Development of Small Stirling Engine Generator

Muhamad Fikri Bin Muhamad Halil
Faculty of Electrical Engineering
Universiti Teknologi MARA Malaysia
40450 Shah Alam, Selangor, Malaysia
E-mail: fikri4667@yahoo.com

Abstract— **This paper describes the basic concepts and principles of designing small Stirling engine generator. Stirling engine generator is a mechanical device that converts heat energy into electrical energy. This engine operates on a closed regenerative thermodynamic cycle, with cyclic compression and expansion of the working fluid at different temperature level [1]. Compare to ordinary fuel engine which is internally combustion, Stirling engine is external combustion engine type where the heat source is constantly supplied. The purpose of this study is to design and build small Stirling engine equipped with alternator to produce electrical (AC) output. The energy output will be roughly estimated and measured at every stage of conversions. The Stirling engine built is gamma type with double heat cylinder and air is used as its working fluid. This engine produce mechanical output through flywheel and alternator is mounted on it. The alternator built is axial flux permanent magnet generator (PMG) type. The magnets used to induce current are neodymium magnet (NdFeB) ,the most powerful magnet on earth [2]. Power output (mechanical) from the Stirling engine will be estimated using Beale formula while alternator power output (electrical) will be estimated based on Faraday's Law.**

Keyword: stirling engine, stirling cycle, axial flux PMG;

I. INTRODUCTION

Recently, the consumption of coal, oil, natural gas or even nuclear in most electric power plants has create serious environmental issues such as global warming and air pollution. Furthermore, those resources are non-renewable and nearly depleted. Therefore, solar energy has greatest potential to become future renewable resources [3]. Solar energy can be converted into electrical energy through photovoltaic and heat engines. Photovoltaic has main weaknesses, which is the generation system is not available during night-time. Contradict to photovoltaic, heat engines (Stirling engine) can be operated all of the times due to the flexibility of the heat source. This means that, with an additional burner, the required heat can also be obtained using fossil fuels (Biogas, etc..). Thus, the systems continuously generate electricity with or without solar energy.[1] Furthermore, modern Stirling engine generator is capable to convert sun power into electrical power up to 40% efficiency rather than photovoltaic system which has efficiency between 15-18% [3].

The Stirling heat engine was first patented in 1816 by Robert Stirling. Since then, several Stirling engines based on his invention have been built in many forms and sizes [1]. In solar power generation system, the solar radiation is converted to electricity in three stages [4]. In the first stage, radiation is converted to heat by focusing the solar radiation onto absorbing heat engine part by means of a parabolic reflector. The concentrated solar radiation produces high intensity of heat energy. In the second stage, the heat is converted to mechanical power by a Stirling engine. In the final stage, the mechanical power is converted to electricity by an alternator. For this study purpose, candles will be used to simulate concentrated solar power in order to get heat energy.

II. THEORETICAL

Basically, a Stirling engine applies the first and second Law of Thermodynamics, which is applicable to all thermal machines [1]. Generally, first and second Law is almost similar which is denied all the supplied energy will go to useful work. Some of that energy will be wasted as heat goes to cooling system or exhaust. In other word, the successive energy conversion is 30% to 40% [1]. The key principle of a Stirling engine is that a fixed amount of a gas is sealed inside the engine. The Stirling cycle involves a series of mechanism that change the pressure of the gas inside the engine, causing it to do work. There are several properties of gasses (pressure, temperature and volume) that are applied to the operation of Stirling engines [1]:

- a fixed amount of gas in a fixed volume of space, if the temperature of that gas is raised, the pressure will increase.
- if a fixed amount of gas being compress (decrease the volume of its space), the temperature of that gas will increase

i) **Boyle's Law** $P_1 \cdot V_1 = P_2 \cdot V_2$ (1)

ii) **Charles's Law** $\frac{V_1}{V_2}=\frac{T_1}{T_2}$ or $\frac{V_1}{T_1}=\frac{V_2}{T_2}$ (2)

iii) **The Ideal Gas Law** $P \cdot V = m \cdot R \cdot T$ (3)

Since Stirling engine operates on a closed regenerative thermodynamic cycle, it utilizes all of these three Gas Laws reciprocally to complete one operating cycle. This cycle is known as Stirling Cycle. The Stirling cycle is similar, in some respects, to the Carnot cycle. Carnot cycle is the most efficient heat engine cycle, consisting of two isothermal processes and two adiabatic processes. Below are the PV and TS Carnot cycle diagrams [8];

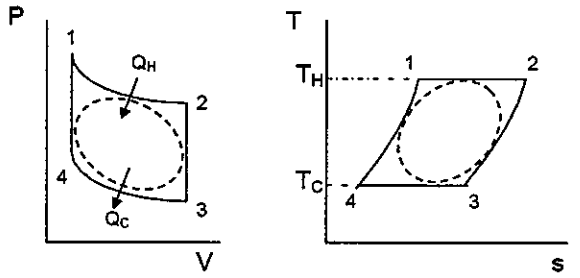

Figure 1: Ideal Stirling cycle Pressure-Volume and Temperature-Entropy diagrams

1 – 2: Isothermal Expansion
2 – 3: Isochoric Displacement (Cooling)
3 – 4: Isothermal Compression
4 – 1: Isochoric Displacement (Heating)

Engine components are designed to do all the two isothermal processes and two adiabatic processes in the engine. Stirling engine components include, heat cylinder, hot piston, cool cylinder, power piston, cooling fin, connecting rod, cranks shaft, flywheel and main shaft [4]. Functions and design process for each component will be described in methodology section. Stirling engine produce mechanical output which is measured by torque and horsepower. Torque is measured in pound-feet (lb-ft) or Newton-meters (Nm). Torque is generated in an engine by the combustion pressure pushing down the hot piston to the bottom of the hot cylinder forcing the crankshaft of the engine to turn. Torque from the crankshaft is then applied to the application, such as lawn mover, an electric generator, or the drive shaft of the vehicle [4]. In this project, flywheel was designed to do work for the engine since it is mounted in the middle of the crankshaft. Beside than provide inertia required for the engine to prevent loss of engine speed, it is also can be used to generate electricity through alternator. Here where the place of energy conversion from mechanical output into electrical output occurred.

The alternator was designed to be mounted on flywheel. There are many types of alternator construction. Alternators generate electricity when the magnetic field around a conductor changes, a current is induced in the conductor. Typically, a rotating magnet called the rotor turns within a stationary set of conductors wound in coils on an iron core, called the stator. The field cuts across the conductors, generating an induced EMF, as the mechanical input causes the rotor to turn. The rotating magnetic field induces an AC voltage in the stator windings. The rotor magnetic field may be produced by induction (in a "brushless" alternator), by permanent magnets (in very small machines), or by a rotor winding energized with direct current through slip rings and brushes [10].

In this project, permanent magnet has been used to produce rotor magnetic field. Beside than simple to construct and maintain, permanent magnet produce higher magnetic flux density in the air gap rather than electromagnetic excitation [4]. In term of renewable energy solution, permanent magnet alternator has great advantage where no external electrical energy required to induce magnetic field in rotor winding. So it becomes rapidly develop by many engineers to be more efficient and high performance.

There are two common configuration in constructing permanent magnet alternator; radial flux permanent magnet (RFPM) generators and axial flux permanent magnet generator (AFPM) [10]. Majority of electrical machines are applying radial flux (RFPM). They are cylindrically shaped and the magnetic field cuts the stator coils in a radial direction. It can be found easily in vehicle alternator construction, ordinary permanent magnet motor etc.

However, geometry called axial flux (AF) is also possible and this is particularly suitable for efficient, high power density machines. As the name suggests, in an AF machine the magnetic field cuts the stators in the axial direction. Whilst electrically similar, AF and RF machines differ significantly in terms of thermal management, mechanical design and assembly process [9].

This set of rotors features round neodymium magnet (NdFeB) magnets. The Neodymium magnet has been a key technological development that allows practical and efficient alternators to be built. The high strength of Neodymium produce high intensity magnetic field to induce current in stator coils. This is common to use round shape magnet on smaller axial-flux alternators, but as they get larger, it is often more practical to use rectangular magnets, which are available in larger sizes, and the wire coils are more compact. It is important that the rotors be made of steel or iron, so that the magnetic flux is conducted by them [10].

III. METHODOLOGY

The block diagram of power flow in converting solar energy into electrical energy using Stirling Engine generator is shown below;

Heat energy	⟹	Mechanical torque	⟹	Electrical energy
Solar radiation		Stirling engine		Alternator

A. Heat Source

Heat energy from solar power can be obtained by focusing sunlight into a heat absorber (Stirling engine hot cylinder). Since, the device to concentrate sunlight is unavailable, candles will be used to simulate solar power and produce heat source. To estimate the heat produced by candle(s), following heat energy transfer equation can be applied. A volume of water has been heated and temperature and time taken data has been acquired.

$$Q_{in} = (U_2 - U_1)\frac{m}{t} \qquad (4)$$

Q_{in} = energy transfer
U_2 = initiate internal energy (kJ/kg)
U_1 = final internal energy (kJ/kg)
m = mass of water volume (kg)
t = time taken (s)

Internal energy data can be obtained through Table A-4 Thermodynamics Properties by measuring temperature T1 – T2

B. Stirling Engine

<u>The Stirling generator design and fabrication process</u>

Background research
↓
Specification of the project tasks
↓
Preliminary engine design using the literature, practical knowledge and Beale number equations. Select the engine configuration
↓
Select the suitable design alternator to be constructed. Determine its characteristics and the required power from the Stirling engine
↓
Calculate the theoretical engine and alternator power output
↓
Manufacture and fabricate engine at FKM machining workshop
↓
Manufacture and fabricate alternator
↓
Test and measure the power output

i) Design and configuration

Figure 5 shows a Stirling engine generator layout that has been fabricated with collaboration Faculty of Mechanical Engineering UiTM. The engine parts have fabricated with limited material resources and machining capability. The engine was designed based on Gamma configuration. Gamma type is combination of Alpha and Beta type where the cool piston is mounted in a separate cylinder alongside the hot piston cylinder, but still connected to the same flywheel. It consisted double heat cylinder and double cool cylinder with the aimed to increased its' output power.

This engine was also designed to have two separate air chambers where the first hot piston are arranged to be 180° ahead of second hot piston. As a result, compression and expansion processes occurred alternately in different chamber by motion of two hot pistons. It was assumed that arrangement of hot pistons 180° to each other would obtained better distribution of torque to force pistons up and down by flywheel. As mention earlier, flywheel provides inertia required for the engine to prevent loss of engine speed. The inertia of rotating flywheel helps hot and cool pistons to do compressions and expansions.

ii) Engine parts and operation

The engine starts to turn when it gets enough external heat energy to force and expand the hot pistons forward. Hot cap will act as heat absorber and transfer the heat energy inside hot cylinder. Before the hot piston is able to move forward, cool piston will do the compression motion to increase air pressure inside hot cylinder. In order to achieve that, starting torque from flywheel is required to move backward cool piston using crank slider. In most modern Stirling engine, they have particular mechanism to acquire starting torque. However for this small engine, starting torque will be produced by spinning the flywheel manually.

When hot piston moves forward, it will force crank slider to spin crank shaft. The crank shaft which mounted along the flywheel will spin the flywheel to give extra inertia. At this point, air expansion occurred in hot cylinder and the hot air will be dragged into cool cylinder by cool piston. Air will be cooled and gas pressure inside hot cylinder will be at minimum level. However, inertia that has been acquired by flywheel will provide momentum to force cool piston backward to do compression process. Simultaneously, hot piston also will be forced backward to begin the new operation cycle again. These processes will be repeated until no heat energy supplied. It is important to arrange hot piston 90° ahead of cool piston on crankshaft in order to ensure the timing of all practical motions is acceptable.

Air has been selected to be used as the working fluid inside this engine. To achieve a high power density, hydrogen is the best working fluid inside Stirling engine.

Helium is next best to hydrogen in terms of good heat-transfer properties and low fluid friction [7]. Since we had a limitation on the tools and material to fabricated the perfect sealed Stirling engine, hydrogen and helium can't be used as working fluid.

iii) Power output estimation

The techniques of analysis for Stirling engines can be categorized with Martini's [4] nomenclature as follows:

- Zero Order Analysis: as Beale formula or West formula.
- First Order Analysis: (Schmidt analysis) was done in 1871 by Gustav Schmidt.
- Second Order Analysis (uncoupled methods): This level of analysis may be based on an adiabatic analysis that subtracts losses caused by heat transfer and flow power losses. It relies on a modified Schmidt analysis and requires nonlinear time integration of the model equations. It assumes adiabatic expansion and compression regions.
- Third Order Analysis (coupled methods): uses control volumes or nodes to directly solve one-dimensional (2D and 3D) governing equations.

The simplest technique to estimate Stirling engine power output is through the Beale number concept. William Beale observed in 1970 that power output of many Stirling engine conformed approximately to the equation [1] ;

$$P = 0.015p \times f \times Vo \tag{5}$$

Where P = engine power (watts)
p = mean cycle pressure (bar)
f = cycle frequency or engine speed
Vo = displacement of cool piston (cm³)

Mean cycle pressure in Stirling engine is similar to mean effective pressure in internal combustion engine. It can be estimated by following equation;

$$p = \left[\frac{(p3 - p2)V3}{(V1 - V2)}\right] \ln\left(\frac{V1}{V2}\right) \tag{6}$$

Cycle frequency can be calculated from flywheel RPM produce;

$$f = \frac{flywheel\ speed\ (RPM)}{60} \tag{7}$$

The equation was found by Beale to be approximately true for all types and sizes of Stirling engines for which data were available including free-piston machines and those with crank mechanisms [1]. However, the application of Beale number is clearly limited since there are many factors and losses contribute to the power output. Among the contributed factors are [1&6];

i) Thermal efficiency
ii) Compression ratio
iii) Cylinder material
iv) Thermal effect
v) Piston side force
vi) Seals
vii) Oil containments and bearings
viii) Actual thermal power
ix) Shuttle heat transfer loss
x) Regenerator net enthalpy loss
xi) Regenerator wall heat leakage
xii) Pumping losses
xiii) Pressure drop loss

Nevertheless, Beale number provides a handy guideline for new projects and new comers to the development of Stirling engine [1].

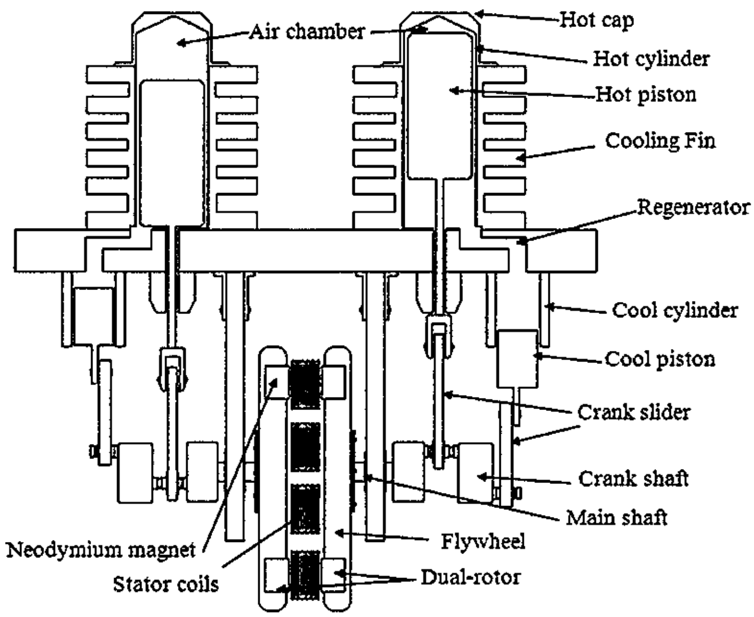

Figure 2: design of Stirling engine generator layout

C. Axial Flux Permanent Magnet Generator

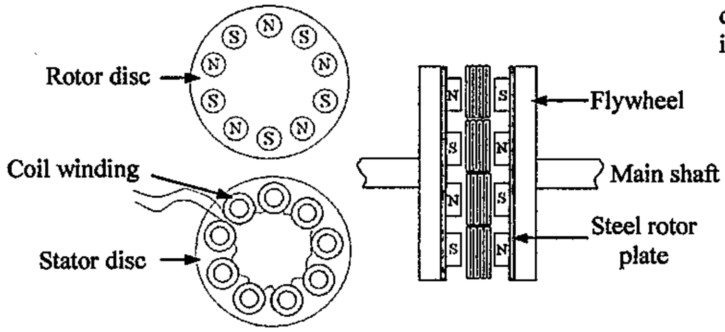

Figure 3: generator topology

In this project, the alternator constructed replicates the construction of most alternators used in small wind turbine. In small wind turbine, many designer prefer to not use any gearing or additional shaft in order to mount their turbine with alternator to generate electricity. Beside than additional cost involve for gearings, certain amount of power will also be dissipated at this point. So that, the best way to mount a small Stirling engine with alternator is by construct it directly on flywheel. The axial flux permanent magnet (AFPM) alternator with dual-rotor is well suited to be constructed on Stirling engine flywheel because it is easy to fabricate and can be made with air as the stator core (iron core make the alternator heavy to turn since small Stirling engine produce low torque), yet it is very efficient if correctly designed.

Total 20 pieces neodymium magnets are arranged in an N-S-N-S pattern around the circumference of the rotors, opposite poles face each other. 10 pieces of magnet are arranged in 1 rotor to form 10-poles alternator. The purpose of this arrangement is to confine and concentrate magnetic flux between two rotors. Figure 4 shows the trace lines of flux, they travel from one magnet face, straight to the magnet face opposite, then travel through the steel rotor plate to the next magnet, and back across the gap. Coils of wire in the gap capture the magnetic energy in those field lines.

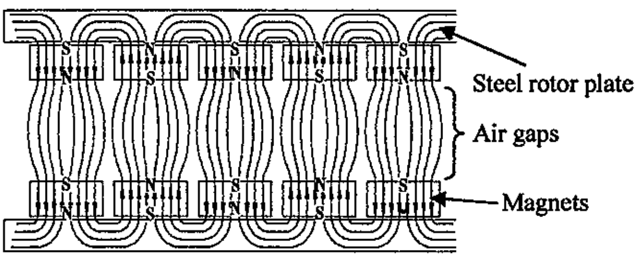

Figure 4: magnet flux path of the dual-rotor

There are 9 coils of enameled copper wired has been wound, each coil consists of approximately 300 turns. They are arranged in series which mean single phase output alternating current is expected. The simple equivalent circuit for this single phase generator is shown in figure 5. This equivalent circuit is assumed to be lossless since losses, magnetic effects and flux density distribution analysis are really complex to be implemented.

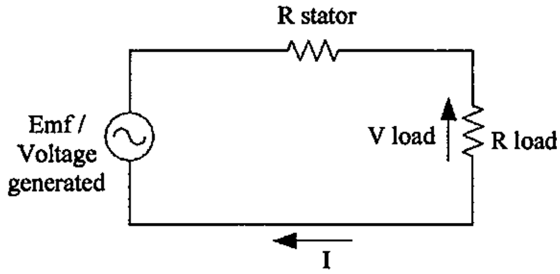

Figure 5: stator equivalent circuit

The generated Emf in a coil can be estimated using Faraday's Law;

$$V_{generated} = -N\left(\frac{\Delta BA}{\Delta t}\right) \tag{8}$$

where N = number of turns
B = magnet Gauss (Tesla)
A = magnet cross area
t = changing time

Table 1: summary of Stirling generator design

Parameter	Value
Engine configuration	Gamma
Crank shaft displacement angle	90°
Working fluid	Air
Hot cylinder Stroke Material	45mm × Ø28mm 20mm Brass
Cold cylinder Stroke Material	40mm × Ø22mm 20mm Aluminum
Hot piston material	95mm × Ø27mm Aluminum
Cold piston material	20mm × Ø20mm Aluminum
Heat source	Candle(s)
Flywheel	Ø140mm
Magnets	NdFeB (N35) 5mm × Ø10mm
Magnets gauss	1.17-1.22 Tesla
Poles	10
Coil wire AWG	26 (Ø0.4mm)
Stator coil Inner radius Outer radius	App. 300turns Ø14mm Ø 24-28mm
Air-gap flux density	0.660T
Air-gap length	16mm
Stator resistance	27.8Ω

IV. RESULTS AND DISCUSSIONS

In order to predict the output power of Stirling engine Beale number had been applied. According to first and second Law of Thermodynamics only 33% of heat energy (Watt) goes to useful work. Heat energy acquired from candle and predicted power output from engine is shown in Table 2.

Table 2: Stirling engine predicted power output from heat source

Heat source (Candle(s))	1	2	3	4	5	6
Qin (Watt)	16	34	51	68	85	102
Pmech (Watt)	4.8	10.2	15.3	20.4	25.5	30.6

From Beale number, RPM produce can be calculated. To measure mean cycle pressure in Stirling engine can't be accomplished since no appropriate equipment available. So the assumption has been made using low pressure operation at 2 bar = 1.974 atm. From the predicted RPM output, we can estimate Voltage AC output from alternator.

Table 3: Predicted output value

Pmech (Watt)	Flywheel (RPM)	Alternator (Vo)
4.8	320	7.4
10.2	430	10.2
15.3	540	12.5
20.4	620	14.4
25.5	710	16.5
30.6	800	18.5

Table 4: Actual Stirling generator output value

Qin (Watt)	Pmech (Watt)	Flywheel (RPM)	Alternator (Vo)
16	NIL	NIL	NIL
34	NIL	NIL	NIL
51	NIL	NIL	NIL
68	NIL	NIL	NIL
85	NIL	NIL	NIL
102	NIL	NIL	NIL

After Stirling engine generator had been completely constructed, it was found that the engine failed to turn and axial flux PMG did not generate electricity as predicted. Many factors that contributed to the failure had been identified. Machining and material limitation was main contributor which make the Stirling engine constructed was not precisely fabricated. The poor fabrication cause the engine not perfectly sealed and create huge friction losses. Furthermore, the flywheel, crankshaft and main shaft were not accurately aligned caused the engine fail to rotate smoothly. In the alternator construction, stator and rotor were failed to be aligned in precise position. It caused the air gap to be elongated and it added losses in magnetic flux. The coils were found not to be wound in correct orientation. It should spiral through the first coil in either a clockwise or counterclockwise direction, and should go the same direction in each of the other coils. Wrong orientation caused the current generate in coils canceled each other when the rotor start to rotate.

V. CONCLUSION

It can be concluded that, the Stirling engine generator built was failed to convert heat to electrical energy as predicted. The generator was designed based on literature review, practical knowledge and under lecturers' supervision, however the poor workmanship of fabrication contributed to the failure. Nevertheless, through this research and development, it provides a handy guideline to understand the basic concept of Stirling engine generator and for future development.

VI. FUTURE WORK AND RECOMMENDATION

It is strongly suggest that sunlight tracker and concentrator system can be built in the future to equip with Stirling engine generator. With the complete solar power generation system, new future renewable energy can be developed and utilized in Malaysia.

VI. REFERENCES

[1] G.Walker, Stirling Engines, Clarendon Press Oxford, pp. 1-123, 1980.

[2] Ron Michaelis, Roger Mutti, Jim Overmyer, Otto Taylor, All About Motors, Thomson Delmar Learning, NJATC Textbook, pp , 2005.

[3] Bancha Kongtragool, Somchai Wongwises, Mechanics, A four power-piston low-temperature differential Stirling engine, Thermal Engineering and Multiphase Flow Research Laboratory (FUTURE).

[4] D M Clucas, J K Raine, Development of a hermetically sealed Stirling engine battery charger, PhD thesis, University of Canterbury, 2006.

[5] R. Bruce Radcliff, Dann L. Roark, Small Engines, American Technical Publishers Inc, Second Edition, pp 50 -145 , 2004.

[6] Jacek F. Gieras, Mitchell Wing, Permanent Magnet Motor Technology Design and Application, Marcell Dekker Inc, Second Edition, pp , 2002

[7] C.M. Hargreaves, The Philips Stirling Engine, Elsevier Science Publisher B.V., pp. 1-206, 1991.

[8] M. Abbas, N. Said and B. Boumeddane, Thermal performances of Stirling engine solar driven, University of Saad Dahleb, 2008.

[9] Yicheng Chen, Pragasen Pillay, Axial-flux PM wind generator with a soft magnetic composite core, Clarkson University Postdam, NY, 2007.

[10] Chalmers, BJ Wu, W. and Spooner E, An axial flux permanent magnet generator for a gearless wind energy system, IEEE Trans. On Energy Conversion, Vol 14, No. 3, June 1999, pp 749-753.