Design and Simulation of Dish-Stirling Solar Thermal Power Plant

Hla Aye Thar#1, Khin Aye Win*2, Soe Win#3

#1 & 3 Department of Electrical Power Engineering, Yangon Technological University
The Republic of the Union of Myanmar

Email - [1]hlaayethar 1970 @gmail.com [2]khinayewin@gmail.com [3]soewin.ep@ytu.edu.mm

Abstract: *The development of green power generation such as solar systems that have become a great interest for several countries especially for Myanmar as it presents a significant solar potential. In this paper, solar thermal has been chosen and designed to be used for rural electrification which is the most suitable technology especially for Myanmar central dry zone. The electricity access rate in Myanmar is about 35 %. It is too small rate compared to neighbouring countries. This research is intended to fulfil the electricity requirement in Myanmar to some extent as a several small off-grid power systems with parabolic dish units in the range of 25kW to 1MW will be proved. Monthly DNI of the absorber and Temperature in Magway location during a year are reported in this paper. Sizing of Parabolic Dish is calculated and designed. Detailed tests of the proposed standalone system was implemented in Matlab/Simulink software, by taking as a case study a measured load profile for a rural house and solar radiation data at the Magway area. In this paper load distribution for 100 households of Magway region and banking of 12V batteries are presented. Finally, it is calculated to a cost evaluation which aim to investigate the financial aspect of investing in a variable speed drive done.*

Key Words: *Concentrated solar power, dish-Stirling system, Parabolic Dish, temperature control.*

1. INTRODUCTION:

Faced with the progressive exhaustion of fossil energy reserves and their harmful impact on the environment, the interest towards sustainable and renewable energy is in continuous growth thanks to its friendliness and their efficiency. Considering 60% of the transmitted sunlight through the atmosphere, it is surprising that the total sun's energy reaching the earth is 1.05×10^5TW [1]. If this energy on only 1% of the terrestrial Surface could be converted into heat and electricity with an efficiency of 10% it would provide about 105TW. That is a great resource base comparing with the total global needed energy for 2050, which is estimated to be about 25–30 TW. In the field of solar power supply systems, there are different technologies such as solar cell with an efficiency of 20%, photovoltaic concentrators (PVs) at about 40% and solar thermal systems ensuring efficiencies of 40–60% [1]. Currently, solar dish Stirling power generators (SDSPG) are classified as the most efficient models by exceeding the efficiency of any other solar conversion technology [3]. They have become of a great interest to countries where solar potential is available with huge amounts such as Myanmar. Several researches for small Scale (SS) SDSPG (<1 MW) have been taken in place that focus on the design and control of standalone power generation systems [5]. In this paper the proposed stand-alone energy system, shown in Fig.1, consists of an induction generator (IG) based variable speed solar dish Stirling system, a battery and a variable AC load. Among different types of machines used in SDSPG, IG has several advantages such as its simple design and its ability of slow operation with remarkable efficiency [5]. Mechanical torque generated by Dish Stirling system depends on weather conditions. And during the night hours when solar power is null, the batteries take the place of generator. The generated AC power is rectified to DC, then inverted to AC power with constant voltage and frequency, as needed by the load side. There are two types of interfaces between the generator and the load. The first configuration is a rectifier with single switch mode (diodes) and an inverter .The second configuration is presented by back-to-back converter to provide a vector control for the IG. For this reason, the latter was adopted in this paper. Hence, this paper proposes an approach to develop model of SDS/IG to study the feasibility and the performance of the standalone system under Magway climatic conditions in order to improve the rural electrification program [5].

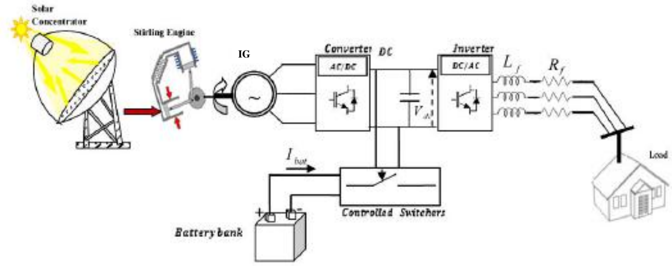

Fig-1: A solar stand-alone Dish Stirling/IG supply system with storage battery

I. DESIGN & CALCULATION OF D.S SOLAR THERMAL POWER PLANT

A.Theoretical Background

The Concentration ratio C is defined as the ratio of the aperture area to the absorber area i.e

$$c = \frac{Aa}{Aabs} \quad (1)$$

Where A_a is the aperture area, the area of the collector that intercepts solar radiation & A_{abs} is the total area of the absorber surface that receives the concentrated solar radiation [4].

B. Optical Efficiency

The optical efficiency is defined as the ratio of the energy absorbed by the absorber to the energy incident on the concentrator aperture [3]. It includes the effect of mirror/lens surface, shape and reflection/transmission losses, tracking accuracy, shading, receiver-cover transmittance, absorptance of the absorber and solar beam incidence effects. The optical efficiency is given as:

$$\eta_o = \frac{P_{abs}}{A_a \bar{I}_D} \qquad (2)$$

Where I_D is the long-term average direct radiation and the optical efficiency of most solar concentrators lies between 0.6 and 0.7 [4].

C. Thermal Efficiency

The thermal efficiency is defined as the ratio of the useful energy delivered to the energy incident at the concentrator aperture:

$$\eta_{th} = \frac{\rho V c_{pf}(T_2 - T_1)}{I_b A_a} \qquad (3)$$

Where I_b = beam radiation, T_2=temperature of heat transfer fluid leaving the collector, T_1=temperature of heat transfer fluid entering the collector [4].

D. Instantaneous Thermal Efficiency

The instantaneous thermal efficiency of a solar concentrator may be calculated from an energy balance on the absorber [4]. The useful thermal energy delivered by a concentrator is given by:

$$q_u = \eta_o I_b A_a - U_L (T^4{}_{abs} - T_a) A_{abs} \qquad (4)$$

Therefore, the instantaneous thermal efficiency may be written as

$$\eta = \frac{q_u}{I_b A_a} = \eta_o - \frac{U_L (T_{abs} - T_a)}{I_b C} \qquad (5)$$

At higher operating temperatures the radiation loss term dominates the convection losses and the energy balance equation may be written as

$$q_u = \eta_o I_b A_a - U_L (T^4{}_{abs} - T^4{}_a) A_{abs} \qquad (6)$$

Instead of Eq. (4).

In Eq. (6) U_L takes into account the accompanying convection and conduction losses also. The instantaneous thermal efficiency η is now given by

$$\eta = \eta o - \frac{U_L (T^4{}_{abs} - T^4{}_a)}{I_b C} \qquad (7)$$

Since the absorber surface temperature is difficult to determine, it is convenient to express the efficiency in terms of the inlet fluid temperature by means of heat removal factor F_R as:

$$\eta = F_R \left[\eta_o - \frac{U_L (T_L - T_a)}{I_b C} \right] \qquad (8)$$

The instantaneous thermal efficiency is dependent on two types of quantities, namely the concentrator design parameters and the parameters characterising the operating conditions. The optical efficiency, heat loss coefficient and heat removal factor are the design dependent parameters while the solar flux, inlet fluid temperature and the ambient temperature define the operating conditions [5]. According to the calculated results, parameters of parabolic dish collector for 30kW are shown in Table.1.

Table. I. The parameters of parabolic dish collector for 30kW

Components	Size
Diameter	7.681m
Aperture Area	46.336m^2
Rim Angle	71.57°
Focal Length	2.664m
Height	1.38m

2. SYSTEM CONFIGURATION AND MODELING:

A solar stand-alone Dish Stirling/IG supply system with storage battery shown in Fig. 1 has been proposed in this paper [3]. The design and modeling of this SDS/IG system have been carried out and simulated by Matlab/SIMULINK software.

A. Simulation strategy

The absorbed heat energy is converted into mechanical energy produced by the linear movement of the two pistons. Then, this linear movement is converted into rotation to drive an induction generator [3] . The models of DSE studied above in a rural area under variables climatic conditions during a day are described in the following block diagram in Fig. 2. The ideal adiabatic model was implemented in MATLAB software and resumed by the algorithm illustrated in Fig. 3.

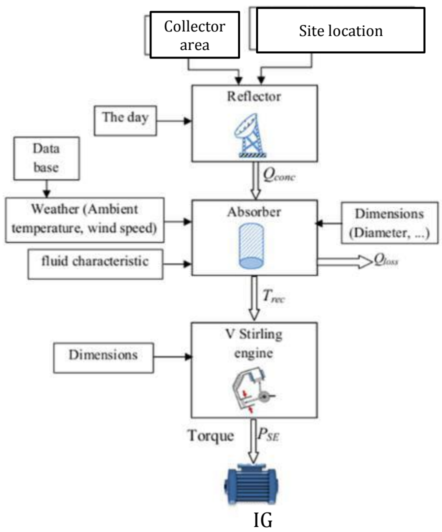

Fig.2 Dish Stirling engine simulation block diagram

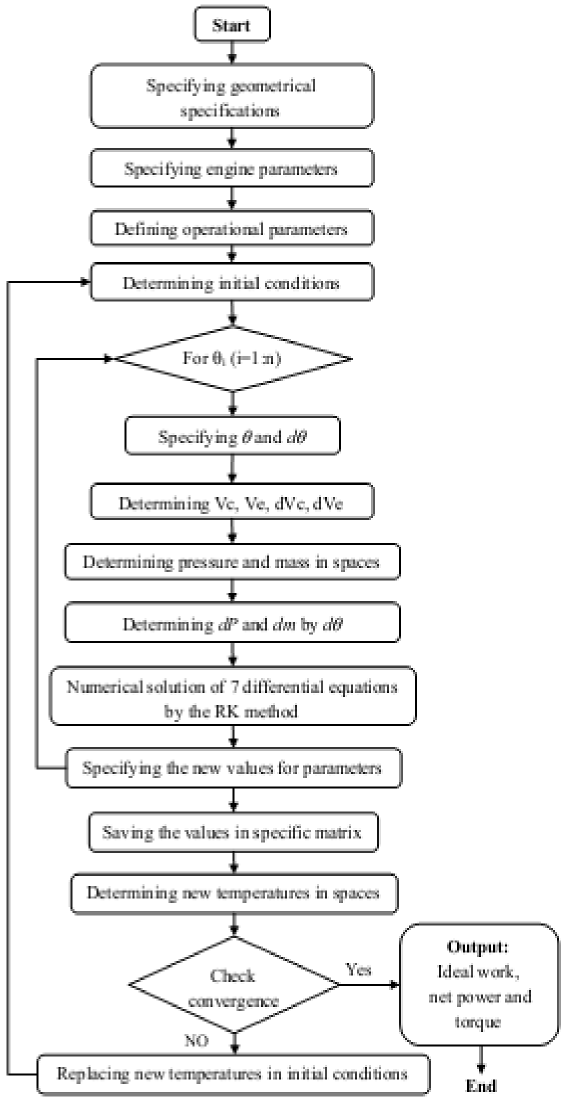

Fig. 3 Resolution algorithm of the ideal adiabatic thermal model.

3. TEMPERATURE CONTROL:

The objective of the temperature control system (TCS) is to maintain the temperature of the absorber at its maximum possible temperature while staying within the thermal limits of the absorber and receiver materials [2]. The temperature is controlled by varying the pressure of the working gas inside the engine. An external high pressure storage tank can supply additional gas to the engine, and thus increase the pressure. During times of high irradiance, the temperature will increase on the absorber surface, so working gas is added from the high pressure storage tank to the engine to regulate the absorber temperature, which also has the effect of increasing the power output of the dish-Stirling system [2]. During times of low irradiance, gas can be removed from the engine by means of a compressor pumping gas back into the high pressure storage tank or by having a separate low pressure tank, where a control valve can be opened to allow gas to flow naturally out of the engine shown in Fig. 4.

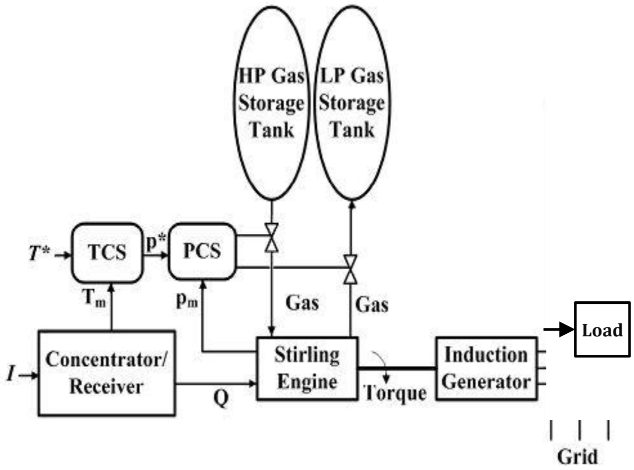

Fig.4. Dish-Stirling temperature control system diagram

When the measured temperature on the absorber is below the temperature set point T_{SET} the command pressure remains at its idle point shown in Fig.5. As the temperature increases above T_{SET}, the command pressure from the TCS increases to regulate the increasing temperature on the absorber. The temperature ΔT_{MAX} defines how much the absorber temperature can increase above the predefined temperature set point and still be regulated by the PCS. Once the absorber temperature exceeds $T_{SET} + \Delta T_{MAX}$, the pressure inside the Stirling engine is at its maximum, and cannot be increased further to regulate the absorber temperature. Under normal operating conditions, the temperature on the absorber varies from T_{SET} to ΔT_{MAX}, independent of irradiance level [3].

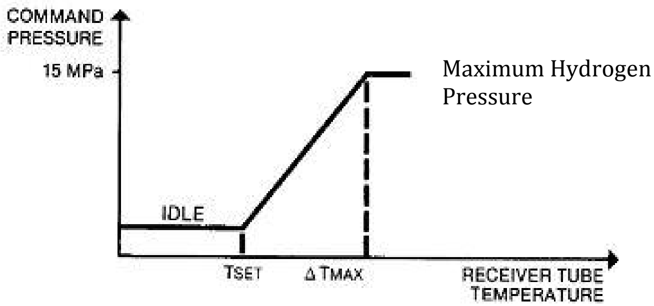

Fig.5 Relationship between absorber temperature and command pressure

4. SIMULATION RESULTS AND DISCUSSION:

The simulation model of the presented standalone SDS/IG supply system with energy storage has been modeled by Matlab/Simulink software under Magway meteorological conditions and for an uncontrollable power load. Fig.6 (a) presents the direct normal irradiation (DNI) data that has been taken from meteorological station of Magway. It clearly shows that the level of monthly average values of the irradiation is high (>400 W/m^2) over the whole year. Fig.6 (b) the peak is reached in March, April and May while small intensities are available from December to January. Hence, Magway Region has a high potential solar radiation encouraging to install dish/Stirling systems.

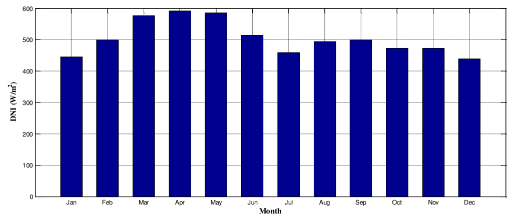

Fig.6 (a). DNI of the absorber

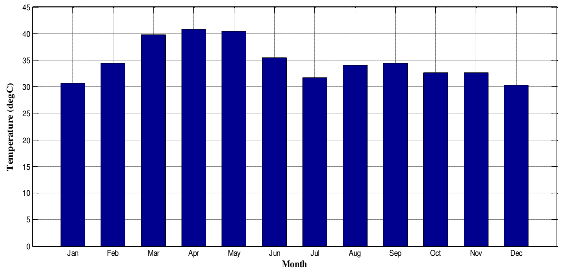

Fig.6 (b). Temperature in Magway location during a year

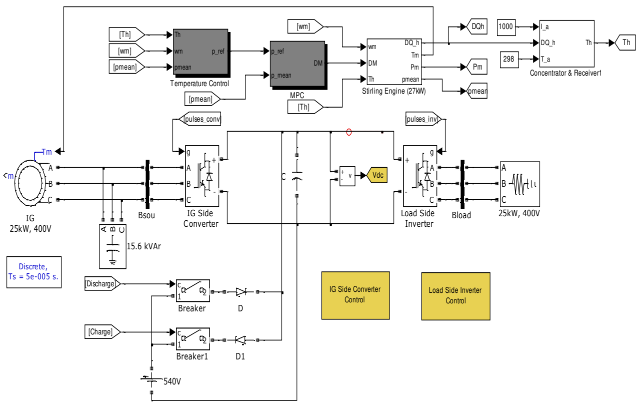

Fig.7 Simulink model of DS solar-thermal power plant

The parameters of the DS system from the simulation are:

- η_{con}= 0.89 ; A_{con}= 46.34m^3; K_r =200; K_l = 14.83; T_a= 298K; K_v=1.0; T_v=0.02s;
- V_{sw} = 95cm^3; V_{cl} = 10cm^3; V_h= 33.08cm^3;
- θ = 0.89π rad; b=0.2
- P_{max}= 20 MPa; P_{min}= 2 MPa; $T_{h,max}$= 1033 K;
- I_{max} = 1000W/m^2 ;
- $P_{m,N}$ = 27 kW; $\omega_{m,N}$ = 157 rad/s.
- P_{IG}=25kW; V=400V; P=4 poles; f=50Hz;
- A 15.6 kVAr static capacitor bank is connected at the terminal of the induction generator for reactive power compensation purpose.

The model of the power system, including that of the DS system, are established in MATLAB/Simulink and is illustrated in Fig. 7. Powers distribution curve, DC-bus voltage, AC output current, AC output voltage of the standalone DSIG system during a day in April are shown in Fig.8 (a) , (b), (c) and (d). Powers distribution curves of the studied system (day in December) is also presented in Fig.9 and the household power consumption for a typical day is shown in Fig.10.

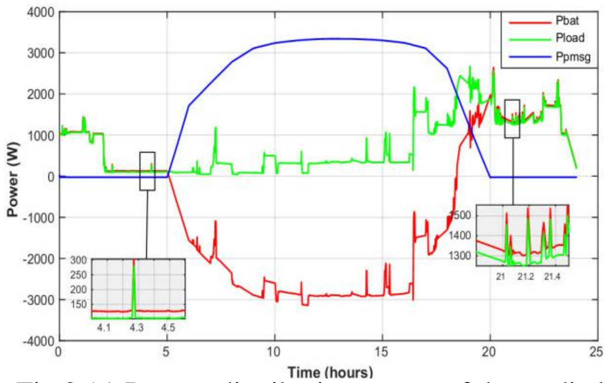

Fig.8 (a) Powers distribution curves of the studied system (day in April)

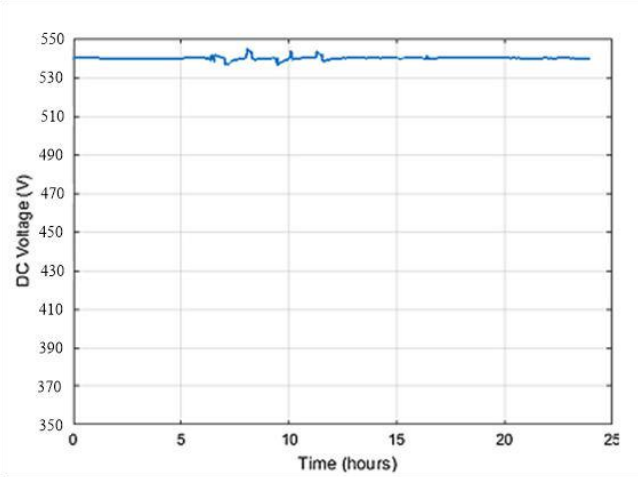

Fig.8 (b) Dc-bus voltage of the standalone DSIG system for a day in April

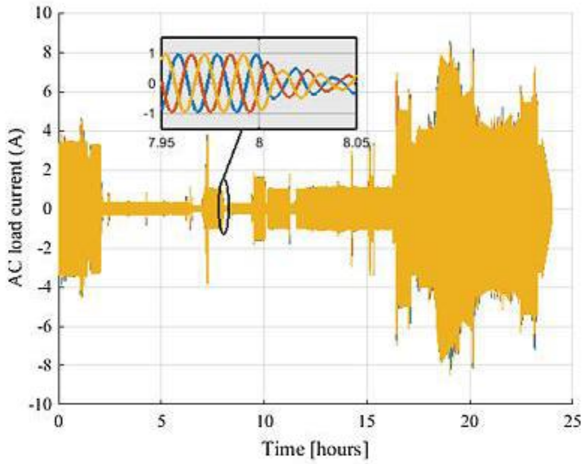

Fig.8 (c) AC output current during a day in April

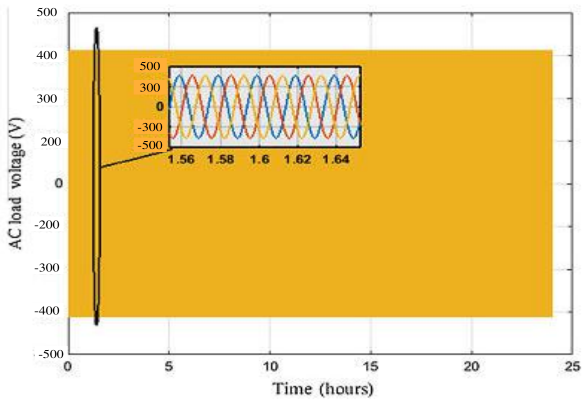

Fig.8 (d) AC output voltage during a day in April

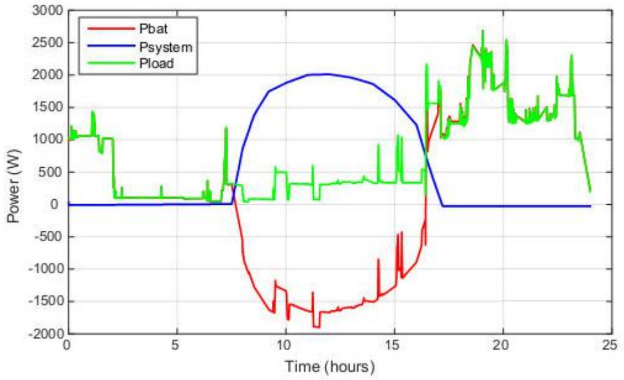

Fig.9 Powers distribution curves of the studied system (day in December)

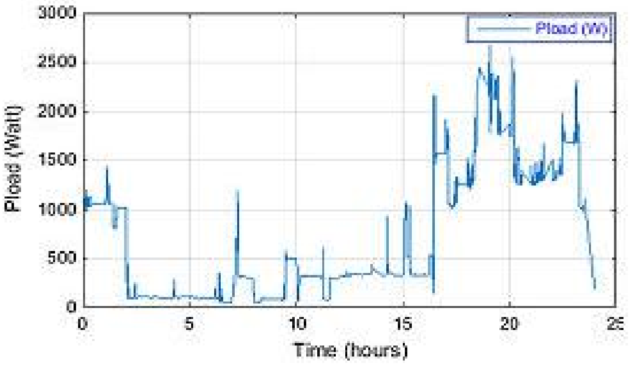

Fig.10 The household power consumption for a typical day

5. CONCLUSION:

If one housed hold used 2.5kW, 10 nos. of household will be supplied from one unit. For one hundred households, 10 nos. of parabolic dishes are required. Outputs from all units are connected in parallel. If 12V batteries are used in this system, 45 nos. of batteries are connected in series to meet 540V of one unit. For 10 nos. of parabolic dishes, 450 nos. of 12 V batteries are required and theses are connected in 10 parallel paths. In each parallel path, 45 nos. of 12 V batteries are connected in series. Important to consider is that the CSP system is to be sold in bigger parks giving many MW output. For a small 1MW power plant site, 40 solar dish Stirling, the net present value without considering maintenance and implementation costs is about 95550 USD. For one of the PDS/IG power plant, the investment cost will be about 2387 USD. Or about 3.2 million kyats/unit. This research can be easily extended by adding more D.S dishes and batteries with same capacity when the incomes of households are increased. The decentralized power generation seems to be a very interesting solution to provide electricity for the rural areas. In this paper, the solar Dish Stiling/induction generator system is presented as a new generation of standalone solar plant by proposing an energy storage device. The proposed standalone solar energy conversion system was modeled in this study for remote house located in Magway. This region sits approximately between north latitude 18˚ 50′ to 22˚ 47′ and east longitude 93˚ 47′ to 95˚ 55′ and a measured solar radiation data for this location. A detailed analysis including dish/Sirling thermal, mechanical and electrical modeling has been developed and implemented in MATLAB Software.

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REFERENCES:

1. Y. Kadri, H. Hadj Abdallah, *"Energy Conversion and Management".*
2. Peter Brunnsaker, Martin Ortling, *"Investigation of feasibility for an inverter-controlled variable speed drive in a stirling CSP application",* Department of Energy and Environment, Division of Electric Power Engineering, Chalmer University Oftechnology G¨oteborg, Sweden 2012.
3. Dustin Howard, Student Member, IEEE and Ronald G. Harley, Fellow, IEEE , *"Modelling of Dish-Stirling Solar Thermal Power*
4. *Generation".*
5. Y. Li, Student Member, IEEE, S. S. Choi, Senior Member, IEEE,C. Yang, *"Dish-Stirling Solar Power Plants: Modeling, Analysis and Control of Receiver Temperature".*
6. Liaw Geok Pheng, Mohd Ruddin Ab Ghani, Rosnani Affandi, Chin Kim Gan, Zanariah Jano, Nur Huda, *"Receiver Temperature Control of the Parabolic Dish Stirling Engine",* Universitiy Teknikal Malaysia Melaka (UTeM), 76100, Durian Tunggal, Melaka, Malaysia.
7. Anna Winkelmann, *"Design, Modeing, and Experimental validation of a Stirling Engine with a Controlled displacer piston",* May, 2015 Nashville, Tennessee.
8. Joshua Dulin, Matthew Hove, Jonathan D. Lilley, *"Stirling Engine – Bringing Electricity to Remote Locations"* , The Faculty of the Mechanical Engineering Department California Polytechnic State University, San Luis Obispo.