DEVELOPMENT OF SMART CONTROLLER MODEL FOR DUAL FUEL GENERATOR SYSTEMS

N. Muchiri[1], P. K. Hinga[2], S. N. Kahiu[3] and S. M. Wanjii[4]
[1]Department of Electrical and Electronic Engineering, Jomo Kenyatta University of Agriculture and Technology, Nairobi
[2]Institute of Energy and Environmental Technology, Jomo Kenyatta University of Agriculture and Technology, Nairobi
[3]Department of mechanical Engineering Jomo Kenyatta University of Agriculture and Technology, Nairobi
Email: nelson.muchiri@students.jkuat.ac.ke

Abstract

Application of dual fuel powered electric generators such as one of diesel and biogas has gained popularity locally both as emergency power supply units and in distributed power systems. Dual fuel generators use two fuel types simultaneously in their operations. This is however faced with challenges in control and fuel regulation since their operation must be economically feasible and convenient. To achieve this, an intelligent controller that regulates generator operations is necessary. This research work, set to determine operation characteristic of these generators and fuel-load relationship of the dual fuel engines in order to design a control system for a dual fuel power generator system. Generator characteristics such as fuel consumption on various loads were obtained through experiments; it was found that injection of biogas in diesel engine saves diesel consumption by approximately 30% on low load and 60% on high load.

The presented model switches the generator when needed and adjusts biogas inlet in steps proportional to the load. It works by monitoring load, injecting a small volume of biogas for loads below 10% and increasing it as the load increases to maximum possible volume for load above 80%. The model was tested through simulation of the obtained data on a Siemens ™ micro Logic controller demonstrating a solution to control challenges. This model logic for control and offers advanced logic electronic control for local applications. It is essential in providing a versatile solution for a middle sized diesel biogas dual fuel power generator control.

1.0 Introduction

Diesel powered electric generators have in the recent past gained popularity locally both as emergency units and in distributed power systems in remote areas. They provide sufficient electric energy to meet power needs for schools, hospitals farms and domestic users. Their application is however faced with cost challenge since diesel is an imported fuel and is expensive. This causes power generated from such units generally costly as compared to power purchased from the national grid whose source is mainly hydro electric and geothermal.

To minimize on fuel cost, a diesel engine can be modified to operate partially on biogas which is a far much cheaper fuel that is locally produced and gives an equivalent power output. Such modified generator systems are suitable for applications in farms institutions and business establishments locally. This study's goal was to determine characteristics of a diesel engine on dual fuel comprising of diesel and biogas in order to design a control system for a dual fuel power generator system. The field work was carried out a dairy farm with such a dual fuel power generators, the findings helped in determination of relationship between fuel usage and electric energy production. A review of previous controllers was made and a model developed to adjust fuels to match load demand and with intelligence to run the generator only on specified times when demand reasonable enough to warrant economical usage.

1.1 Background of the Study

For a successful design of the control system, it was important first to identify from previous research properties of fuels involved with respect to their ability to generate electricity, then identify the properties of electric generators, from this information it was hence possible to develop a controller for one application then modify it to suit the other two.

1.2 Fuel Properties

Power in this case is generated from two fuels, the understanding of their properties is vital in the development of the model thus a review of the exiting literature regarding their properties was made, a brief summary presented.

1.3 Diesel

Diesel is a liquid fossil fuel obtained by the distillation of crude oil. The important properties of diesel fuels are volatility, calorific value, ignition quality/cetane number, viscosity, low-temperature flow, lubricity, storage stability, component compatibility, and sulphur content (Marcus, 1999). Some of their values are as shown on the table1 below (Duc & Wattanavichien, 2007).

Table 6: Diesel properties

Property	Units	Value
Specific gravity	No units	0.82
Cetane index	No units	45-55
Flash point	°C	52
Low Heat Value	kJ/kg	42,500
Calorific value	kJ/L	36240
Carbon residue	wt%	0.01
Water	Vol%	0.05

Among the above properties the fuels calorific value and cetane number are the ones that mainly determine the energy that can be obtained from the fuel. In this case the class of diesel that is locally used has calorific value of 36240kJ/L and its Cetane No is 45 (John Bacha et al, 2007).

1.4 Biogas

Biogas originates from bacteria in the process of biodegradation of organic material under anaerobic (without air) conditions (Thomas Hoerz). It is a clean fuel for internal combustion engines. Essential details of biogas are summarized on table 2 It serves as a promising alternative fuel, for diesel engines, when substituted for a considerable amount of fossil fuels (Duc & Wattanavichien, 2007).

Table 7: Biogas properties

Constituent	Volume	Mass
CO_2	10%-30%	37%
N_2	6.5%	8%
O_2	1.5%	2%
CH_4	60%-80%	52%
H_2S	$\ll$1%	$\ll$1%

The property that determines energy value in biogas is the Methane content; this value for locally produced biogas was found to differ depending on the source (Elmar, et al, 2010). This is illustrated in table 3

Table 8: Methane in Biogas

SOURCE	BIOGAS CONTENT (M^3/TON)	METHANE % IN BIOGAS
Pineapple waste water	375	75
Slaughterhouse waste	340	69
Daily waste water	367	60
Chicken manure	435	63
Vegetable waste	525	55

SOURCE	BIOGAS CONTENT (M^3/TON)	METHANE % IN BIOGAS
Municipal sewage	398	64
Pig manure	525	55

Biogas consist also approximately 40% carbon dioxide and traces of impurities hence it needs to be cleaned before being used in engines to avoid corrosion. This cleaning incorporates removal of Hydrogen Sulphide (H_2S) and of dust, water, halogenated hydrocarbons and siloxanes (A.J. Bruijstens;et al, 2008). The actual energy density of biogas was determined from the percentage methane in biogas. In this study, biogas source was from dairy waste of approximately 60% methane content.

1.5 Dual Fuel Engine

Dual-Fuel engines are engines modified to operate simultaneously on two fuels, they are capable of burning both conventional or heavy fuel oil gas fuel with oil fuel pilot injection and changing over between the two modes of operation when required (Branch, 2007). In this case, diesel fuel is used to ignite the mixture while the majority of the fuel burned is biogas. This allows retention of the diesel efficiency while burning cheap and clean natural gas. Based on their gaseous nature, the gaseous hydrocarbon fuels mix more thoroughly with air oxidizer. This makes them combust more completely, faster and generally at higher temperatures than the liquid hydrocarbon fuels (Huber J. T., 1999). Diesel engines are modified to run on dual fuel either by Low Pressure Injected Gas, High Pressure Injected Gas or Combustion Gas Integration where the gas is introduced with intake combustion air just prior to the turbocharger (Generac Power System inc, p. 2008). Combustion Gas Integration is the most commonly used in the cases of biogas engine since it is economical as modification components costs are minimized. In this case, a control system is essential in order to provide the precision and a response necessary for fuel regulation.

1.6 Biogas injection

Biogas is injected as shown on figure 1

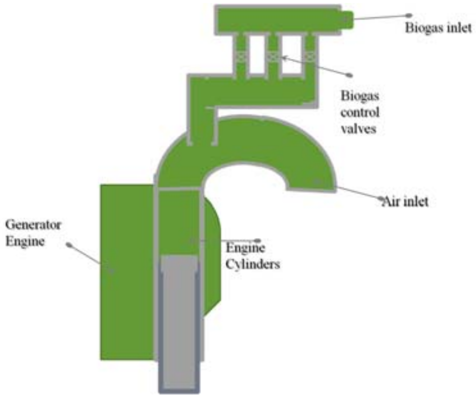


Figure 10 Engine Modification (Generac Power System inc.)

The biogas flow is regulated by three valves where the control system may open one, two or all as programmed. Biogas is injected based on the load being driven. Studies were conducted to determine fuel cost when running generator on dual fuel and running various loads, results are as tabulated on table A1 (appendix) and load-fuel relationship developed as shown below.

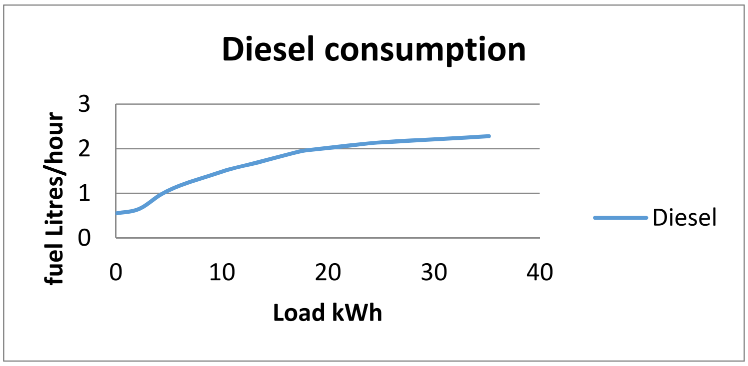


Figure 11: Fuel usage over time(source appendix A1))

At low loads, only a small percentage can be substituted, while at high load more gas is added. So the cost per kWh reduces as load size increases, this is compared with the cost of purchase of power from the grid in order to determine the economic operation range as shown below.

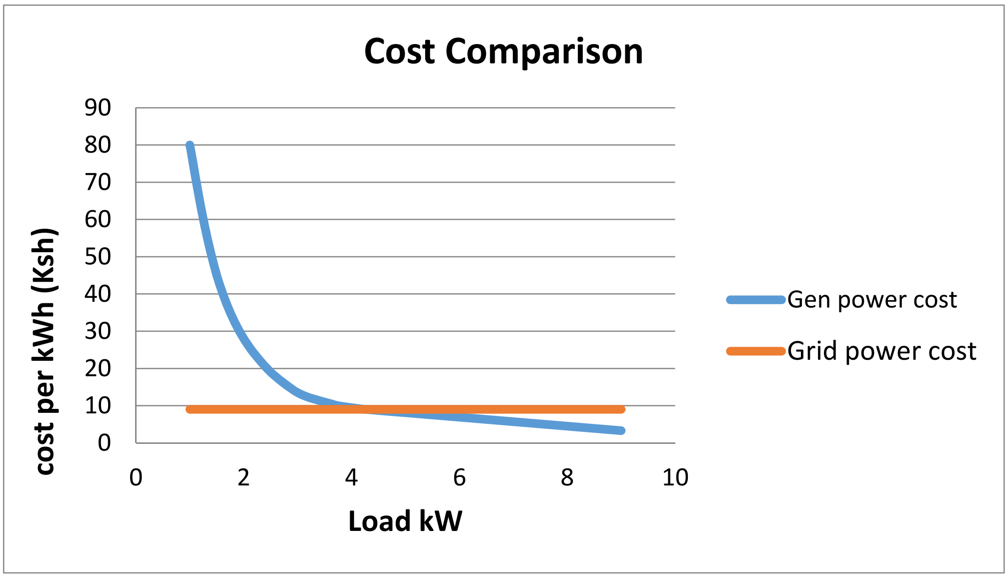


Figure 12 Cost compare (source (Elmar,et al, 2010))

From above graph it is only viable to operate the generator for loads over 5kW. This is achieved by use of a control system.

1.7 Dual Fuel Engine Control

Various inventions have been applied to control dual fuel engines, some have shown that there is also a minimum amount of diesel necessary for good operation of the engine, at low loads it is best to use about three times as much diesel as gas (Wering etal, 1981). As load increases, it is important to increase the amount of gas so that at full load the gas used is about three times diesel used. This is possible through valve and control system design that increases the biogas 16 times faster than diesel. More recent designs come with governing circuit that evaluates the engine parameters and automatically regulates the fuel ratio (Huber J. T., ,1999).

Early developments provided an automatic control system for diesel dual fuel internal combustion engine for gas and liquid fuel, comprising liquid fuel flow rate control, and gaseous fuel flow rate control means, the liquid fuel and gaseous fuel flow rate control means being adapted to control the relative proportions of each fuel supplied to the engine, and permitting the relative proportion of liquid fuel to be varied in a range (Smith, ,1987).

A recent innovation provided a dual fuel control system for use with an internal combustion engine. It has a throttle mechanism for controlling flow of liquid fuel, air/fuel mixer means for mixing liquid fuel flowing to the engine with air and gaseous fuel controlling means for the flow of gaseous fuel to the engine (J.Davis, ,1999). Another innovation by Huber uses engine oil pressure to control the engine dual fuel based on relays, timers and current sensors (Huber J. T., 1999). The innovation utilizes a current transformer for load measurement and diesel control valves for fuel control.

Several other related monitoring and control technologies for dual-fuel engines have been made such as a patent issued to Bedford, et al. which described control of dual-fuel injection rates by computerized control in response to fuel pressure (Bedford etal, 1986). Basing on existence of such systems, a more versatile system can be developed to use affordable techniques and meet the desired results. This forms the ground for the design. The innovation utilizes a relation between the speed and the fuel ratios for optimization. Whereas the named innovations above worked based on engines with speed variations, for engines used for power generators the speeds are constant, since they are synchronous (Laughton & Warne, ,2003). Speed is related to frequency and should remain constant; variation on loads hence leads to variation of fuel intake to maintain other parameters constant. This forms a basis of a design of a load based fuel regulation for generators

1.8 Control System Design

There exist several designs for monitoring and controlling dual-fuel engines, but none with the effectiveness, reliability and low cost made possible by this invention. Such control technologies include direct injection of second fuel in diesel-engine cylinders separately timed. Rotation based actuator controlled where gaseous and liquid fuel conveyed to an internal-combustion engine in response to a sensor of rotational speed, and a dual fuel control system based on current sensor (Huber J. T., 1999) (Bedford etal, 1986).

This design seeks to improve the already existing monitoring and control systems, by adding intelligence in to the design. This includes a mechanism that actuates, varies, terminates and reactivates fumigation of a biogas fuel in response to predetermined generator load and demand times. To achieve these, a study is carried out on an existing plant to determine exact dual fuelling parameters and demand sequence.

2.0 Methodology

A performance study was carried out on a dual fuel generator set in a dairy farm. The generator was made to run on diesel fuel under various electrical loads, then run on a combination of diesel and biogas as explained in the following sections.

2.1 Experimental Set-up

2.1.1 Single Fuel Test

To determine the amount of biogas for a load, experiments were conducted as follows. The generator was made to run under no load for one hour and diesel fuel consumption (idle mode) noted as D_i. The energy equivalence (E_e) of the diesel consumed in one hour was calculated using equation (1)

$$E_e = D_i \times E_d \qquad (1)$$

Where E_d is Energy density of diesel; 36.4 MJ/litre ≈ 10.192kWh/litre

From the test, D_i was found to be 1000ml.

It is hence deduced that the engine consumes 1litre per hour when running on diesel only, the energy from diesel fuel to drive the engine on idle mode is therefore 10.192kWh and this can be illustrated diagrammatically as follows

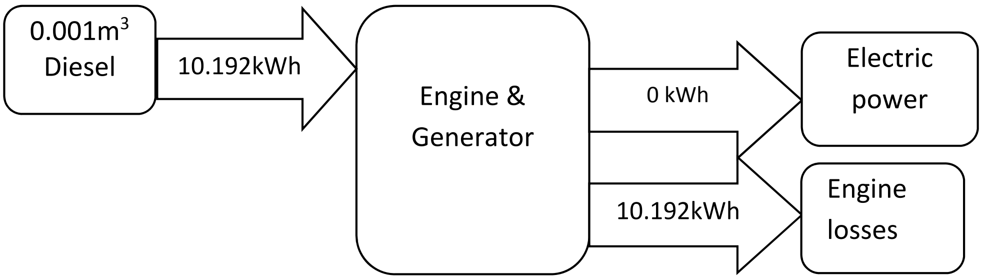


Figure 13: Energy flow for single fuel idle test

Figure 4 above shows the energy source for the generator and the energy destinations where the entire energy is drawn from diesel fuel and is lost in engine functions since no electric power is produced.

2.1.2 Dual Fuel Test

The same experiment was carried out when running on dual fuel. Excessive biogas was supplied with all valves opened manually and the effective gas at no load was determined from the energy density of biogas. Methane (CH_4) is the combustible component of biogas and the determinant factor of its energy value. From table 3 the methane content of biogas used when conducting the tests from daily waste water is approximately 60%. Methane has energy density of 39.820MJ/m^3 (equivalent to 11.06kWh/m^3) :The energy content of biogas from dairy waste E_b is therefore expressed using equation 2

$$E_b \, {}^{60}\!/_{100} \times 11.06 = 6.64kWh/m^3 \quad \text{……(2)}$$

When on dual fuel under no load, it was found that the engine consumed much less diesel that is 720ml (0.00072m^3) per one hour therefore regardless of the biogas supply being excessive, the engine only takes in a small percentage, called effective biogas (B_E), this is determined by first determining the energy from 720ml diesel (D_E) calculated using equation 3 below,

$$D_E = \frac{720}{1000} \times 10.19 = 7.34kWh \quad \text{……(3)}$$

Since the engine has no load its energy consumption remains the same at 10.19kWh. Energy drawn from biogas is determined using equation 4 below,

$$E_B = E_D - D_E = 3.57 \text{ kWh} \quad (4)$$

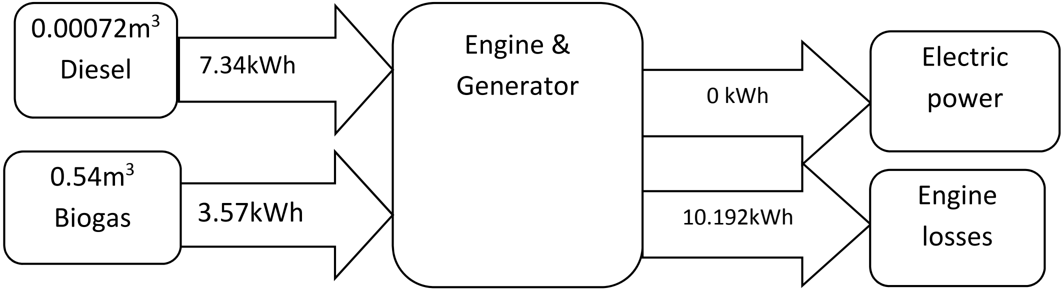


Figure 14: Energy flow on Dual fuel

Given that 1m^3 of biogas has 6.64kWh energy, 3.57kWh of energy is from 0.54m^3. This is illustrated diagrammatically in figure 5.

As illustrated in figure 4 the first valve is designed to allow flow Q of approximately 0.6m^3per hour to cater for no load condition and low load conditions. This is possible by setting an appropriate pipe diameter. This was determined experimentally and supported by calculations from equations of gas flow under constant pressure.

$$Q=C\frac{T_b}{P_b}D^{2.5}e\left(\frac{P_1^2-P_2^2}{LGT_aZf}\right)^5 \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (5)$$

For general flow of gas where gas precision is not of much concern like this application, the equation (5) is simplified to equation (6) (Schroeder, ,2001).

$$Q=1350D^{2.5}\left(\frac{P_1^2-P_2^2}{LG}\right)^5 \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(6)$$

Where Q is flow rate m^3/hr, D is pipe diameter m, P_1 and P_2 is inlet pressure and outlet pressure respectively, G is gas specific gravity and L is pipe length.

The experiments were repeated on increasing loads. Electric loads of known ratings were connected to the generator in order to determine effective biogas intake. It was found that as the load was increased, the effective biogas intake increased. To meet this condition, the design demanded an additional solenoid valve to allow more flow of biogas as load increased therefore VALVE2 and VALVE3 were included in the design for medium loads and high loads respectively. The valves were interconnected as shown in figure 6 below

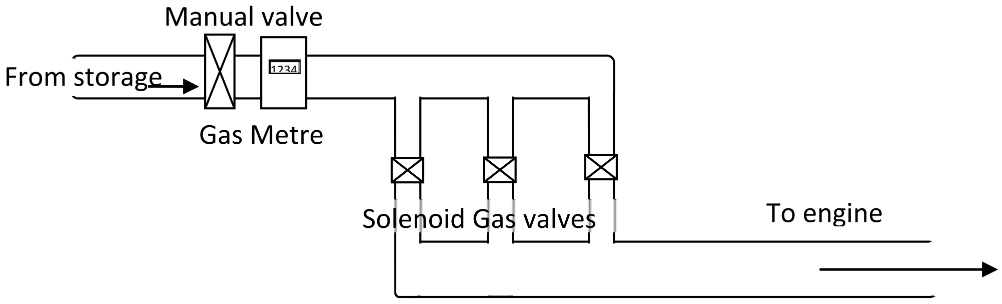


Figure 6: Valves Arrangement

The valves included in the design are electronically actuated in a sequence so as to regulate biogas as the load increases in a pattern shown in table 4.

Table 9: Biogas control look-up Table

Valves	**Maximum gas flow(m^3/hr)**	**Load size(kWh)**
Valve 1	1	0-5
Valve 1&2	2	5-10
Valve 1,2&3	3	10-15

From table 4 it is seen that the fuel ratio changes as the load increases. By drawing more energy from biogas as the load increases, the engine reduces the diesel intake hence saves on operational costs as shown in table 5

Table 5 Fuel consumption characteristics

Load	Rated value kW	Average Diesel per minute (ml)	
		Single fuel	Dual fuel
Zero	0	16	9.6
Low	2	18	10.9
High	11	41.2	28

The controller comes in handy to regulate the fuels. Further case studies were carried out to determine when it is important to run the generator.

2.2 Case Studies and Design

The dual fuel engine was applied in a dairy farm; the results provided in this paper are for a middle sized dairy farm for operation of some farm machinery, such as chaff cutter milking machine and water pump. Data regarding demand patterns was collected and presented in a load curve in figure 7.

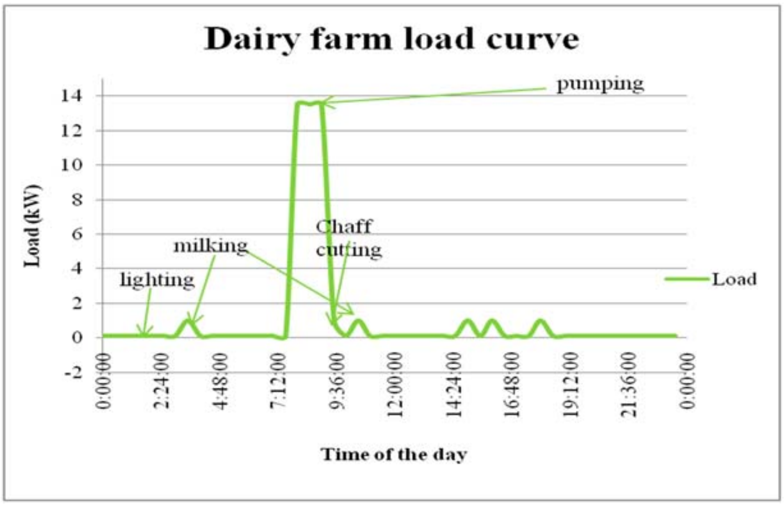


Figure 15: Farm power pattern

From figure 7, it is observed that power is demanded in low quantities over short period of times. The controller is made to switch on and off the generator at the times required.

Studies were conducted in order to determine when it is economically viable to operate the generator. Under low load, it is cheaper to use grid power which in this case costs Ksh 9 per kWh. At some load, it is possible to substitute more of diesel fuel with biogas up to a point that the total cost of production of power is less than purchase from grid. The controller is designed to switch on and off the generator system at times; this is illustrated in figure 8.

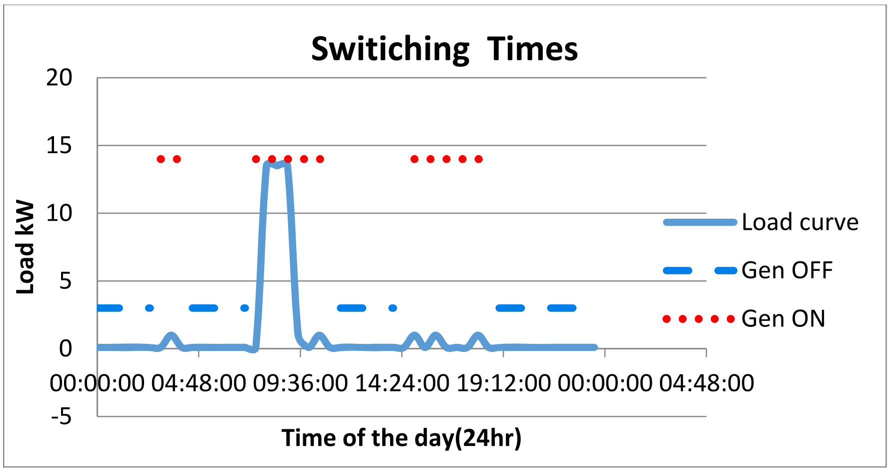


Figure 16 switching curve

From figure 8, the generator is only switched when the demand is higher than 1kWh.

2.3 The Controller model

To meet the requirements above, versatile, dynamic and reliable equipment are essential. The model was designed in a way that it can be easily embedded to the existing dual fuel systems. The choice of the control hardware was made based on;

i. Low power equipment,
ii. Handy equipment and not affected by field,
iii. They are also easy to modify,
iv. User friendly,

The design is could be Relay & timer based controller, Computer based, microcontroller based or PLC (Programmable Logic Controller) based. The PLC based control was preferred for the following reasons.

i. Low cost ; since it is only one component (low cost Siemens PLC logo™)
ii. Versatility; software based control algorithm.
iii. Adaptable to generator; powered using 12V dc from the generator battery.

It is then implanted on the existing dual fuel generator control panel.

(i) Sensor Mechanism

Diesel generator panel Comprises a voltage & current measurement equipment. From this, power can be effectively monitored and analysed using equations 7 below

$$P = \sqrt{3} VI \cos\theta \qquad (7)$$

Where P is power, V is for voltage and I for current and *cos ϑ* the power factor. For example, when running a load of say 6kW and power factor of 0.8 and 415 Volts, equation 7 indicates that the panel current reading is 10.5 Amps as shown in equation 8.

$$I = \frac{P}{\sqrt{3}V\cos\theta} = \frac{6000}{\sqrt{3}\times 415\times 0.8} = 10.45 \qquad (8)$$

The generator is designed to give a constant voltage; hence current is directly proportional to power. Generator phase current is measured using current transformers, as shown in the arrangement in figure 9.

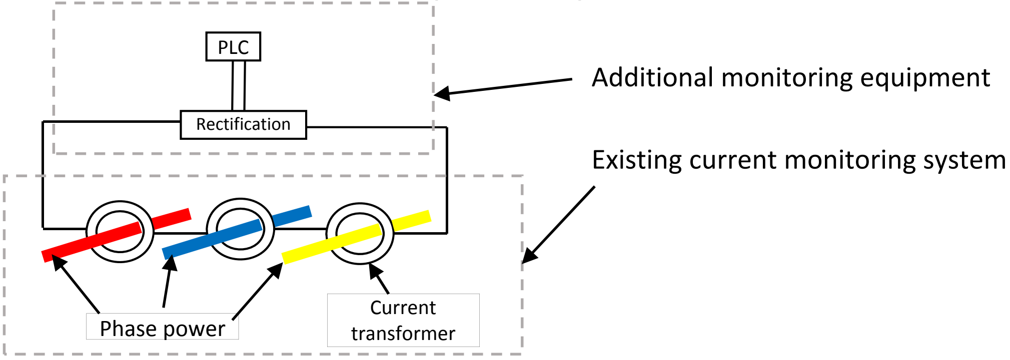


Figure 17: Current Measurement Setup

The current transformer has a primary coil which takes the high current from generator output produces a proportional small output in the secondary coil which is then rectified then summed to give a 0-20mA output which is taken as the input to the PLC.

(ii) Control Mechanism

Once the current signal is fed to the PLC, an action is taken by the program in figure 10 that regulates biogas. The program was written using function block diagrams, one of the programming languages of IEC 1131-3(international standard for PLC programming) whose details are summarized in Table A2 in the appendix.

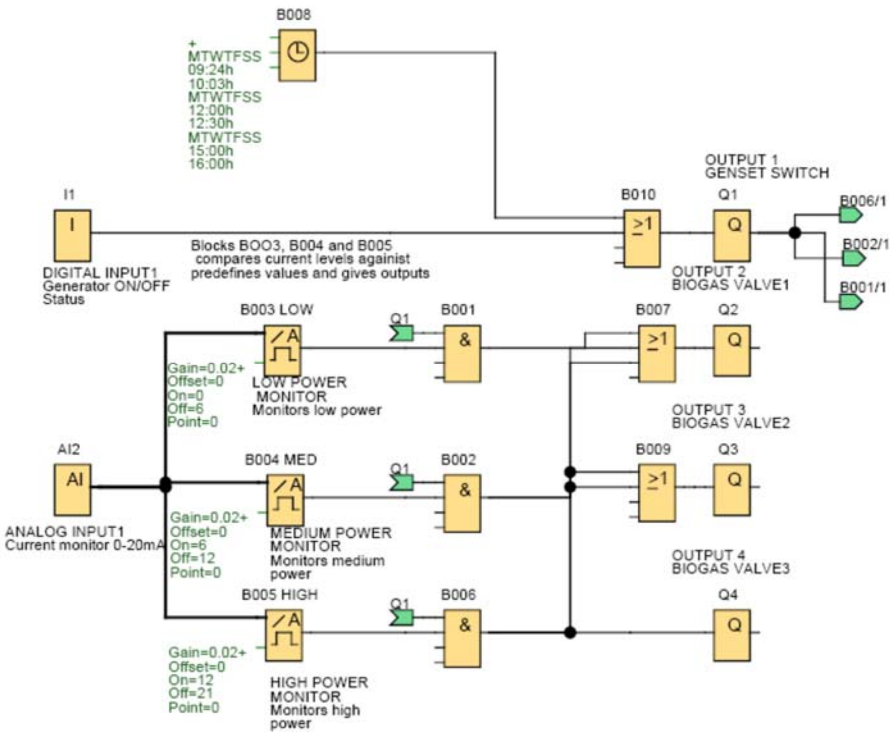


Figure 18: Logic Program for Control

The software is based on simple function blocks of a program that can be modified on site. It can be varied as the application change from one generator to another The program’s function blocks in figure 10 performs the operations from left to right where the inputs to the program are on the left and the outputs are on the right. Block I1 and B008 are input blocks that determines the generator switching through output Q1.

Blocks B010, B007, B009 and B001, B0002, and B006 perform the logic operations, while Blocks Q1- Q4 give an output to the generator & valves. B003 monitor low loads while B004 and B005 monitors medium and high loads respectively. The chevron shaped blocks labelled Q1 shows a linkage of their location to output Q1.

The controller consequently feeds the biogas step-wise based on the level of demand by the generator as in figure 11.

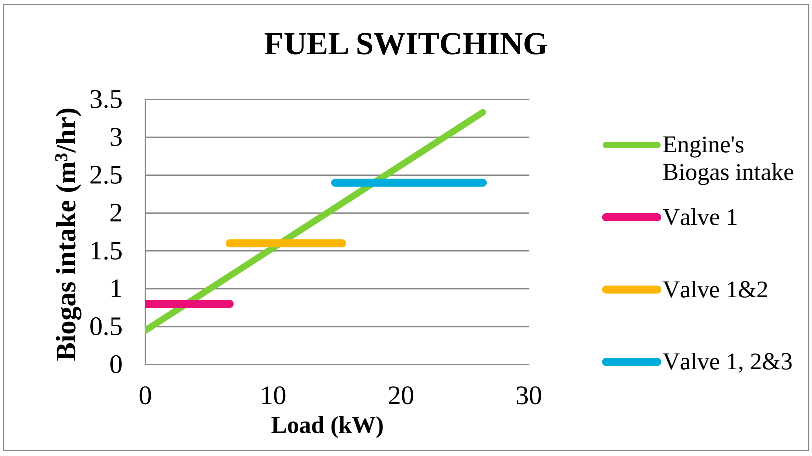


Figure 19: Fuel Feeding Sequence

The diagonal line shows the gas intake by the engine while the horizontal lines show biogas delivery stepwise using valves.

(iii) Actuator Mechanism

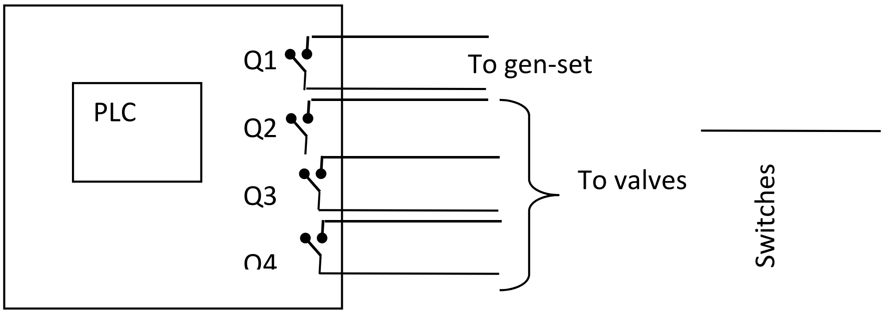
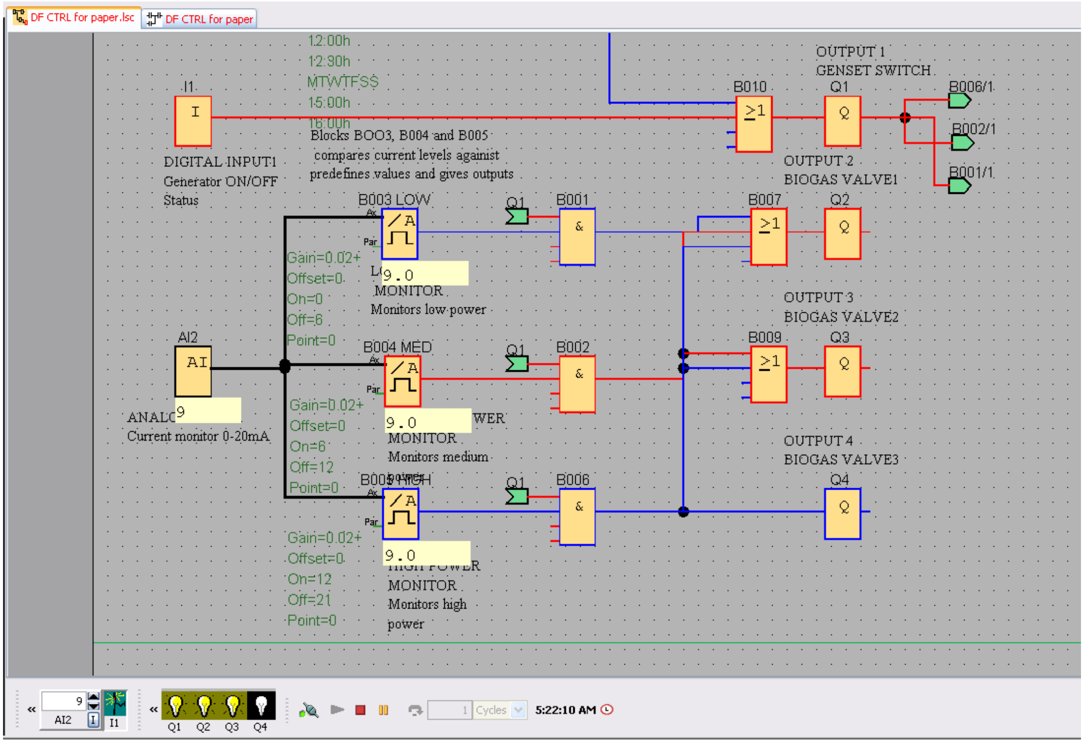


Figure 20: PLC Connections

Based on the inference of the controller, the system actuates gas control valves using relay switches; this is illustrated in figure 12.

3.0 Discussions

The model's program was tested by using various load which imitate actual loads on site, the program's response was monitored in real time using a computer, the snapshot on figure 14 shows a sample response when running a load of 9kW.



Blocks BOO3, B004 and B005 compares current levels againist predefines values and gives outputs

Gain=0.02+
Offset=0
On=0
Off=6
Point=0

Gain=0.02+
Offset=0
On=6
Off=12
Point=0

Gain=0.02+
Offset=0
On=12
Off=21
Point=0

Figure 21 Snapshot of the program when running

It was observed from figure 11 that 9kW, fall within the medium range, the program's simulation snapshot shows the medium load monitor active. This causes the logic block B002 to actuate outputs Q2 and Q3 hence opening valves V1 and V2 just as the design prescription on table 4. Comparing this output with the existing manual control, this form of automated controller provides a convenient way of generator control and fuel regulation.

4.0 Conclusion

Characteristics of dual fuel diesel engines were successfully studied; Challenges faced in manual control were established. It was found that injection of biogas in diesel engine saves diesel consumption by about 30% on low load and 60% on high load. The work's further findings showed variation of biogas-diesel ratio on different loads and different routine power demands for different applications. A design of an intelligent controller as a solution to control challenges is developed. The presented model switches the generator when needed and adjusts biogas inlet in steps proportional to the load. It works by monitoring load, injecting a small volume of biogas for loads below 10% and increasing it as the load increases to maximum possible volume for load above 80%.

A model of automatic controller was developed and tested through simulation proved effective in engine control. It applies Fuzzy logic algorithm for control and offers advanced logic electronic control for local applications. Control functions are enhanced and costs of operation minimized since the single component (PLC) replaces human operators and is field adjustable to suit applications in-case of changes.

This and other findings may be implemented on a wide scale and facilitate the development of a local mechanism that uses diesel as a pilot fuel and biogas as substitute fuel. This is to provide affordable electrical power for remote locations especially rural areas and for emergency power supply units.

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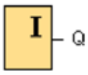
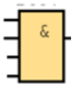
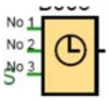
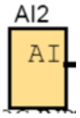
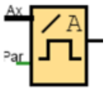
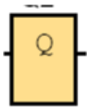
Appendix

Table a1: load- fuel relationship for a diesel power generator[1]

LOAD (kW)	**DIESEL** (L/hr)
0	0.55
2.2	0.65
4.4	0.995
6.6	1.2225
8.8	1.39
11	1.5575
13.2	1.68
15.4	1.82
17.6	1.95
19.8	2.01
22	2.07
24.2	2.13
26.4	2.16
28.6	2.19
30.8	2.22
33	2.25
35.2	2.28

[1] generator tested using purely resistive load and diesel class from the local supplies

Table A2: Control Blocks Description

Block symbol	**Block name**	**Function**
	Digital Input	Takes the input of the PLC as a Hi or a Low
	AND	Gives a HI when all inputs are HI
	OR	Gives a HI when any of inputs are HI
	Weekly Timer	Has a 24 hour clock and days of the week. The block executes a Hi on the specified times of the week.
	Analogue input	Takes in current of 0-20mA and has adjustable gain
	Analogue threshold trigger	Gives an output of hi when the input is within a programmed range
	Output	Give a digital output that is indicated on the hardware of the PLC