Design of output power control system based on mass flow rate comparison of air and fuel ratio (AFR) on dual fuel generator set by using pid control method

M B Toriki, B L Widjiastoro and A Abdurrakhman

Department of Physics Engineering, Institut Teknologi Sepuluh Nopember,
Jl. Arif Rahman Hakim, Sukolilo, Surabaya, Indonesia.

bereltoriki11@gmail.com

Abstract. Generator set is a tool that is used to generate energy or electrical power. The electric power generated by the generator set is used to supply the electrical loads in this thesis is lamp. Power that can be produced by a generator set is ranged between 100-1200 watt. The power generated by generator set is influenced by a mixture of air and fuel. Generator set used is dual fuel generator set. From the results of this study, a stable response with overshoot value below 0% and its error is 2%. In addition, the best obtained value of Air Fuel Ratio (AFR) is 15.06. Furthermore, the stability of the power generated by the generator set is also influenced by the flowrate mass of the fuel injected into the combustion chamber. From the simulation results when given a power set point at 1200 watt, obtained value of the air mass flowrate is 0.03754 kg/s, mass flowrate of biogas is 0.002367 kg/s, and gasoline constant mass flowrate is 0.000125 kg/s. Meanwhile, when given a set point of 100 watts of power, a value of 0.009928 kg/s air mass flowrate is injected to the chamber, mass flowrate of biogas is 0.0005341 kg/s and the mass flowrate of gasoline is 0.000125 kg/s. The goal of output power control on generator set is to make generator working to produce output power in accordance to required load.

1. Introduction

The surge of world oil prices, followed by rising prices of fossil fuels. On the other hand, global environmental issues that demand high levels of environmental quality, encourage the various energy experts to develop more environmentally-friendly energy and support the sustainable supply security. Currently fossil energy reserves had been nearly depleted, and the research of new source has been difficult to do, even predicted in 2030 Indonesia will truly become a net importer of energy, because the balance between production and domestic energy consumption occurred in 2030. Starting this year, the production of domestic energy (fossil and EBT) is no longer able to meet domestic consumption and Indonesia changed its status into a net importer of energy. [1]

This makes the renewable energy development is growing especially Indonesia has huge potential for it. Based on the geographic state, Indonesia is blessed with a high amount of energy resources ranging from hydro, geothermal, biomass, solar, wind, even the ocean. But unfortunately such property has not
been widely used as an energy source that can replace fossil energy sources that nearly depleted. One source of renewable energy that are being highly used is biogas, especially for household scale. However, the development of biogas in Indonesia is still relatively slow due to various factors, ranging from people who are still not comfortable with the energy of dirt, to biogas purification problems and the implementation of the generator set. [2]

Based on data from the Directorate General of Livestock and Animal Health, while the number of beef cattle numbers in 2015 reached 15 million. One cow capable of producing dirt as much as 23.6 kg of solid waste a day and 9.1 kg of liquid waste a day. [3] In 1 kg of cow / buffalo manure can be expected 0,023 to 0,040 m\(^3\) of biogas is produced [4]. So that the maximum potential value of biogas from manure as high as 14.16 million m\(^3\) /day. Methane amount is 9,912 million m\(^3\) /day and CO\(_2\) of 4,248 million m\(^3\) /day. In other words, within a year Indonesia will contribute 1,55 billion m\(^3\) of CO\(_2\) greenhouse gas. That means with the contribution of methane gas, will be equivalent to 135.8 million tons of CO\(_2\) per year, meaning that in addition of this gasses in the atmosphere, the methane gas is equivalent to 135.8 million tonnes worth of CO\(_2\) gasses a year, and if summarized with Indonesia will contribute 138,573 million tonnes worth of CO\(_2\) meaning that if cow waste or manure is not used properly will negatively affect the environment wildlife as the greenhouse gasses is the cause of depletion of ozone gasses in the atmosphere.

Dual fuel generator set is the standard gasoline engine with biogas fuel added in its combustion chamber and the ignition of the engine is carried by the gas spray called pilot fuel. In other word liquid or gaseous fuels can be injected to the engine by making a hole in the intake manifold of the engine itself. Depending on the type of the added fuel, when the fuel type is liquid such as ethanol or methanol, carburetor is added to the system and make the fuel pumped at certain pressure and atomized as the fuel are injected to the air intake of generator engines. As for the fuel gas is not needed anymore because the gas fuel carburetor already has its own pressure. [3]

Dual fuel system benefit is to conserve the use of gasoline as a fuel, production costs can be reduced, as well as generator set modification costs relatively cheaper than converting to the whole gas engine. Furthermore, the application of biogas with a dual fuel system on the generator set can improve the performance and efficiency of the engine [8]. The utilization of biogas generator set would not change the composition of machine tools and only adds to the system equipment such as mixer ventury on the suction channel. While the use of dual fuel intended to reduce the use of gasoline in the combustion process, as it would be the partial substitution of gasoline by biogas.

On generator set using dual fuel system is still a lot to do in development phase, one is controls of the output power of the generator set. Control of output power on generator set needs to be done, so that the generator set can produce a maximum and stable output power, and in accordance with the needs of electrical energy that can be used for everyday needs. In order to make the generator set produce a stable output power for the demand, the mass flow rate of fuel and air in the combustion chamber of engine should be in accordance with the required power demand. If higher power produced by generator output is required, then the mass flow rate of air and fuel (petrol and biogas) that entering the combustion chamber is also getting bigger. Additionally, the mixture of fuel and air must be in accordance with the rules of the combustion reaction. Therefore to obtain optimum combustion, calculation of Air Fuel Ratio (AFR) is done by stoichiometric equation.

2. Research Methodology
On this research, dual fuel generator set is used as research object. The characteristic of engine is spark ignition engine with 4 step. Gasoline and biogas is fuel that is used to get combustion on the engine
cylinder. While the use of dual fuel intended to reduce the use of gasoline in the combustion process. On the other hand, to get complete combustion and optimum power, the air is also injected into cylinder chamber. To inject gasoline, biogas, and air into combustion chamber is used ratio control algorithm. Ratio control is an algorithm that working based on value that was determine by using dual fuel Air Fuel Ratio (AFR) calculation.

![Image](image1.png)

**Figure 1.** (a) Experiment Tools, (b) Block Diagram of Power Control Output System Dual Fuel Generator Set

3. Modelling of The System

The calculation of the value of AFR (Air Fuel Ratio) for dual fuel is used to determine the ratio between the mass air flowrate and mass flowrate of fuel (petrol and biogas). To obtain dual fuel AFR value calculation using the following equation.\[4\]

\[
AFR_{sto} = \frac{\left(\alpha \left(\frac{x_d + \beta}{2}\right) + \beta \left(\frac{x_g + \gamma}{2}\right)\right) \cdot MW_{air}}{\alpha \left(\frac{x_d \cdot MW_C + \frac{y_d}{M} \cdot MW_H}{\gamma}\right) + \beta \left(\frac{x_g \cdot MW_C + \frac{y_g}{M} \cdot MW_H}{\gamma}\right)}
\]

Where:
- MW C = molecular Weight atom C
- MW H = molecular Weight H atom
- MWair = molecular Weight air
- \(\alpha\) = Mass of gasoline to the total mass of fuel
- \(\beta\) = Mass biogas to the total mass of fuel
- \(X_d\) = Number of C atoms in the gas compound
- \(Y_d\) = The number of H atoms in the compound of gasoline
- \(x_g\) = The number of carbon atoms in the compound of biogas

**Throttle valve** is an actuator which regulates the amount of air mass flow into the combustion chamber of the engine. To calculate the number of mass air flow (ideal gas) that passes through the throttle valve can be used follows Bernoulli equation.

\[
q(t) = C_d \left[1 - \cos(u)\right] \frac{D^2}{4} \frac{P_{in}}{\sqrt{RT_{in}}} f(P_{in}, P_{out})
\]

Based on the equation 2 above, the air flow can be adjusted via the throttle valve opening (u) between 0° to 90°. The non-linear function that connects the input pressure and output pressure is as follows.
Mathematical modeling of the subsystems of the intake manifold can be approximated using the ideal gas equation as follows.

\[
\begin{align*}
\frac{d}{dt} m(t) &= \dot{m}_{in}(t) - \dot{m}_{out}(t) \\
\frac{d}{dt} U(t) &= \dot{H}_{in}(t) - \dot{H}_{out}(t)
\end{align*}
\]  

(4)

(5)

It is assumed that the fluid flow is modeled using the ideal gas equation as follows

\[
p(t) \cdot V = m(t) \cdot R \cdot \vartheta(t)
\]  

(6)

When connected with a caloric value

\[
U(t) = c_p \cdot \vartheta(t) \cdot m(t)
\]  

(7)

\[
U(t) = c_p \cdot \vartheta(t) \cdot m(t)
\]  

(8)

\[
\dot{H}_{in}(t) = c_p \cdot \vartheta(t) \cdot \dot{m}_{in}(t)
\]  

(9)

\[
\dot{H}_{out}(t) = c_p \cdot \vartheta(t) \cdot \dot{m}_{out}(t)
\]  

(10)

Substitution into equation

\[
\frac{d}{dt} p(t) = \frac{k_R}{V} \left[ \dot{m}_{in}(t) \cdot \vartheta_{in}(t) - \dot{m}_{out}(t) \cdot \vartheta(t) \right]
\]  

(11)

\[
\frac{d}{dt} \vartheta = \frac{c_p}{p \cdot V \cdot c_p} \left[ c_p \cdot \dot{m}_{in}(t) \cdot \vartheta_{in} - c_p \cdot \dot{m}_{out}(t) \cdot \vartheta - c_p \cdot (\dot{m}_{in} - \dot{m}_{out}) \cdot \vartheta \right]
\]  

(12)

\[
\frac{d}{dt} p_m = k_m (\dot{m}_{ai} - \dot{m}_{ao}) (T) = \frac{R \cdot \dot{H}_{in}(t)}{V_m} (\dot{m}_{ai} - \dot{m}_{ao}) (T)
\]  

(13)

(14)

After going through the intake manifold, air will enter into the combustion chamber or cylinder. Engine mass flow is the mass flow of air is injected into the combustion chamber with the air pressure of the calculation in a part of the intake manifold. Based on the air system, the engine characteristics can be assumed as a volumetric pump. And the amount of mass flow of air needed for combustion in the cylinder can be defined based on the speed-density equation.[5]

\[
q_{cyl} = \frac{\eta_p P_{out} V_d \omega}{2 \pi N R T}
\]  

(15)

Where :

\[
q_{cyl} = \text{Mass Flowrate Air Entering The Combustion Chamber (kg / s)}
\]

\[
\eta_p = \text{Volumetric Efficiency (\%)}
\]

\[
P_{out} = \text{Pressure Output of The Intake Manifold (Pa)}
\]
\[ \omega = \text{Speed (Radians per minute)} \]
\[ R = \text{Gas Constant (J / kg K)} \]
\[ N = \text{Number Revolution Per Cycle (2 for 4 stroke)} \]
\[ T = \text{Temperature (K)} \]

A modern fuel injection system set up so that the comparison mass flowrate of air and fuel mass flowrate is kept constant to achieve volumetric efficiency without changes. Density and mass flow measurement of air is used to control the fuel is injected. So that the power generated by the engine is obtained by the following equation.[5]

\[
P = \frac{\eta_c \eta_e P_{out} V_d \omega H \left( \frac{F}{A} \right)}{2\pi NRT_{in}} \tag{16}
\]

Where:
\[ \eta_c = \text{The Combustion Efficiency (\%)} \]
\[ \eta_e = \text{Efficiency Electric Generator (\%)} \]
\[ F/A = \text{Fuel to Air Ratio} \]
\[ V_d = \text{Displacement Volume (m}^3) \]

Spark ignited engine, the combustion process occurs because there is a mixture of fuel in this case is a gas and biogas with air in the cylinder engine and ignited by a spark plug, causing sparks and combustion occurs as described in the previous chapter. The combustion process will drive the piston and crankshaft so that it will turn a generator to the torque produced by the engine speed and can produce output power. This is the equation of torque generated from the combustion of air-fuel ratio according to the stoichiometric equation.[5]

\[
\dot{\omega} = \frac{1}{J} \left[ \left( \eta_c \eta_e P_{out} V_d H \left( \frac{F}{A} \right) \right) \frac{2\pi NRT_{in}}{T_e} - T_e \right] - bw \tag{17}
\]

Where
\[ J = \text{Inertia} \]
\[ T_m = \text{Torque Produced by The Engine Speed (Nm)} \]
\[ T_e = \text{Torque Electrically or Load (Nm)} \]

4. Relation Between Power and Mass Flowrate

![Figure 2](image1.png)

(a) Relation Graph Between Power and Air Mass Flowrate, (b) Relation Graph Between Power and Biogas Mass Flowrate
Figure 2 is relation between power and mass flow rate. The higher the required power it needs to air and fuel will increase. Because the engine requires a greater supply of energy to produce a greater output power anyway. From the graph, it can be seen that the change in the air mass flowrate and mass flowrate is not the same biogas or not linear at each change of set point power. The most substantial change of air mass flowrate and biogas is when the change set point 100 watts to 200 watts with a value of 0.259 kg / s and 0.018 kg / s. While for the most minor changes from the mass flowrate of air and biogas that is when the change set point power 1100 watts to 1200 watts with a value of 0.093 kg / s and 0.007 kg / s.

4.1. Tracking Set Point Up 33%

In testing of the set point tracking is raising the set point of 33% of the initial set point. On the change of set point values obtained for settling time (Ts) of 1.25 sec, rise time (Tr) of 1.25 seconds, Td 0.03 seconds, maximum overshoot (Mp) 0% and error steady state (Ess) 0%. The value of the rise time and settling time together for the first time reached the set point directly system stable. In this test indicate that a change set point capable followed by process variables. The response of tracking the set point up 33% shown in the figure 3.

Figure 3. Graph of Output Power Response with Set Point Tracking Up 33%

4.2. Tracking Set Point Down 33%

In testing the set point tracking lowers the set point of 33% of the initial set point. On the change of set point values obtained for settling time (Ts) of 1.2 seconds, the rise time (Tr) of 1.2 seconds, Td 0.018 seconds, maximum overshoot (Mp) 0% and error steady state (Ess) 0%. The value of the rise time and settling time together for the first time reached the set point directly system stable. In this test indicate that a change set point capable followed by process variables. The response from the set point tracking down 33% found in Figure 4.

Figure 4. Graph of Output Power Response with Set Point Tracking Down 33%
4.3. Tracking Set Point Up 10%
In testing the set point tracking is raising the set point of 10% of the initial set point. On the change of set point values obtained for settling time (Ts) of 1.45 sec, rise time (Tr) of 1.45 seconds, Td 0.01 seconds, maximum overshoot (Mp) 0% and error steady state (Ess) 0% , The value of the rise time and settling time together for the first time reached the setpointdirect system stable. In this test indicate that a change set point capable followed by process variables. The response of tracking the set point up 10% found in Figure 5.

![Figure 5. Graph of Output Power Response with Set Point Tracking Up 10%](image1)

4.4. Tracking Set Point Down 10%
In testing the set point tracking lowers the set point of 10% of the initial set point. On the change of set point values obtained for settling time (Ts) of 0.7 seconds, the rise time (Tr) of 0.7 seconds, Td 0.005 seconds, maximum overshoot(Mp) 0% and error steady state (Ess) 0%. The value of the rise time and settling time together for the first time reached the set point directly system stable. In this test indicate that a change set point capable followed by process variables. The response of tracking down 10% set point shown in the figure 6.

![Figure 6. Graph of Output Power Response with Set Point Tracking Down 10%](image2)
5. Result of System Modelling

To test the results of modelling in simulink by entering the set point value required power ranged at 100-1200 watts. If the higher power is required, then the mass flowrate of air and biogas will be great as well, but in this study gas mass flowrate is constant.

Table 1. Relation between Mass flowrate Power of Air and Fuel

| Power (Watt) | Gas Mass Flowrate (Kg/s) | Biogas Mass Flowrate (Kg/s) | Air Mass Flowrate (Kg/s) |
|-------------|--------------------------|-----------------------------|--------------------------|
| 100         | 0,01                     | 0,029                       | 0,560                    |
| 200         | 0,01                     | 0,047                       | 0,819                    |
| 300         | 0,01                     | 0,060                       | 1,022                    |
| 400         | 0,01                     | 0,071                       | 1,192                    |
| 500         | 0,01                     | 0,081                       | 1,341                    |
| 600         | 0,01                     | 0,090                       | 1,476                    |
| 700         | 0,01                     | 0,098                       | 1,601                    |
| 800         | 0,01                     | 0,106                       | 1,716                    |
| 900         | 0,01                     | 0,113                       | 1,825                    |
| 1000        | 0,01                     | 0,120                       | 1,928                    |
| 1100        | 0,01                     | 0,126                       | 2,025                    |
| 1200        | 0,01                     | 0,133                       | 2,118                    |

Table 1 is relation between power and mass flowrate. The higher required power it needs to air and fuel will increase. Because the engine requires a greater supply of energy to produce a greater output power anyway. The most substantial change of air mass flowrate and biogas that is when the change set point 100 watts to 200 watts with a value of 0.259 kg / s and 0.018 Kg / s. While for the most minor changes from the air mass flowrate and biogas that is when the change set point power 1100 watts to 1200 watts with a value of 0.093 kg / s and 0.007 kg / s.

Table 2. Comparison Between Fuel Mass Flowrate From Simulation Result and From Plan

| Power (Watt) | Biogas Mass Flowrate (Simulation) Kg/s | Biogas Mass Flowrate (Plan) Kg/s |
|-------------|---------------------------------------|---------------------------------|
| 100         | 0,029                                 | 0,032                           |
| 200         | 0,047                                 | 0,049                           |
| 300         | 0,060                                 | 0,064                           |
| 400         | 0,071                                 | 0,075                           |
| 500         | 0,081                                 | 0,086                           |
| 600         | 0,090                                 | 0,095                           |
| 700         | 0,098                                 | 0,103                           |
| 800         | 0,106                                 | 0,111                           |
| 900         | 0,113                                 | 0,117                           |
| 1000        | 0,120                                 | 0,125                           |
| 1100        | 0,126                                 | 0,133                           |
| 1200        | 0,133                                 | 0,142                           |

Table 2 represents the relation of the mass flowrate of fuel and the real plant simulation results when the value of a certain power. While Table 3 is the relation of mass air flowrate simulation results and real plant during a certain power value. From these data it appears that the greater the power output is required, then the mass flowrate of fuel and air will also increase. The relation of power, fuel, and air are comparable. However, there are differences between the mass flowrate of fuel and air from the plant simulation and real data. This is due to the results of the simulation are several engine parameters taken in ideal conditions, such as pressure on the intake manifold and the others. In addition, because there are some parameters that use the approach through a number of journals and the results of previous research.
Table 3. Comparison Between Air Mass Flowrate From Simulation Result and From Plan

| Power (Watt) | Air Mass Flowrate (Simulation) Kg/s | Air Mass Flowrate (Plan) Kg/s |
|-------------|-------------------------------------|-------------------------------|
| 100         | 0.560                               | 0.601                         |
| 200         | 0.819                               | 0.871                         |
| 300         | 1.022                               | 1.092                         |
| 400         | 1.192                               | 1.255                         |
| 500         | 1.341                               | 1.419                         |
| 600         | 1.476                               | 1.571                         |
| 700         | 1.601                               | 1.682                         |
| 800         | 1.716                               | 1.789                         |
| 900         | 1.825                               | 1.896                         |
| 1000        | 1.928                               | 1.995                         |
| 1100        | 2.025                               | 2.099                         |
| 1200        | 2.118                               | 2.224                         |

**6. Conclusion**

Based on the results of this research, it was found that a stable output power response with overshoot maximum value averaging below 20% and the error value below 2% in each of the set point value 100-1200 watts. In addition, the PID parameter values didiapatkan with $K_p = 120$, $K_i = 0.1$, and $K_d = 15.2$. While the PID parameter values for flowrate control of biogas that is $K_p = 5$, $K_i = 3$, and $K_d = 1$. In addition, there is a difference between the simulation and the mass flow rate of the average data plan for biogas mass flow rate at 6.94% and the mass air flow rate of 7.36%.

The higher power that generated by generator set, the mass flowrate of air and fuel will increase. For maximum power is 1200 watts, obtained air mass flowrate amounted to 2.118 Kg / s, mass flowrate of biogas amounted to 0.133 Kg / s, and gasoline mass flowrate amounted to 0.01 kg / s. As for the minimum power, obtained air mass flowrate amounted to 0.560 Kg / s, mass flowrate of biogas amounted to 0.029 Kg / s, and the gas mass flow rate amounted to 0.01 kg / s.

In this research, value of Air Fuel Ratio (AFR) for complete combustion on dual fuel system that is 15.06.

**References**

[1] The Agency for The Assessment and Application of Technology (BPPT) 2015 *Energy Development to Support Sustainable Development Indonesia Energy Outlook*

[2] A Abdurrakhman, T Soehartanto and B Sudarmanta 2013 *Physic Eng* 12

[3] A I Setiawan 2002 *Harnessing The Livestock Manure Utilization Problem Solution Environment and Alternative Energy* (Jakarta: Third Printing Spreaders Swadya)

[4] J Stewart, A Clarke and R Chen 2007 *Autom. Eng. (Proc. IMEchE)* 221 943

[5] H Bastida, E Carlos, and M Abeyesekerra 2017 *Sch. Eng.* 142 1282-1287