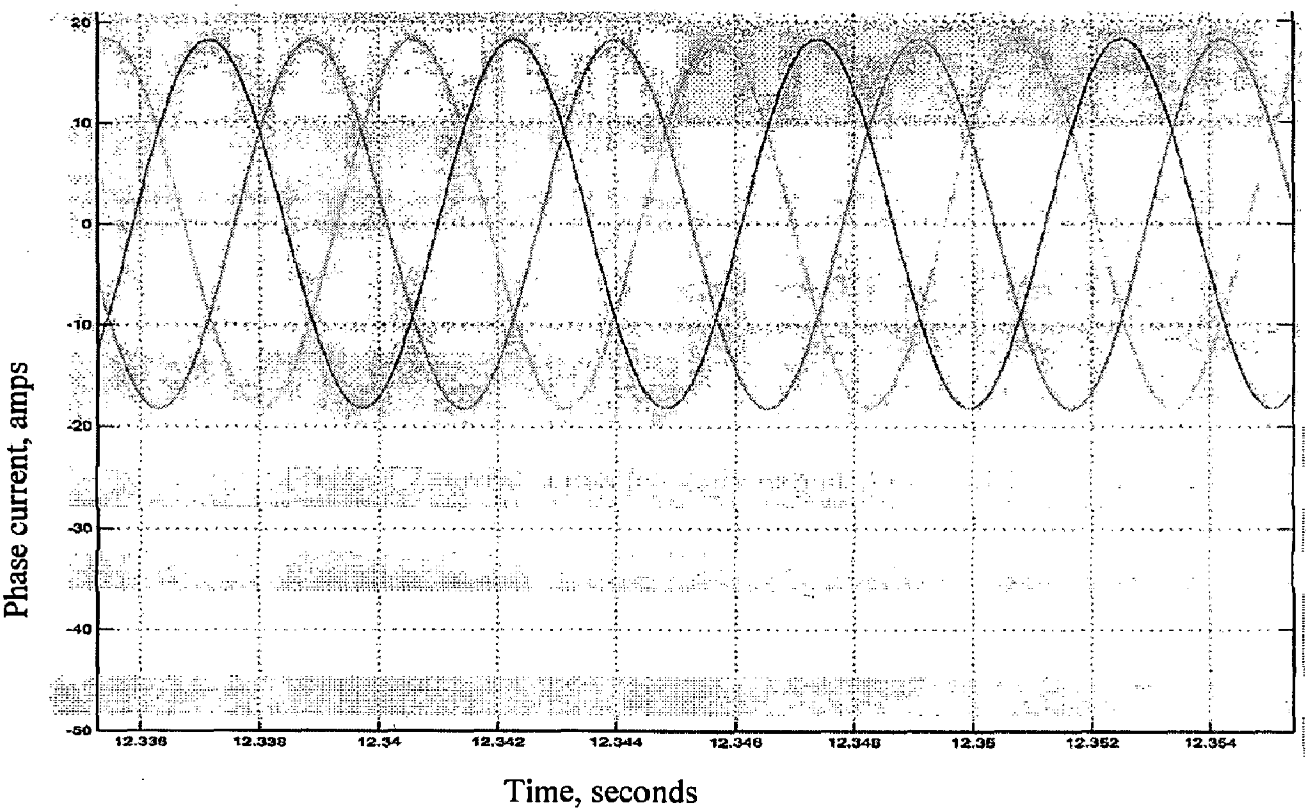


Figure 5.8, To show the frequency of PMSG with out power electronics Interface

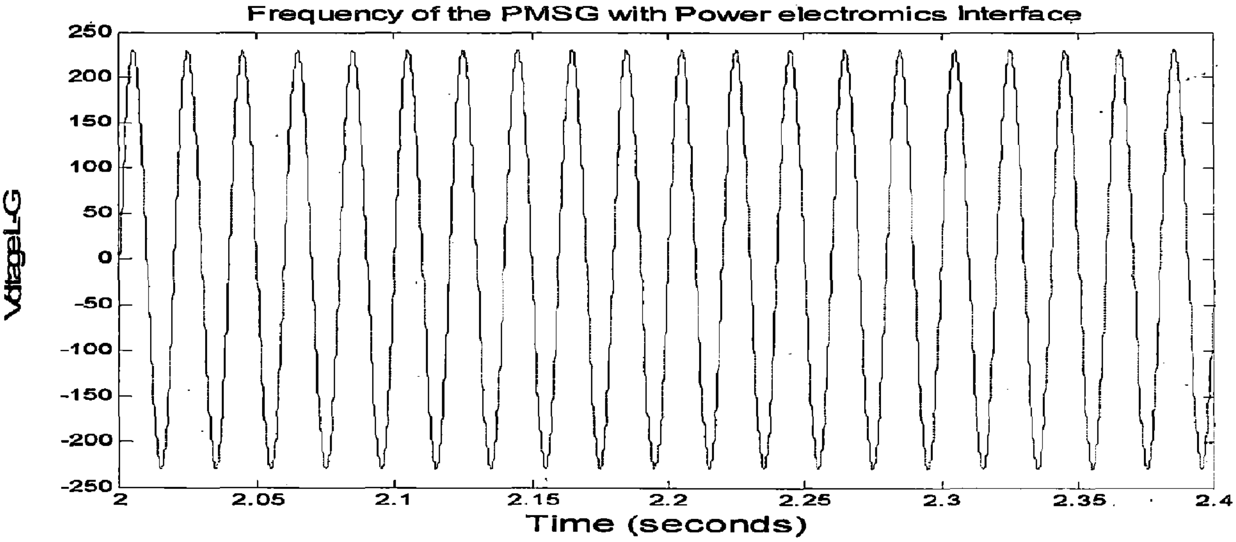


Figure 5.9 shows the Frequency of PMSG with Power electronics Interface

Figure 5.9 shows the frequency of the PMSG with power electronics Interface.

From the Figure 5.7 and 5.8 shows the no-load to 34Kw load currents, in this Figures , I want show that without Power electronics interface the frequency is high approximately 200Hz .

Calculated as: from the Figure 5.8 chosen one cycle that is from time period in seconds (from 12.342 to 12.346) + 1e-3.

So that 12.346-12.342= 4e-3

Then 4e-3 + 1e-3 =5e-3

Where f = 1/ t

f = 1/5e-3

f =200Hz.

From the Figure 5.9 shows the phase to ground voltage with power electronics interface in order to maintain the frequency 50Hz. In Figure 5.9 , I want to show that with Power electronics interface the frequency is approximately 50Hz.

Calculated as: from the Figure 5.9 chosen cycles from time period in seconds (from 2.1 to 2.15) in this period we have 2.5 cycles , so that per one how much?

i.e. difference 2.15-2.1= 0.05

For 2.5 cycles – 0.05 time (seconds)

For 1 cycle ----- x time (seconds)

Therefore x = 0.05 / 2.5

x = 0.02 seconds

Where f = 1/t, f = 1/ 0.02, f = 50 Hz.

5.2.2 Case 2: At constant load:

Initially the system is operating at no-load. At t = 5 seconds a load of 34kW is applied on the microturbine system, Figure 5.10 and 5.10.1 shows the fuel consumed and fuel flow by the microturbine for applied constant load . The fuel demand is equal to 23% (0.23 p.u.) Until the load is applied on the system at t = 5 seconds, increasing the amount of fuel required to keep the combustion alive. Note that the fuel demand signal is 0.85 p.u. at 34kW load.

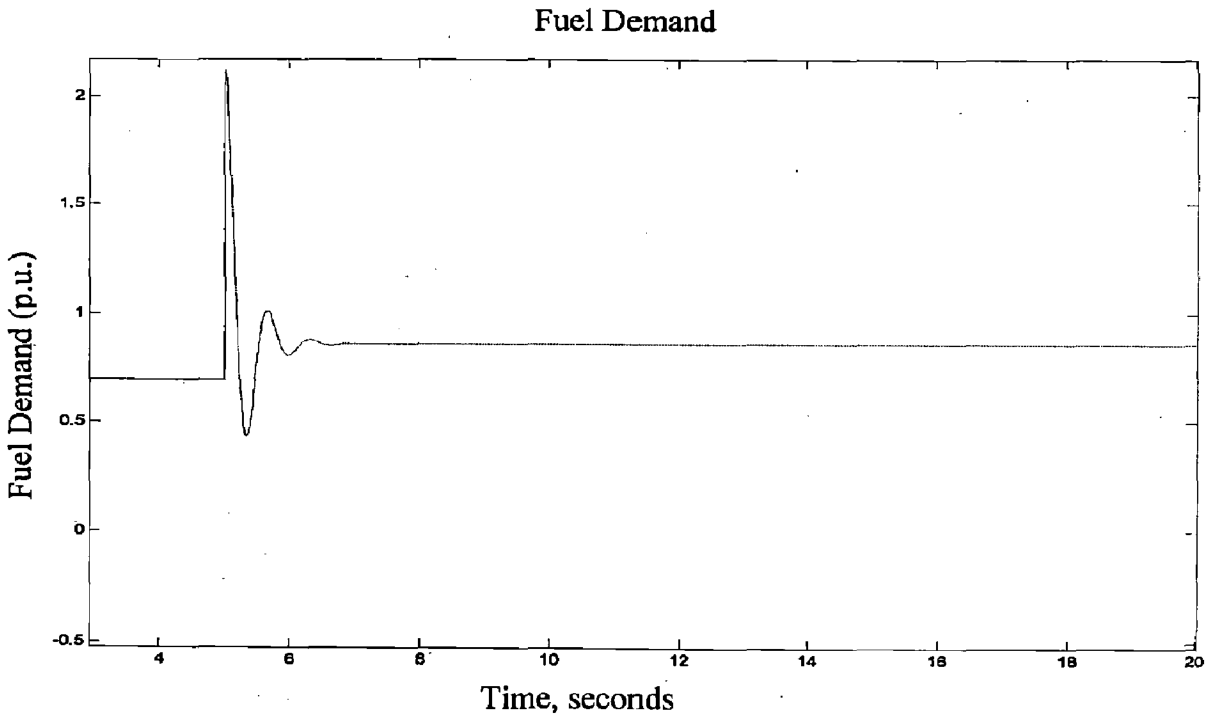


Figure 5.10 Fuel Demand signal of the micro turbine at constant load

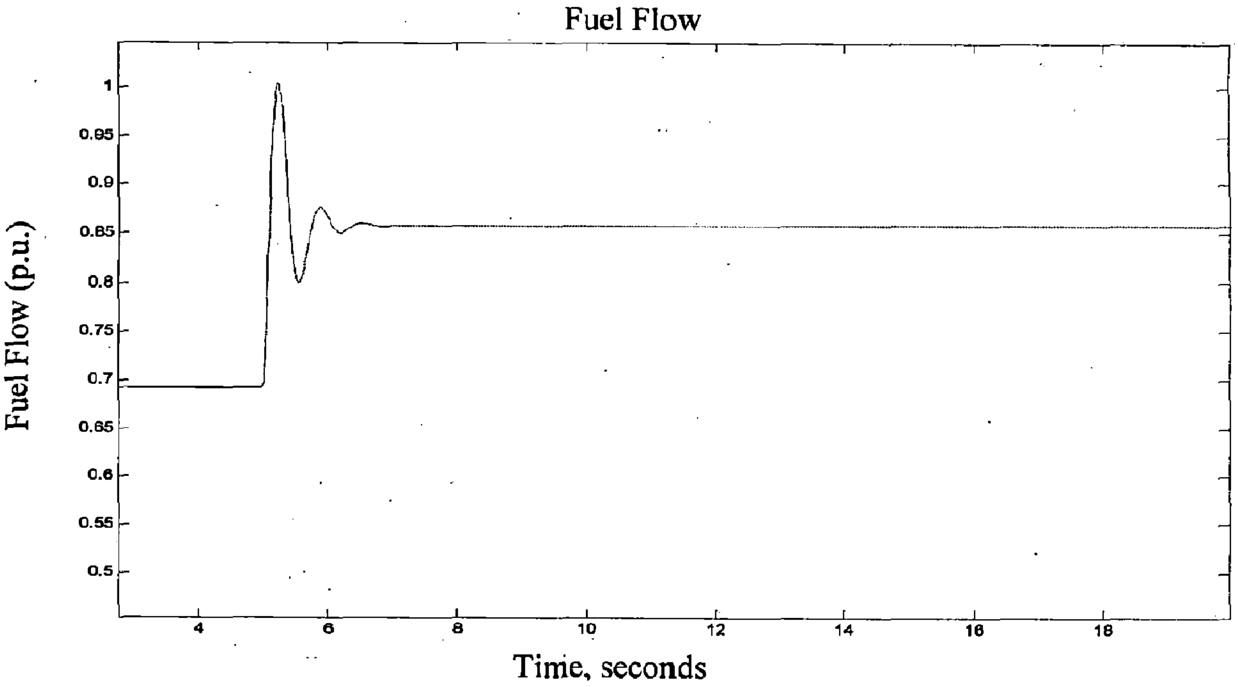


Figure 5.10.1 Fuel Flow signal of the Microturbine with constant load

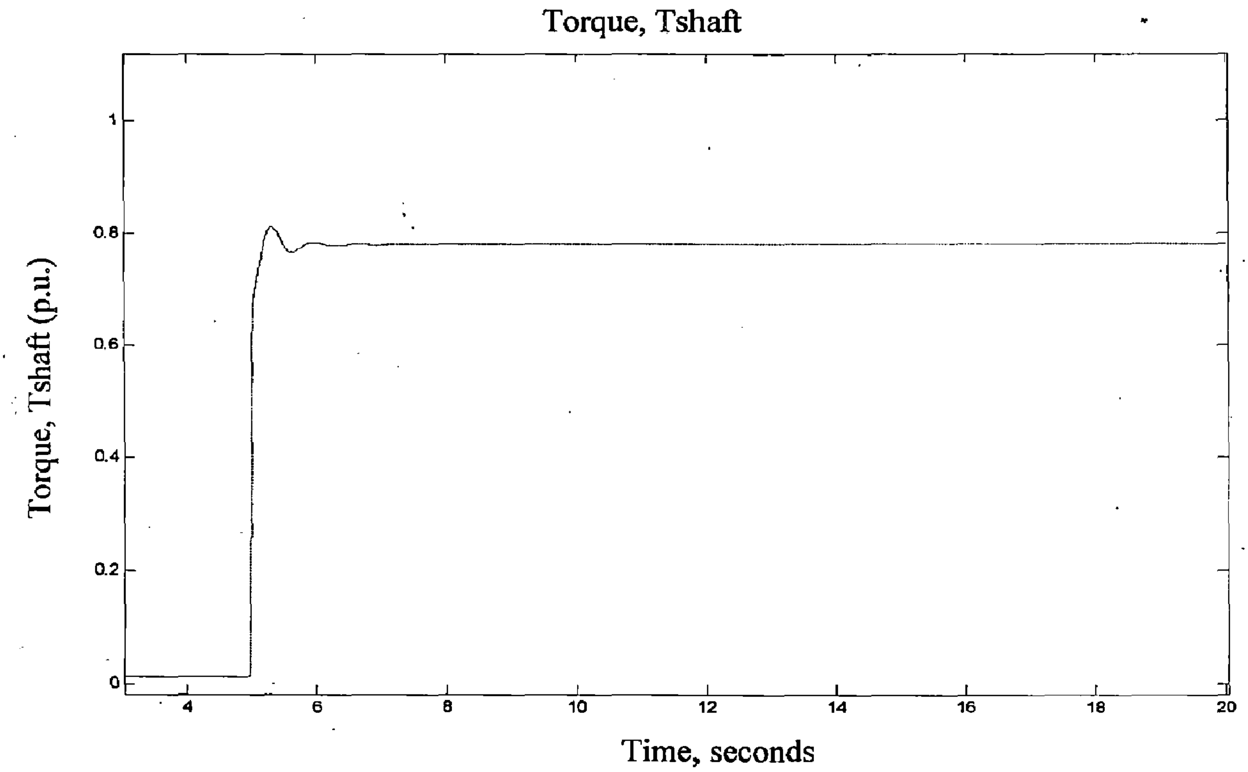


Figure 5.11 Variation of Shaft Torque generated at constant load

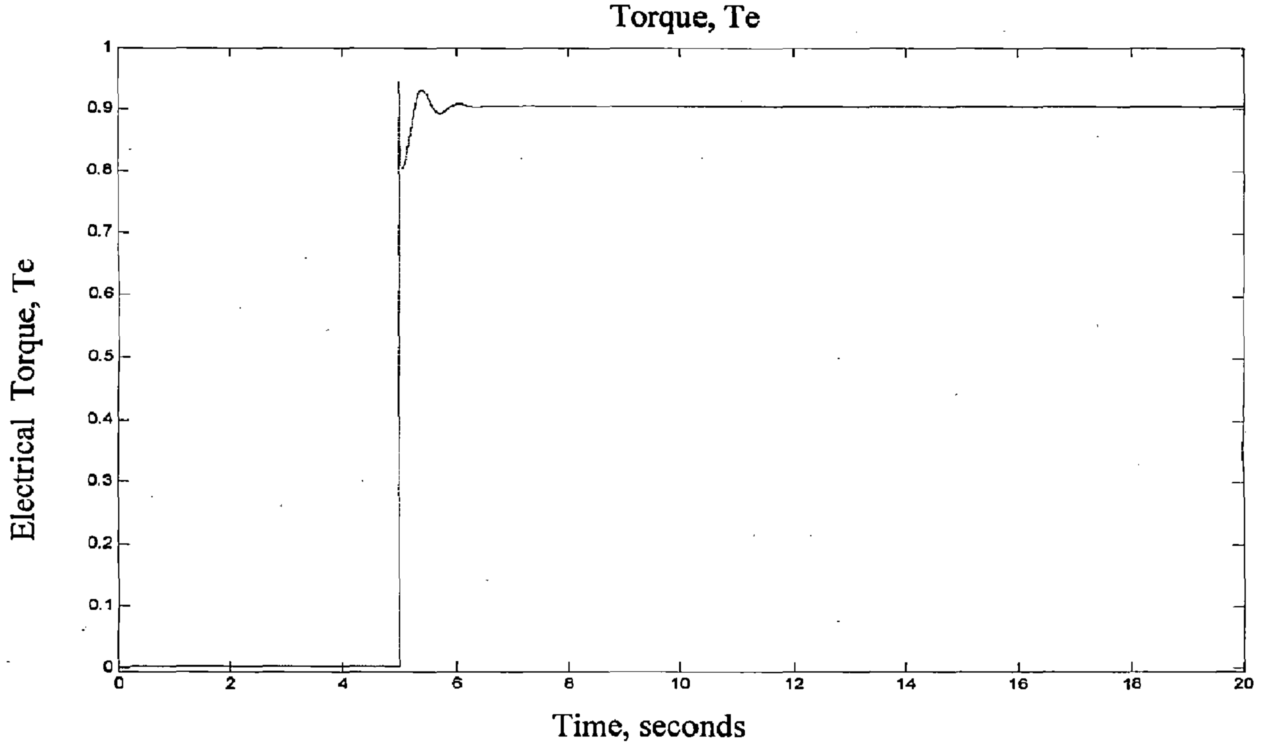


Figure 5.12 Variation of electric torque generated

Figure 5.11 and 5.12 shows the shaft torque (Tshaft) produced by the microturbine, which drives the PMSG, and the electromagnetic torque (T_e) generated by the PMSG. The generator torque is approximately same as the shaft torque produced by the microturbine at steady-state. At no load the electromagnetic torque is equal to zero; it increases to about 0.9 p.u. at 34kW.

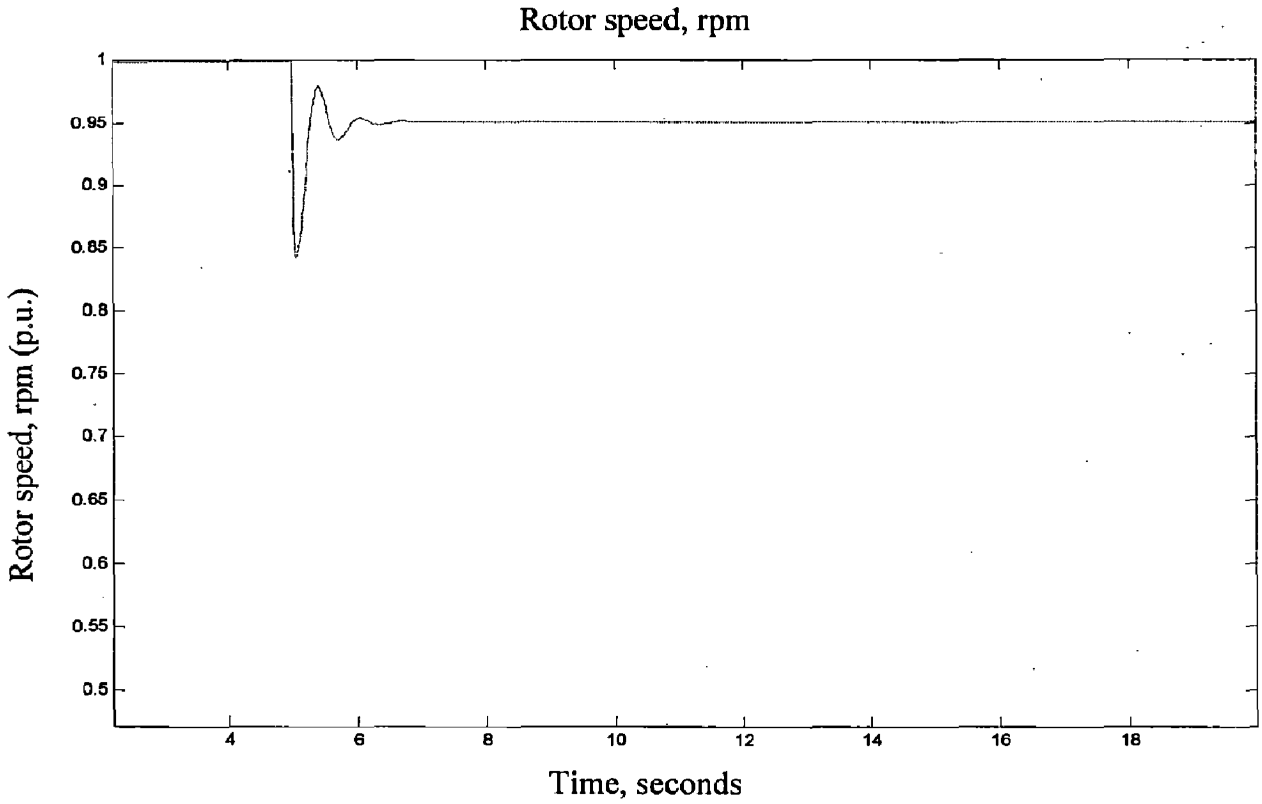


Figure 5.13 Rotor Speed variation with constant load

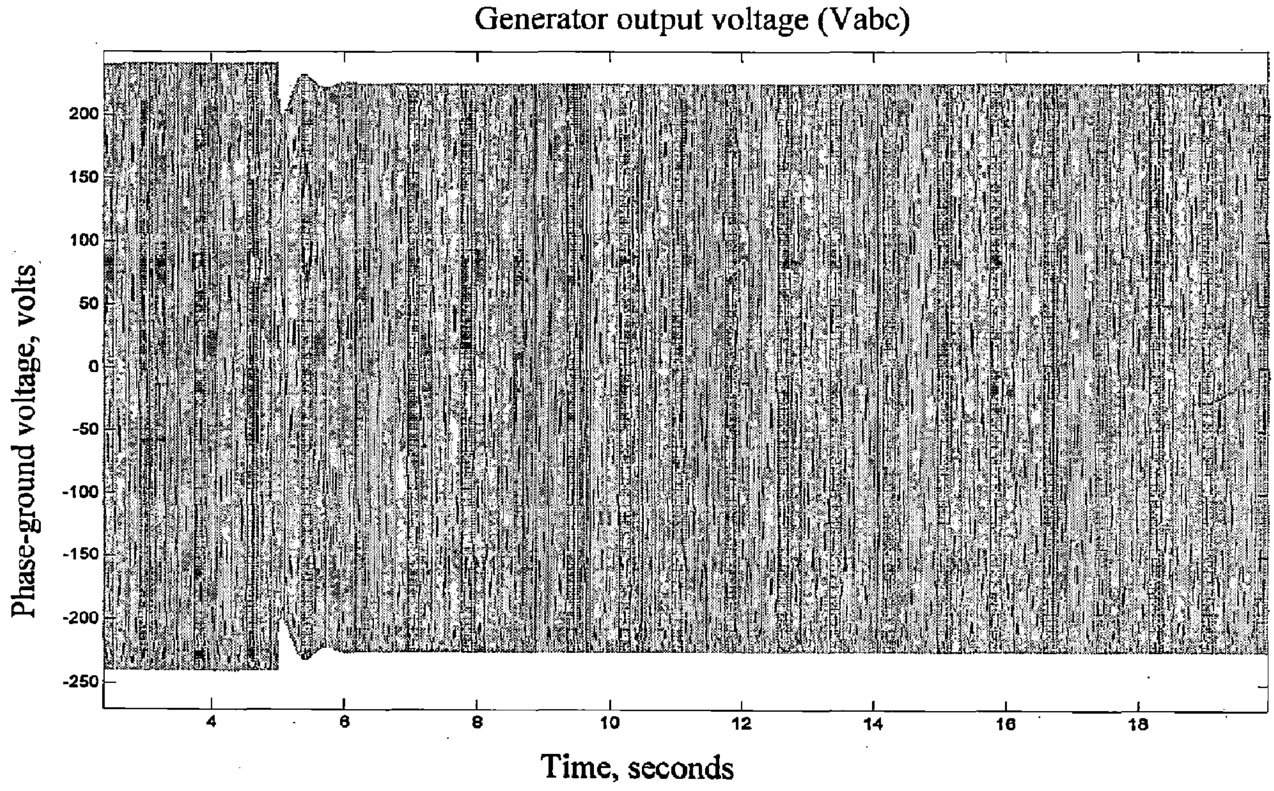


Figure 5.14 phase-ground voltage across the stator terminals of PMSG with constant

Figure 5.13 and 5.14 shows the rotor speed and output voltage of the PMSG. When the Microturbine generation is operated at no-load, the speed of the rotor is equal to 1 p.u. and the stator line voltage of PMSG reaches no- load steady-state value of approximately 240 volts.(as shown in Figure 5.14) . When the PMSG is loaded at t=5 seconds, the voltage decreases from no-load value to approximately 230 volts respectively.

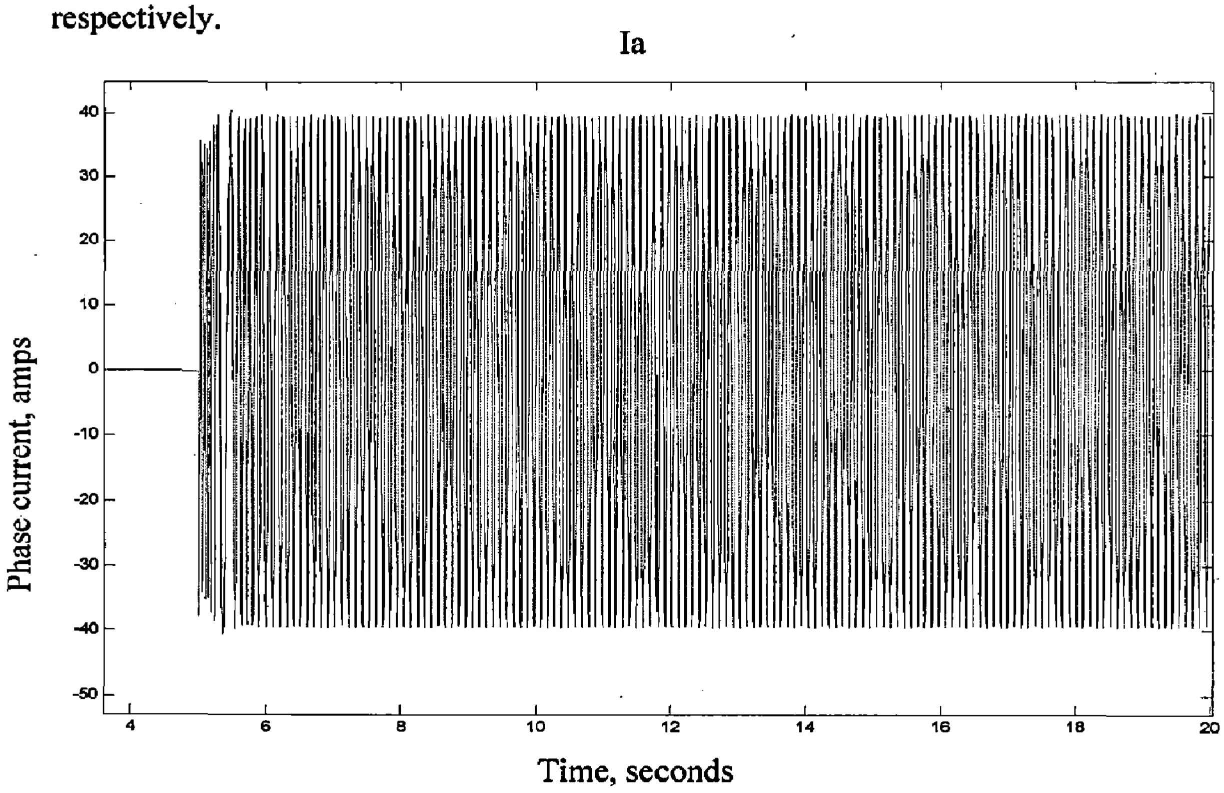

Ia

Figure 5.15 Phase current across the stator terminals of PMSG

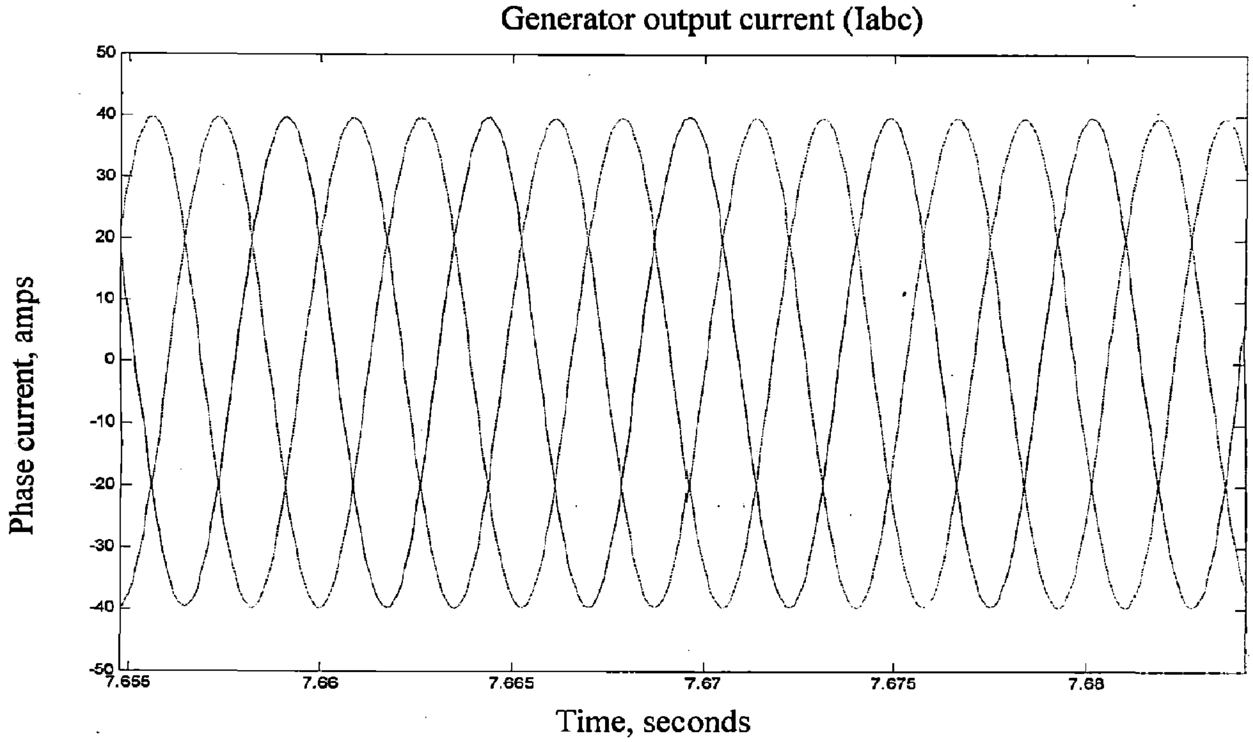

Generator output current (Iabc)

Figure 5.16 To show the Frequency of PMSG without Power electronics interface

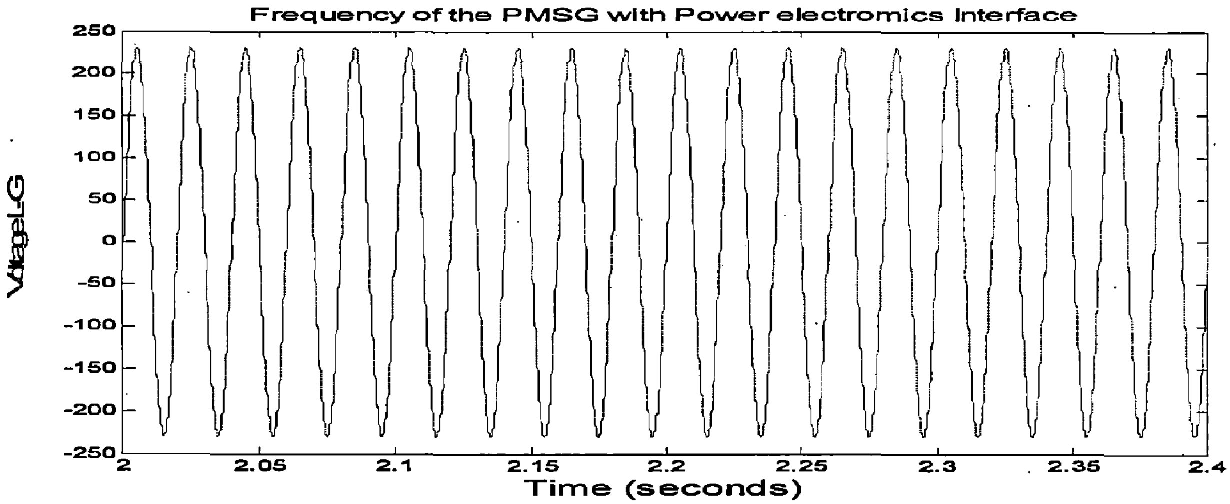


Figure 5.17 shows the frequency of the PMSG with power electronics Interface

From the figures 5.15 , 5.16 and 5.17 shows the stator current, in which the frequency is high approximately 200Hz without power electronics interface , in order to get 50Hz the power electronics are used as shown the voltage and frequency maintaining the requirements in Figure 5.17. Respectively.

5.2.3 Case 3: At Constant load with LLL-G fault:

Initially the system is operating at no-load at t = 5 seconds a load of 34kW is applied on the microturbine system, and at t=10 – 11 seconds the transient 3L-G fault is occurred. Then what are the responses and how the speed Governor Will controls the oscillations is the main strategy of this following section

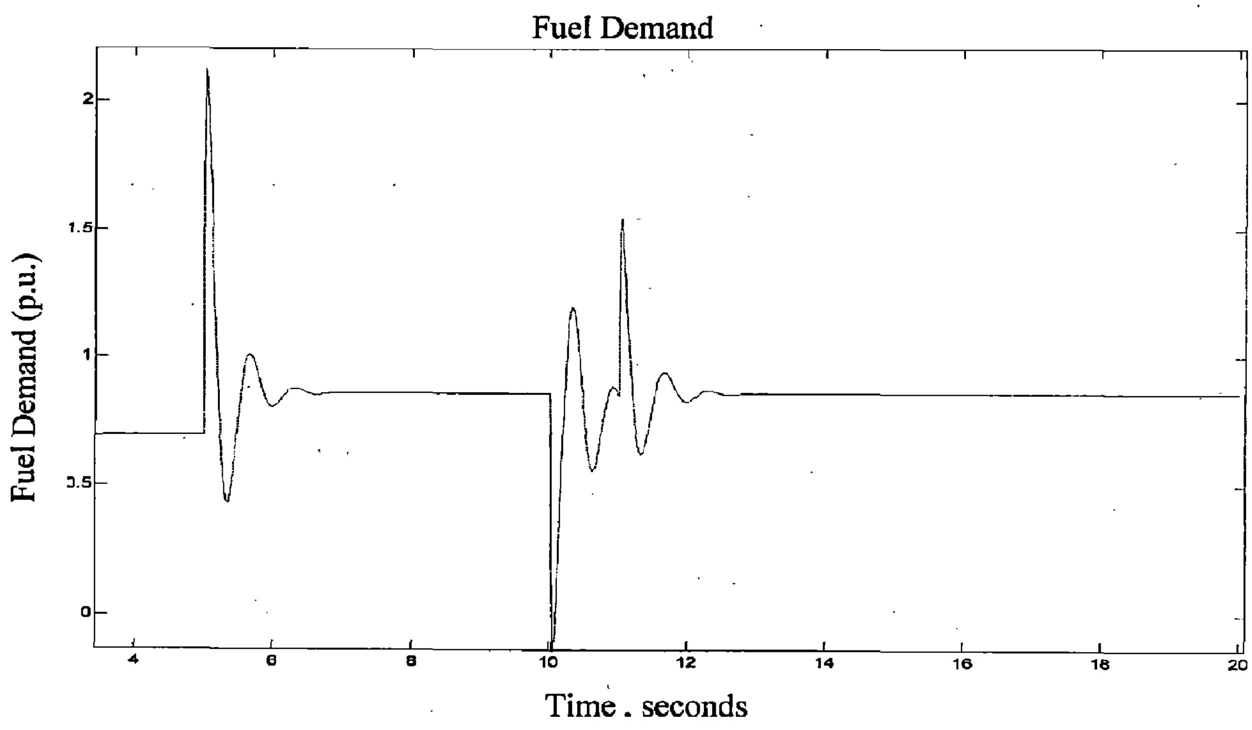


Figure 5.18 Fuel Demand signal when 3L-G fault occurred

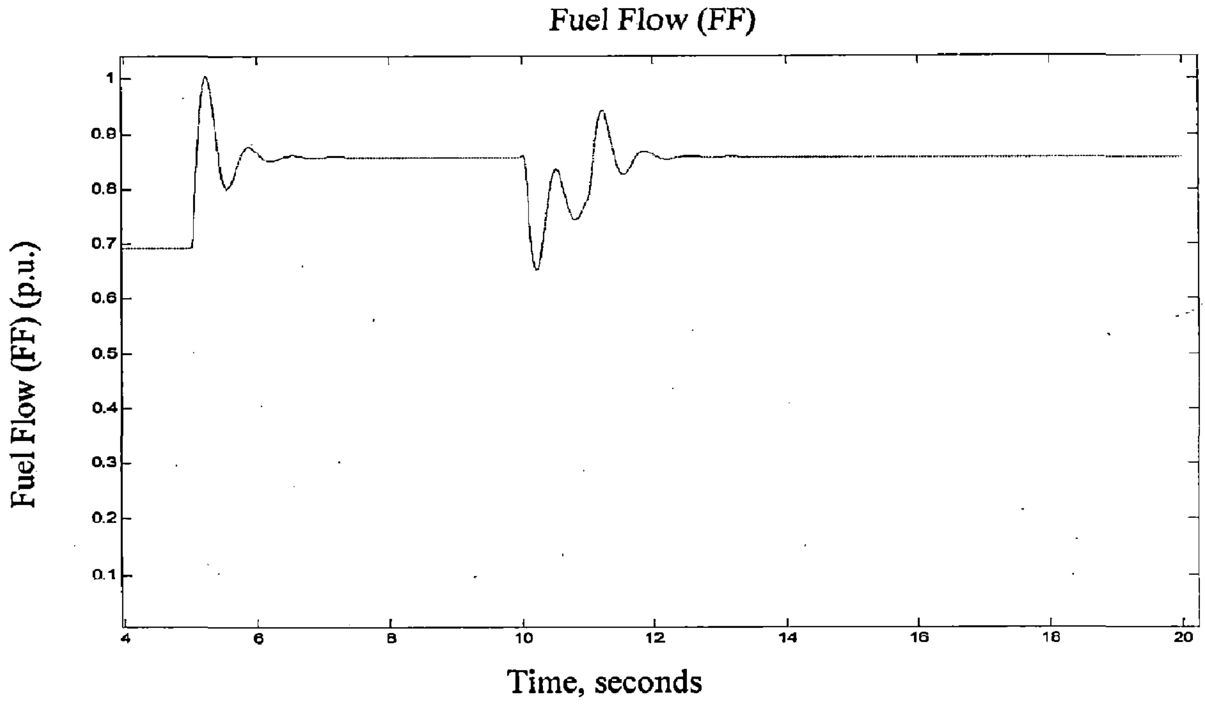


Figure 5.19 Fuel Flow signal when 3L-G fault

Figure 5.18 and 5.19 shows the fuel consumed & fuel flow by the microturbine for the applied load condition and when the 3L-G fault occurred. The fuel demand is equal to 23% (0.23 p.u.) until the load is applied on the system at t= 5 seconds, increasing the amount of fuel required to keep the combustion process alive. Note that the fuel demand signal is 0.85 p.u. at 34kW load and when the 3L-G fault occurred at t=10-11 seconds transient period the fuel demand will goes to zero p.u. but instantly the speed governor pick-up the turbine to alive state with in the transient state and after the transient period the turbine will woks as earlier before transient period this is due to the lead-lag speed governor controller.

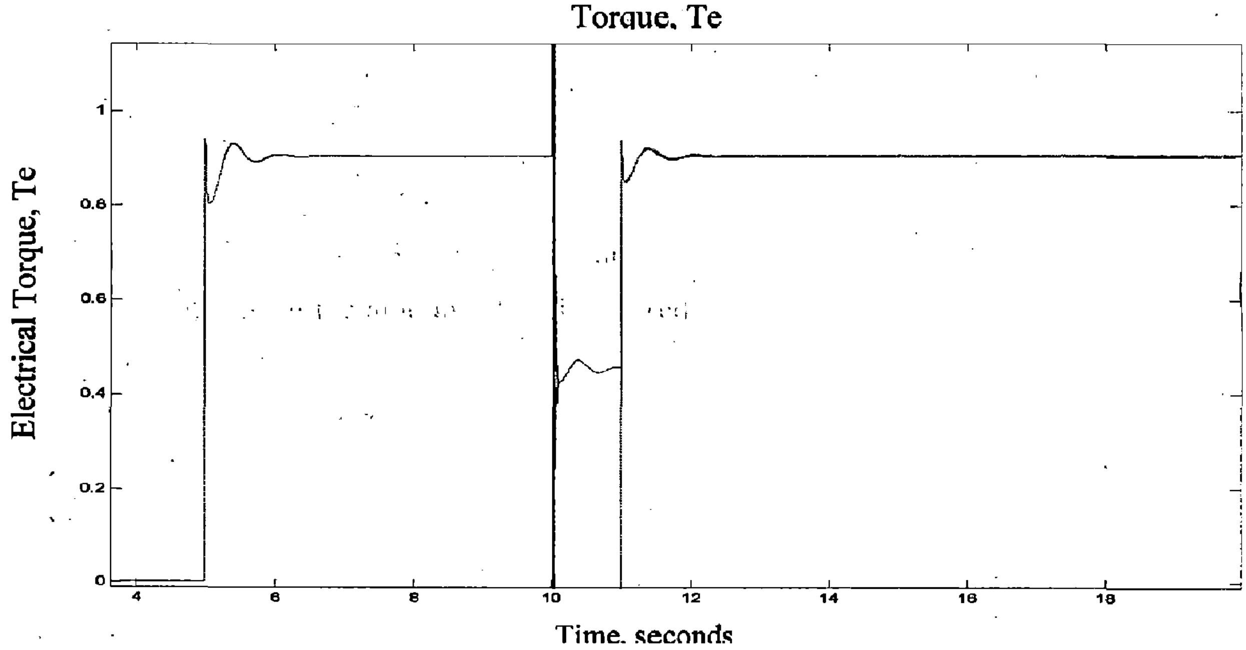


Figure 5.20 variation of electrical torque generated at 3L-G fault

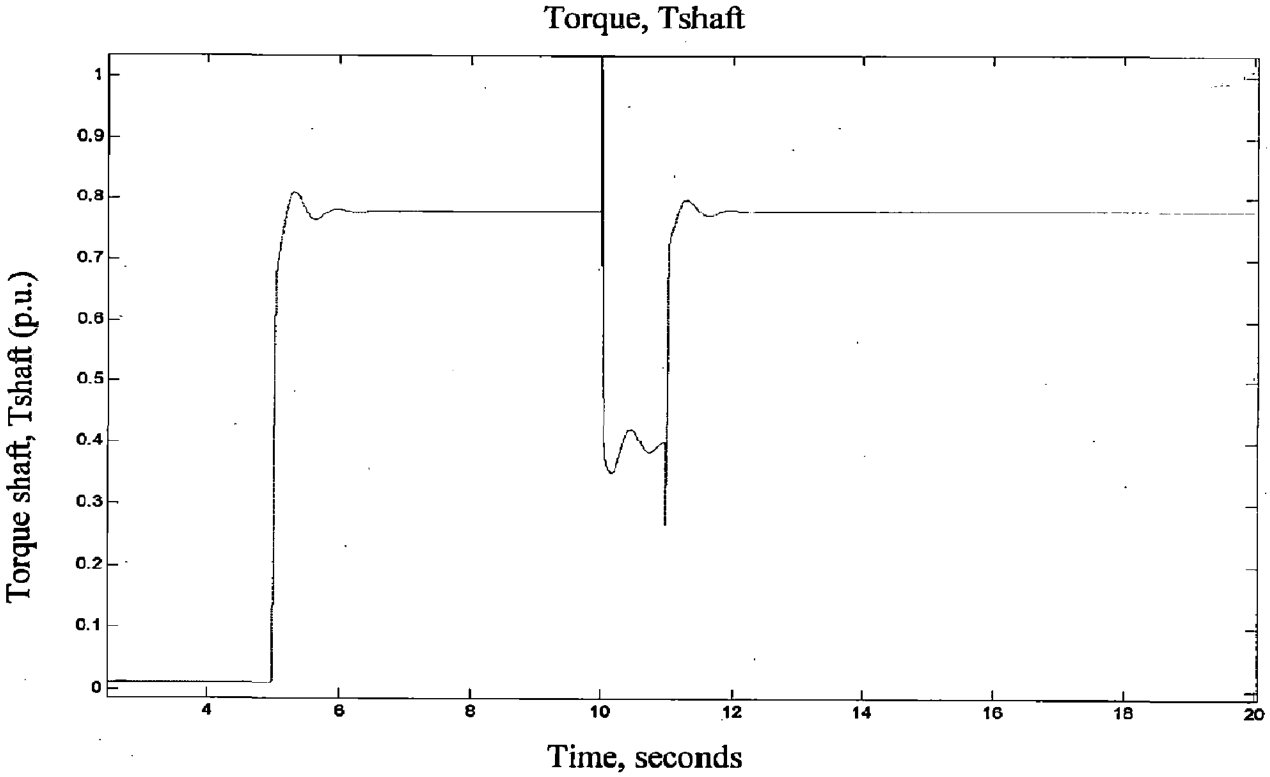


Figure 5.21 variation of shaft Torque at 3L-G fault condition

Figure 5.20 and 5.21 shows the shaft torque (Tshaft) produced by the microturbine, which drives the PMSG, and the electromagnetic torque (Te) generated by the PMSG. The generator torque is approximately same as the shaft torque produced by microturbine at steady state. At no-load the electric torque is equal to zero; it increases to about 0.85 p.u. at 34kW load. At t=10-11seconds 3L-G fault occurs then electromagnetic torque (Te) will be almost all goes to zero. But due to the lead –lag controller the PMSG will recovers its original state. The torque (Te) will be recovered at 0.4 p.u. up to Transient period after that the system will comes to its original positions as earlier.

Figure 5.22, 5.23 and 5.24 shows the rotor speed and output voltage and current of the PMSG. When the microtubine generation system is operating at no-load, the speed of the rotor is equal to 1 p.u. and the phase-ground voltage of the PMSG reaches no-load steady-state value of 240 volts. When the PMSG is loaded at t=5 seconds, the voltage decreases from no-load value to 230 volts respectively. As the 3L-G fault occurred at t = 10 – 11 seconds , then PMSG will not produce any voltage that is almost all no-voltage (zero) at that period , after the transient period the PMSG will produce the voltage . Where as the current will be very high due to the fault of the system.

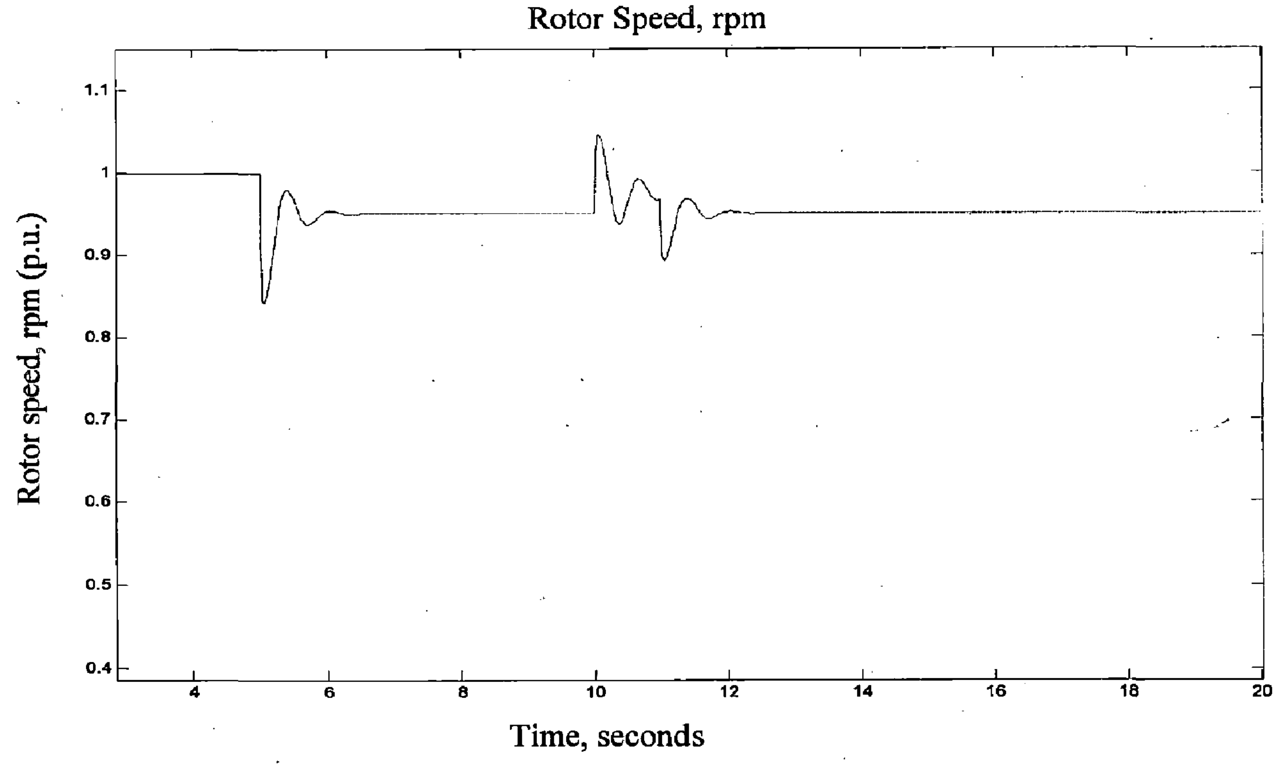


Figure 5.22 Rotor speed variation with load and 3L-G fault

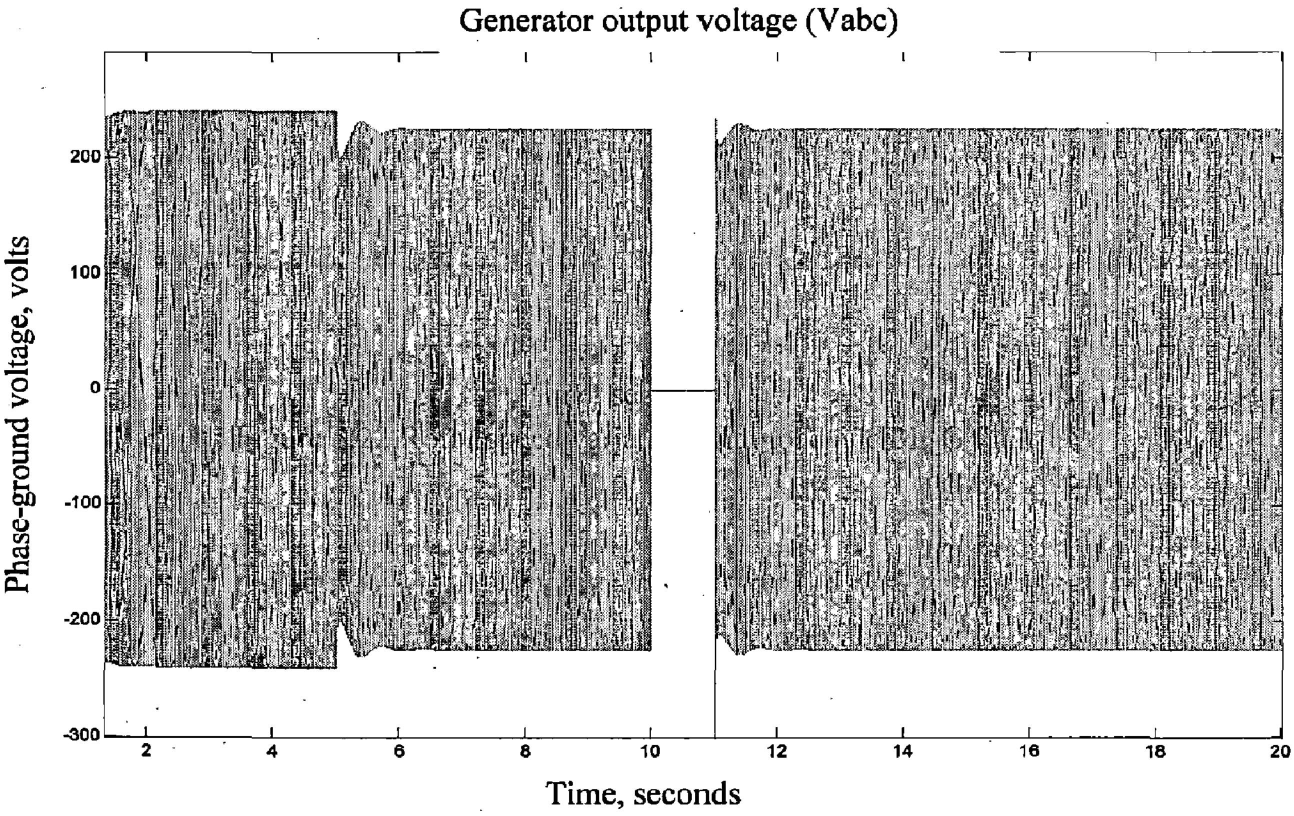


Figure 5.23 phase-ground voltage across the stator terminals of PMSG with 3L-G fault

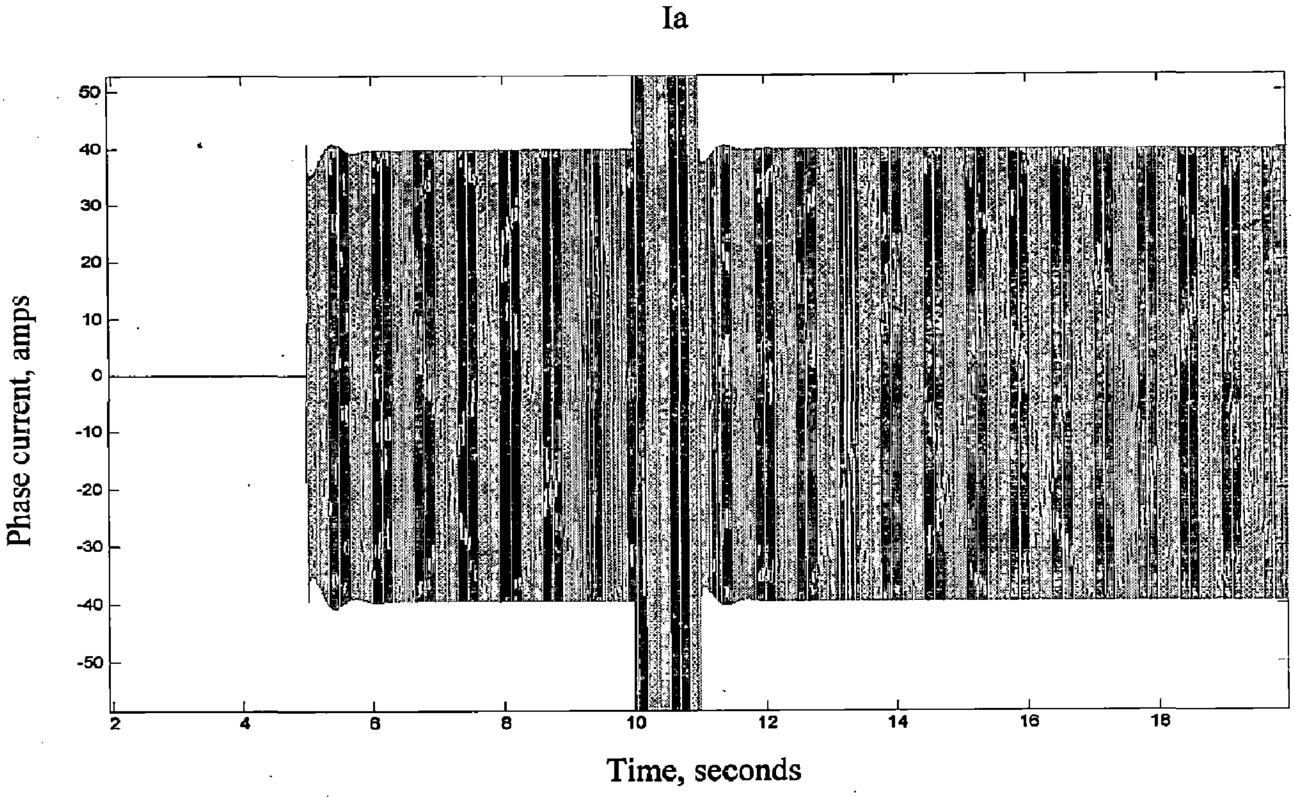


Figure 5.24 current across the stator terminals of PMSG with 3L-G fault.

5.3 Section-II: Self-Excited Induction Generator:

Microturbine ratings: 3.7kW (max), 1500 rpm.

Parameters used for the self -Excited Induction Generator [50].

$r_s = 0.016$ Ohms, $X_{ls} = X_{lr} = 0.06$ ohms $r_r = 0.015$ Ohms

Pairs of poles 'p' = 2.

For Induction generator for self excitation in order to supply the reactive power to the self excited induction generator here using the device capacitor banks of 25e-6 to35e-6 farads. And feed back rotor speed of the self excited induction generator have been reduced to half of the rated speed so that it means gear is using between the microturbine system and SEIG in order to protect the SEIG system from high torque 1:2 ratio of gear of speed is used to run the machine above the rated speed and also the capacitor banks makes the main role for the excitation of the SEIG system. In order to run in steady state capacitor banks choosing is the main task for the self excited Induction generator system.

5.3.1 Case -1 at constant load: -

Initially the system is operated with load. At starting induction generator will produce high voltage in order to obtain above rated speed microturbine will produce high torque. After that the lead-lag speed governor controller will control the microturbine in order to maintain the constant speed above the rated speed. From the Figures 5.25 and 5.26 shows the fuel consumed by the microturbine for the applied load conditions .the fuel demand is equal to 23% (0.23 p.u.) until the rotor speed is above the rated speed the fuel demand is more corresponding to the fuel flow we can see the at 0.8 p.u. the fuel demand and fuel flow will be stabilized as shown in the Figures. Fuel demand is increasing because to keep the combustion process alive. Note that the fuel demand signal and fuel flow signals are stabilized at 0.8 p.u. for load of 3kW.

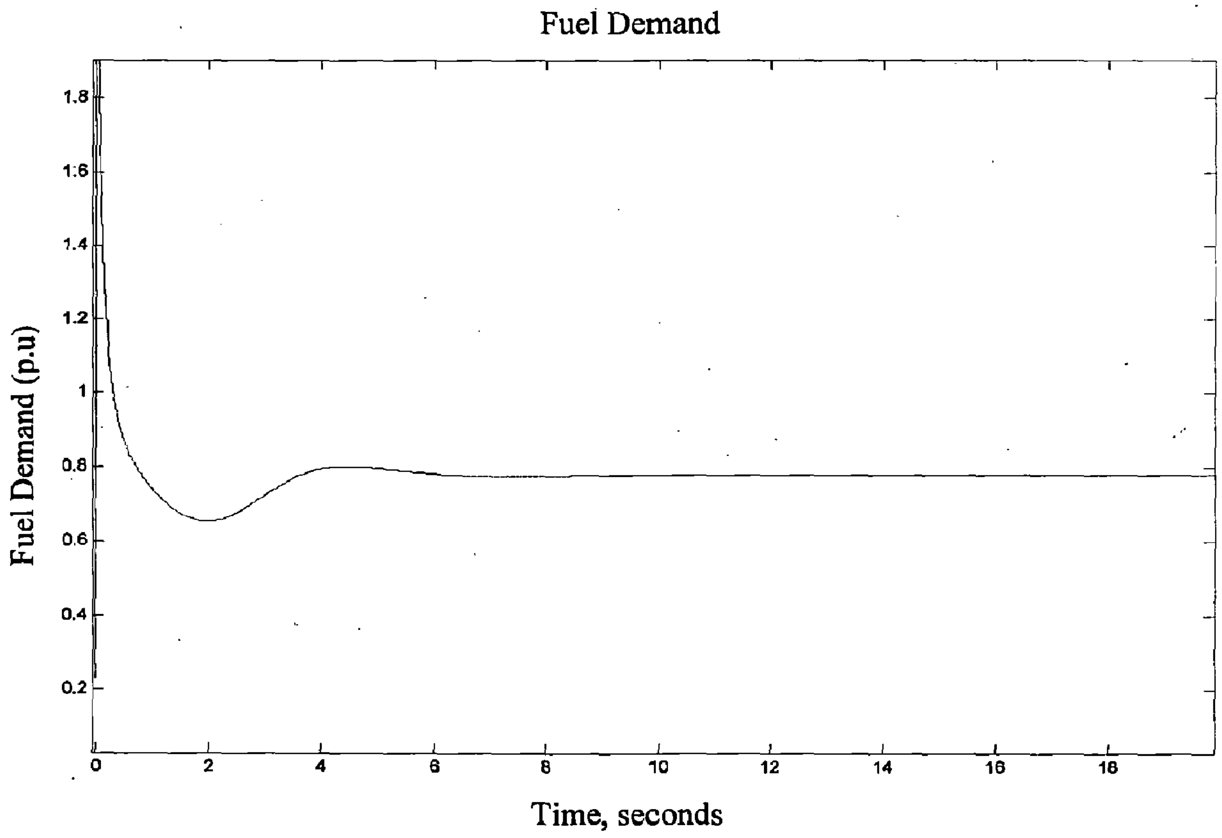


Figure 5.25 Fuel Demand Signal of Microturbine with SEIG

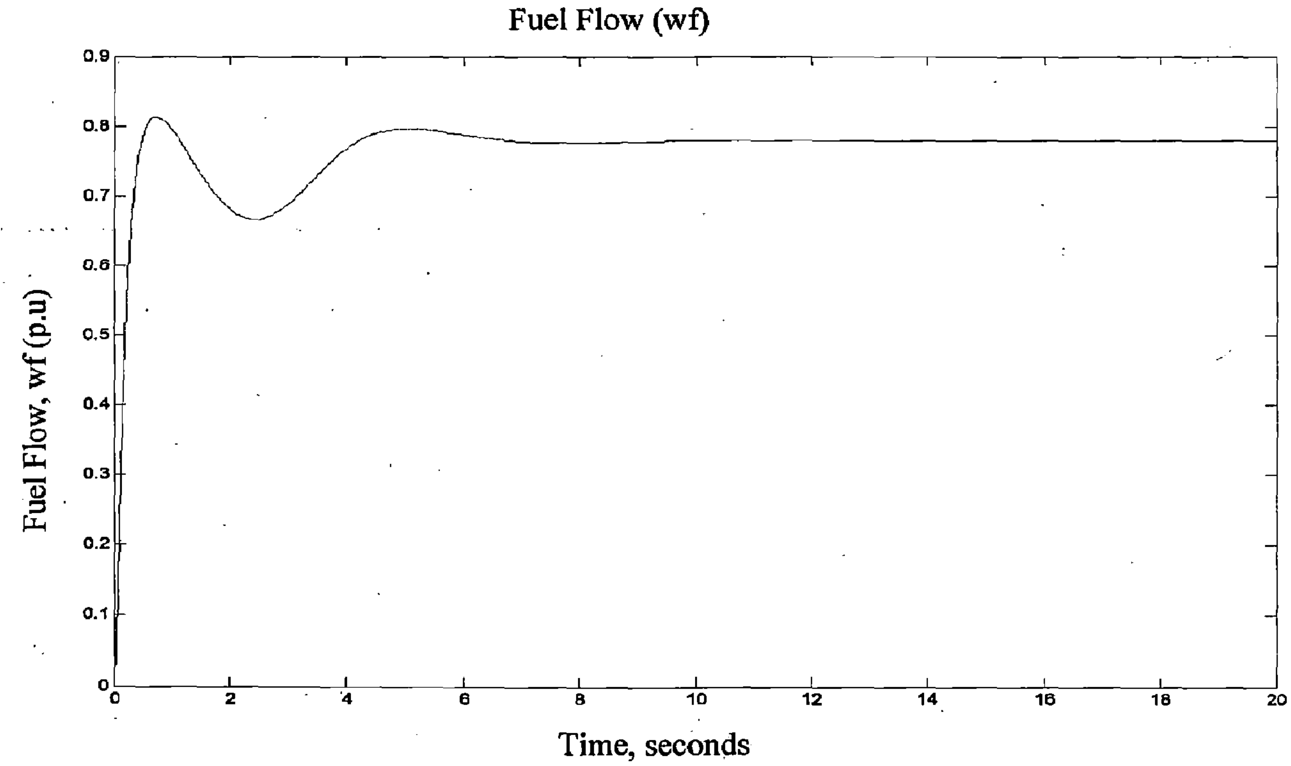


Figure 5.26 Fuel Flow signal of the microturbine with SEIG

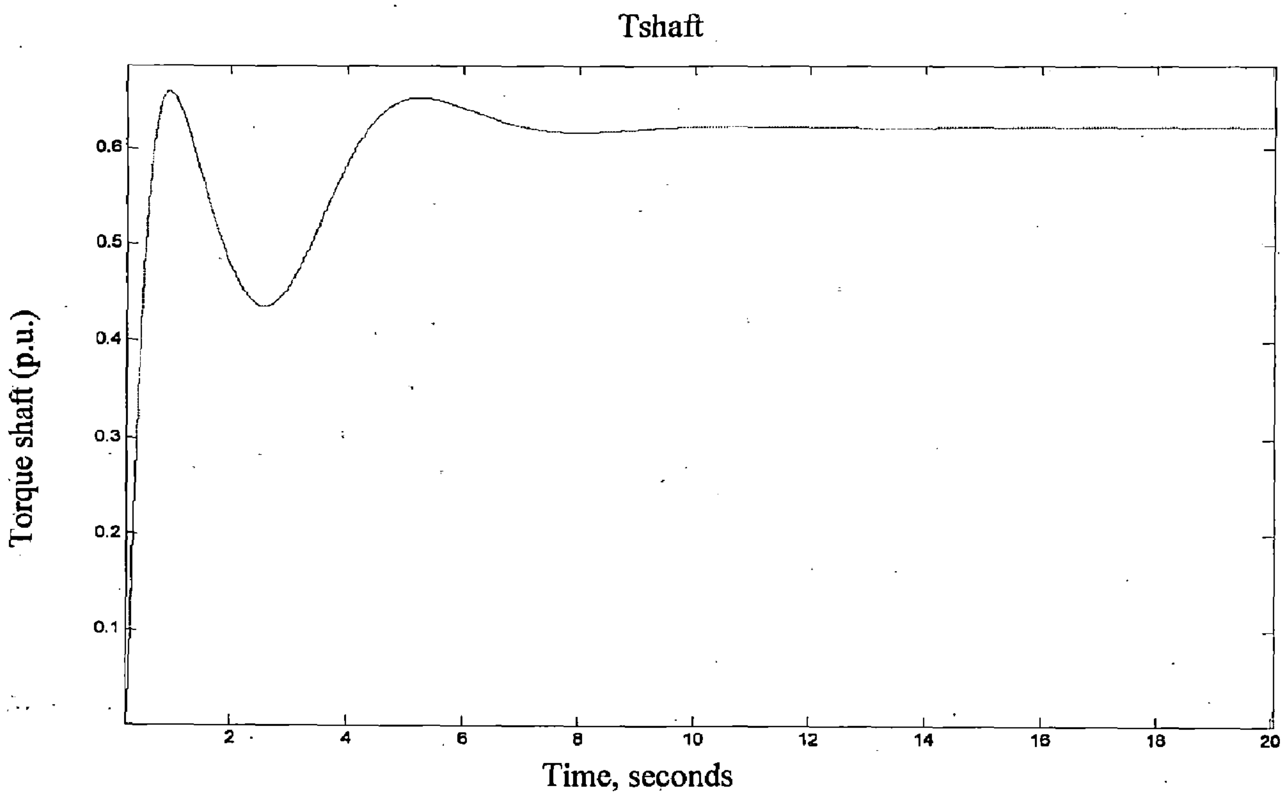


Figure 5.27 Variation of shaft torque generated in microturbine with SEIG

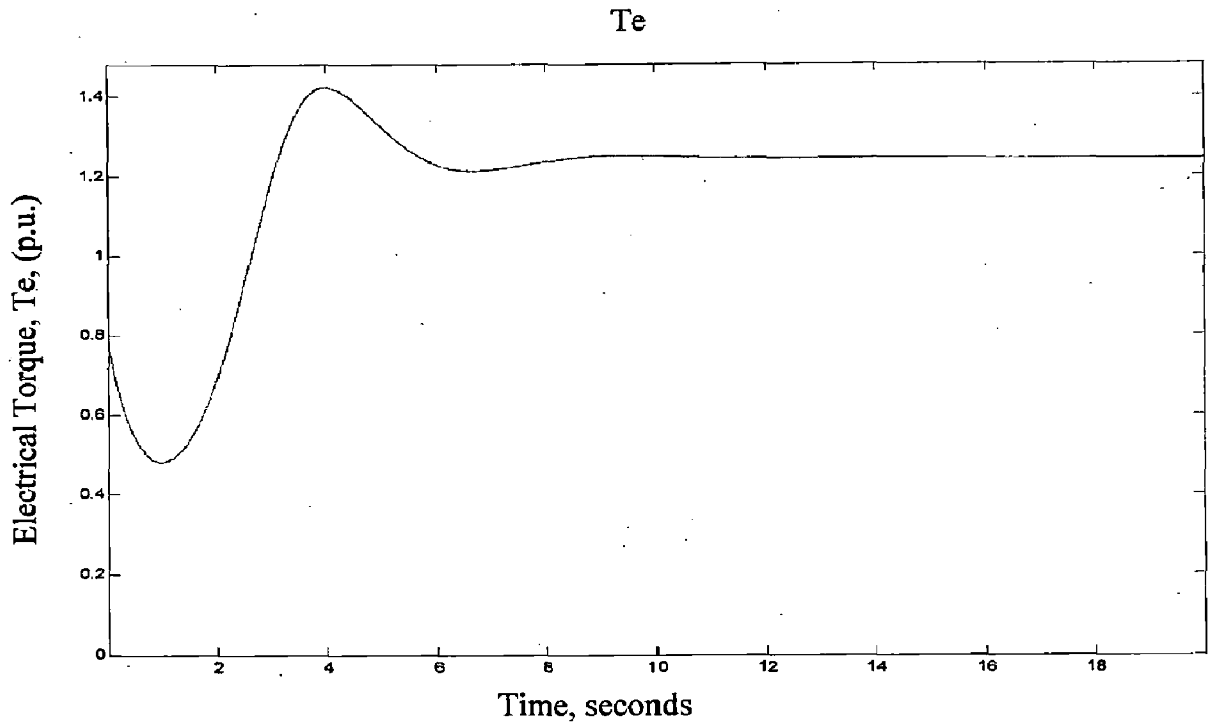


Figure 5.28 Variation of electric torque generated in SEIG

Figure 5.27 and 5.28 shows the shaft torque (Tshaft) produced by the microtubine, which drives the SEIG, and the electromagnetic torque (Te) generated by the SEIG. The generator torque is approximately double the shaft torque produced by the microturbine at steady state. That is the depending upon the torque needed to the SEIG the gear is used. At load 3kw the electromagnetic torque is 1.24 p.u. where as shaft torque is 0.62 p.u.

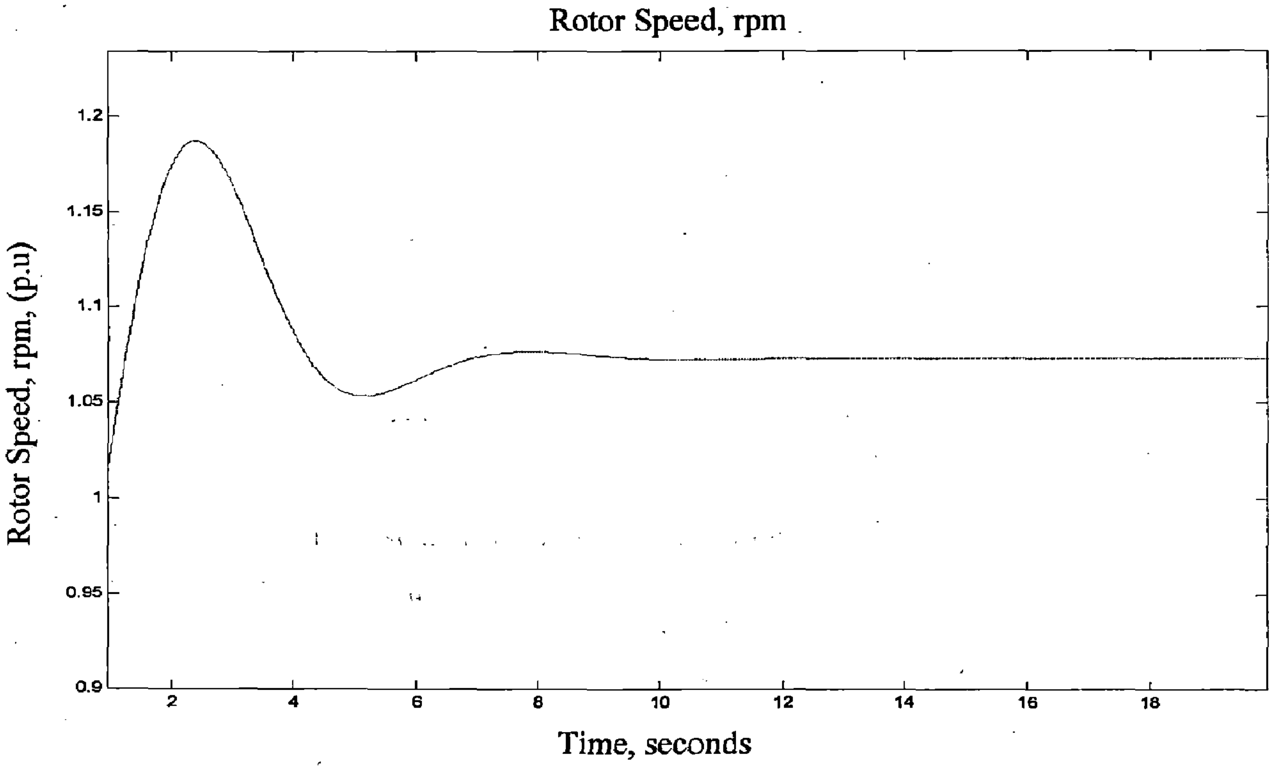


Figure 5.29 Rotor Speed variations with load in SEIG

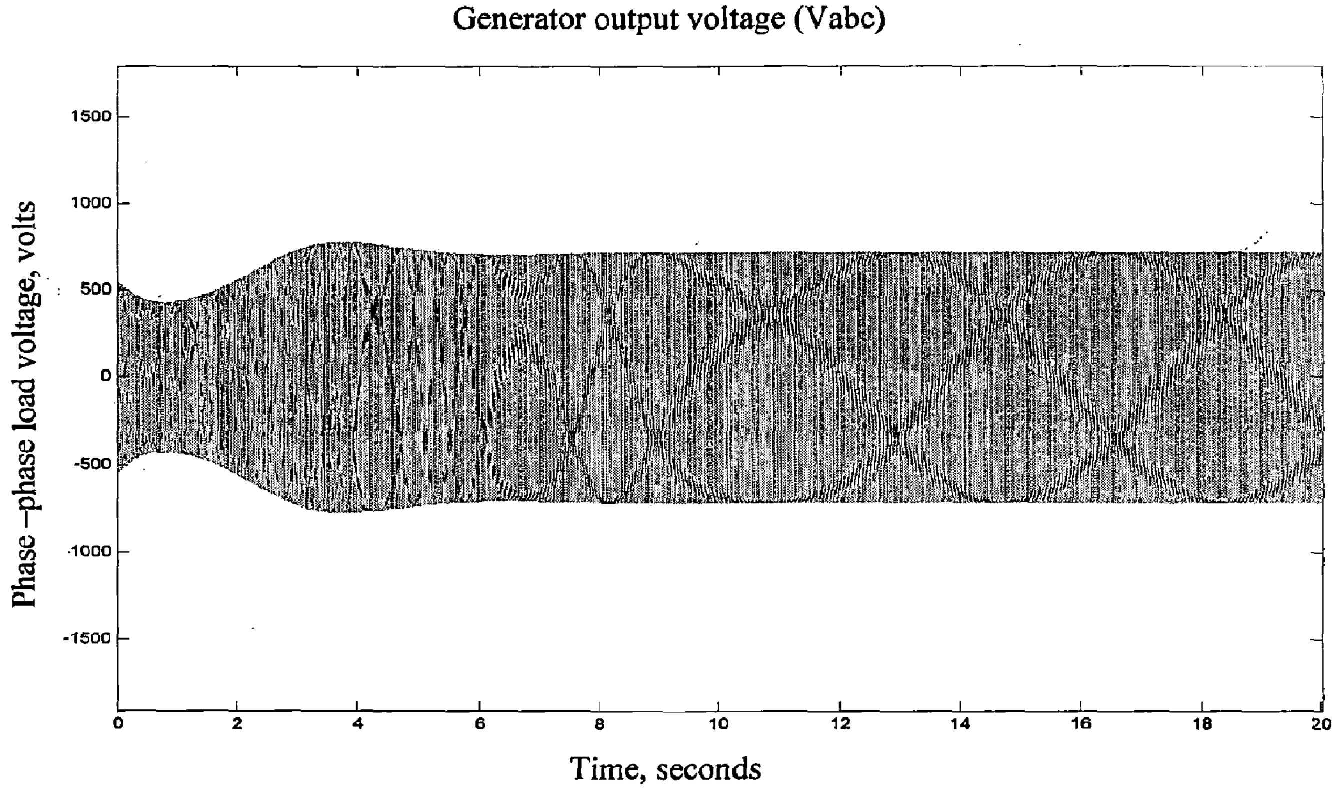


Figure 5.30 Phase –Phase voltage across the stator terminals of SEIG

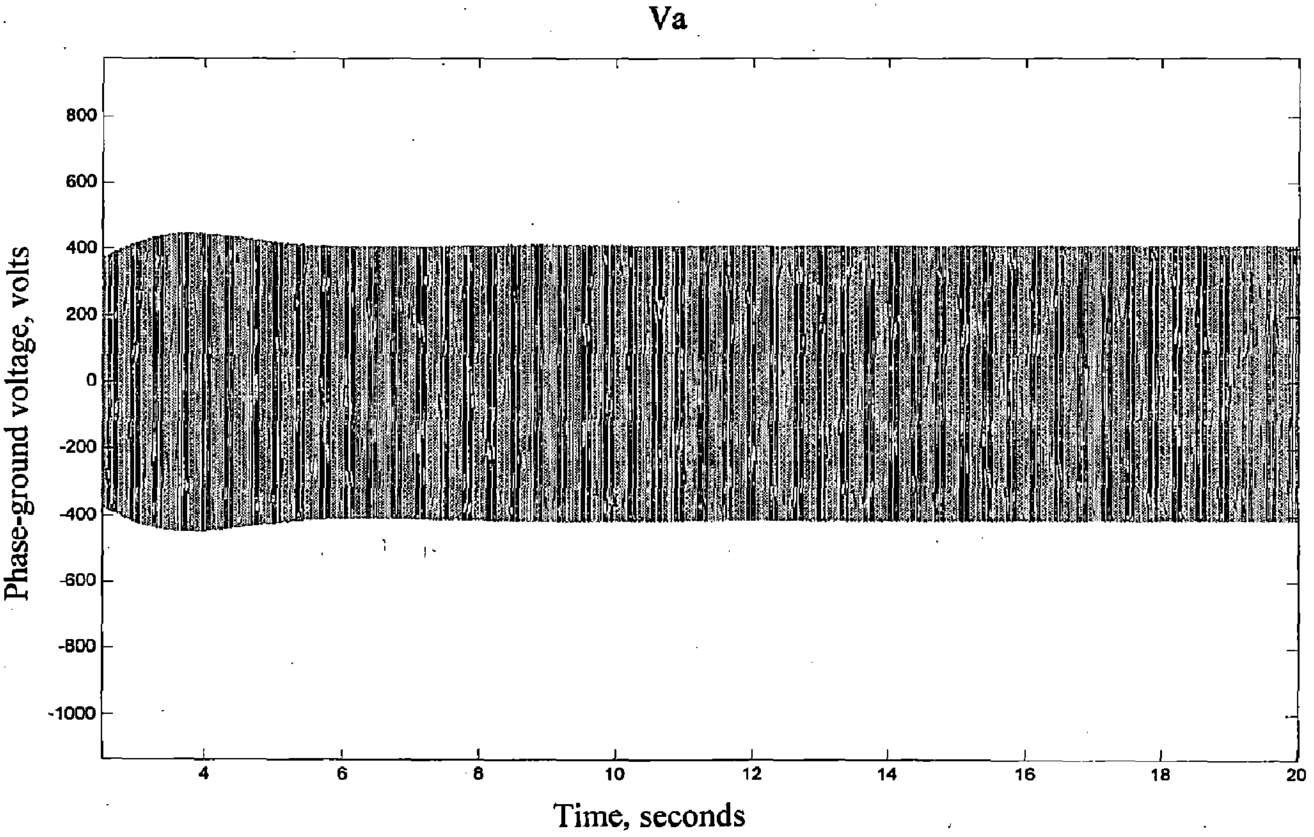


Figure 5.31 Phase – ground voltage across the stator terminals of SEIG

Figures 5.29, 5.30 and 5.31 shows the rotor speed and output voltage of the SEIG. When the SEIG is operated at load 3kW, the speed is above the rated speed approximately 1.08 p.u. And the stator line and phase to ground voltages pf the SEIG reaches the steady-state value from 4 seconds onwards as shown in the Figures.

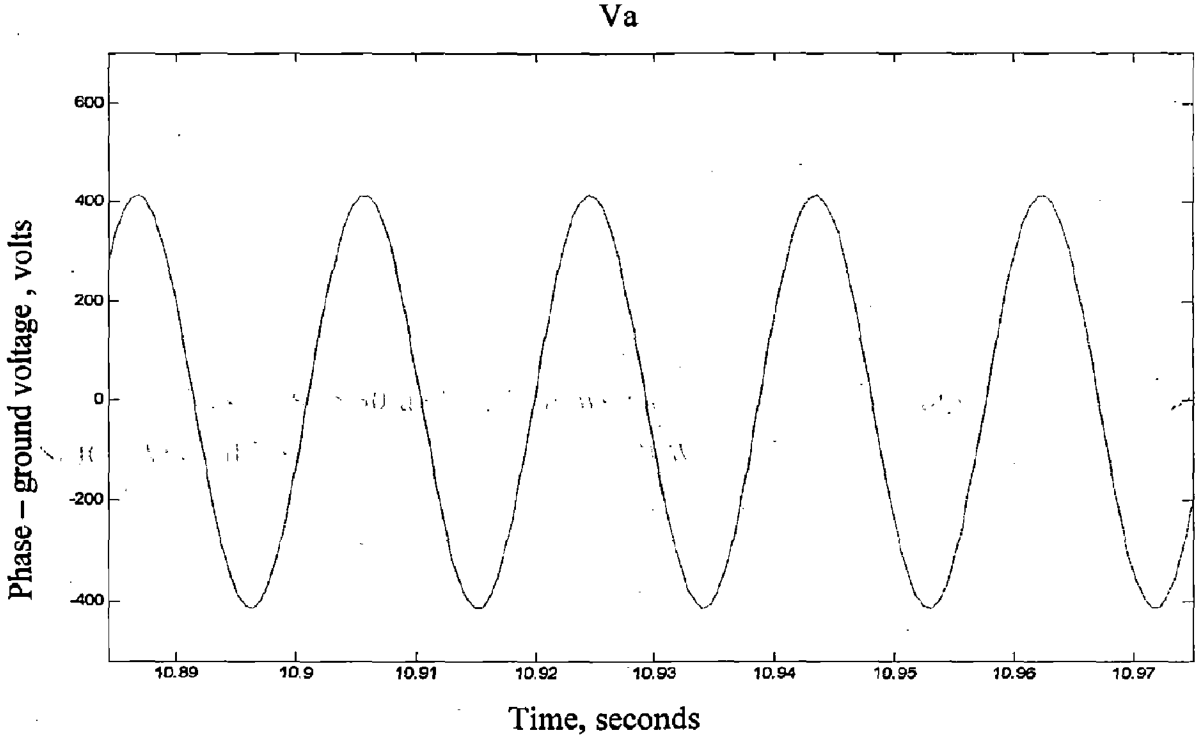


Figure 5.32 Shows the Frequency (50Hz) of SEIG

Figure 5.32 shows the frequency produced by SEIG, which is approximately 50Hz; here I want to point out that no need of power electronics interface for the SEIG with microturbine generation system.

Calculated as: from the Figure 5.32

I cycle from the time period (seconds) 10.89 to 10.91

So difference is 10.91-10.89 = 0.02

Where f = 1/t= 1/0.02

f = 50 Hz.

5.3.2 Case 2 <u>at variable load</u>: -

from the figure 5.33 and 5.34 , initially the SEIG will run on-load of 3kw with capacitor bank of 25e-6 farads and the rated voltage of approximately 400 volts will be maintained and at t=10second the load is increased to 3.5Kw so that reactive power from capacitor banks should be increased capacitance switching (5e-6 farads) arrangement have been done to maintain the voltage constant but at t=10sec when load increases the SEIG will not be stabilized immediately it will take time around 1 second to get steady state this is the draw back of self excited with the capacitor banks . Depending upon the load demand the fuel consumption are shown in the Figures.

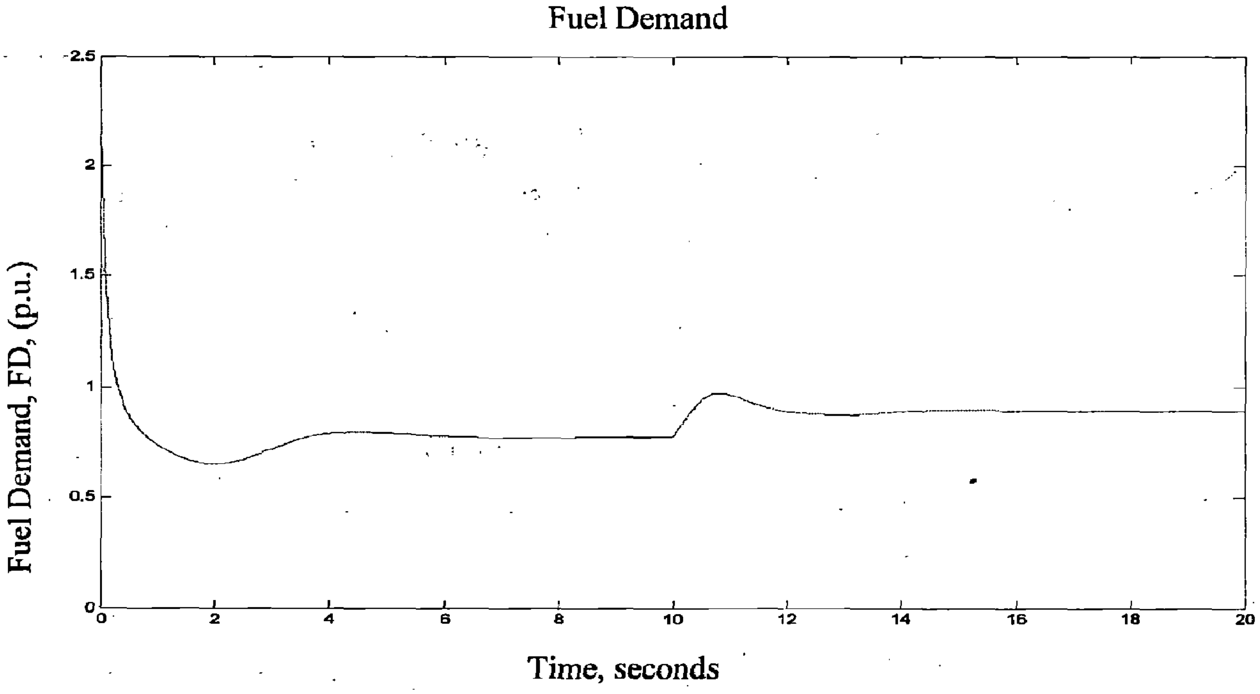


Figure 5.33 Fuel Demand Signal of the Microturbine with SEIG at variable load

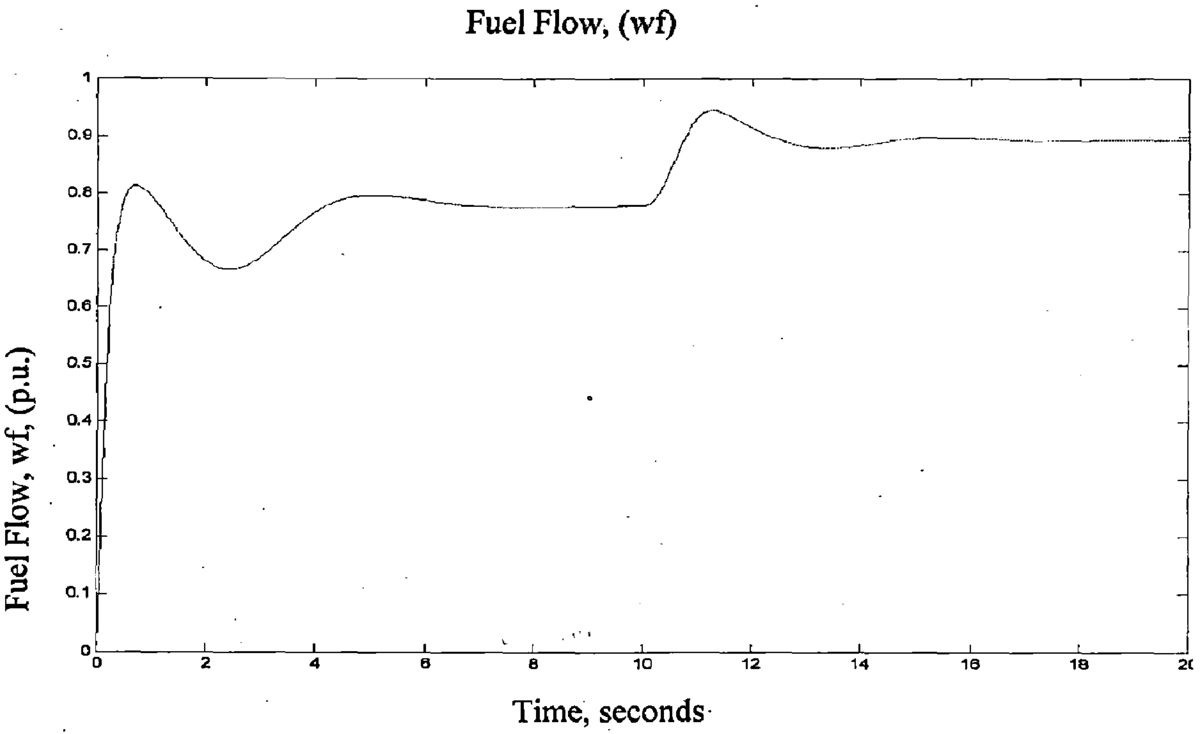


Figure 5.34 Fuel Flow Signal of microturbine with SEIG at variable load

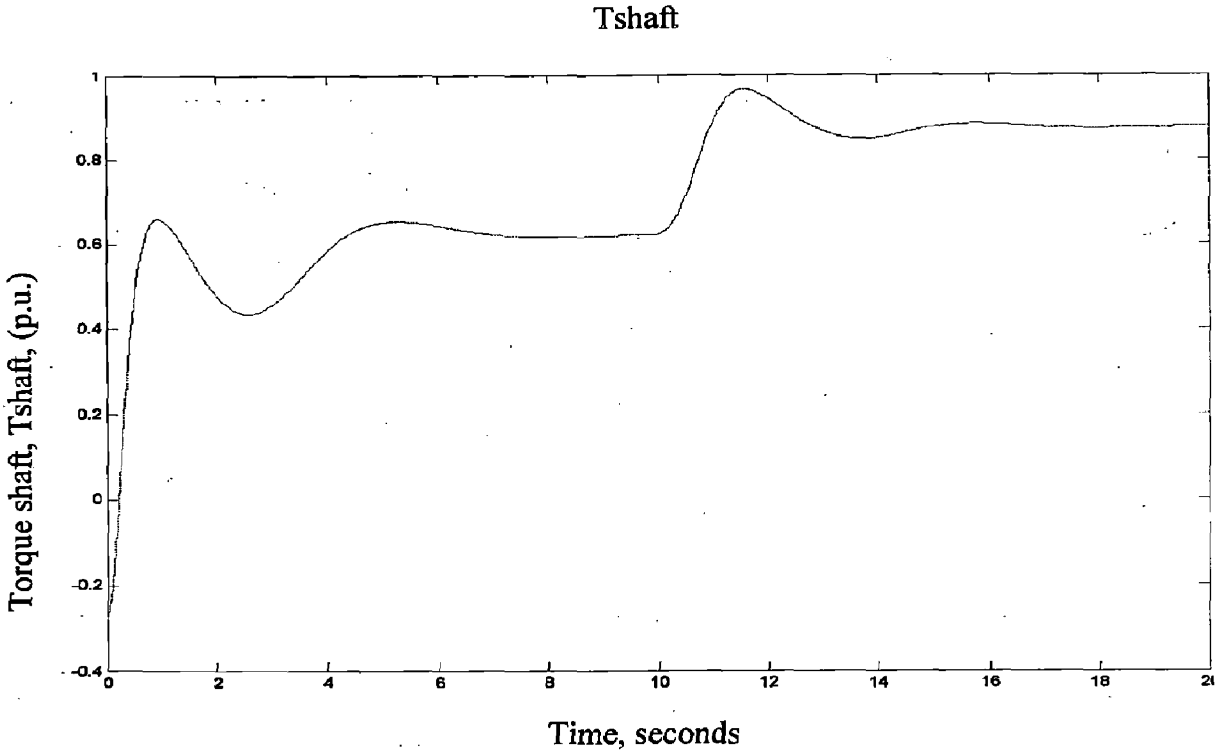


Figure 5.35 variation of shaft torque generated with SEIG at variable load

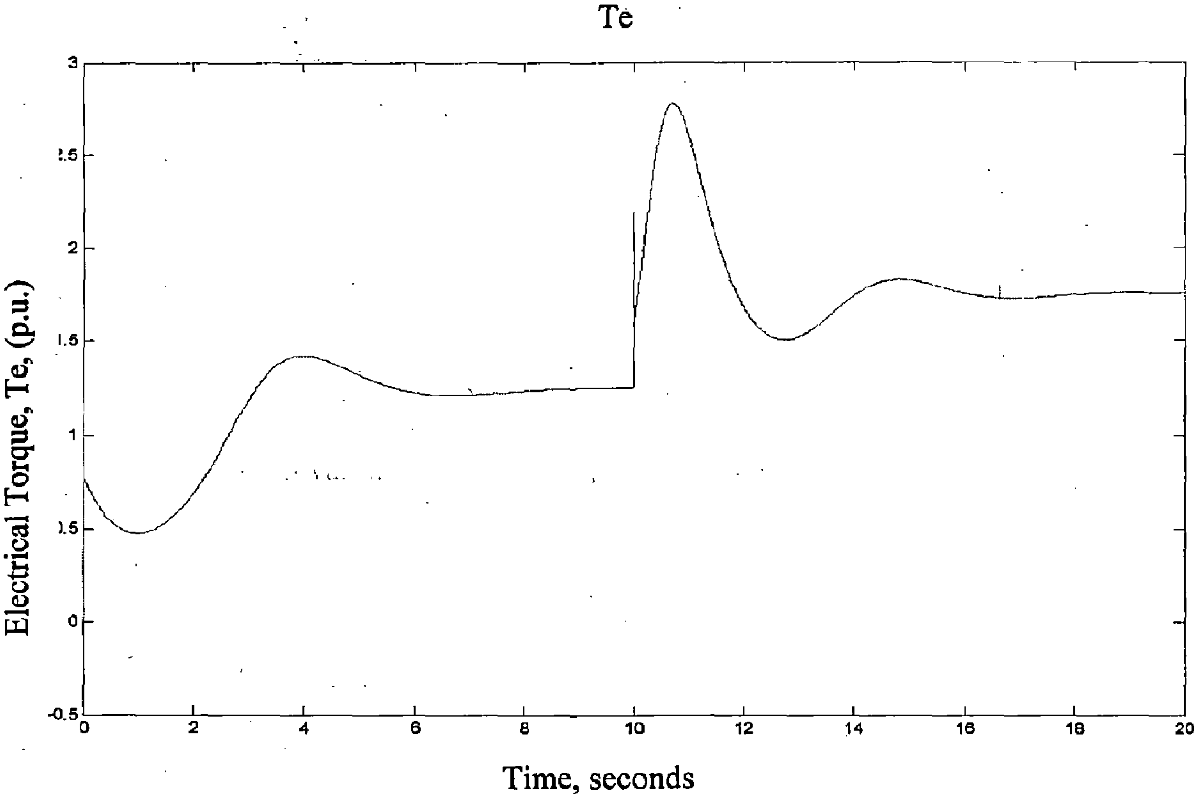


Figure 5.36 variation of electric Torque generated in SEIG with variable load

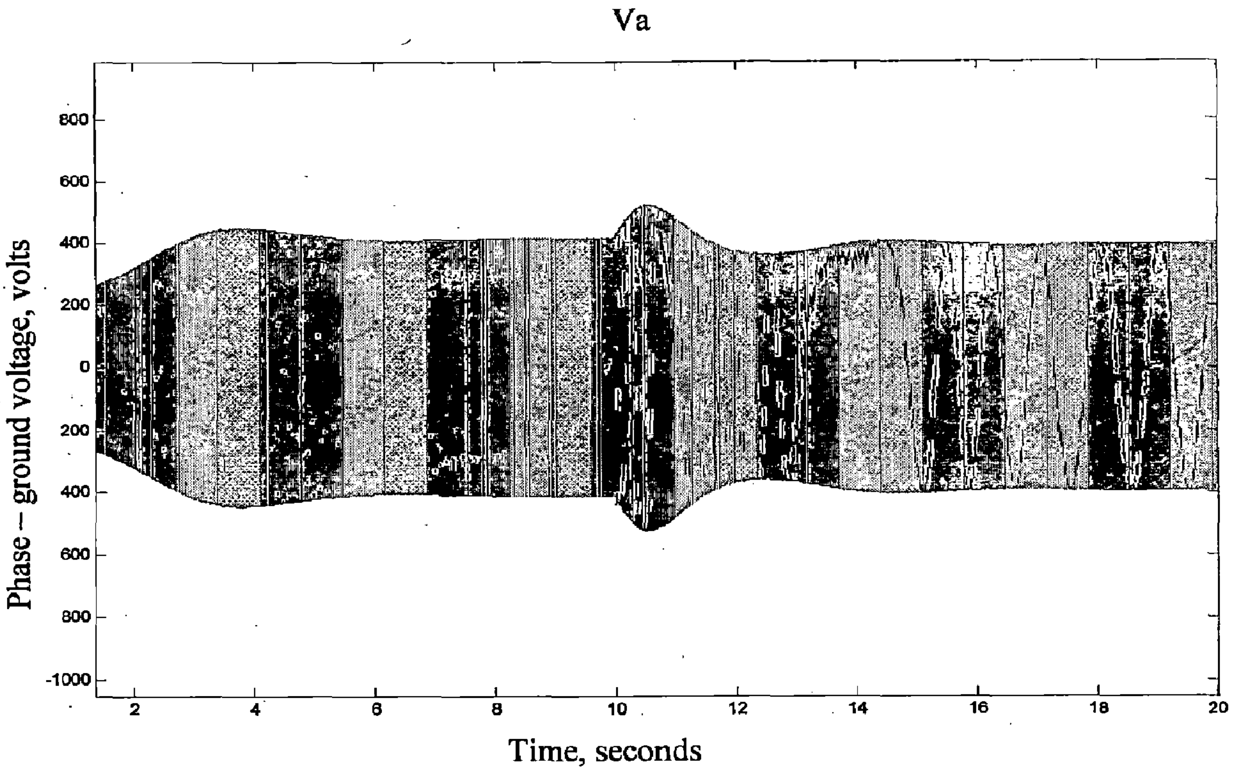


Figure 5.37 phase – ground voltage of the stator terminals of SEIG with variable load

Figures 5.35, 5.36 and 5.37 shows the torques of shaft, electric torque generated and phase to ground voltage, this figures shows the load variations with respective to the capacitance switching banks. At t=10 seconds the load is increased to 0.5kW, so the sudden switching of the load creates the system unstable but due to switching the capacitance in order to supply the reactive power to the SEIG the system will be stabilized depending upon the lead-lag controller system . but in my case by using the switching the capacitance is reliable to supply the reactive power to the system . Better to use SVC to SEIG, so that the time response will be small as compare to the capacitance switching devices.

5.4 **Diesel Engine Generation System**:

A mathematical model of the diesel engine system as explained in the chapter -4 sections is built in MATLAB/Simulink using SimPowerSystem block set. An inbuilt model of the synchronous machine in the SimPowerSystems block set, used to simulate the synchronous machine by applying mechanical power to the model .All the parameters values used for the simulation are given in Tables-[II]. The block diagram of the simulated diesel engine generation system is given in Figure 4.2, Appendix-[A4] followed by the simulation results for operating conditions.

All time functions are in seconds.

Diesel engine system ratings: 8.1kW, 1500 rpm, 50 Hz, ph- ground votage 410 volts

Synchronous Machine parameters [50]:

R_s=0.003(p.u),

$(X_d = 1.8, X'_d = 0.184, X''_d = 0.115, X_q = 0.895, X''_q = 0.207, Xl = 0.072)\,p.u.$

H(s) = 0.1406 (p.u.), pairs of poles ‘p’ = 2.

5.4.1Case 1. At constant load:

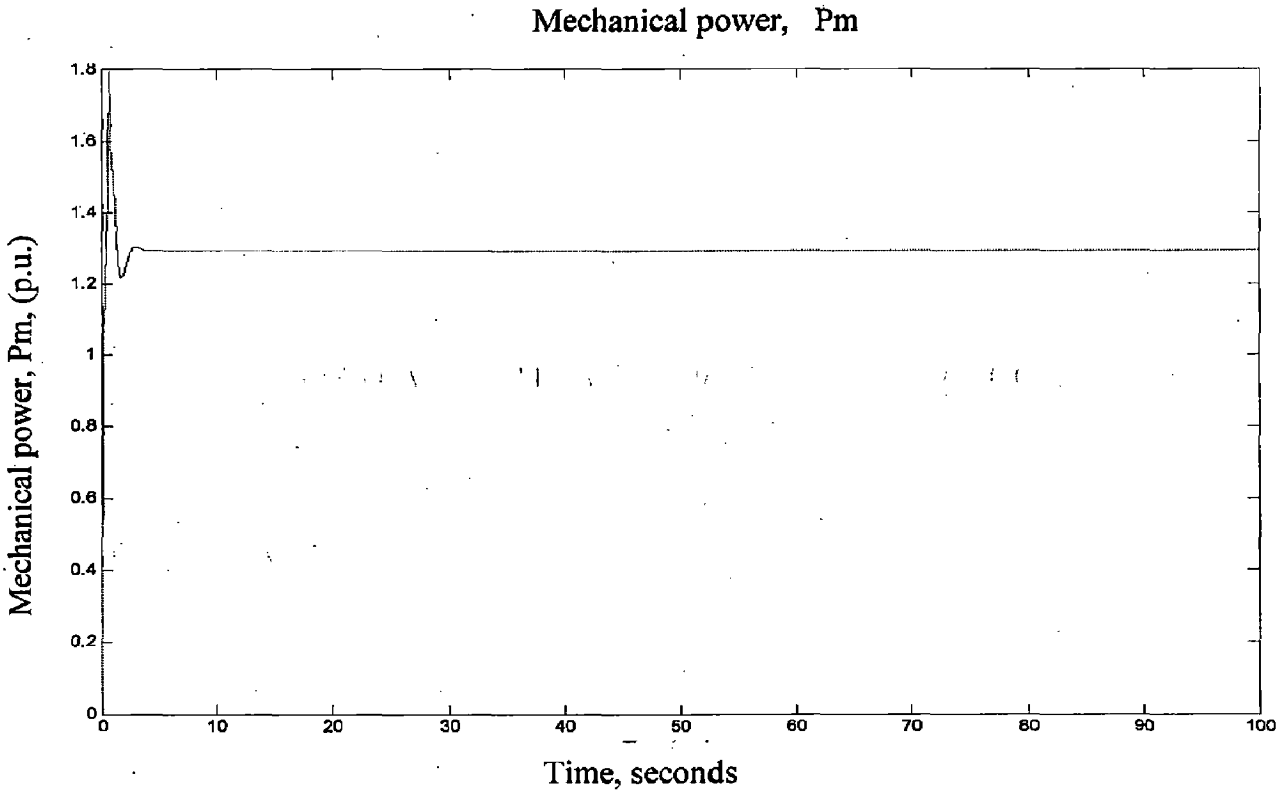


Figure 5.38 Variation of mechanical Power of the diesel engine w.r.t.constant load

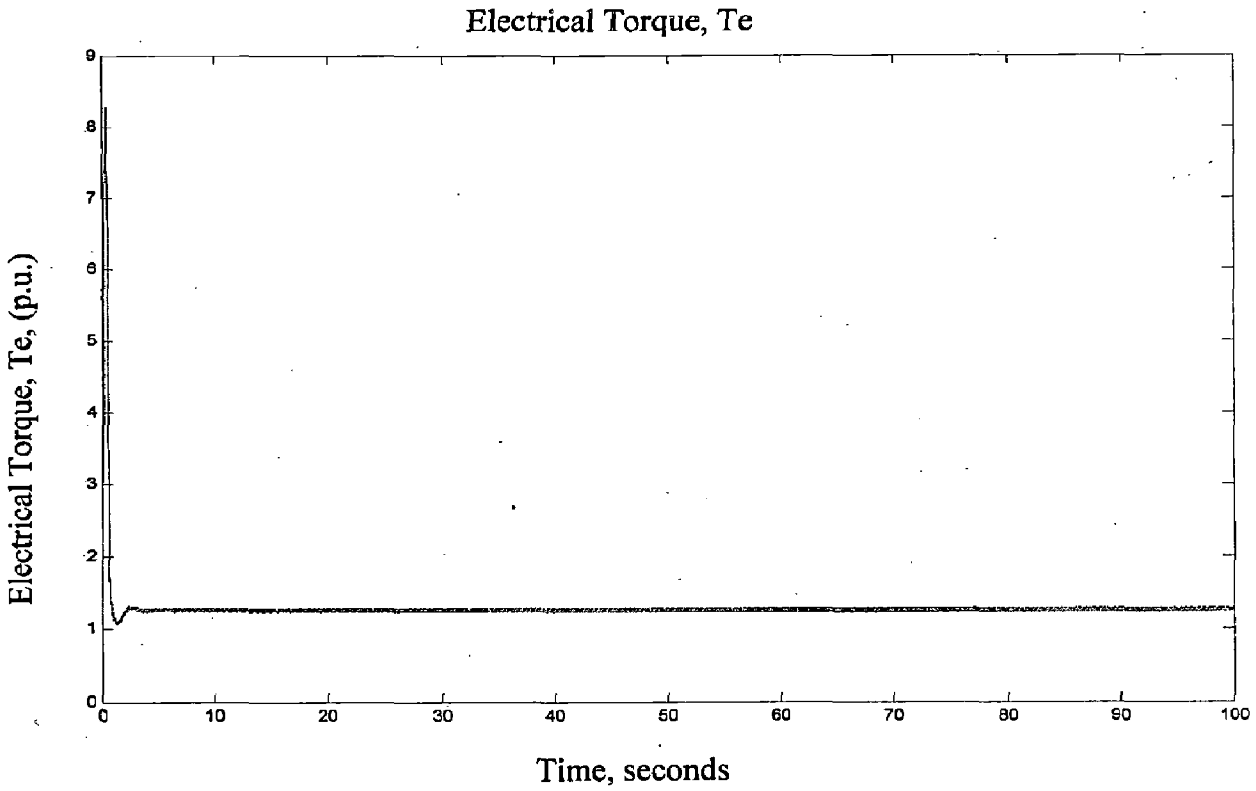


Figure 5.39 variation of electrical torque generated w.r.t load

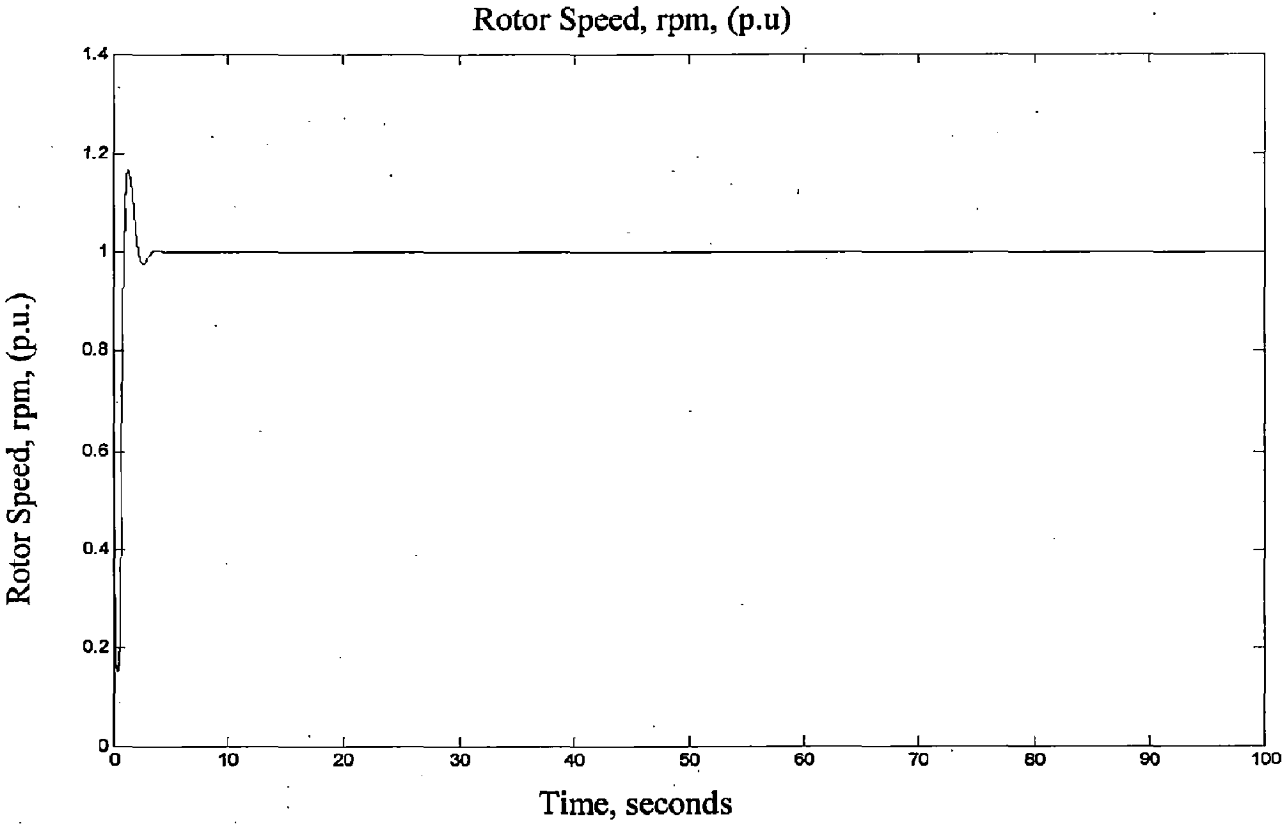


Figure 5.40 Rotor speed variation with load

A figure 5.38, 5.39 and 5.40 shows the performance of diesel engine mechanical power, electric torque and rotor speed. Where the system is depending upon the rated speed that is 1.p.u. at full load 8.1kW. speed is control by the lead-lag controller speed governor as the signal from the speed governor is send to the actuator the valves be opened according the load conditions so that the engine will ignition takes place that is delay as in Matlab/simulink . Then the mechanical power will be produced that is at full load approximately 1.23 p.u. and the electrical torque of synchronous machine is same as the mechanical power. Where the rotor speed is 1 p.u as shown in the Figures.

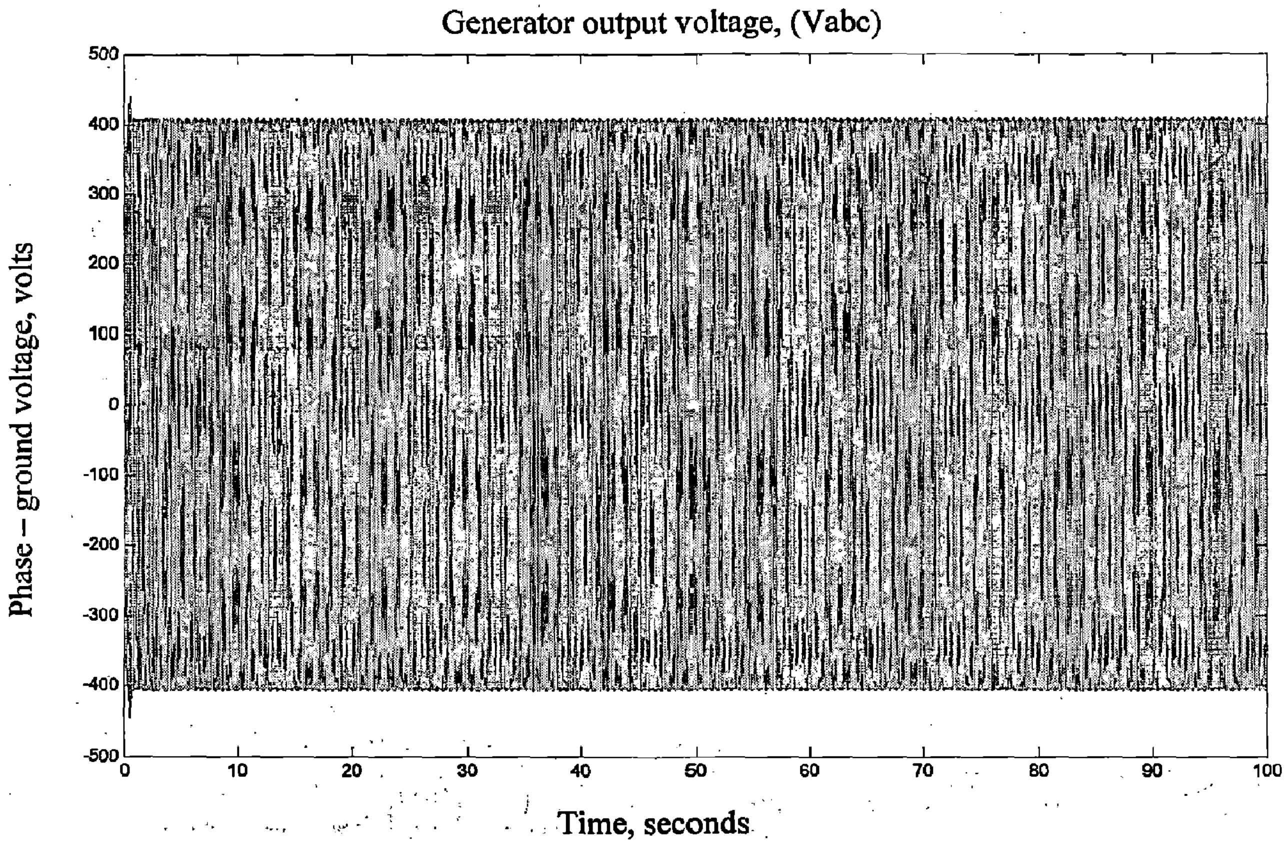


Figure 5.41 phase – ground voltage of the stator terminals of salient-pole synchronous machine

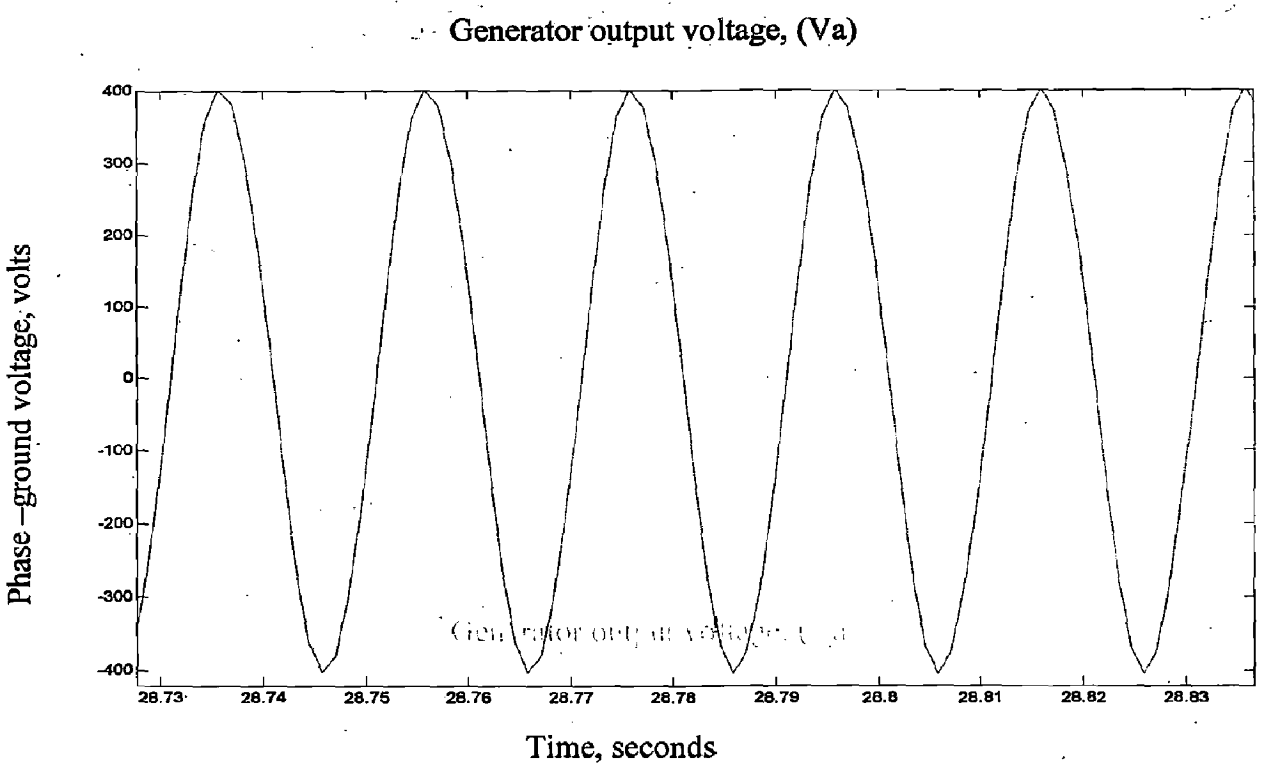


Figure 5.42 to show the Frequency (50 Hz) of the system (SM)

Figures 5.41 and 5.42 shows the phase-ground voltage and frequency of the system at full load 8.1kW of the system.

5.4.2 Case 2 .at variable load :

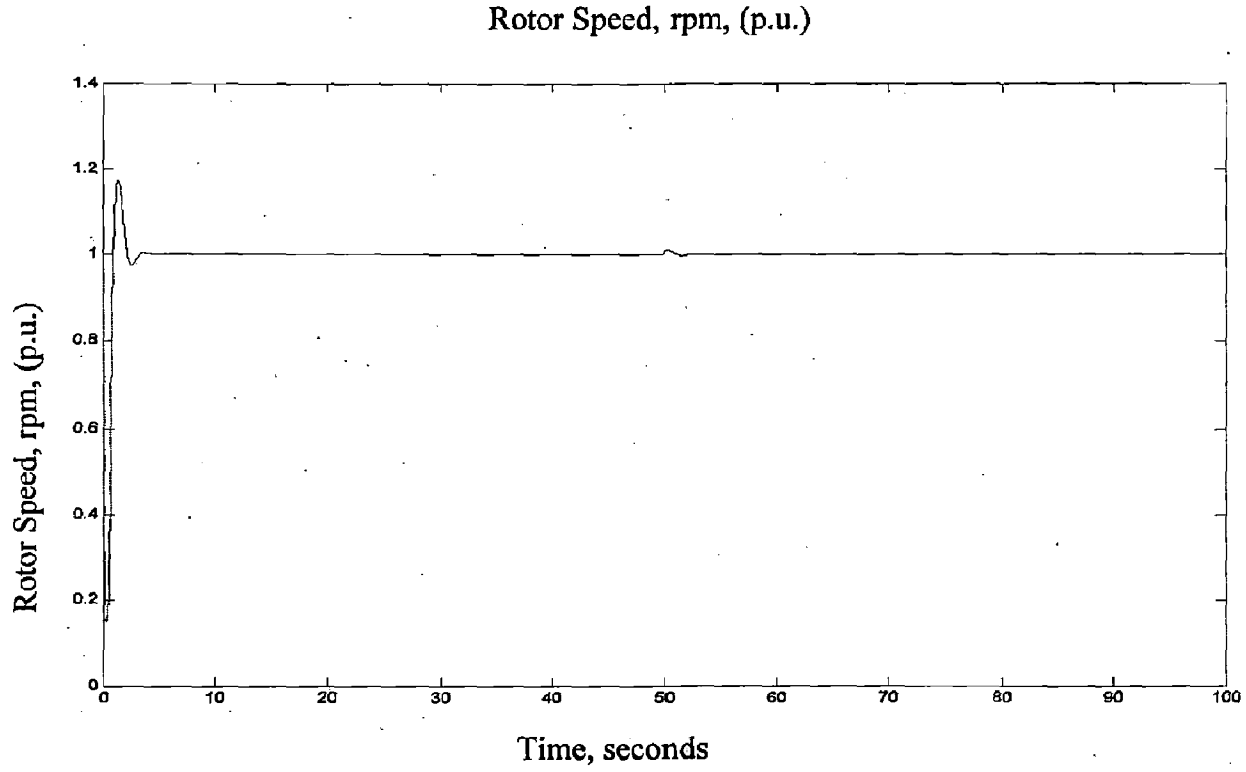


Figure 5.43 Rotor speed variation with load on SM

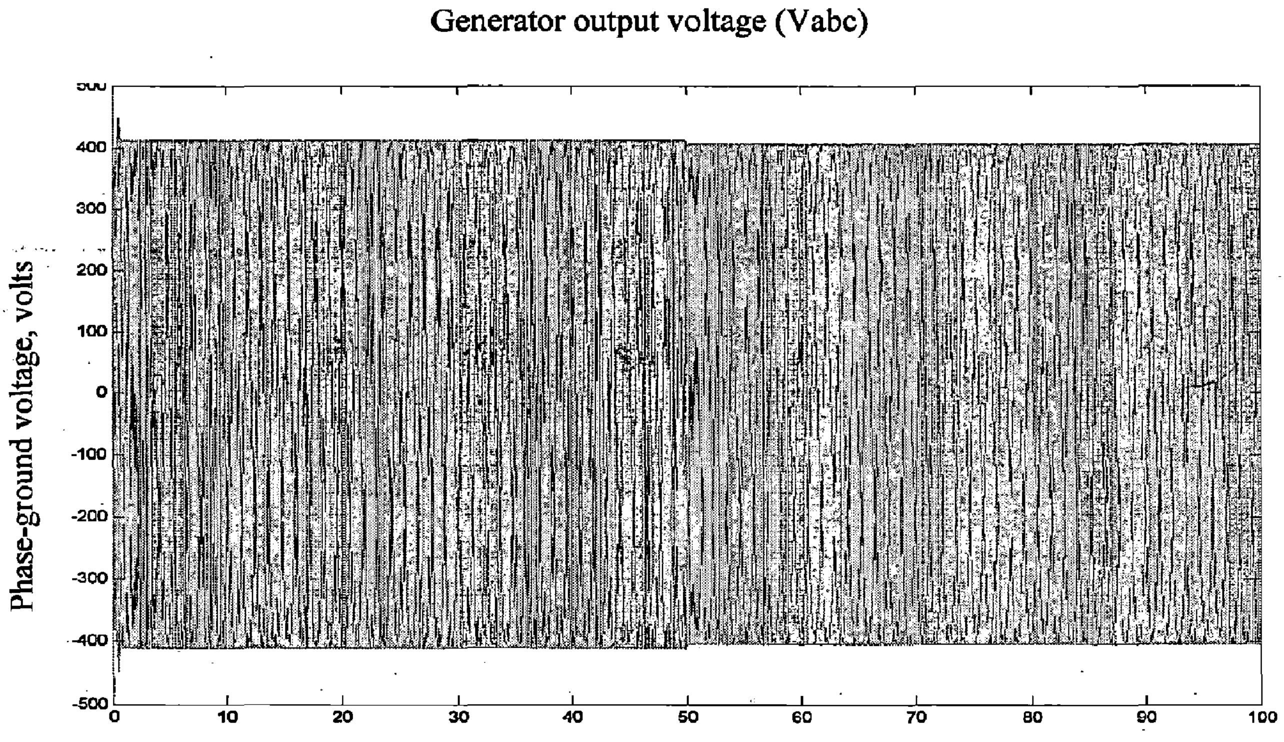


Figure 5.44 phase-ground voltage of the stator terminals of SM with variable load

Figures 5.43 and 5.44 shows the rotor speed and output voltage of the SM. when the diesel engine is operating at 8kW load, the speed of the rotor is equal to 1 p.u and the stator phase-ground voltage of the SM reaches steady-state value of 400 volts. When the SM is loaded at t = 50decond then there will be variation in the speed but with in 1 second the machine will comes to steady state. Where the voltage is slightly decreased.

CHAPTER-6

CONCLUSIONS

The modeling of a single-shaft microturbine generation system suitable for power management in DG applications is presented in this thesis. The model is good for both, power only and CHP applications. Detailed mathematical modeling of the control systems of the microturbine is given and simulation of the developed Microturbine Generation systems model is carried out. A MATLAB/Simulink model of the proposed Microturbine Generation systems was implemented in the SimPowerSystems blockset. Different load conditions are applied on the Microturbine Generation systems. The simulation results show that the developed model of the Microturbine Generation systems has the ability to meet the power requirements of the load, within MTG's rating. Also, simulations results show that the power electronics interfacing maintained the output voltage and frequency of the 3-phase inverter at the prescribed values during the entire period of operation.

Where the diesel engine model involved a speed governor and an actuator model, as well. These models didn't include the nonlinearity; however, the maximum and the minimum values have been included in the model because the power sources can't afford the extreme operation conditions. The model is good for both power only and CHP applications. A simple mathematical modeling of the control systems of diesel engine system is given and simulation of the developed diesel engine generation system model is carried out. A MATLAB/Simulink model of the proposed diesel engine generation system was implemented in the SimPowerSystems blockset.the results shows that the system has the ability to meet the power requirements of the load.

FUTURE WORK

In this thesis, the Microturbine and diesel engine models were only considered. Since the other models such as a solar cell, wind turbine and small hydro power plants can be used in the distributed generation, these models must be considered to study power quality issues on the distributed generation. Once the models are obtained, these models can be used to other applications such as three-phase faults, voltages, and currents. There are several kinds of distribution feeders in the power distribution system. Another area of research will be modeling of distributed feeders with unbalanced load and distributed generation.

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APPENDIX A
TABLES

Table- I

Microturbine Simulation Parameters:

S.no	Description		Value
1.	Controller gain	K	14
2.	Governor lead time constant	T_1	0.4
3.	Governor lag time constant	T_2	1.0
4.	Constant [Governor mode (droop or isochronous)]	Z	9
5.	Valve Positioner	K_v	1
6.	Valve Positioner Time constant	T_v	0.05
7.	Constant	C	1
8.	Gain (value of V_{ce} is scaled by the gain K_3)	K_3	0.77
9.	Minimum amount of fuel flow at no-load rated speed	K_6	0.23
10.	Fuel system actuator	K_f	1
11.	Time constant of delay	T	0
12.	Fuel system actuator time constant	T_f	0.04
13.	Small delay associated with combustion reaction	T_{CR}	0.01
14.	Time lag with compressor discharge volume	T_{TD}	0.04
15.	Transport delay of gas (combustion through turbine)	T_{CD}	0.2
16.	Coefficient of higher heating valve of gas steam	K_{HHV}	1.2
17.	Constant associated with radiation shield	K_4	0.8
18.	Constant associated with radiation shield	K_5	0.2
19.	Time constant associated radiation shield	T_3	15
20.	Time constant associated with thermocouple	T_4	2.5
21.	Time constant associate with temperature controller	T_5	3.3
22.	Temperature controller integration rate	T_t	450° F
23.	Reference Temperature	T_R	950° F

Note: Speed Controller Parameters: From 1 to 4 respectively.
Fuel System Parameters : From 5 to 12 respectively.
Compressor-Turbine Combination Parameters: From 13 to 16 respectively.
Temperature Controller Parameters: From 17 to 23 respectively.

Table- II

Diesel Engine Parameters:

S.no	Description		Value
1.	Controller gain	K	14
2.	Governor lead time constant	T_1	0.4
3.	Governor lag time constant	T_2	1.0
4.	Constant [Governor mode (droop or isochronous)]	Z	9
5.	Time constant for actuator	T_3	0.25
6.	Time constant for actuator	T_4	0.009
7.	Time constant for actuator	T_5	0.0385
8.	Time delay for diesel engine	T_6	0.024

Note: Speed Controller Parameters: From 1 to 4 respectively.
Time constants all are in seconds.

APPENDIX B
SIMULATION DIAGRAMS

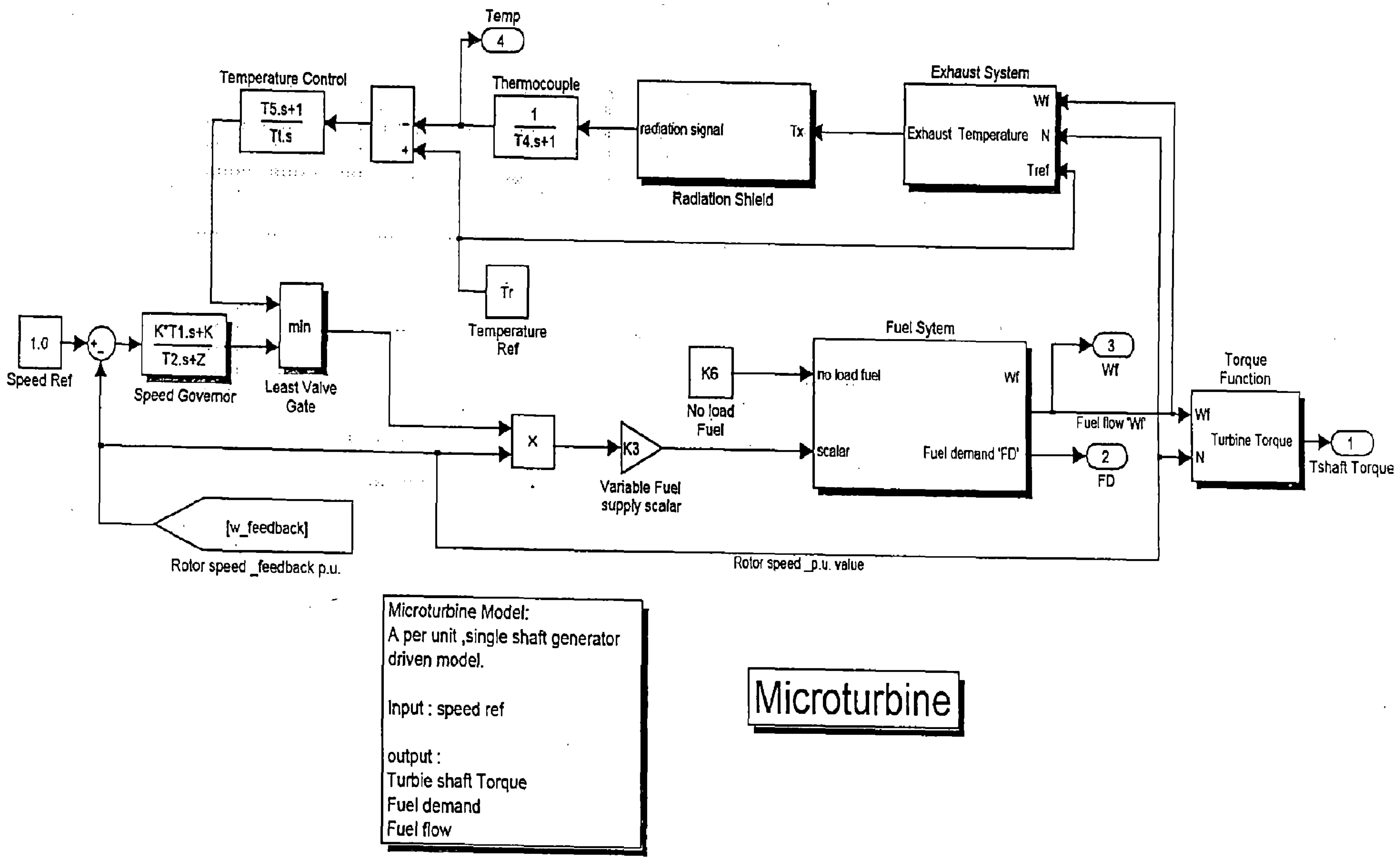

Figure A1.Simulink model of the microturbine

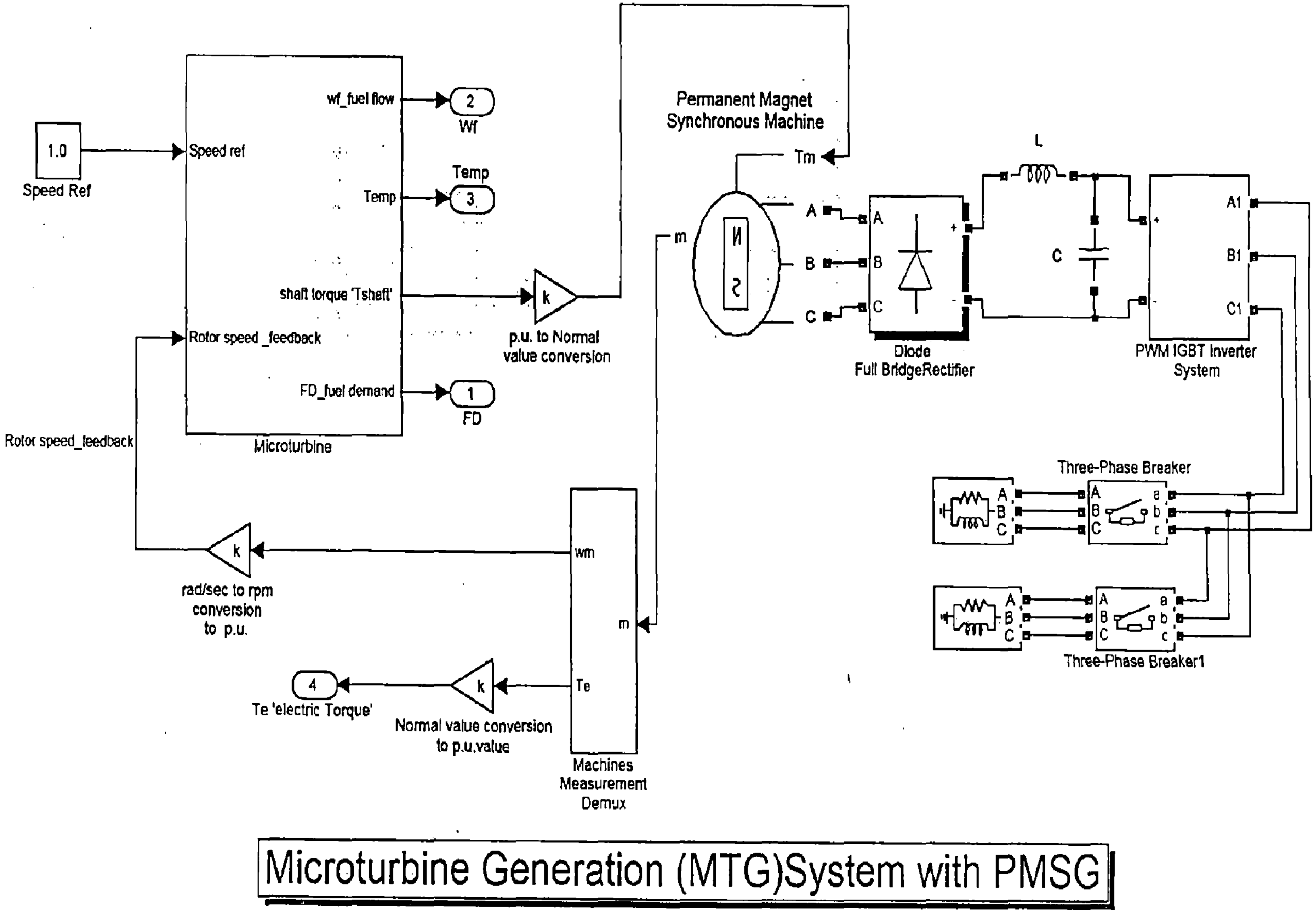

Figure A2.Simulink model of the microturbine generation system with PMSG

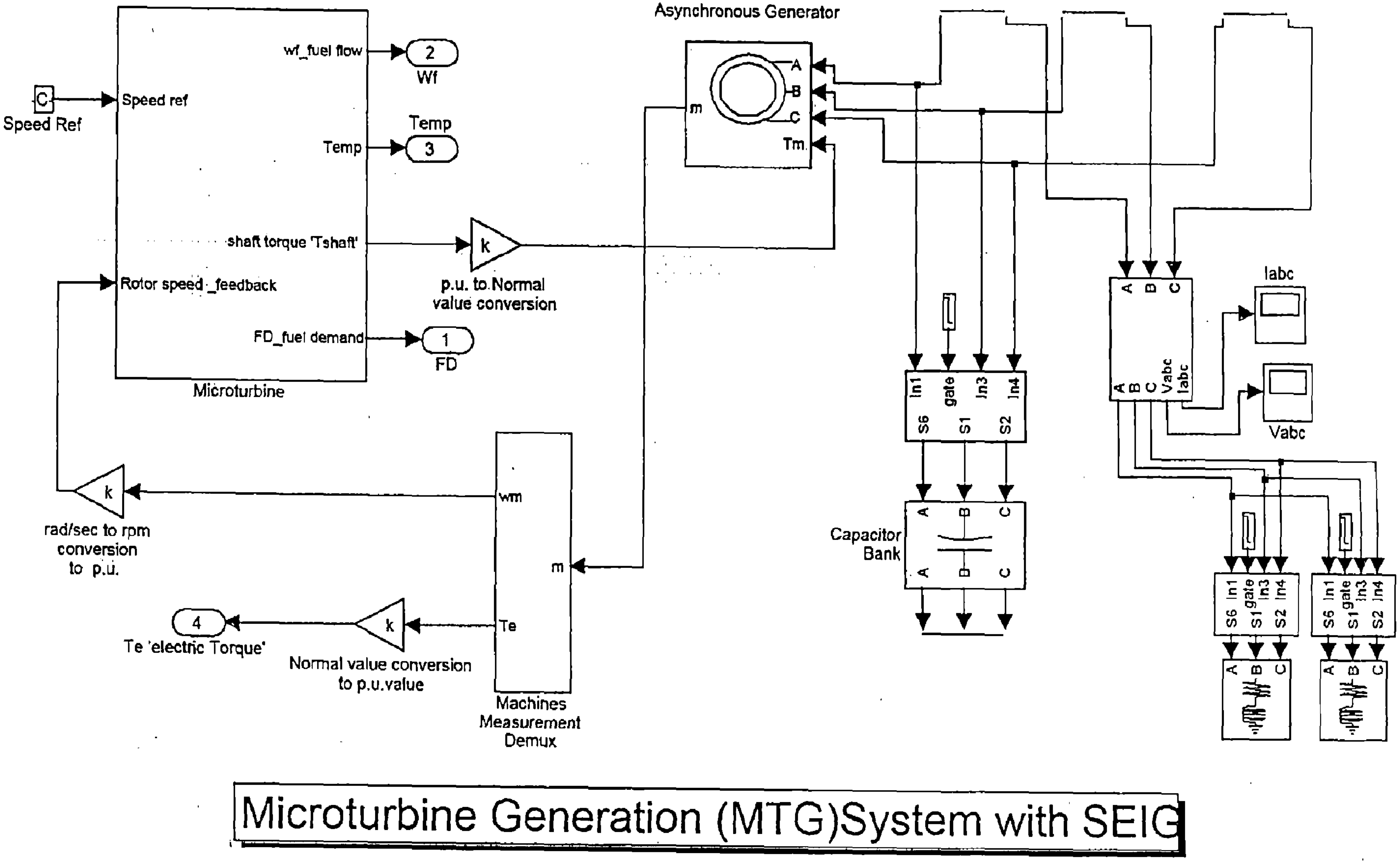

Figure A3.Simulink model of the microturbine generation system with SEIG

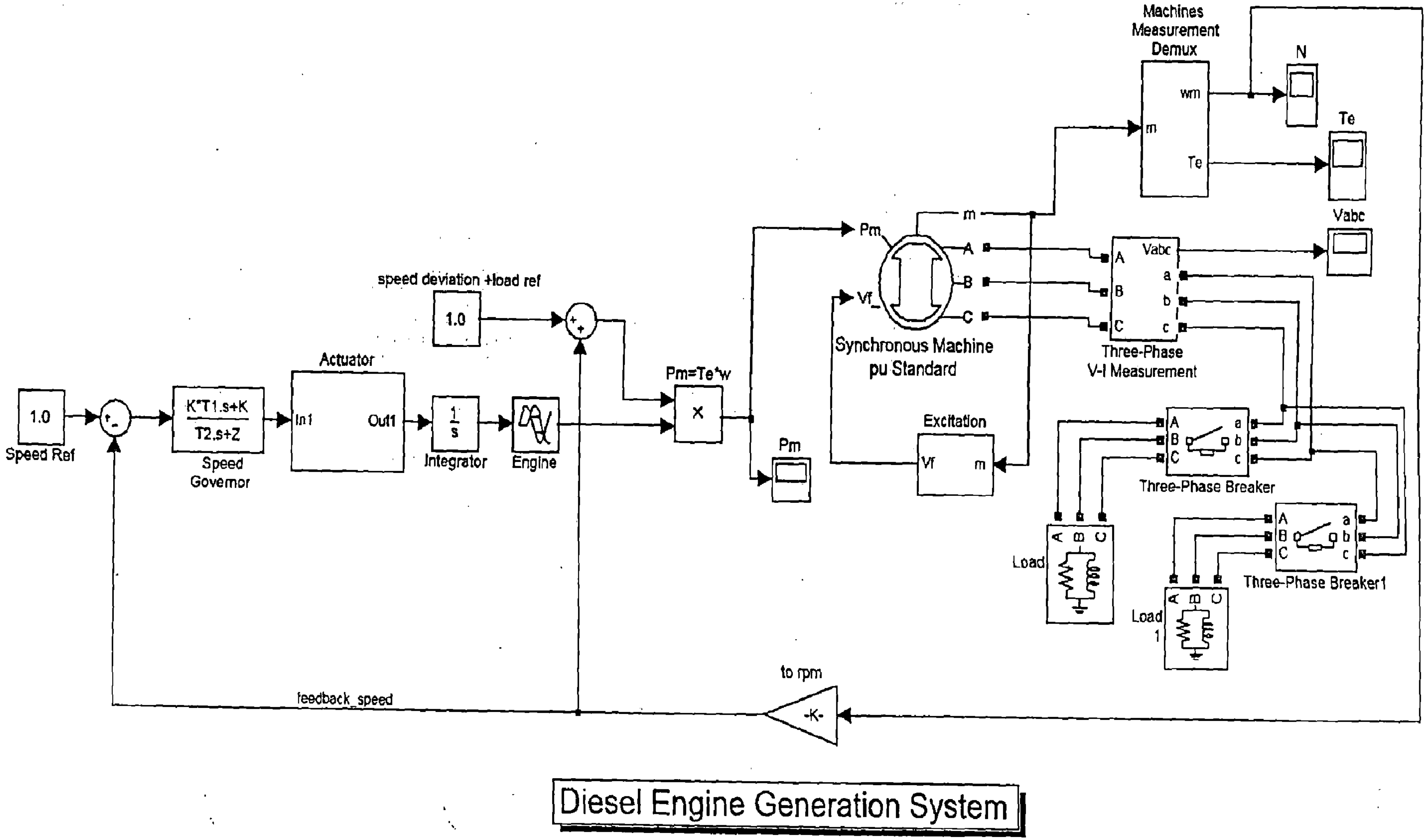

Figure A4. Simulation model of the diesel engine generation system