An Experimental Investigation Leading To Design Of Bi-Fuel System

Mirza Muhammad Amir, Dr. Roz Halliwell, Ashad Mustafa

Abstract: Since the beginning of time, energy has pervaded our earth. We rely on it to advance in any development. As the energy sources become scarcer, it is important to learn how to save and economize energy. A perfect energy should be cheap and efficient. Bi-Fuel system is such a concept, which combines the best of Diesel and Gas driven engines. Diesel driven engines though provide high power density but own the drawback of high cost and high on-site fuel storage. Gas driven engines provide low cost but own the drawback of low power density. A Bi-Fuel system is Compression ignited engine, which runs on the simultaneous combustion of Diesel and Natural gas. It works by introducing gas to the engine via various technologies and then electronically controlling flow dependent on output. This greatly extends the runtimes and limits the amount of diesel fuel that must be stored on site. This research work is about Bi-Fuel system and all this is intended to reflect this idea, whose time has come!

Index Terms: Bi-Fuel System, Compression Ignited Engine, Diesel and gas, Extended runtimes, Simultaneous Combustion.

1 Introduction

Can Diesel engine work on the simultaneous combustion of natural gas and diesel without effecting overall engine performance [1]? What is the benefit of doing it? Well off course, it definitely worths doing so, since natural gas is much cheaper than diesel and burns cleaner than diesel due to having inherently low carbon content [2]. Diesel although excellent in output power density but requires large quantity of it to be stored on site, which requires maintenance to prevent contamination and degradation [1]. Hurricanes and storms closing roads add up further to the extra disadvantages like refueling infrastructure and most importantly the high cost of diesel fuel forces to replace the diesel generators by natural gas generators [1]. Natural gas generators although a big solution to problems like high cost, refueling, on-site fuel storage and so but has a big drawback of low power density output. To overcome these problems, there must be some third energy alternative, which removes the drawbacks of both diesel and natural gas generators and still produces power density like diesel and owns the cost like natural gas.

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2 LITERATURE REVIEW

Since the beginning of time, energy has pervaded our earth. Starting from the discovery of fire to the discovery of nuclear energy, the changes in the fundamental sources of energy have evolved human society. Weather it is environment, economy, transportation or whatever in short, energy has been playing a central and fundamental role as a dimension of this evolution, which implies that these evolved societies will last as long as these sources will. Because almost all the current energy sources will last at some point of time, the future of this human society is in danger, until new and renewable sources of energy are discovered. Besides discovering these sources of energy, it is also necessary how to conserve energy i.e. how to save and economize energy. A perfect energy should be cheap and efficient i.e. it should produce maximum possible power or power density at a cost of minimum possible power resource consumed. In universe, there are two classes of energy i.e. potential energy and kinetic energy. The kinetic energy is the energy, which any body possess due to its motion i.e. amount of work required to bring a change in the state of rest or of motion [3]. The potential energy, on the other hand, is either due to its position or the arrangement of the particles of the system [4]. In the universe, the nature is such that kinetic energy is required to be achieved from some sources whereas energy is stored as potential energy. There are so many sources of energy, which have their potential content vary with its type. Fuel is one of the important sources, which stores potential energy and this potential energy can be converted to kinetic energy through the process of combustion [5]. There are various types of fuels. Some are naturally occurring and other are extracted through some process from the primary natural sources of energy [6]. The fuel can be solid, liquid or gaseous as illustrated in the table [6].

Table 1- Types of Fuel [6]

	Primary (Natural)	Secondary (Artificial)
Solid Fuel	Wood, Coal, Peat, Dung etc	Coke, Charcoal
Liquid Fuel	Petroleum	Diesel, Gasoline, Kerosene, LPG, CNG
Gaseous Fuel	Natural Gas	Hydrogen, propane, Coal Gas, Water Gas, CNG etc

All these types of sources differ in their chemical content of energy and are used according to the application. For industrial applications, two types of fuels are used that is either natural gas or diesel to produce power. Both diesel and natural gas have their advantages and disadvantages over each other, which obligate a need of third alternative for industrial applications to produce power. Petrol is not a choice due to its high cost. Hence diesel and/or natural gas must be used in such a way so as to achieve the desired results free of any major drawbacks. To achieve a task, let's start by looking at how the four strokes diesel and natural gas engine works [7].

2.1 Natural Gas Vs Diesel Engine

A natural gas is 'Spark Ignited Engine', whereas diesel engine is 'Compression Ignited Engine [7]. The reason lies in the strokes of engine as follows:

Inlet Stroke: In natural gas engine, the mixture of natural gas/ air is in taken through the inlet valve whereas in diesel engine, there is intake of only air [7].

Compression Stroke: In natural gas engine, the mixture is compressed to $1/8^{th}$ to $1/12^{th}$ of its original size whereas in diesel engine, the air is compressed to $1/14^{th}$ to $1/25^{th}$ of its original size [7].

Power Stroke: At peak compression in natural gas engine, spark plug provides a spark igniting the mixture. This causes the piston to go back down whereas in diesel engine at peak compression, the temperature reaches 1000F in combustion chamber, while diesel ignition temperature is 500-700F. When diesel is sprayed at this point, it ignites without spark plug because of high degree of compression temperature [7].

Exhaust Stroke: The burnt mixture of air and fuel is pushed out of the cylinder in both diesel and natural gas engine [7].

Since diesel engine requires high compression ratio, therefore thick cylinders, heavy pistons, rods and valves are used [8], [9]. This is the reason why diesel engine produces more torque and thus able to do more work on piston producing more power and thus more powerful than natural gas engine. The natural gas takes time to give its energy to the piston and thus gives it slower and slower as the piston moves towards the end of power stroke [8], [9]. Since power is the rate of energy extracted;

$$Power = EnergyExtracted / Time \quad [10] \qquad (1)$$

Hence natural gas engines are not able to produce enough power as diesel engines. To extract more power out of it, half used gas is needed to be expelled out and fresh one is needed to be in taken but this would reduce the efficiency of the engine [8], [9]. Whether it is natural gas or diesel, when combustion takes place, work is done on the piston of cylinder. The rate of this work done by the fuel on the piston is called the **Indicated Power** of the engine and is given by;

$$P_i = P_e ALNn \quad [11] \qquad (2)$$

(Where P_e is the mean effective pressure, A is the area of piston; L is the length of displacement, N is the revolutions per minute and n is the number of cylinders [11]. For four strokes engine N=1/2) [11]. Most of the fuel energy is wasted as heat [12]. The indicated power is the energy present in combustion chamber after these

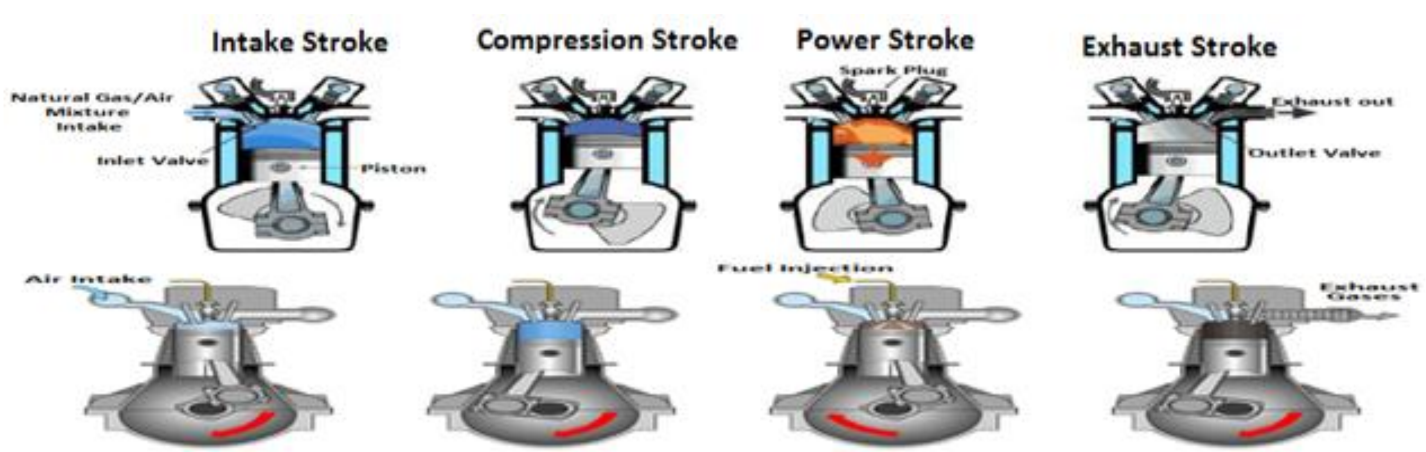


Fig.1. Four Strokes of Natural Gas Engine (Up) versus Diesel Engine (down) [7]

losses [12]. The power output of an engine is always less than the indicated power because of friction [12]. The mechanical power of an engine is given by;

$$P_m = \tau\omega \quad [13] \quad (3)$$

(Where τ is the torque on rotor and ω the angular velocity of rotor) [13]. The frictional losses are the difference between the indicated power in the combustion chamber and the output mechanical power produced by it;

$$P_f = P_i - P_m \quad [11] \quad (4)$$

The mechanical efficiency of an engine is the ratio between the output mechanical power to the indicated power inside the engine;

$$\eta_m = P_m / P_i \quad [12] \quad (5)$$

It is around 80% to 90% [11]. The overall fuel conversion efficiency i.e. the mechanical output power produced by the engine per amount of fuel consumed is given by;

$$\eta_{bt} = Mechanical Energy / Fuel Energy \quad [11] \quad (6)$$

Where η_{bt} is called the brake thermal efficiency or simply the thermal efficiency of an engine;

$$\eta_{bt} = P_m / m_f * Q_{net.V} \quad [11] \quad (7)$$

Where m_f is the mass of fuel consumed per unit time and $Q_{net.V}$ is the calorific value or the chemical energy of fuel [11]. In the Internal Combustion Chamber of an engine, it is the adiabatic process that takes place, according to which all the change in internal energy of the system is consumed in doing work plus losses i.e. the more of fuel energy is converted to mechanical work (mechanical energy) the more will be the efficiency of the engine [14], [15]. The following equation explains it why;

$$W = K(V_1^{1-r} - V_2^{1-r})/1-r \quad [9] \quad (8)$$
$$\because r = C_P / C_V$$

Where C_P is the molar specific heat of gas at constant pressure, C_V is the molar specific heat of gas at constant volume and K is a constant. V_1 and V_2 are the volume of gas at the start and at the end of compression respectively. Because in diesel engine, the gas is compressed to much larger level as compared to natural gas engine, the difference of V_1 and V_2 is larger and therefore more heat energy of fuel is converted to mechanical work [9]. Therefore thermal efficiency of diesel engine can be up to 40% but that of natural gas is less than 25% [16]. Natural gas has volumetric energy density 25% of diesel [16], [17].

2.2 Electrical Load To Fuel Relation

Since in electric generator, the electric power is the output and chemical power of the fuel is the input, therefore relating them to each other in certain steps as follows:-

Step-1:
As demand for electric power increases due to increase of load I_L;

$$P_{electrical} = \sqrt{3} V_L I_L \cos\phi \quad [13] \quad (9)$$

(Where V_L is the line voltage and cos∅ is the power factor). The result is a step-2

Step-2:

I. V_L drops due to drop in magnetic field produced by field coil. This drop in magnetic field is due to the drop in field coil current as explained by Lenz's law.
II. f (frequency) drops due to the drop in the speed of the rotor (*n*) since;

$$f = \eta P/120 \quad [18] \quad 10)$$

(Where *P* are the poles of the generator). The rotor speed drops due to the opposing force applied by armature coil field. This force is given by;

$$F = BIL \sin\theta \quad (11)$$

(Where B is the magnetic field produced by armature coil current, I is the current flowing through field coil and L is the length of field coil. θ is the angle between B and L). The voltage at generator terminals is given by;

$$V_L = \sqrt{3} V_{ind} \quad [18] \quad (12)$$

(Where V_{ind} is the voltage induced in each of armature coil).

$$\because V_{ind} = NB\omega A \quad [18]$$

(Where N is the number of turns of armature coil, B is the magnetic field produced by field coil; A is the area of armature coil and ω is the angular velocity of the rotor).

$$\Rightarrow V_L = \sqrt{3} NB(2\pi f)A$$
$$\Rightarrow V_L = (2\pi\sqrt{3}NA)Bf$$

2π√3NA = Constant (For a given generator)

$$\Rightarrow V_L = (Constant)Bf$$

Step-3:
Governor increases the fuel supply i.e. mass flow rate m_f of fuel is increased. The fuel power is given by;

$$P_{fuel} = m_f * Q_{net.V} = P_{chemical} \quad [12] \quad (13)$$

This increases the mechanical power output since;

$$P_{mechanical} = P_{fuel} - P_{losses} \quad [12] \quad (14)$$
$$\because P_{losses} = P_{friction} + P_{heat} + P_{incomplete combustion}$$

The increase of mechanical power increases torque to maintain speed of rotor and thus frequency brought back to the constant value as in "(3)";

$$P_{mechanical} = \tau\omega \quad [13]$$

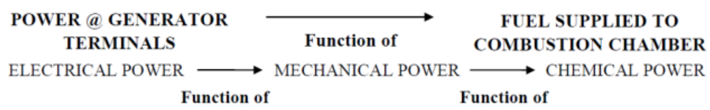
That's how constant frequency is produced.

AVR (Automatic Voltage Regulator) feeds more current to the field coil to bring back the magnetic field of field coil to a constant value by overcoming the opposing force of magnetic field produced by load current. Since;

$$V_L = (Constant)\ Bf$$

- *B* brought back to a constant value by AVR
- *f* brought back to a constant value by Governor.

That is how constant voltage at generator terminals is produced and that's how:



Hence finally;

$$P_{electrical} = P_{mechanical} - P_{loss}(mech) - P_{loss}(elect) \quad [19] \quad (15)$$
$$P_{mechanical} = P_{Chemical} - P_{loss}(chem) \quad [12] \quad (16)$$

Combining (15) and (16);

$$P_{electrical} = P_{chemical} - P_{loss}(elect) - P_{loss}(mech) - P_{loss}(chem)$$
$$\because P_{loss}(total) = P_{loss}(elect) + P_{loss}(mech) + P_{loss}(chem)$$

Where;

$P_{loss}(elec) = P$(field+armature+eddy+hysteresis+brushes)[19] (17)
$P_{loss}(mech) = P$(windage + bearing) [19] (18)
$P_{loss}(chem) = P$(heat + incomplete combustion) [12] (19)

Hence;

$$\Rightarrow P_{electrical} = P_{chemical} - P_{loss}(total)$$

Using (9) and (13);

$$\Rightarrow (\sqrt{3}V_L \cos\phi) I_L = m_f . Q_{net.V} - P_{loss}(total)$$
$$\Rightarrow \text{(Constant) } I_L = m_f . \text{(Constant)} - \text{(Constant)}$$

Hence; m_f (mass of fuel consumed) $\propto$ I_L (Load)

2.3 Existing Technologies

The existing Bi-Fuel control technologies involve an electronic control unit that intercepts with the ADEM (Advance Diesel Engine Management) using a software [20]. The ECU communicates with the ADEM and issues signals for the diesel injectors to spray diesel of specific quantity at specific time [20]. At the same time, the ECU also sends signals to the natural gas injectors based on charge air temperature [17]. Fuel mapping is done as according to the following graph to select the best ratio of two fuels [1]. Fuel mapping allows the best combination of efficiency and exhaust gases emissions [17],[21].

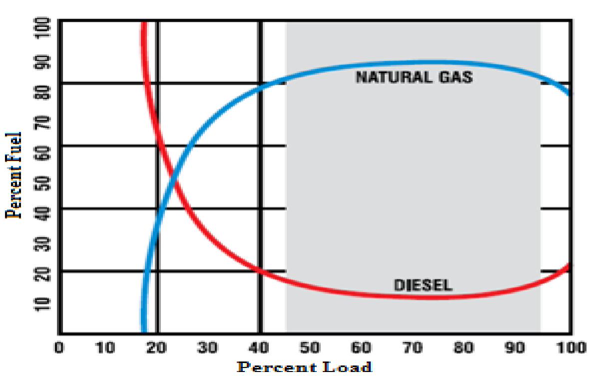


Fig.2. Fuel Usage as % of Load [1]

The main drawback of this technology is that it bypasses the governor of the engine which may result in either self destructing the engine due to over speed or not being able to handle the load due to slow speed in case if Bi-Fuel malfunctions.

3 METHODOLOGY

3.1 Evolution of Bi-Fuel Concept

Natural gas when compressed in combustion chamber requires spark from spark plug at peak compression as its ignition temperature is 1150-1200F [1]. In combustion chamber of diesel engine, temperature reaches 1000F, while diesel ignition temperature is 500-700F, so diesel itself works as a spark source [1]. So why not use diesel as an ignition source for natural gas! This is the basic idea or concept behind Bi-Fuel system.

3.2 Bi-Fuel System

To design a control, it is necessary to first analyze the physical phenomenon and realize what are physical or process requirements. The next phase is to determine what control technique and sensors are required to fulfill the requirements. As according to the idea, diesel has to work as an ignition source for natural gas, requires that the engine should be 'Compression-Ignited Engine'. Since diesel ignition temperature is 500-700F and natural gas ignition temperature is 1150-1200F and at peak compression in diesel engine, the temperature reaches 1000F, therefore after installing Bi-Fuel System, the engine works on diesel alone as well but not alone on natural gas [1]. Keeping these things in consideration, there is no need to do almost any modification in the diesel generator but only have to install Bi-fuel system externally. Even when generator works solely on diesel, it maintains its constant output voltage and frequency. This is because of diesel engine **'Governor'.** To maintain the constant rotor speed, the governor varies the amount of diesel fuel. Since in this case, natural gas is also entered, the amount of diesel fuel required to maintain the rotor speed will be reduced.

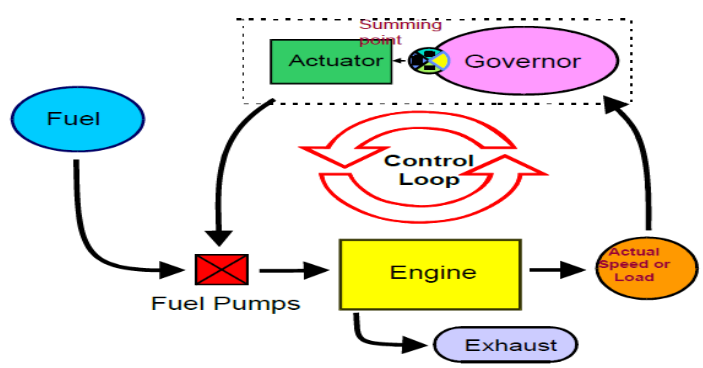


Fig.3. Governor Control [22]

Because the governor maintains the constant rotor speed hence constant output frequency is produced as in "(10)";

$$N = 120 f / P \quad [18]$$

Because of constant frequency, constant output voltage is produced since;

$$V_{rms} = 4.44NBfA \ [18] \quad (20)$$

Where V_{rms} is the effective output voltage of generator, N is the number of turns of armature coil (constant), A is the area of armature coil (constant) and B is the magnetic field produced by field coil wound around rotor (B is kept constant by AVR i.e. Automatic Voltage Regulator). Since governor and AVR together makes sure of constant and stable generator output, therefore all that is required is to control the amount of natural gas being supplied. The idea is to keep natural gas at insufficient levels to let governor utilize diesel in order to fulfill the load fuel requirements. The natural gas must therefore enter at normal gas distribution pressure (14kPa) and at the rate of 8scfh/kW [2]. The pressure regulator maintains this required pressure.

$$P = F/A \quad [23] \qquad (21)$$

Where P is the pressure of gas, F is the force applied by gas on per unit area and A is the area of pressure regulator through which gas flows. But;

$$F = ma \quad [23] \qquad (22)$$

Combining (21) and (22);

$$P = ma/A \qquad (23)$$

Since P is fixed at 2psi, it is area of gas that the regulator varies with the variation in the mass of gas through regulator to maintain the pressure at 14kPa. How much gas needs to enter combustion chamber? Off course the electronic control unit takes this decision on the basis of load feedback from the alternator. A set of five valves is used. This set has one inlet and one outlet and between this inlet and outlet are five valves that can be fully open or close. The gas enters the valves through the inlet and from outlet, it enters into the engine i.e. gas supply is proportional to the number of valves opened.

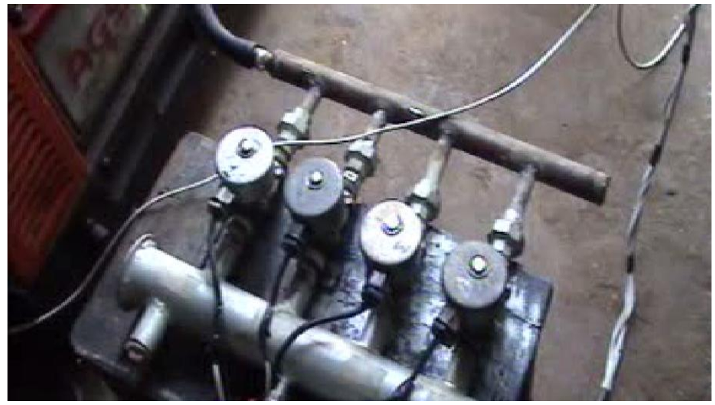


Fig.4. Gas control Valves

The gas after coming out of control valves is then mixed with air. Air contains oxygen. Any fuel cannot be ignited without oxygen. Therefore oxygen entering the chamber must be adequate to ignite fuel properly. The mixture is passed through

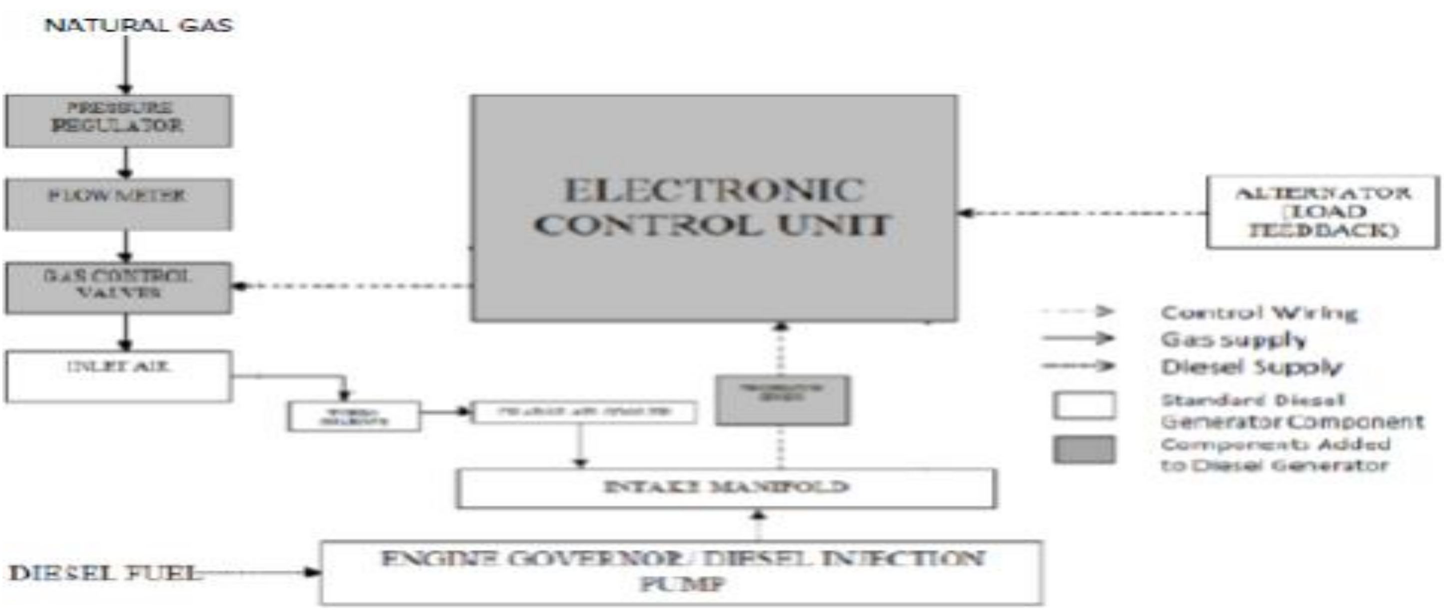


Fig.5. Block Diagram of Bi-Fuel System

the turbocharger. The turbocharger increases the mass of air entering the chamber, which increases the efficiency [24]. The mixture then enters charge air cooler for isochoric cooling [18]. This cooling makes the mixture denser because according to Charles Law:

$$V \propto T \quad [23]$$

Where V is the volume and T is the temperature of gas and since;

$$D = m/V \quad [23] \qquad (24)$$

Where D is the density and m is the mass of gas. Hence as T decreases due to cooling, V also decreases and as V decreases, D increases making the gas denser. The benefit of making the gas denser is that more air and fuel is combusted per engine cycle and that increases the output power of the engine [25]. The temperature feedback using a temperature controller is employed, so that in case of engine temperature going above a specified value of engine, the electronic control unit immediately cuts off the gas supply to the valves and the Bi-Fuel operation is shut off to shift it to diesel only mode.

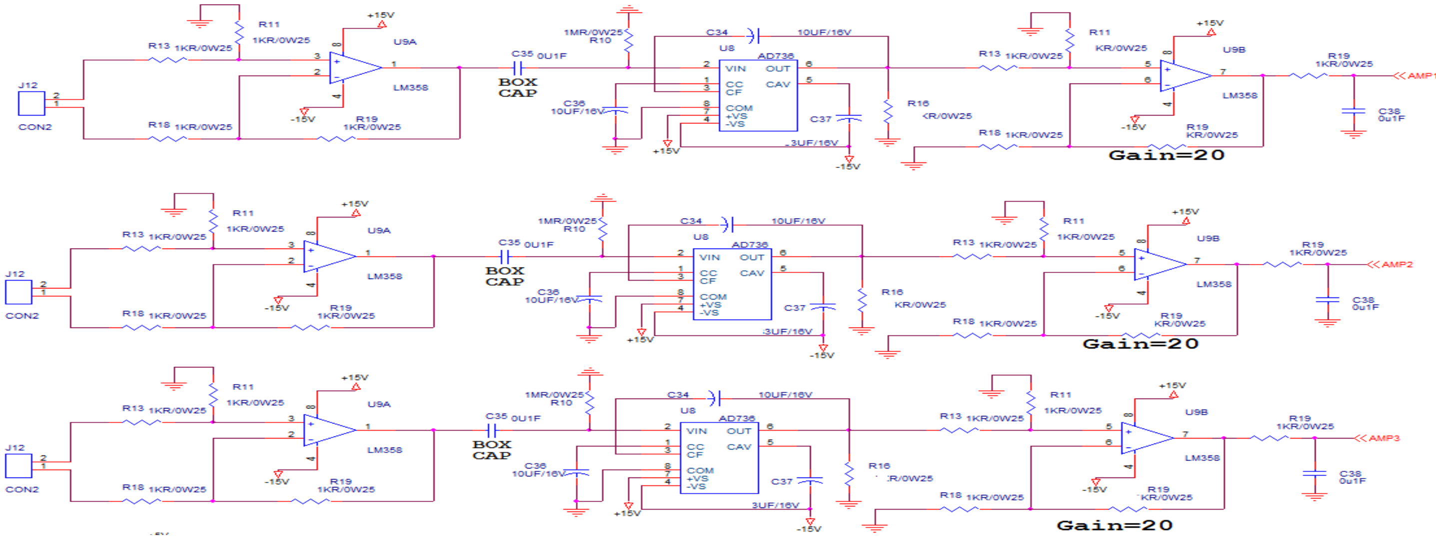


Fig.6. Schematic for 3 Phase AC Input

3.3 The Electronic Control Unit (ECU)

The electronic control unit of Bi-Fuel system is an electronic card, whose central control unit is 8051 microcontroller. The inputs and outputs of ECU are as follows:-

- **Inputs**
  - AC Phase 1 Load (Analog)
  - AC Phase 2 Load (Analog)
  - AC Phase 3 Load (Analog)
  - Temperature of Engine (Digital)
- **Outputs**
  - Gas Valve 1 (Digital)
  - Gas Valve 2 (Digital)
  - Gas Valve 3 (Digital)
  - Gas Valve 4 (Digital)
  - Gas Valve 5 (Digital)

3.4 Design and Function

Since the inputs to the ECU are three phase load currents and temperature of engine, the following design has been made for the input of AC current. As illustrated in the circuit diagram, there are three connectors each for three phases. The connectors are connected to the output of CTs (Current Transformer). The actual load current of the generator is an input to the CT. Since the current is too much to be sensed by the electronic circuit, hence it is scaled down using CTs. The output of a CT is 0 to 5 Amperes. In parallel to each connector, is connected a 0.1`Ω resistor, so that a current of 1A becomes a 0.1V for the connector and so on. Hence with the variation of load, phase current will vary producing 0 to 0.5V as a load input to the ECU. This 0 to 0.5V at a connector is an input to a non-inverting OpApm stage. The non-inverting opAmp stage resistor values are so selected to have a gain of 2. Hence at the output of this opAmp stage, the AC voltage will vary from 0 to 1V, which is then input to rms-to-dc converter. The rms-to-dc converter converts the AC voltage to true RMS-DC voltage, so that it can be measured. For example a $1V_{peak}$ produces $0.707V_{rms}$ at its output. Therefore with the variation of 0 to $1V_{peak}$ at the input of AD736, the output of 0 to $0.707V_{rms}$ is produced at its output, which is then input to the other non-inverting op-Amp stage with a gain of 20. This stage of op-Amp then produces 0 to 14.14V at its output. Since this is the output for each of the three phases of the generator and they must be converted from analog to digital before inputting them to microcontroller, hence these inputs are inputted to ADC i.e. AD574A. since there are three such analog inputs and ADC can only convert one at a time, hence multiplexer IC 4051 is used as shown in the figure 6.

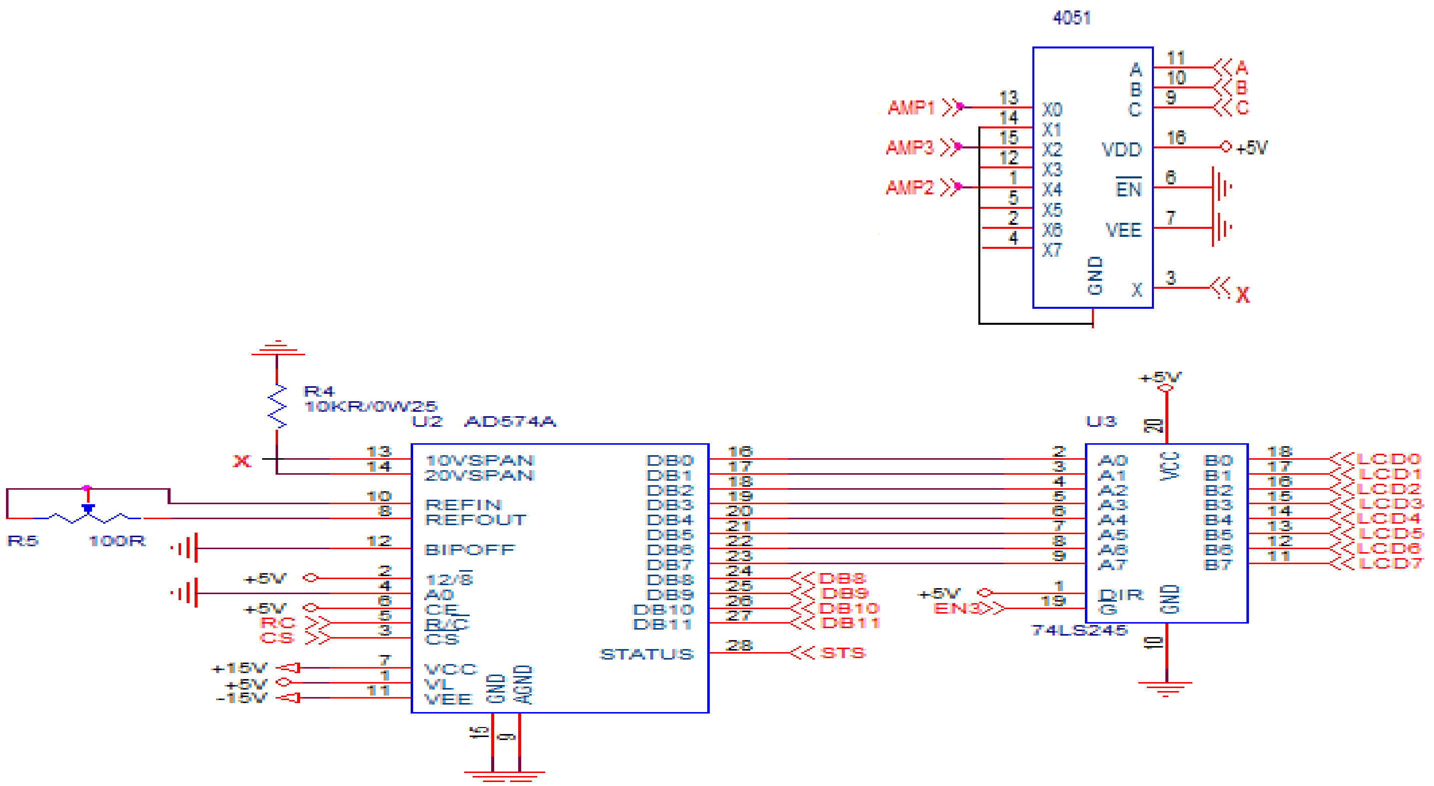


Fig.7. Multiplexer Connections

The X0, X2 and X4 inputs of multiplexer are used for inputting AMP1, AMP2 and AMP3, which are the outputs of previous op-Amp stage and represent respectively the three phase's currents. Since X0, X2 and X4 corresponds to the values of A, B, C (The input selecting bits of multiplexer with C as most significant bit) as 000,010 and 100 i.e. A is always 0, hence it is grounded and only B and C inputs are controlled by microcontroller to select the three analog inputs to be inputted to ADC (one at a time) for conversion via the output X of the multiplexer. Referring to figure 7, the R/C pin is an input pin to ADC. To convert the analog input to digital out, microcontroller must send a 'Low' signal to it and for reading the digital output; microcontroller must send a 'High' signal to it. The status pin is the output pin of ADC and an input pin to microcontroller to let microcontroller know the status of conversion i.e. whether the analog input has been converted to the digital output or not. The ADC produces a 12-bit digital output. The 4 MSB bits are directly inputted to microcontroller, whereas other 8 bits are inputted to microcontroller through an octal bus transceiver IC i.e. 74245, so that the same pins of microcontroller can be used to input the ADC output as well as to the data bits of LCD. The microcontroller only reads these 8 bits of ADC digital output, when it sends a 'Low' signal to pin#19 of 74245, which is an input to 74245 because this pin is 'Output Enable' pin of 74245. The other input to the ECU is from temperature controller. The temperature controller senses the engine temperature using the PT100 temperature sensor. The output of the temperature controller is its normally open and normally closed contacts. These contacts with the common contact are connected to the connector of ECU as shown in figure 8.

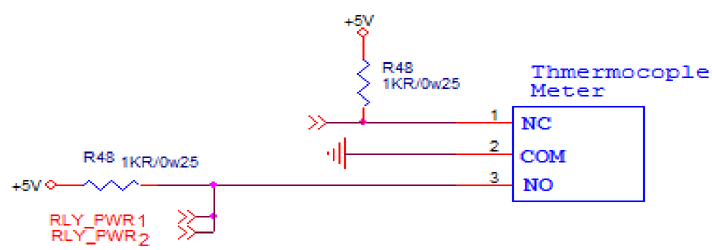


Fig.9. Temperature Controller Contacts Connection to ECU

The temperature as set on temperature controller is 518∘ F. therefore unless temperature of the engine does not reach 518∘ F, the normally open contacts of temperature controller are closed and normally close are open. When the engine temperature reaches 518∘ F, through the contacts of temperature controller, the two relays mounted on ECU are energized and through the contacts of these relays, the 220V supply is provided to the gas control valves. Hence even if microcontroller keeps on outputting the signals to activate the gas control valves, they will not be activated since their supply is through the contacts of these relays i.e. temperature controller works in parallel to the microcontroller for the safety purposes.

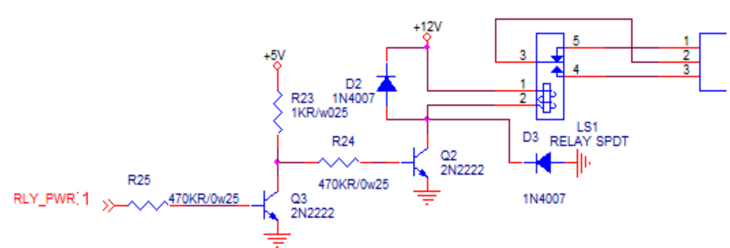


Fig.10. Schematic for Driving Gas Valve Supply Relay 1

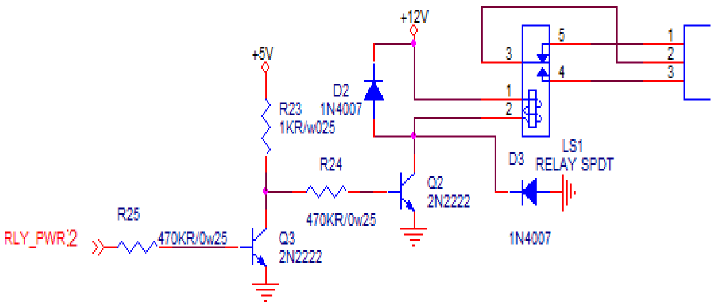


Fig.11. Schematic for Driving Gas Valve Supply Relay 2

The load current of each phase and the total 3 phase load current is continuously displayed on LCD.

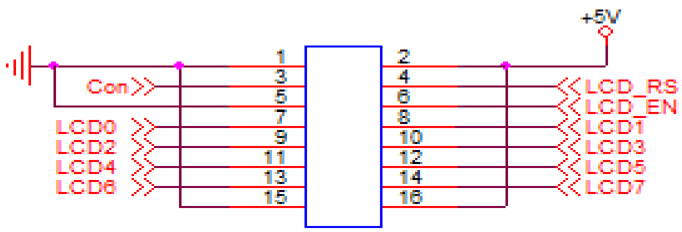


Fig.12. LCD Connector Connections

The data bits of LCD are LCD0 to LCD7, which are connected to the microcontroller. The LCD_RS pin is for selecting the command or data needed to be sent to the LCD. LCD_EN pin is an input pin for LCD. The microcontroller must send a high to low pulse to LCD_RS pin to send a data on its ports to the LCD. The "Con" is an input for LCD to control its display using a potentiometer as shown in figure 12. The outputs of ECU are for controlling five 220V gas control valves. As mentioned earlier, the 220V supply of these

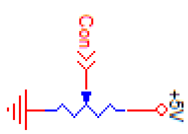


Fig.13. LCD Display Control

valves is through the contacts of RLY_PWR 1 and RLY_PWR 2. Each of this relay supply 220V to two gas valves each. Every gas valve is connected to any of these two relay's contacts through one relay RLY_1, RLY_2, RLY_3, RLY_4 or RLY_5 each. If the temperature of the engine is more than 518∘ F (518F), then each of the five valves are dependent on RLY_1, RLY_2, RLY_3, RLY_4 or RLY_5 to vary the gas flow to the engine. The design to drive each of these five relays through the output of microcontroller is given as under. Two npn transistors are used for driving each relay since microcontroller output current is not enough to drive these relays, hence pair of transistors increases the current, so that relay can be driven through the output of microcontroller. Since all of these are npn transistors, hence valves are operated on the active low outputs of microcontroller. The ECU can work with diesel generator of any power rating with a little change in the hardware and software. The change in the hardware is the size of current transformer and the change in the software is the amount of load current on which each gas valve should operate. Since this circuit is tested on 350 KVA generators, whose per phase load current is around 500A, hence 500/5 CTs are used. The total three phase load can thus be up to 1500A. The Bi-Fuel operation starts only when at least 10% of the load is accepted by the generator so as to avoid a probability of over speeding the engine. For 350 KVA generators, the 10% load is 150A. Hence as the load is at least 150A, the microcontroller outputs a 'Low' signal at RLY_1. Thus gas valve 1 is opened allowing gas to enter the combustion chamber and thus Bi-Fuel operation starts.

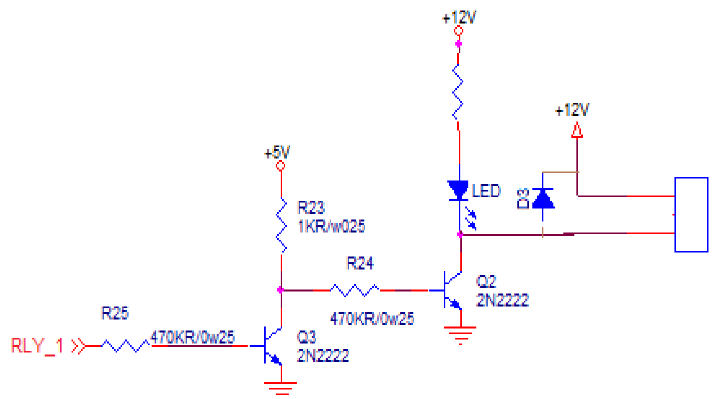


Fig.14. Schematic for Driving Gas Valve Control Relay 1

To keep the Bi-Fuel operation smooth and for the sake of safety, the next gas valve is opened only after the other 100A load is accepted by the generator that is when total load accepted by the generator is 250A. When the total load is at least 400A, the microcontroller outputs a 'Low' signal at RLY_3 to open the gas valve 3.

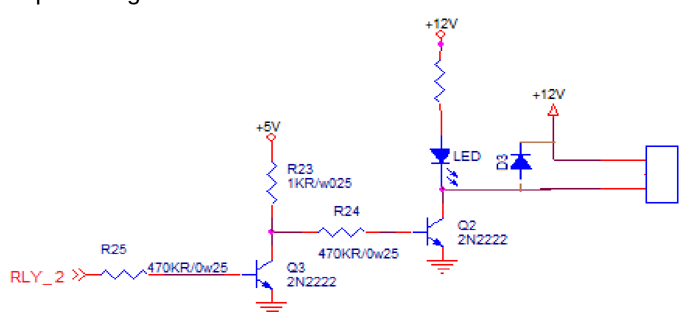


Fig.15. Schematic for Driving Gas Valve Control Relay 2

Remember the amount of gas supplied to the generator according to the load is minimum and rest of the fuel requirement to handle the load is fulfilled by diesel, which is varied by the mechanical governor to keep the engine frequency constant at 50Hz.

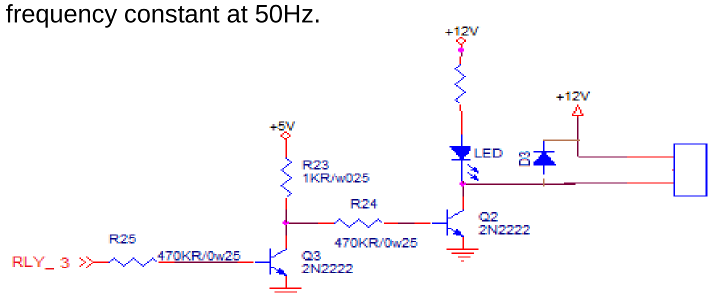


Fig.16. Schematic for Driving Gas Valve Control Relay 3

Other than gas Valve 2, all the gas valves are opened on every 10% of the load accepted by the generator. therefore when the total load accepted by the generator is 550A, the gas valve 4 is opened to increase the gas supply.

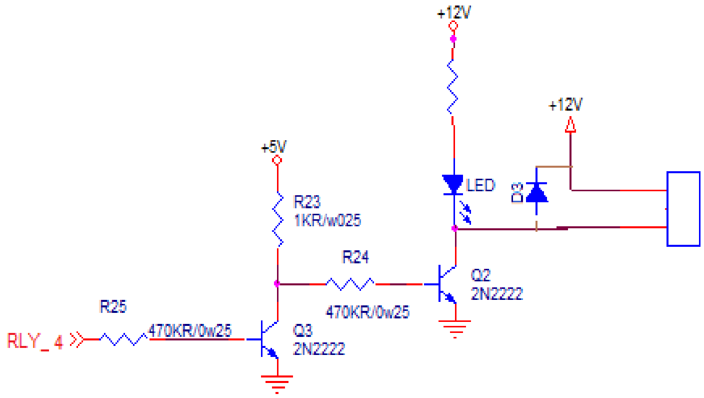


Fig.17. Schematic for Driving Gas Valve Control Relay 4

The last gas valve (gas valve 5) is opened when the total load accepted by the generator is at least 700A, all the gas valves are opened, and that is, maximum amount of gas is being supplied. Further increase in load only increases diesel fuel supply by the governor of the engine.

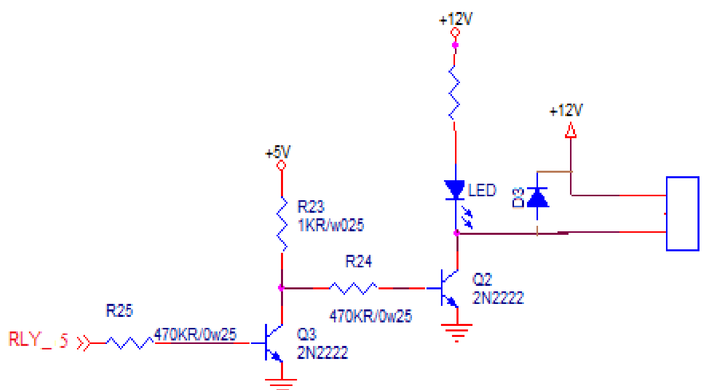


Fig.18. Schematic for Driving Gas Valve Control Relay 5

The following schematic shows the connection of microcontroller with all the circuit and design explained above in this section. It completes the hardware design of Bi-Fuel. The crystal oscillator is 11.0592MHz oscillator used to provide clock pulse to the microcontroller. The Bi-Fuel process as explained is then controlled by the source code, written in C language and its Hex file is burnt into the ROM of microcontroller. The code is written using KIEL software and simulated using OrCAD software.

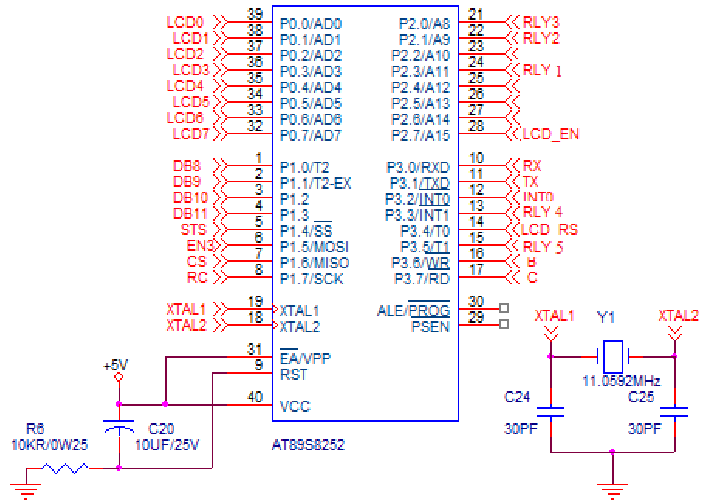


Fig.19. Schematic for Microcontroller Connections

3.5 Bi-Fuel Operation

Initially, all gas valve control relays are deactivated. Then two operations take place simultaneously at all the time as indicated in the following flowchart. One operation is this, that the temperature of the engine is continuously monitored. If the temperature of the engine is above 518∘ F, the gas valve supply relays are activated otherwise deactivated. The other operation is to control the valve control relays and display the load on LCD. To make this operation happen, multiplexer selects only one phase at a time, then conversion of AC signal to DC takes place followed by conversion of analog DC to a digital count using RMS-to-DC converter and ADC

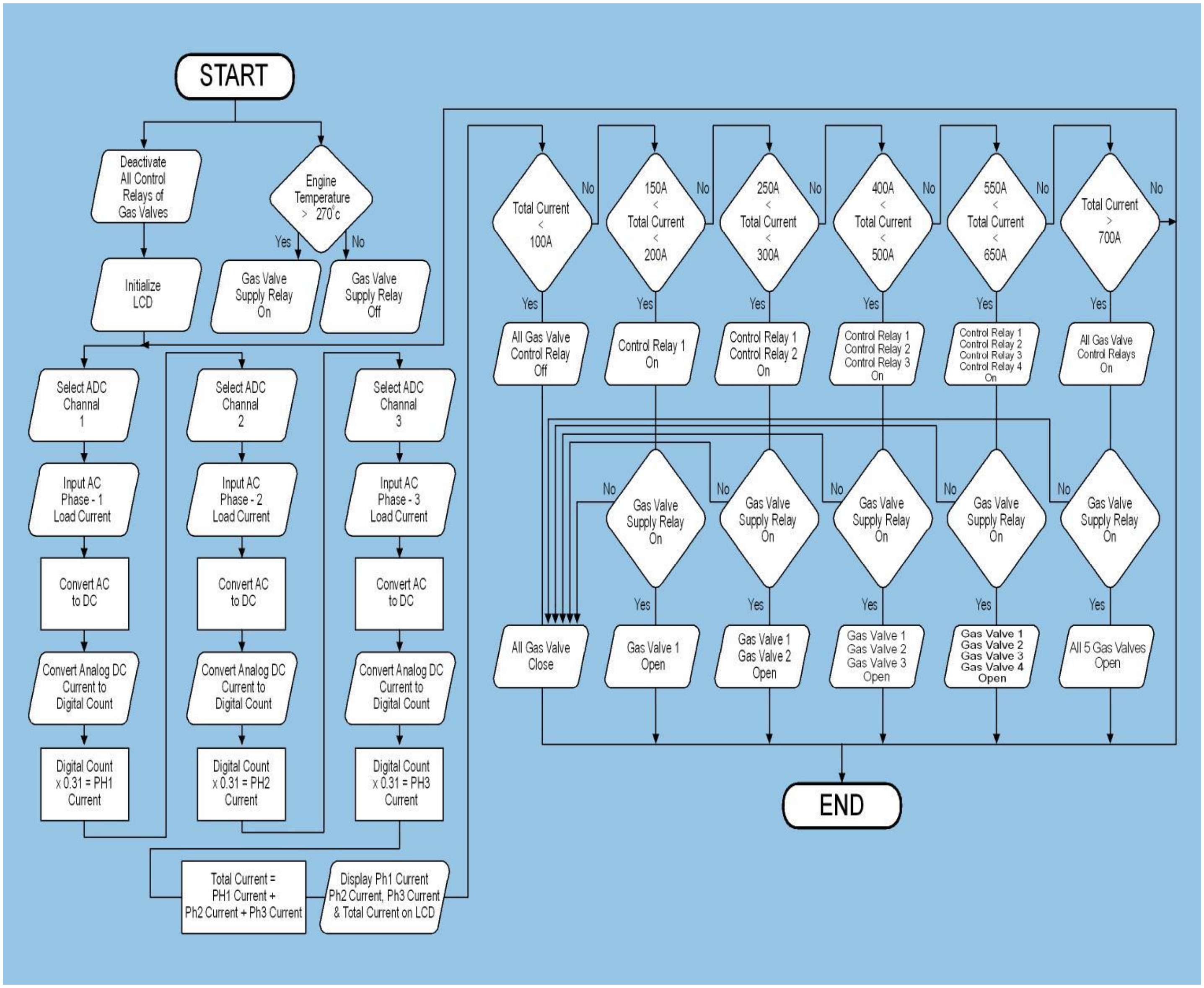


Fig.20. of Bi-Fuel system Operation

respectively. The digital count is multiplied by a constant to get actual load current value. Then same steps repeat for AC phase 2 and AC phase 3 as well, when multiplexer select those phases one after another. Then total load current is calculated by taking the sum of all three phase currents. The individual and total load current values are displayed on LCD. The decision of activating the control relays are taken on the basis of total load current. If the current is then 100A, no control relay is activated and if it is more than 700A, all five control relays are activated. If current is more than 150A and less than 200A, control relay 1 is activated. If total current is more than 250A but less than 300A, two control relays are activated. If total current is more than 400A but less than 500A, three control relays are activated. If the total load current is more than 550A but less than 650A, four control relays are activated. If valve supply relays are on, then on the activation of control relay 1, control relay 2, control relay 3, control relay 4, and control relay 5, the gas valve 1, gas valve 2, gas valve 3, gas valve 4, and gas valve 5 are opened respectively. This is how the gas supply to the engine is increased with the increase of load.

4 RESULTS

The Bi-Fuel system works with generator of any power rating from 10KVA to 500KVA. The only change in hardware with the change in power rating is the size of current transformer used to scale down the current measurement. Since for three phases, three current transformer are used to scale down current of each phase, hence size of current transformer for a given power rating of generator must be at least the maximum load that can be handled by that generator per phase. Therefore the following graph depicts what are load current requirements per phase for the following sets of power ratings of generators. The current rating is calculated as according to the equation.

$$I = (P_{KVA} * 1000) / (\sqrt{3} * V_{LINE}) \quad [13] \qquad (25)$$

Where P_{KVA} is the generator rated power in Kilo Volt-Ampere which is its apparent power and V_{Line} is the line voltage.

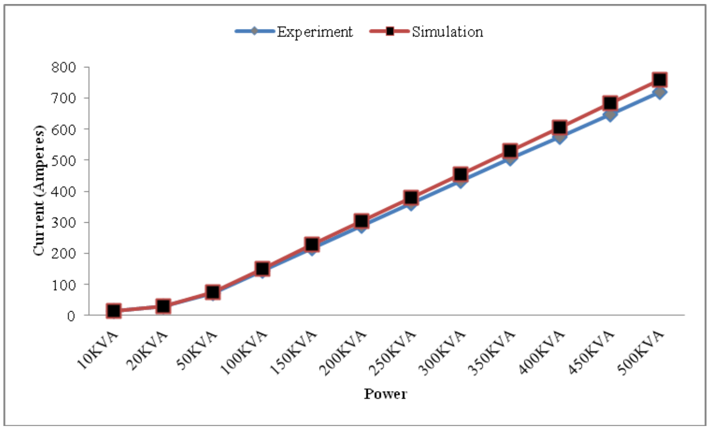


Fig.21. Load Per Phase

The following table provides details for the amperage ratings of the CTs that may be used to scale down the load phase current of each phase.

Table 2- Current Transformer Size

Generator Power Rating (KVA)	CT (Current Transformer) Size
10	15/5
20	30/5
50	75/5
100	150/5
150	225/5
200	300/5
250	350/5
300	450/5
350	500/5
400	600/5
450	650/5
500	750/5

The total load that the generator can handle is the sum of all three phase load currents. The variation of gas supply with respect to load then depends on the total load that the generator is running at a given time. The figure 22 depicts the maximum load that a generator of given power rating can handle. No matter how much is the load that the generator is currently running, the voltage at its terminals remains constant due to the fact that frequency is kept constant at 50Hz by the engine governor and AVR feeds current to field coils of generator to produce constant magnetic field. The voltage at generator terminals as in "(20)";

$$V_{rms} = (4.44NA)Bf$$
[18]
$$V_{rms} = (Cons\tan t)Bf$$

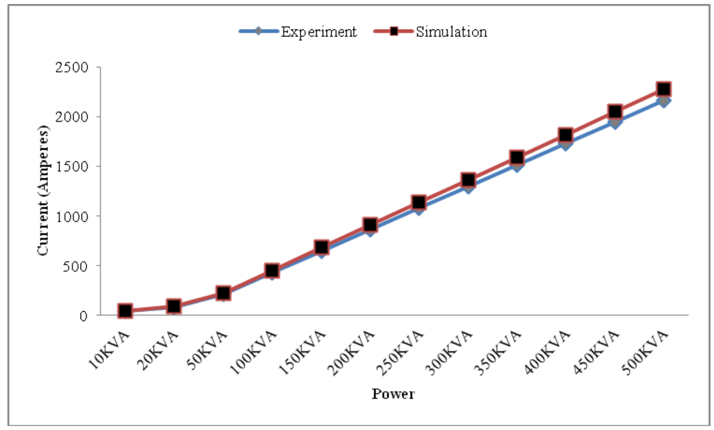


Fig.22. Total Load 3 Phase

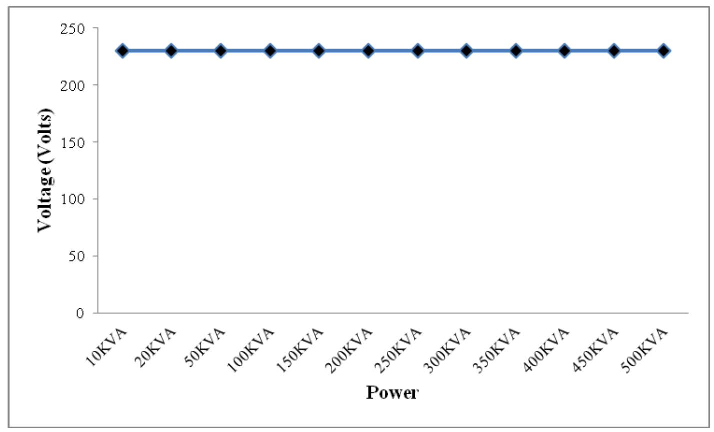


Fig.23. Output Voltage

The power rating of generator is always its apparent power. The true power that the generator can actually supply depends upon the power factor. Practically most of the industrial and domestic load is inductive and actual power factor is 0.8 no matter what is the power rating of the generator is, as depicted in the following figure.

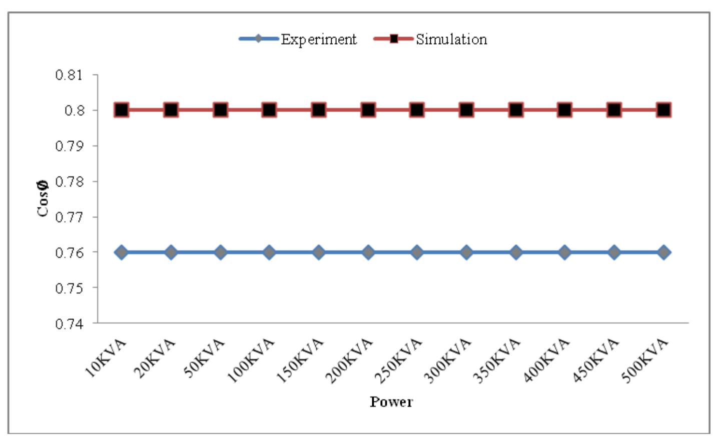


Fig.24. Power Factor

This means that the generator can handle load up to 80% of the rated power of the generator. It is the true power of the generator and is given by;

$$P_{True}(KW) = P_{Apparent}(KVA) * 0.8$$ [13] (26)

Therefore power output these generators can actually produce is illustrated by the following figure.

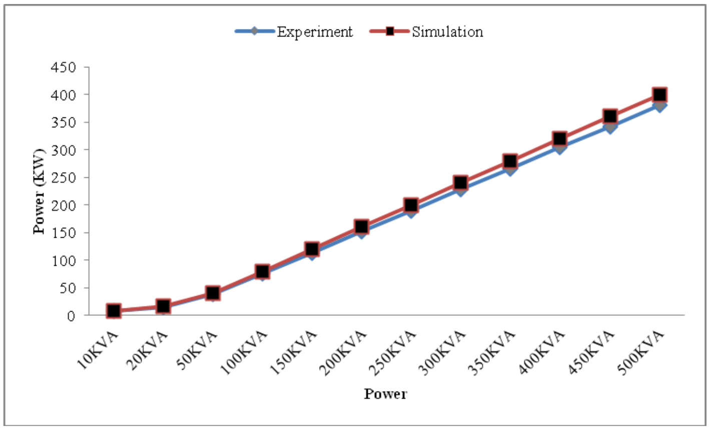


Fig.25. True Power

Although this Bi-Fuel system is valid for generators of all power ratings as mentioned, but only 350KVA generator has been chosen so as to limit the number of results presented in the paper. As can be seen in figure 21, the current per phase for 350KVA generator is 504A, therefore the current transformers selected have a size of 500/5, which means the output current of these CTs is 100 times less than the actual per phase load current as depicted by the following figure.

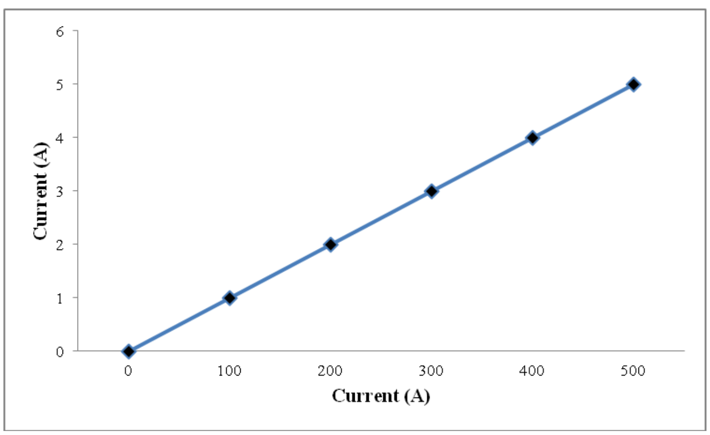


Fig.26. CT Output Current

The outputs of each of the three CTs are converted to voltage using 0.1`Ω resistors each so that it can be inputted to rms-to-dc converter.

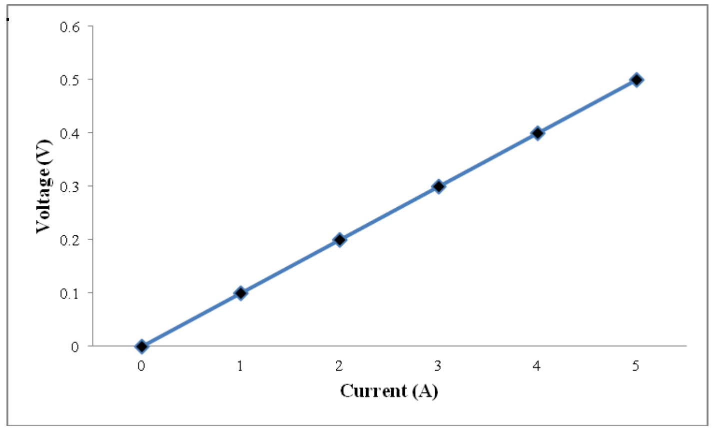


Fig.27. CT Output Voltage

This 0 to 0.5V signal is attenuated since the rms-to-dc converter employed is rated for the input of 0 to 0.3V only. The attenuation is done using opAmp and the attenuated output is depicted by the following figure.

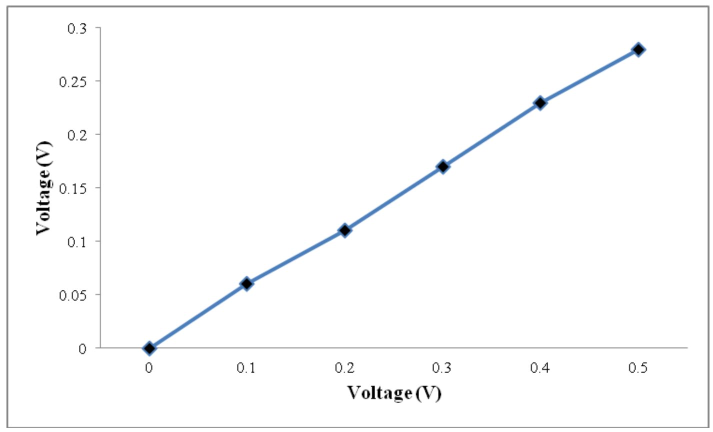


Fig.28. Attenuated CT Output

The load current of of the three phases of generator are thus in the form to be converted to DC using an RMS-to-DC converter IC. The ADC736 returns a DC signal equivalent to RMS value for the signal that is inputted to it;

$$V_{rms} = 0.707 * V_{Peak}$$ [13] (27)

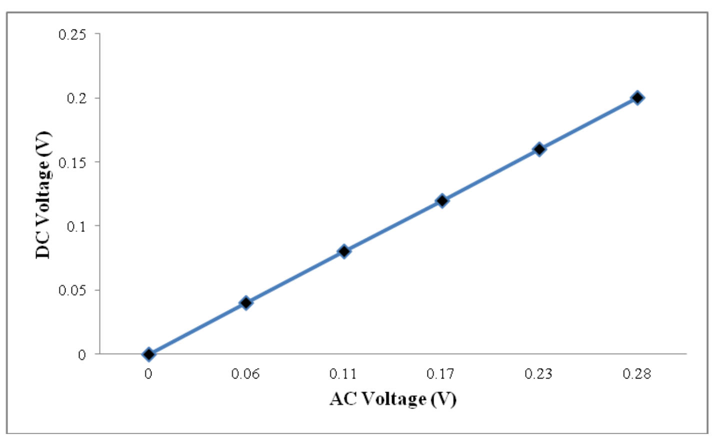


Fig.29. DC Output Voltage

This 0 to 0.3V signal (V_i) is then multiplied by a gain of 20 so that so that ADC can read these analog DC voltage levels. The analog input of the ADC can accept values from 0 to 10V.

$$V_0 = V_i * Gain \quad (28)$$

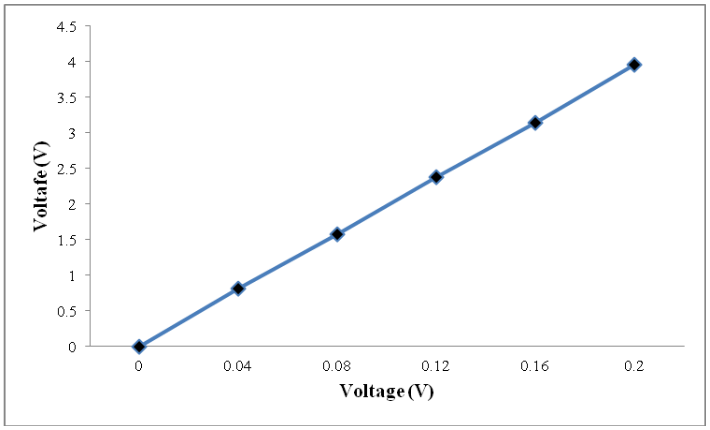


Fig.30. Amplified Output

That's how the load current of each phase is converted to analog dc levels which is then ready to be converted to digital output by ADC, so that microcontroller can read those values and take an action accordingly. The step size of ADC is 2.44mV i.e. for every change of 2.44mV at its input, it changes its digital output by 1.

$$ADC_{Output} = ADC_{Input} / 2.44mV$$
$$\because StepSize = 2.44mV \quad (29)$$

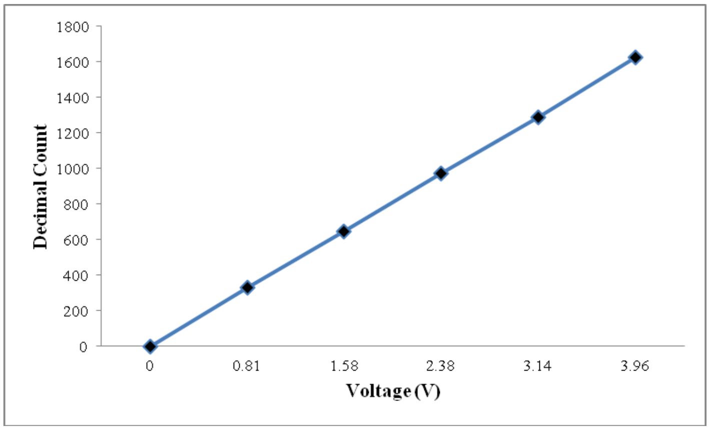


Fig.31. ADC Output

After the load current has been converted to a digital value by ADC, microcontroller reads a value at its port. This digital value is again converted back to an equivalent load phase current so that it can be displayed on LCD and the respective action can be taken by the microcontroller to either turn on or off the gas valve relays. The following figure depicts what is the ADC count for the actual load phase current.

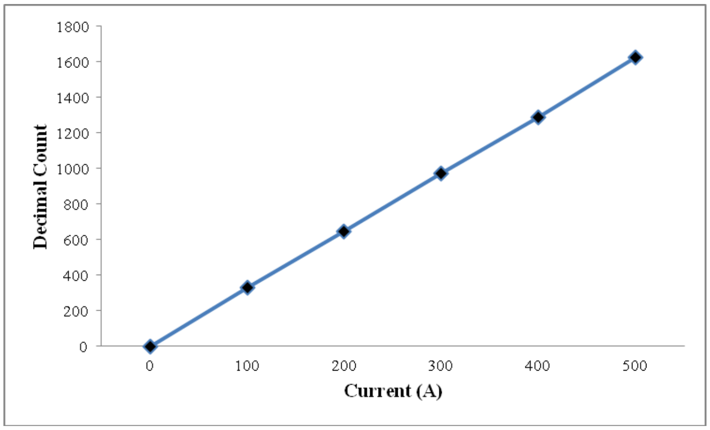


Fig.32. ADC Count Vs Load

The preceding figure depicts the ADC count for the actual load phase current of 350KVA generator. To convert the digital values back to actual load phase current, these digital values are needed to be multiplied by a constant, which has to be different for different power rating generators. This constant is computed by dividing the actual load phase current by the respective ADC count.

$$Bi - Fuel_{Constant} = LoadCurrent / ADCcount \quad (30)$$

Since this constant varies with the power rating of a generator, therefore the following table provides this constant for generators of various power ratings between 10KVA to 500KVA.

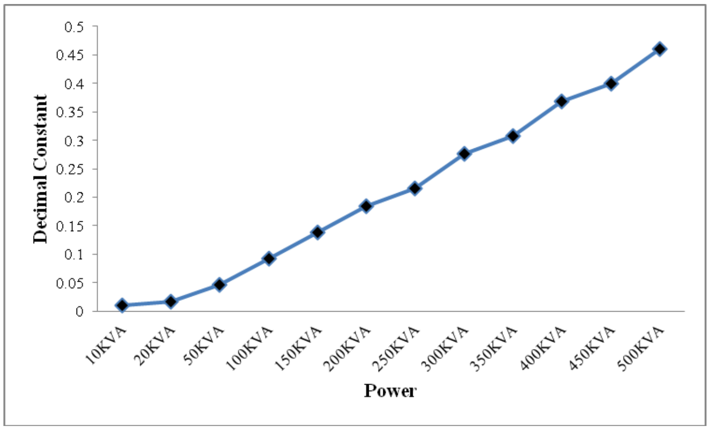


Fig.33. Bi-Fuel Constant

Since the paper focuses on only 350KVA generator, hence considering only the constant for 350KVA generator, which is 0.31 as depicted in the preceding figure. This constant is then multiplied by the ADC count, so that value of current in microcontroller's RAM and the actual load current is same.

$$EstimatedLoadCurrent = ADCcount * 0.31 \quad (31)$$

The following figure depicts the values of estimated load current in microcontroller for the ADC count values.

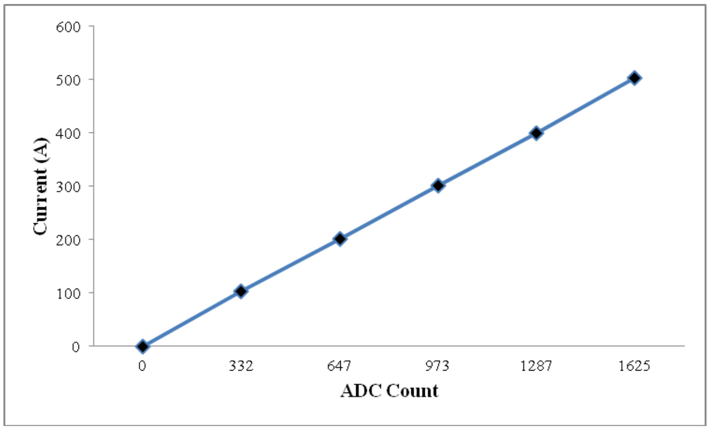


Fig.34. Estimated Current Vs ADC Count

The estimated load current values of each phase with the total load are displayed on LCD. The total load current is the sum of all three phase currents (phase1, phase2 and phase3):

$$TotalLoad = Ph1Load + Ph2Load + Ph3Load \quad (32)$$

The load current of each of the three phases may be different or same but the decision of opening or closing the relays for gas valves is dependent on the total load. The following table depicts the values of total load current for which these relays are activated.

Table 3- Gas Control Relay Status

Total Load (Amperes)	Activated Gas Control Relay
< 100A	No Relay
>150A & < 200A	Relay 1
> 250A & < 300A	Relay 1 & Relay 2
> 400A & <500A	Relay1, Relay2 & Relay3
>550A & <650A	Relay1, Relay2, Relay3 & Relay4
>700A	Relay1, Relay2, Relay3, Relay4 & Relay5

The engine temperature is measured using temperature controller and PT100 temperature sensor. The PT100 changes its resistance by 0.375`Ω for every change of 1C in temperature. The following figure depicts the values of PT100 resistance with the variation in temperature.

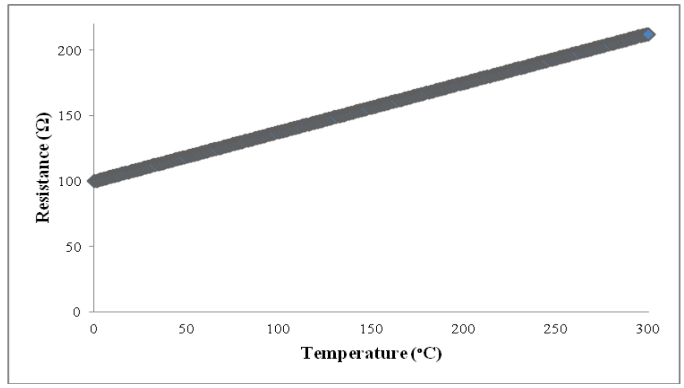


Fig.35. PT100 Resistance Vs Temperature

The Bi-Fuel operation cannot start unless the minimum engine temperature is 518∘ F. As soon as engine temperature reaches this value, temperature controller activates the supply relays for gas control valves.

Table 4- Gas Valve Supply Relay Status

Engine Temperature	Gas Valve Supply Relay
Engine Temperature < 518∘ F	OFF
Engine Temperature >= 518∘ F	ON

Since the gas supply relay is in series with the gas valve control relay, therefore the condition of opening of gas valves is depicted by the following table.

Table 5- Gas Valves Status

Total Load (Amperes)	Activated Gas Control Relays	Gas Valve Supply Relay	Opened Gas Valves
< 100A	No Relay	OFF	No Valve
		ON	No Valve
>150A & <200A	Relay1	OFF	No Valve
		ON	Valve 1
>250A & <300A	Relay1 Relay2	OFF	No Valve
		ON	Valve1 Valve2
>400A & <500A	Relay1 Relay2 Relay3	OFF	No Valve
		ON	Valve1 Valve2 Valve3
>550A & <650A	Relay1 Relay2 Relay3 Relay4	OFF	No Valve
		ON	Valve1 Valve2 Valve3 Valve4
>700A	Relay1 Relay2 Relay3 Relay4 Relay5	OFF	No Valve
		ON	Valve1 Valve2 Valve3 Valve4 Valve5

As mentioned earlier, the supply of gas to the generator through these gas valves is insufficient at any load, so as to let diesel fulfill rest of load fuel requirements. The governor of the engine provides diesel to the engine, so that engine frequency is kept constant. The following waveform is the resultant waveform of the generator output voltage versus time, which depicts that generator, maintains smooth output voltage during Bi-Fuel operation.

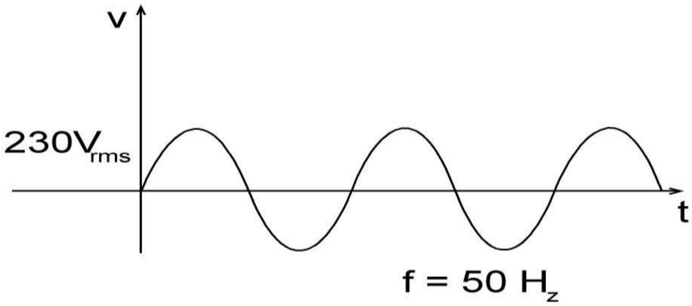


Fig.36. Generator Output Waveform

To compare how engine performs with diesel only and with Bi-fuel operation, the torque and power has been measured for both systems. The following figure depicts the resulting torque with various engine speeds for both diesel and Bi-Fuel operation.

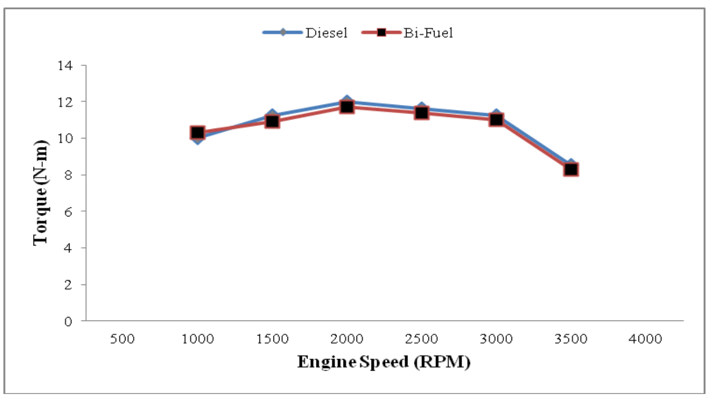


Fig.37. Experimental Torque Output

The power of the engine with respect to various engine speeds for both diesel only and Bi-Fuel operation has been measured. The following figure depicts these values. It can be seen that Bi-Fuel performs as good as diesel only system.

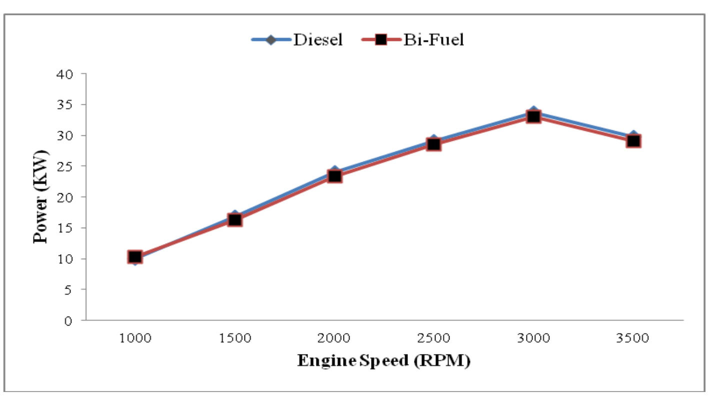


Fig.38. Experimental Power Output

4.2 Deduction from Results & Its Validity

➢ **Reduced Fuel Storage**

Consequently, diesel fuel storage is no more an issue as it has been reduced up to 70%. Fuel installation capacity as per local codes can now be followed and fuel contamination and degradation may also be reduced [1].

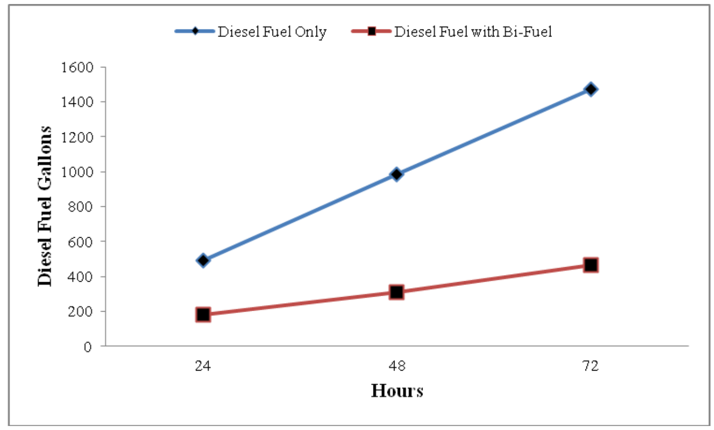


Fig.39. Diesel Fuel Storage Requirements

➢ **Extended Runtimes**

As much of the load fuel requirements are fulfilled by natural gas whose supply is endless through pipelines, therefore for a given amount of diesel fuel, generators runtimes are significantly improved as depicted by the following table [1].

Table 5- Runtimes Comparison

Diesel Fuel Quantity	Diesel Runtimes	Bi-Fuel Runtimes
12"tall/183 gallons	7.5 hours	44.6 hours (1.8 days)
24"tall/438 gallons	20.5 hours	108.7 hours (4.5 days)
36"tall/693 gallons	31.2 hours	189.9 hours (7.9 days)

➢ **Financial Savings on Bi-Fuel**

Since Natural gas produces power at much lower rates than diesel fuel, therefore huge amount of money can be save using Bi-fuel system. This idea is depicted by the following figures.

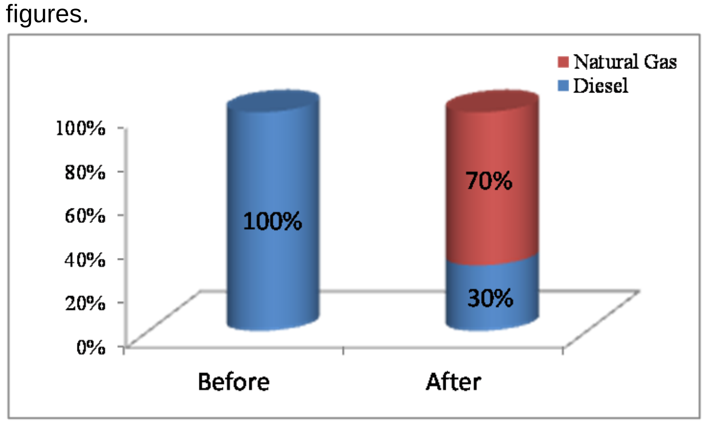


Fig.40. Fuel Consumption at Nominal Output

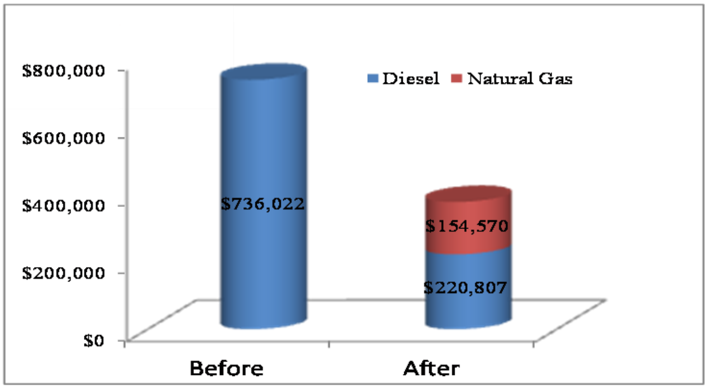


Fig.41. Fuel Cost per Year

- The amount of fuel as required by the engine increases with the increase of load. This amount is controlled by the governor of the engine. The Bi-Fuel operation does not disturb the original operation of generator primarily because of the reason that its governor system has not been altered at all.

5 CONCLUSION

We are living in a 21st century and this is the time, when science has already made such great miracles, that mankind only dreamt of even few years back. Invention of rocket and walking on moon are in fact the achievements made ages before. But science could have achieved nothing if had not discovered new sources of energy every now and then. Almost no energy source will last forever, causing ever increasing demand requirements compared to supply and consequently forcing to pay more per unit energy all the time. As a result, we are compelled to find new energy alternatives besides discovering new sources. The motive is to make energy more and more efficient and simultaneously cutting on the cost. The Bi-Fuel system technology is one of the upshots of this motivation. Gathering the best of diesel driven engines and natural gas engines at one place was the intension and simultaneously eradicating the drawbacks associated with each system. The benefits of Bi-Fuel technology substantiates the legitimacy of this study. Motivation of discovering and finding new energy alternatives will last as long as this earth will. Who knows what is still yet to come!

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