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RESEARCH ARTICLE

DESIGN ANDSIMULATION OF DISH-STIRLING SOLAR THERMAL POWER PLANTIN TROPICAL REGION

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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 tropical region of Myanmar. In solar thermal electricity generation, Dish-Stirling solar power generation has emerged as an efficient and reliable source of renewable energy. As the technology moves into commercialization, models become necessary to predict system behavior under various operating conditions. 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 this paper, the thermal, electrical, and control systems of the dish-Stirling system are presented, along with a method for simulation. The modeling and simulation is executed in detailed for the proposed standalone system by using Matlab/Simulink software.

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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 $1.05x10^5$TW (Peter Brunnsaker, 2012). 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% (Peter Brunnsaker, 2012). Currently, solar dish Stirling power generators (SDSPG) are classified as the most efficient models by exceeding the efficiency of any other solar conversion technology (Li*et al*., 2014). They have become of a great interest to countries where solar potential is available with huge amounts such as Myanmar.

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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 (Dustin Howard, 2010). In this paper the proposed stand-alone energy system, shown in Figure 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 (Dustin Howard, 2010). 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. 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 (Dustin Howard, 2010).

Design and calculation of d.s solar thermal power plant

Theoretical Background

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

$$c = \frac{Aa}{Aabs}$$ Equation 1

Where A_a is the aperture area, the area of the collector that intercepts solar radiation and A_{abs} is the total area of the absorber surface that receives the concentrated solar radiation (Dustin Howard, 2010).

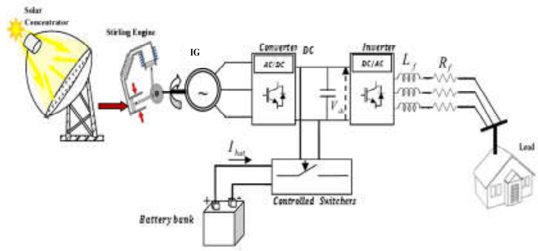

Figure 1. A Solar stand-alone Dish Stirling/IG Supp System with Storage Battery

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(Li, 2014). 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:

$$\eta_o = \frac{P_{abs}}{A_a \bar{I}_D}$$ Equation 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(Dustin Howard, 2010).

Thermal Efficiency

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

$$\eta_{th} = \frac{\rho V c_{pf}(T_2 - T_1)}{I_b A_a}$$ Equation 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 (Dustin Howard, 2010).

Instantaneous Thermal Efficiency

The instantaneous thermal efficiency of a solar concentrator may be calculated from an energy balance on the absorber (Dustin Howard, 2010).The useful thermal energy delivered by a concentrator is given by:

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

Therefore, the instantaneous thermal efficiency may be written as

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

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

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

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

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

According to equation 8, the instantaneous thermal efficiency is dependent on two types of quantities, namely concentrator design parameters and parameters characterising the operating conditions(Dustin Howard, 2010). According to calculated results, parameters of parabolic dish collector for 30kW are shown in Table 1.

Table 1. 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

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 (Anna Winkelmann, 2015). 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 (Anna Winkelmann, 2015). 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 Figure 2.

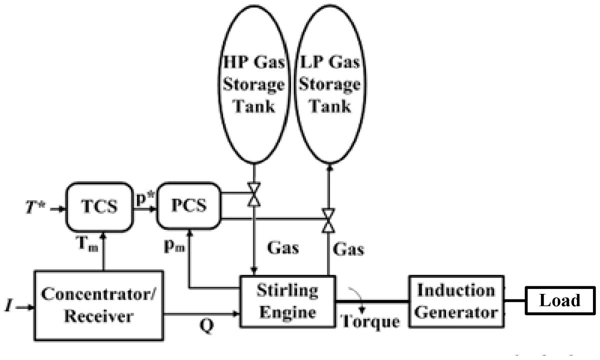

Figure 2. Dish-Stirling temperature control system diagram

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 figure 3. 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 (Li, 2014).

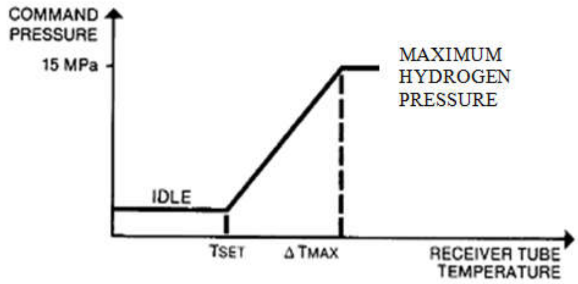

Figure 3. Relationship between absorber temperature and command pressure

System modeling and simulation

A solar stand-alone Dish Stirling/IG supply system with storage battery shown in figure 1, has been proposed in this paper (Li, 2014). The design and modeling of this SDS/IG system have been carried out and simulated by Matlab/ SIMULINK software.

Modeling of the System

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 (Li, 2014). 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 figure 4. The ideal adiabatic model was implemented in MATLAB software and resumed by the algorithm illustrated in Figure 5.

Simulink Model of the SDS/IG System

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.

Figure 6(a) presents the direct normalirradiation (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. Figure 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. The model of the power system, including that of the DS system, are established in MATLAB/Simulink and is illustrated in Figure 7.

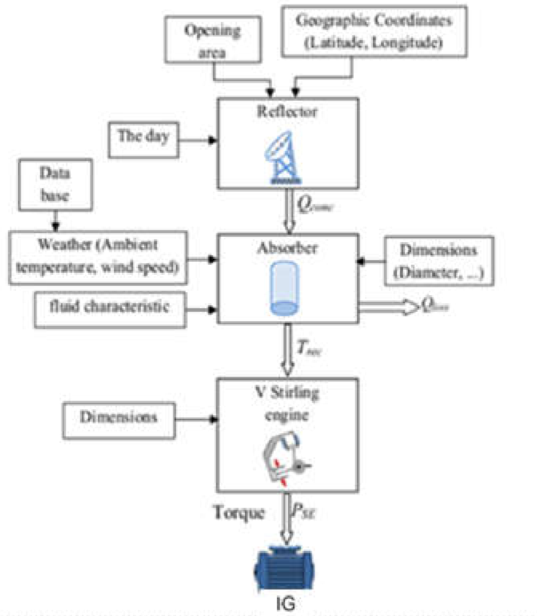

Figure 4. Dish Stirling Engine Simulation Block Diagram

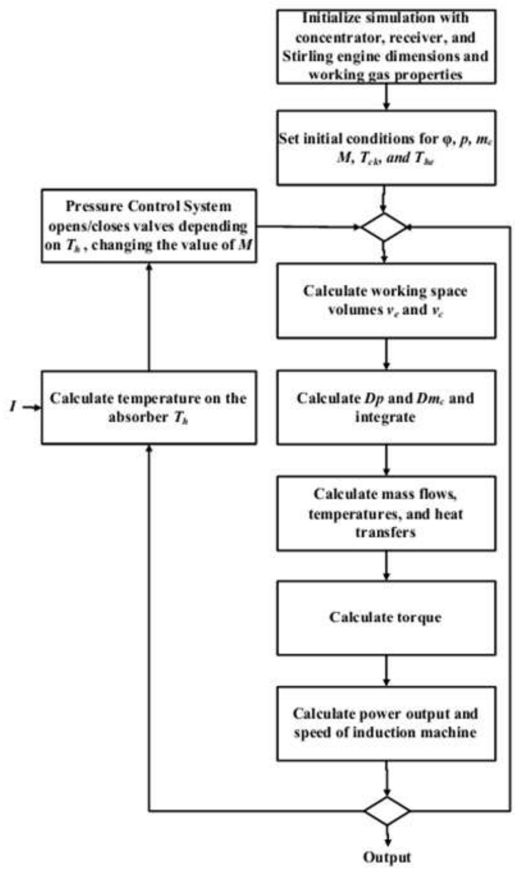

Figure 5. The Ideal Adiabatic Model of the SDS/IG System

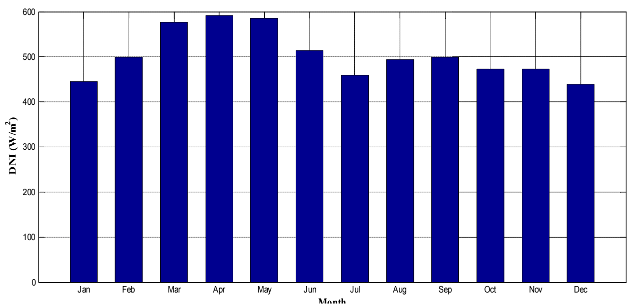

Figure 6 (a) DNI of the Absorber

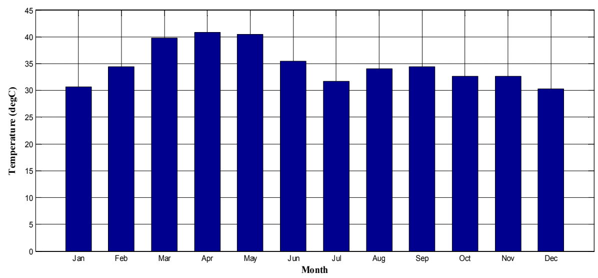

Figure 6 (b) Temperature in Magway Location during a Year

It can be seen that the present model reveals reasonable agreement with the experimental data. In the next section, the proposed micro plant power generation is mainly driven by a parabolic dish of 46.336 m^{2}as opening area. The reflector is oriented in order to harvest maximum sunlight and concentrate it in the focal point where located the cylindrical absorber, which contains a fluid that is heated by thesolar radiation.

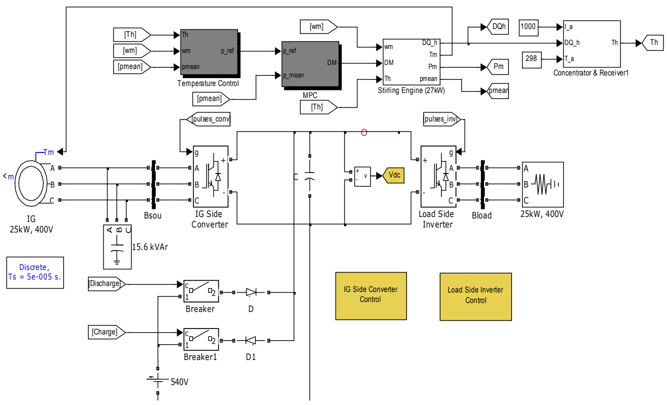

Figure 7. Simulink Model of DS Solar-Thermal Power Plant

SIMULATION RESULTS AND DISCUSSION

The parameters of the DS system from the simulation results are shown in Table 2. A 15.6 kVAr static capacitor bank is connected at the terminal of the induction generator for reactive power compensation purpose.

Table 2. The parameters of the ds system from the simulation results

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	I_{max} = 1000 W/m^2
V_{sw}= 95cm^3	V_d = 10cm^3	V_h = 0.08cm^3	$T_{h,max}$= 1033 K
$P_{m,N}$= 27 kW	$\omega_{m,N}$= 157rad/s	P_{max}= 20MPa	P_{min} = 2 MPa
P_{IG} =25kW	V = 400V	P = 4 poles	F = 50Hz

Powers distribution curve, DC-bus voltage, AC output current, AC output voltage of the standalone DSIG system during a day in April from simulation are shown in figure 8(a), (b), (c) and (d). Powers distribution curves of studied system (day in March) and (day in December) are also presented in figure 9 and 10.

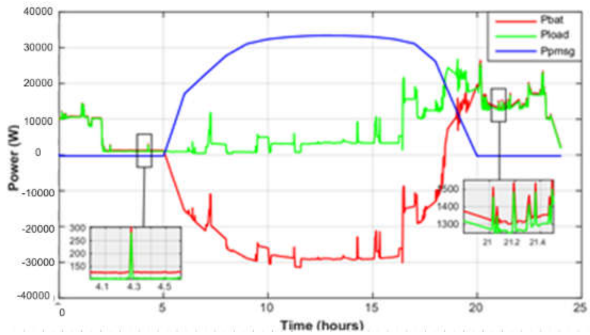

Figure 8. (a) Powers Distribution Curves of the Studied System (April)

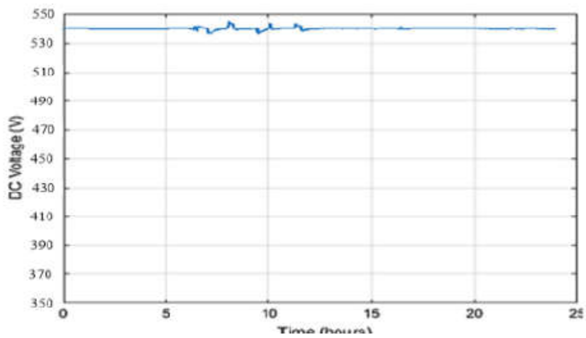

Figure 8. (b) Dc-bus Voltage of the Standalone DSIG System

Performance Analysis

From figure 8(a), the energy consumption exceeds the amount of renewable power generated at night while it is lower, during the day, when solar radiation intensity is significant. In fact, during the period from 10 h to 14 h, the solar radiation is higher than 600 W/m^2. This increases the power produced by SDS/IG system to reach more than 25 kW. From the previous results, it is seen that energy consumption is higher than renewable electricity at night to reach the peak at 7 p.m. of about 26.7 kW while it is lower during daylight when solar radiation intensity is important. The detailed analysis of the figure 7 has shown the following:

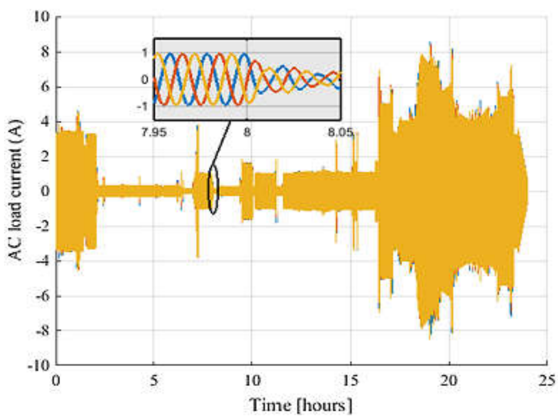

Figure 8 (c) AC Output Current

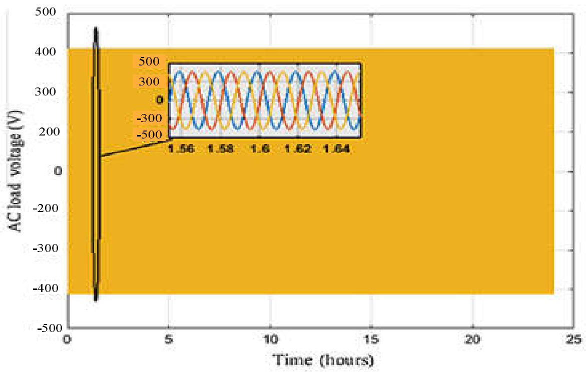

Figure 8. (d) AC Output Voltage

At daylight (from 5 a.m. to 7 p.m.) the diode D_1 is switched on if the power consumption is lower that the renewable power, the amount in excess is stored in batteries.From sunset to sunrise (from 8 p.m. at 5 a.m.), because of the absence of solar rays, renewable power is not enough to meet the increase of load, so the diode D is switched on. In addition to the DSIG power the batteries bank is used to feed the costumers.Itis seen that the performance of the controller of the switching relays is satisfactory because of the changes of the power from the battery bank (charges/discharges) in order to ensure system power stability under varying conditions of load demand and DNI. The DC-link voltage has been maintained at constant value of 540 V for the variation of load and radiation during the day as shown in figure 8(b). The peaks in the curve of DC-bus have very low values of ±4% V. They show that the DC link is in an acceptable range and the standalone dish Stirling system maintains its stability in different load conditions.

The output AC current is varying according to the user consumption during the long of day as shown in figure 8(c). The zoom applied in this figure shows the decrease of AC current when the load power decreases at simulation time 7.95 s to 8.05 s and similar phenomenon occurred when load power increases the current output increases.For above load profile, load voltage for the whole day has been shown in figure 8(d). It is seen that the load side inverter (LSI) presents satisfactory performance because it keeps the stability of load voltage at 400V during the solar and load power variation.

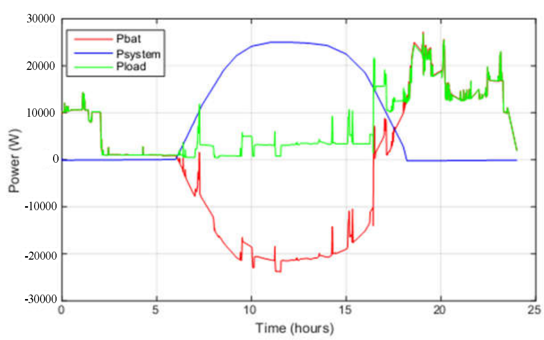

Figure 9. Powers distribution curves of studied system (day in March)

Simulations results presented in figure 8, 9 and 10 were performed using for three cases of calculated solar radiation; hot, average and cold seasons. The analysis of the obtained results proves that the proposed SDS/IG system fulfils the energetic objectives; the relays switching ensure the system autonomy and then the continuity of power supply for the intermittent load under different meteorological conditions.

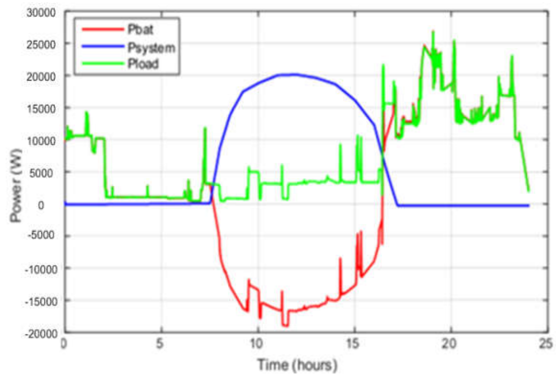

Figure 10. Power distribution curves of studied system (day in December)

A load profile representing the consumption of a rural house located in the Myanmar tropical zone (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 was used.Figure 11 shows an hourly model of household power consumption during a day. It has been observed that maximum load of 1300–2500 W between 5 and 12 p.m. During this period, the inhabitants are at home. However, in the rest of day, they are out of home and this reduces electricity demand.

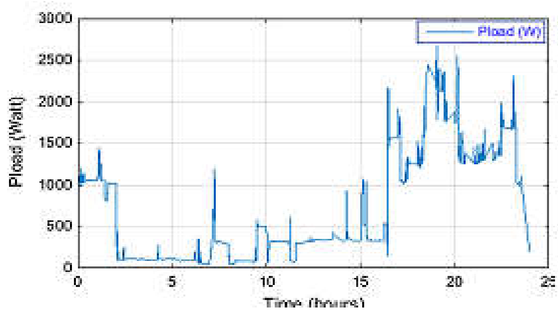

Figure 11. The household power consumption for a typical day

RESULTS AND CONCLUSIONS

According to figure 11, this design would like to supply about ten household of Myanmar Tropical zone. For hundred households, ten number of parabolic dishes are required and 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 of DS/IG system. 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. In this paper, 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. 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 Stirling/induction generator system is presented as a new generation of standalone solar plant by proposing an energy storage device. A detailed analysis including dish/Stirling thermal, mechanical and electrical modeling has been developed and implemented in MATLAB software.

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