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Modeling and Simulation of PMSG Based Biogas Power Plant

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Abstract—*Biogas is a renewable energy source, which can be produced by the breakdown of organic matter in the lack of oxygen. In this paper, a biogas plant model is developed which can provide enough power supply for one or more farmlands in rural areas. The proposed model constitutes of reactor, micro turbine(MT) and permanent magnet synchronous generator (PMSG). The methane gas is generated from the feed which we provide as input to the reactor and it is allowed to flow through the micro turbine which is connected with PMSG. The rate of generation of methane gas can be controlled with amount of feed or temperature or both. The performance of the plant is noted under both transient and steady state conditions. Also the type of feeder and temperature is changed and the respective performance is noted down. PI controllers are used for the control of fuel flow rate and temperature which are essential in the generation of Methane gas, and load changes effectiveness of generator and the micro turbine are tested and the results are noted. The model is developed and simulated in MATLAB/Simulink software package.*

Keywords: *Biogas Process, Biogas Reactor, Micro Turbine, PMSG, Transient Electrical Loading.*

1. INTRODUCTION

Renewable energy sources are of high necessity to the increasing consumption of electrical energy. Among third world countries, Biomass is one of the community used renewable sources of energy. Due to the latest developments in renewable resources usage techniques, the scope of the biomass energy extraction is increasing. Biomass is derived from animal and plant matters with water, co_2 and the reaction of sunlight from the atmosphere. The sources for biomass are agriculture production, residual forest resources, manure from various animal production units. It is of least environmental risks, cheap and efficient and widely available source of renewable energy. The bioreactor is the most important section of biomass energy conversion system as it is responsible for microbial growth and generation of biogas. The performance of the bioreactor can be improved by size and structure of the reactor, transfer and mixing characteristics, types of feeds and waste dump removal. The conversion of biomass energy resources into electrical energy is governed by various factors such as ash and moisture content. The process of converting biomass into electrical or other usable energies can be affected by the volume of the biomass. Anaerobic Digestion (AD) is an essential part of the energy conversion process in which the raw biomass content is used to generate biogas. In the process of fermentation, different kinds of biomass can be used such as crop residues, animal and food wastes, etc., and various studies have analyzed of the methods adopted for production, process, and usage of biogas. An analysis of anaerobic co-digestion of lingo-cellulosic feedstock and animal manure is made for the production of biogas. Fig.1 shows the total renewable energy consumption per year.

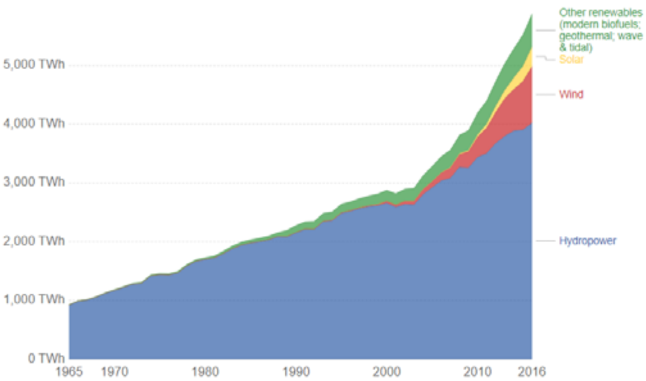

Fig. 1: Total Renewable energy consumption per year

A summary of the latest trends and techniques in the production of biogas from the AD process is documented. Various components of the biogas power plants are modeled and simulated with different types of feeds. Using ode solver and Euler's technique, the Modified model of Hill is simulated and studied with the change of methane production with time in Matlab environment. A dynamic model of AD bioreactor using

i) Swine

ii) Beef,

iii) Poultry and

iv) Dairy manure as feeds to study both dynamic and steady state conditions.

A mathematical model is analyzed to predict the methane gas production and the pH value using different hydraulic retention times. The characteristic processing variables of the AD is simulated with maize, grain silage and sugar beet were compared different structures of model. The effect of sludge processing, recycling and stability of pilot scale of AD plant in case of organic fraction of source isolated food waste treatment procedure was studied. The anaerobic reactor including recycling is continuously stirred and simulated is applied on ADBI. A quantitative Fuzzy evaluation of the benefits of AD with food waste related to economy and environment is presented. At last, a two-stage model was developed based on the model of two-step mass-balance and studied. It mainly composed of a permanent magnet synchronous generator, reactor, micro-turbine and uncontrolled rectifier setup.

In this work, a complete well versed model that fully simulates a power plant with biogas as fuel is developed. The proposed system is comprised of three separate units which includes a biogas reactor, a micro turbine generation system(MTGS) and a DC load system. Each unit can be implemented separately or combined to build the biogas power plant and simulate it. The plant can operate under any transient and steady-state conditions by developing an adaptive controller.

2. ANAEROBIC DIGESTION PROCESS

AD is a process of conversion of biomass organic substances into organic acids, which again gets converted into methane gas by the microbes with carbon dioxide as another byproduct. The above process is conducted under anaerobic conditions (without oxygen). The above mentioned treatment generally eliminates Chemical Oxygen Demand (COD) by as the organics are boiled down to methane. And also the COD of the methane generated in an anaerobic system is often having the same effect as to the amount of COD removed. Fig. 2 gives classification of biogas microbes.

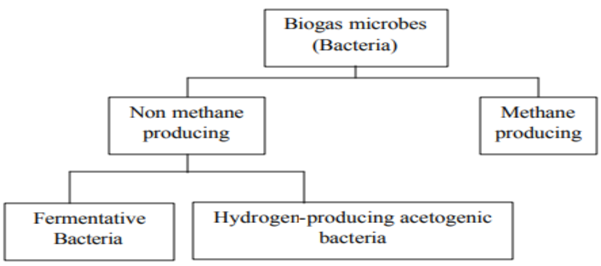

Fig. 2: Classification of Biogas microbes types

The proposed model consists of three main parts; biogas reactor, Micro turbine and permanent magnet synchronous generator.

2.1 Modeling of Bio Reactor:

The bioreactor's modeling equation is

$$\frac{dx_1}{dt} = (\mu - D)x_1 \quad (1)$$

$$\frac{dx_2}{dt} = D\left(x_{2_f} - x_2\right) - \frac{\mu x_1}{\gamma} \quad (2)$$

where

x_1 = concentration of biomass in cell,

and

x_2 = concentration ofsubstrate

D = rate of dilution

x_{2_f} = concentration of substrate feed

Two expressions formulated for the specific growth rate are monod and substrate inhibition kinetics, which is explained below:

2.2 Monod

The Michaelis-Menten kinetics is applied to cellular system of single species is known as the monod equation

$$\mu = \frac{\mu_{rax} x_2}{K_r + x_2} \quad (3)$$

μ_{rax} is the maximum rate specific growth ($S \gg K_r$)

$x_2$is the concentration of the substrate concentration

$K_r$is the half-velocity constant or saturation concentration

When the specific growth rate is ½ the maximum equals the rate-limiting concentration of the substrate, S.

2.3Substrate Inhibition

Substrate inhibition is a special case of uncompetitive inhibition occurs during high substrate concentrations in about 20% of the enzymes (e.g. invertase is inhibited by sucrose). It is primarily caused by insufficient active sites in which more than one substrate molecule binding to such sites, and also by different substrate molecules binding to different sub-sites within single site. A reduction in the reaction rate is caused by the resultant complex which is inactive with this type of inhibition, at high concentration of substrate**.** Fig. 3 shows the block diagram of substrate inhibition process model diagram.

$$\mu = \frac{\mu_{rax} x_2}{K_r + x_2 + k_1 x_2^2} \quad (4)$$

From the above mentioned equations, we can find that the monod growth rate is a subset of the substrate inhibition model.

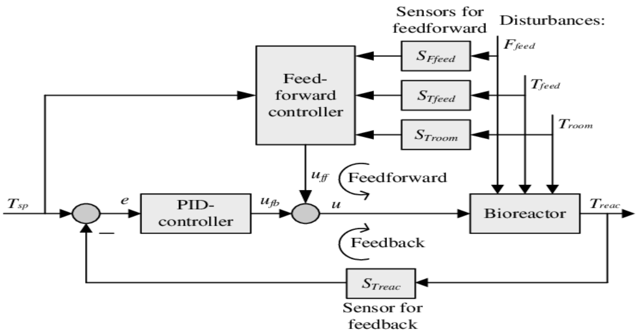

Fig. 3: Substrate inhibition process model diagram

We are using the following parameters for a substrate inhibition model for the study of control loop:

μ_{rax}=0.32hr^{-1}

K_r=1.328*10^-5g/litre

K_1=1.1litr/g

γ=0.0133

The transfer function for the control of stable fuel system is given as follows in equation 5

Gc2 =

(s^7 + 1.1 s^6 + 0.51 s^5 + 0.14 s^4 + 0.023 s^3 + 0.0023 s^2 + 0.00012 s + 2.1e-06)/(0.024 s^7 + 0.046 s^6 + 0.033 s^5 + 0.012 s^4 + 0.0025 s^3 + 0.0003 s^2 + 1.9e-05 s + 4.2e-07) (5)

Similarly the transfer function for the system which control of temperature is given below in equation 6

Gcff =

-(1.0*(0.015*s^8 + 0.02*s^7 + 0.011*s^6 + 3.9e-3*s^5 + 8.4e-4*s^4 + 1.2e-4*s^3 + 9.7e-6*s^2 + 4.4e-7*s + 7.3e-9))/(0.023*s^8 + 0.031*s^7 + 0.019*s^6 + 6.5e-3*s^5 + 1.4e-3*s^4 + 2.0e-4*s^3 + 1.8e-5*s^2 + 8.8e-7*s + 1.7e-8)

(6)

2.4 Modeling and Control of a Microturbine:

MTs are small gas turbines which burns liquid or gaseous fuels to generate high energy stream of gas which is used to drive an electrical generator. MT produces electrical power with the help of a high-speed generator directly driven by the shaft of the turbo-compressor. Here the gearbox which can increase or reduce the shaft speed to match with that of the speed of conventional electrical machines is eliminated as we are using small gas turbines or in other words micro turbine.

The dynamics of an MT are analyzed for both steady state and transient simulation environment in the proposed model.

Both the exhaust temperature and torque characteristics of a single-shaft gas turbine is directly linear with fuel flow and turbine speed. Fig. 4 shows the control circuit diagram for bioreactor.

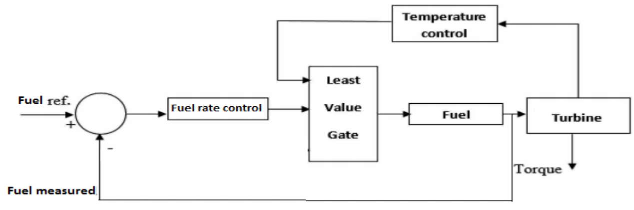

Fig. 4 Control circuit diagram for bio reactor

The mechanical torque generated by the micro turbine which drives the electric generator is provided below:

$$T=KH(W_f-0.23) +0.5(1-N) \quad (7)$$

The temperature of the turbine is calculated as

$$T_x =T_R-700(1-W_f) +550(1-N) \quad (8)$$

where KH is the enthalpy coefficient of the gas stream in combustion chamber, T_R is the temperature reference, N is the turbine speed(in p.u) and W_f is the fuel demand(in p.u).

The input to the reactor is fuel demand W_f and output of the micro turbine is the torque which is used to drive the generator. A complete Simulink model including MT and all of its control systems are modeled and simulated.

2.5 Modeling of PMSG:

The dynamic model of the PMSG is produced from the two phase synchronous reference frame, in which the quadrature axis is 90 degree leading with the direct axis with respect to the direction of rotation. Phase locked loops are used to maintain the synchronization between the d-q rotating frame. The dq reference frame for salient -pole synchronous machine is showing in Fig. 5.

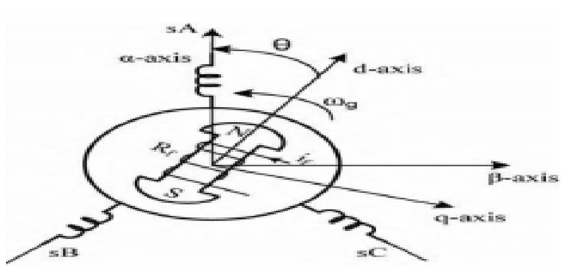

Fig. 5: Vector diagram for PMSG

where θ is the angle between the stator q axis and the rotor d axis, i.e mechanical angle. The stator windings are kept sinusoidal along with the air-gap as far as the mutual to that of the rotor.

The following assumptions are made for the operation of the PMSG:

The setup consists of symmetrical stator winding,

No consideration of the damping windings,

the capacitive effect can be neglected for all the windings. The mathematical model of the PMSG in the synchronous reference frame is

$$V_d = R_s i_d + \frac{d\varphi_d}{dt} - \omega_e \varphi_q \quad (9)$$

$$V_q = R_s i_q + \frac{d\varphi_q}{dt} + \omega_e \varphi_d \quad (10)$$

V_d is the direct axis voltage, V_q is the quadrature axis voltage ,i_d is the direct axis current, i_q is the quadratue axis current,, R_s is the stator resistance, φ_d, φ_q are the direct axis and quadrature axis flux linkage respectively, ωe is the electrical speed.

The general equation for the mechanics of the machine is

$$\frac{d\omega_r}{dt} = \frac{T_m - T_e}{J} - \frac{B\omega_r}{J} \quad (11)$$

The mathematical model of PMSG is

$$\frac{di_d}{dt} = -\frac{R_s}{L} i_d + \frac{P}{2} i_q \omega_r - \frac{1}{L} V_d \quad (12)$$

$$\frac{di_q}{dt} = -\frac{R_s}{L} i_q - \frac{P}{2}\left(i_d - \frac{\varphi_m}{L}\right)\omega_r - \frac{1}{L} V_q \quad (13)$$

$$\frac{d\omega_r}{dt} = -\frac{T_m}{J} i_d - \frac{K_t}{J} i_q - \frac{B}{J}\omega_r \quad (14)$$

Where,

L_q = quadrature axis inductance

L_d= direct axis inductance

R_s = Resistance of the stator windings

i_q= quadrature axis current

i_d = direct axis current

v_q = quadrature axis voltage

v_d = direct axis voltage

ω= rotor speed in terms Angular velocity

ψ_a = Amplitude of induced flux

p =Number of pairs of the poles

3. SIMULATION RESULTS AND DISCUSSION

The reactor is connected to micro turbine which in turn is connected with the rotor of PMSG. The PMSG can generate 8.5KVA and stator voltage will be of 400V. We have provided the dc loads with the help of diode rectifier. The simulation circuit is provided in the Fig. 6.

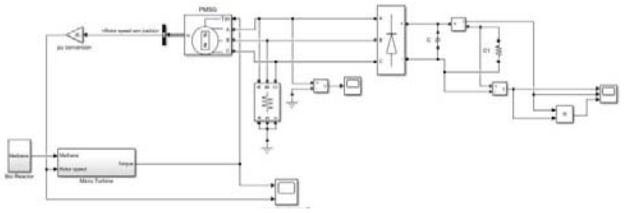

Fig. 6 Simulation circuit diagram for bioreactor based power generation

The reactor intakes the raw substrate feed and generates the methane gas which depends on the type of feed provided to the feeder. The various types of feeder is provided in the following table:

Table 1

Types of feeder with respective biodegradable content[10]

Types of feed	Concentration of biodegradable (kg/m^3)
Swine	0.9
Beef	0.65
Poultry	0.7
Daily Manure	0.36

The simulation circuit for the feeder is shown in the following Fig. 7

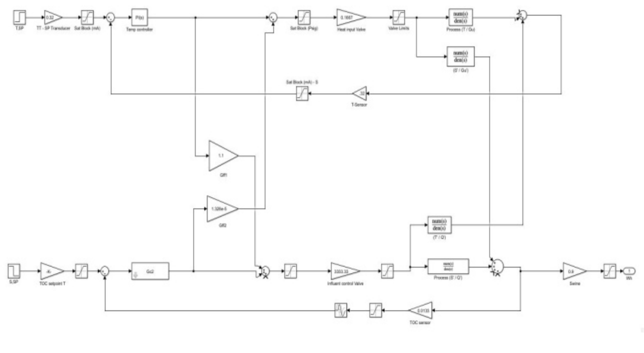

Fig. 7: Simulation circuit for control of bioreactor

In this the reference feed and temperature is provided and the methane gas is to be generated and the rate of flow of the gas depends on the feed volume and temperature. The methane gas generated for different types of feeds at 300^{0}C is shown in Fig. 8.

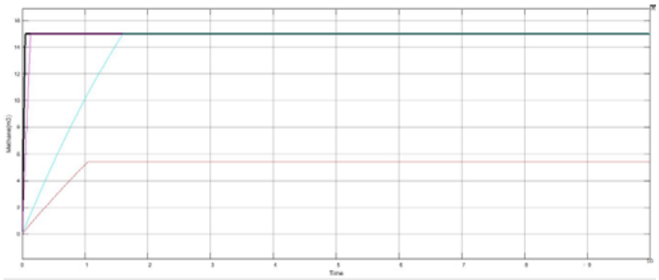

Fig. 8 Methane gas generated for different feeds for 300°C

When the temperature is changed to 100°C, the generation of methane gas is provided as shown in Fig. 9

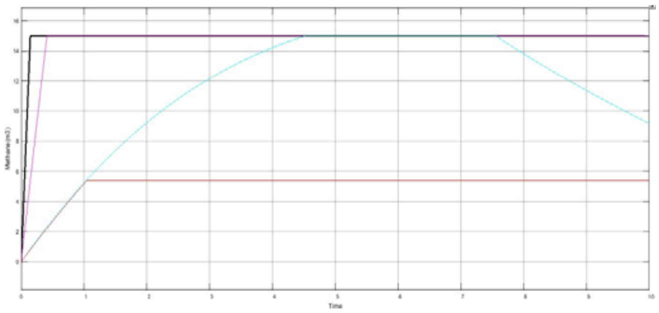

Fig. 9 Methane gas generated for different feeds for change in temperature from 300°C to 100°C

The simulation circuit for the micro turbine is shown in Fig. 10.

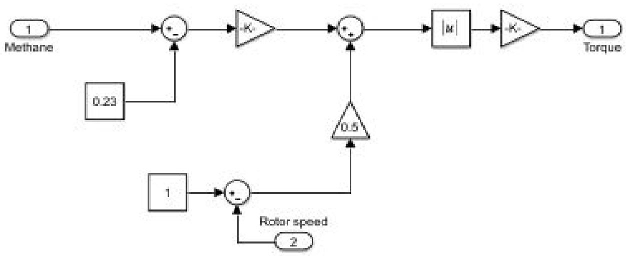

Fig. 10 Simulation circuit diagram for Microturbine

In this as per the rate of flow of methane gas and the generator speed, the torque will be generated which is given to PMSG for power generation.

The torque and generator speed waveforms are given in the following Fig. 11.

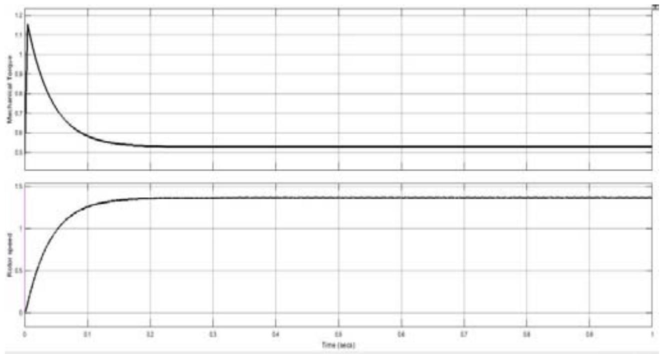

Fig. 11 Torque and speed waveforms for generator

The stator voltage of the PMSG for phase 'A' is provided as shown in Fig. 1

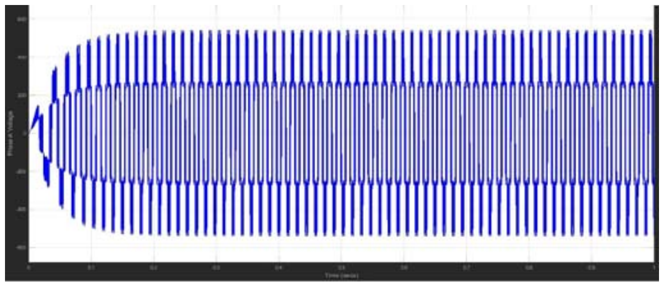

Fig. 11 Stator voltage of PMSG

The dc load parameters are given in the following waveforms as shown in Fig. 12.

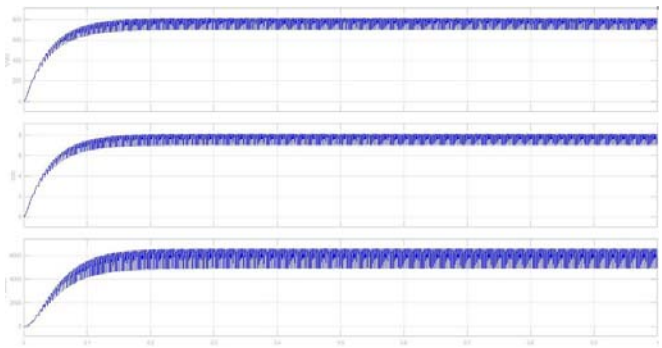

Fig. 12 DC load parameters

The DC load voltage is around 600V and the power generated is around 6KW. It can be further increased up to the rated power which is 8.5KVA by increasing the rate of flow of methane gas which will increase the torque generated by micro turbine.

In this, the load connected is doubled at t=0.5s, then the changes in the load parameter waveforms are shown below in Fig. 13.

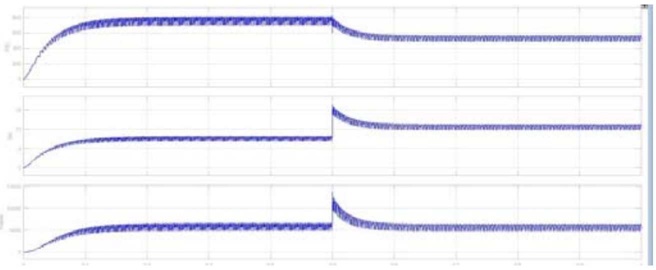

Fig. 13 DC load parameters when additional load is added

Here the dc voltage gets reduced as the power generated is insufficient to the present demands. The speed and torque waveforms are shown in Fig. 14 below after the load gets changed:

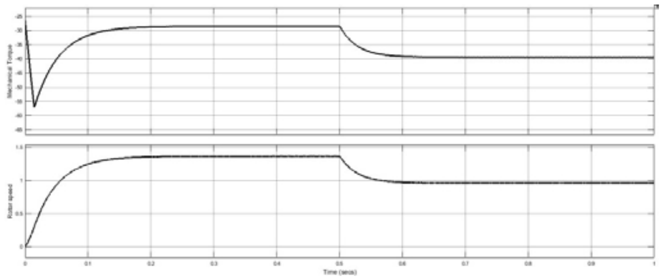

Fig. 14 PMSG speed and torque waveforms with change in load

In future, we can enable to provide the power generation according to the load demand. When the load increased, the consumption of the feed will increase as the rate of flow of methane gas will be increased. The amount of gas generated will be changed along with the load demand. Also we can introduce energy storage systems such as batteries, super capacitors, etc., so we can generate more power when the raw feed is highly available and store excess energy in such devices which can be utilized later.

4. CONCLUSION

A biogas plant model was developed which can provide enough power supply for one or more farmlands in rural areas. The proposed model constitutes of reactor, microturbine and PMSG. The power generated by PMSG was provided to dc loads with the help of rectifier. The performance of the plant is noted under both transient and steady state conditions. Also, the type of feeder and temperature is changed and the respective performance of the reactor and generator is noted down. Sudden load changes are also made and the effectiveness of the generator and the microturbine is tested and the results are noted.

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