Design and Implementation of a Low Cost Dual-Axis Heliostat Mirror System for Power Production Purposes

Umar Farooq, Muhammad Salman Tahir, Nauman Haider, Hafiz Muhammad Ishtiaq Awan, and Muzzamil Janjua

***Abstract*—this paper aims to provide a prototype design for future large scale power production to mitigate energy crisis faced by Pakistan these days. The design is based on an inexpensive dual axis heliostat mirror assembly which tracks the sun and concentrates the solar energy at point where thermoelectric generators are installed to produce electrical power. The sensor less tracking of sun and movement of the system is governed by complex astronomical calculations which give the location of the sun at a particular latitude, longitude and time. The system employs accurate gear assemblies and feedback control system to achieve precise and smooth motion required for tracking. Maintenance free software of the system needs only to be configured once. It only has one time manufacturing cost and its maintenance cost is negligible with respect to output of the system. The paper concludes with the accuracy and stability of tracking system for future development usage.**

***Index Terms*—Solar energy, Heliostat mirror assembly, Sensor less sun tracking, Thermoelectric generators, Feedback control theory, Microcontroller implementation**

I. Introduction

Even in today's world market, with all of the vast technology advancements and improvements, there are still people who live in darkness at night and use candle light or kerosene lamps to study. These people have the knowledge that electricity exists; however, the area in which they reside lacks the infrastructure and resources for such an amenity. Also, throughout the world, the demand for useable energy is increasing rapidly, with electricity being the energy of choice. The electricity production, however, does not come for free. There is cost associated with the infrastructure for setting up new power production facilities and the rising cost and lack of natural resources such as oil, coal, and natural gas imposes another constraint. One solution is to steer away from conventional methods and look for novel, alternative, renewable energy resources, such as solar energy. The sun is an excellent source of radiant energy, and is the world's most abundant source of energy. It emits electromagnetic radiation with an average irradiance of 1353 W/m^2 on the earth's surface [1, 2]. The solar radiation incident on the Earth's surface is comprised of two types of radiation – beam and diffuse, ranging in the wavelengths from the ultraviolet to the infrared (300 to 200 nm), which is characterized by an average solar surface temperature of approximately 6000°K [10]. The amount of this solar energy that is intercepted is 5000 times greater than the sum of all other inputs – terrestrial nuclear, geothermal and gravitational energies, and lunar gravitational energy [1]. To put this into perspective, if the energy produced by 25 acres of the surface of the sun were harvested, there would be enough energy to supply the current energy demand of the world. In order to extract electrical energy from solar energy, some sort of concentrating body need to be employed.

The concentrating body has most crucial importance among all parts as any irregularity in concentrator shape can make the focus point arbitrary and non effective. In this regard, Shuai et al. [3] proposed new design for concentrator/cavity receiver systems using the Monte-Carlo ray-tracing method. In the study, the radiation flux distribution inside the receiver was calculated, and, by performing ray-tracing analysis for different geometry of receivers, they proposed the "upside-down pear cavity" as the cavity receiver that presents the most stable energy flux through its aperture.

This paper uses heliostat mirror assembly as a concentrating body. Heliostat is a device consisting of an assembly which revolves slowly occupying a tracking mechanism so as to converge sunlight at a fixed focus. The concentrated sunlight at the focus provides better solar energy concentration usage. Heliostats have been used to concentrate solar energy for many years. Among the challenges to be overcome are energy losses and sun tracking. Chen et al. [4] proposed a fixed asymmetric curvature with the spinning-elevation tracking method. This restriction was intended to equalize the manufacture cost of the new heliostat with that of traditional heliostats with azimuth-elevation tracking and spherical curvature. The results showed that the new heliostat design could reduce the receiver spillage loss by 10–30%, and provided good uniform performance without large variations with time of day. Instead of performing tracking motions in discrete steps as it is done in most heliostat systems, Kribus et al. [5] proposed a continuous tracking methodology. A significant reduction of tracking error by smooth continuous tracking was achieved. Measurements of heliostat motion showed that aiming error due to tracking intervals was practically eliminated. In order

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to avoid shading of the dish by the receiver, Kribus and Ries [6] proposed a new concentrator design for small systems with a constraint of limited mobility of the receiver which is accomplished by using a first polar axis and a second axis that is aligned with the normal to the ecliptic plane. The new design features resulted in limited motion of the receiver; off-axis reflector to eliminate shading; constant rotation speed in both axes; and constant flux distribution on the receiver.

A heliostat must track the sun position with a high degree of accuracy so various forms of tracking mechanisms, varying from simple to complex have been proposed. They are mainly mechanical or electric/electronic system. Generally, the electronic system can exhibit better reliability and tracking accuracy. These include motors controlled electronically by various sensors, which detect the magnitude of solar illumination. Another approach which is used in this research is to calculate the position of sun using astronomical calculations which provides high accuracy to the system. A complex tracking system generally use controlled motors with feedback system. Conventionally, a dual axis azimuth-elevation tracking mode heliostat is more common.

In the early history of heliostat's development, it was mostly used in astronomy field for solar observation. It was also used to study other celestial bodies and for spacecraft instrument calibration. In solar energy research field, heliostat has been applied mostly in the high temperature solar furnace, solar power station and stirling engine based solar concentrators. Hybrid systems for solar (renewable) energy utilization have attracted considerable attention from scientists and engineers during the last decade because of their higher efficiency and stability of performance in comparison to individual solar devices [7]. They make use of waste heat and solar energy for generation of electricity, or even for direct applications such as heating of water, refrigeration or air conditioning.

Since solar energy input is only available during the day, solar systems require the use of some thermal storage strategy for later energy reuse. Much research has been conducted on thermal accumulation systems, for many types of systems that have an interrupted energy input (e.g., clouds, night periods). For the sake of brevity, and as examples of solar energy thermal storage systems, two recent studies by Salomoni et al. [8] and Vaivudh et al. [9] can be cited for better handling of heat storage plants.

II. System Architecture

A. Master Controller

AVR ATMEGA32 is used as master controller. It is used because of its high speed and memory which makes it ideal to perform astronomical calculations. Also, it provides ADC channels which are utilized to implement feedback control system. USART communication is used to interface it with the slave controller. It is also responsible for controlling motors in turn achieving precise tracking of sun.

B. Slave Controller

Atmel AT89S52 is used as a slave controller. It provides built in multiplexed address/data bus which is used to interface it with RTC. It reads time from the RTC and sends the time to the master controller through USART. It is also responsible for LCD and Keypad operation for better user interface with the system.

C. RTC

DS12887 is used as a Real Time Clock (RTC) for the system. It has a multiplexed address/data bus through which it can be interfaced with microcontroller.

D. Position Controller

Position controller is implemented inside master controller i.e. ATMEGA32. It takes the position of the sun which is calculated and forwards it to the stepper controller. For accurate tracking, feedback system is also employed. It takes the feedback from the POTs which are installed at the both axis of motion of the system.

E. Stepper Controller

Stepper Controller is responsible for driving the motors as directed by the position controller. It takes the position of the sun from the position controller and moves the system to the desired position. The block diagram describing system architecture is shown in Fig. 1.

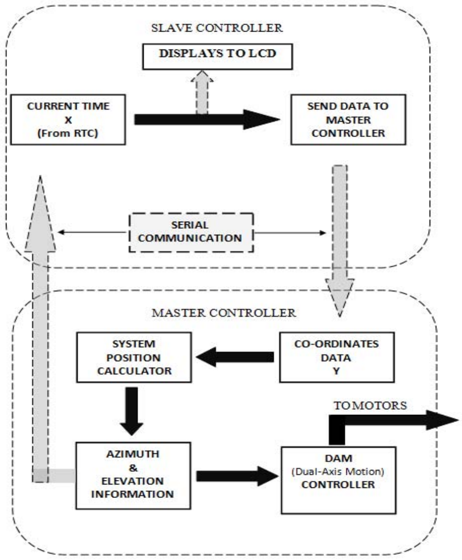


Fig. 1. System Architecture

III. Mechanical System Design

System mechanical design is mainly composed of four parts which includes:

A. Parabolic Reflector

Parabolic reflector is used to converge sunlight at the focus. The size and the depth of the reflector are chosen according to the desired output and design of the system. We designed a parabolic reflector to converge sunlight at the focus and utilize it for producing power. The size of the parabolic reflector is chosen to be 4 ft. for our prototype. The reflector is designed to have its focus at 2 ft. For reflection, mirror coated acrylic sheet is used which provides excellent reflectivity and achieves desired results quite comfortably. The reflector area is 11.56 ft.2 which provides us with enough solar energy to achieve our goals. The parabolic reflector is shown in Fig. 2.

Fig. 2. Parabolic Reflector

B. *Fork Assembly*

Fork assembly is responsible for the elevation motion. It comprises of a fork shaped frame which holds the parabolic reflector frame, stepper motor and a harmonic gear drive which is used with the stepper motor to achieve better accuracy. Stepper motor used is of 200 steps/rev. Harmonic drive provides a ratio of 80:1 which provides system with smooth elevation movement. The fork assembly is shown in Fig. 3.

C. *Base Assembly*

Base assembly includes worm gear assembly which is responsible for azimuth motion. Worm gear ratio is 1:120. Fork assembly is mounted through thrust bearing on this base assembly. The base assembly is shown in Fig. 4.

D. *Power Production Unit*

Thermoelectric generators are devices which convert heat (temperature differences) directly into electrical energy, using a phenomenon called the "Seebeck effect" (or "thermoelectric effect"). Their typical efficiencies are around 5-10%. Older Seebeck-based devices used bimetallic junctions and were bulky while more recent devices use bismuth telluride (Bi2Te3) semiconductor p-n junctions and can have thicknesses in the millimeter range.

Fig. 3. Fork Assembly

Fig. 4. Base Assembly

1) Thermoelectric Generators (TEGs) Setup: A special generator assembly is designed to provide the proper environment for TEGs to operate. It nearly requires a difference temperature of around 150^{o}C between its two surfaces. One TEG cell produces up to 5W of power depending upon the intensity of heat. So a hybrid serial-parallel combination is used in which 4 TEGs series group is connected in parallel with the other to enhance current rating.

All TEGs, as shown in Fig. 5, are placed on a flat surface of aluminum sheet with thermal grease between their surfaces to provide continual access of heat from heated sheet to the TEG cell surface.

After placing and wiring of the cells another aluminum sheet is placed over them with thermal grease in between sheet and cell surfaces to seal TEGs in with polyester foam in between sheets. It is illustrated in Fig. 6.

2) Heat Sinks: A heat sink is a term for a component or assembly that transfers heat generated within a solid material to a fluid medium, such as air or a liquid. Examples of heat sinks are the heat exchangers used in refrigeration and air conditioning systems and the radiator (also a heat exchanger) in a car. Heat sinks also help to cool electronic and optoelectronic devices, such as higher-power lasers and light emitting diodes (LEDs).

Heat sinks are used to remove heat from another side of thermoelectric generators so that seebeck effect can take place. So they are placed over the upper aluminum surface with thermal grease in between surface contacts. The heat sink setup is shown in Fig. 7.

3) Sealing Acrylic Box: Fully sealed acrylic sheet box is used to seal the whole heat sinks so that a coolant can be easily introduced without any leakage which controls heat sink's temperature to shoot. The sealing box is shown in Fig. 8.

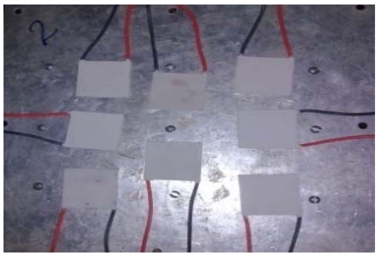


Fig. 5. Thermoelectric Generators Setup

Fig. 6. Sealed TEGs

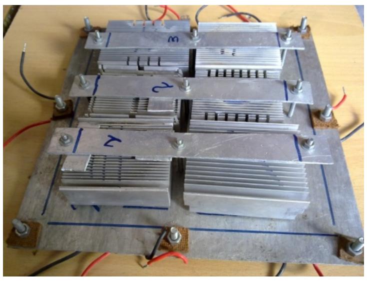


Fig. 7. Heat Sink Setup

Fig. 8. Sealing Box

4) Heat Removing Oil: Transformer oil or heat removing oil is usually a highly-refined mineral oil that is stable at high temperatures and has excellent electrical insulating properties. It is used in oil-filled transformers, some types of high voltage capacitors, fluorescent lamp ballasts, and some types of high voltage switches and circuit breakers. Its functions are to insulate, suppress corona and arcing, and to serve as a coolant.

Insulating oil is introduced to the sealed chamber where it helps to cool the heat sinks owing to its good characteristics as a coolant. The completed TEGs assembly is shown in Fig. 9.

5) Wooden Box: A 121 sq. inch wooden box is made to prevent the TEG assembly to the direct exposition to sunlight. First of all a heat insulator thermo pole sheet is placed and glued over the entire box and then completed assembly is placed in it. The designed power generation box is shown in Fig. 10 while the complete mechanical assembly of the system is shown in Fig. 11.

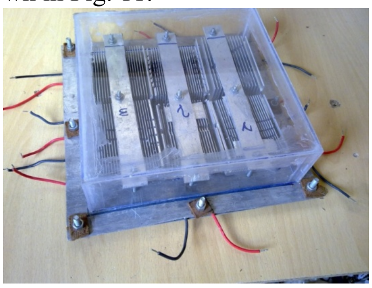
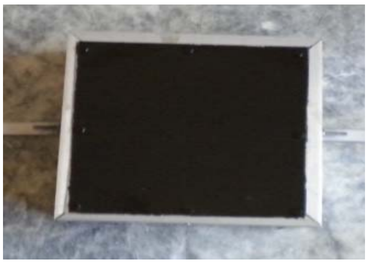


Fig. 9. Compelete TEGs Assembly



(a)

(b)

Fig. 10. Power Production Box (a) Front View (b) Rear View

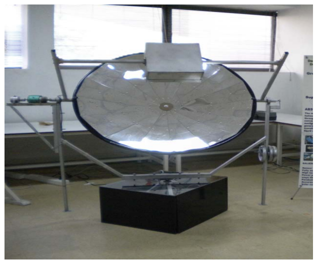
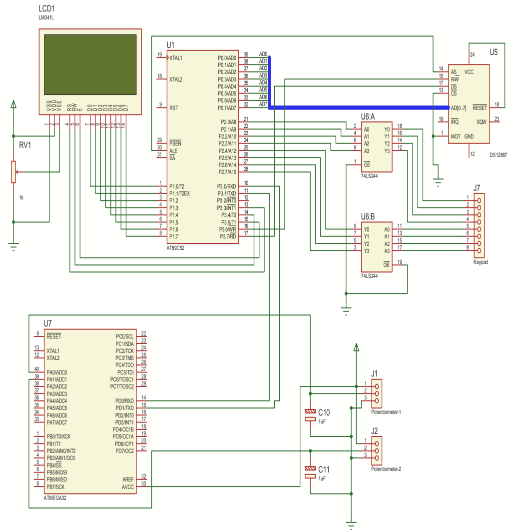


Fig. 11. The Completed Mechanical Assembly of Heliostat System

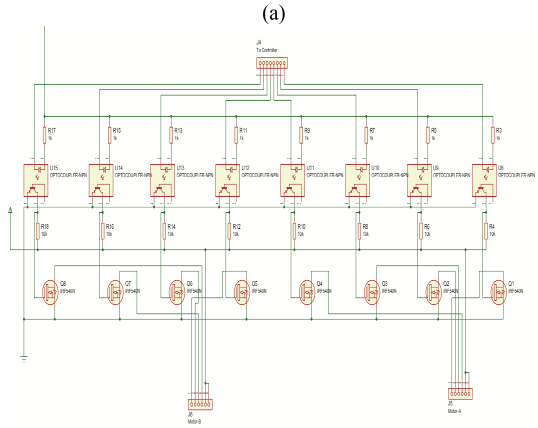
IV. Electrical System Design

The main purpose of the electrical system is to drive the mechanical assembly and perform accurate tracking of the sun. The main functions of the setup are to perform azimuth and elevation calculations, drive motors, interface with real time clock, interface with LCD & Keypad for user interaction.

AVR ATMEGA32 is used to perform the calculations because it operates at 8 MIPS, so it can also execute the control algorithms and drive the stepper motors accordingly. AT89S52 is used to interface with Real Time Clock (DS12877) which provides the current time for calculations. LCD & Keypad are interfaced with AT89S52 for user interaction and both controllers communicate through serial port. The connection diagram of system is shown in Fig. 12 while the designed printed circuit board is shown in Fig 13.



(a)



(b)

Fig. 12. System Wiring Diagram (a) Microcontroller Interfacing Circuit (b) Motor Driver Circuit

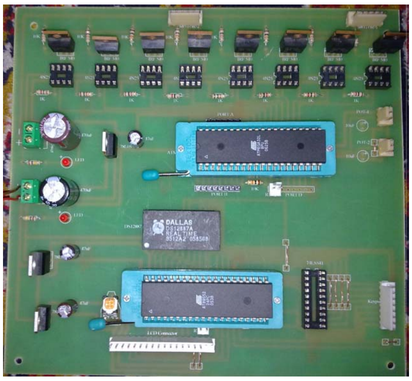


Fig. 13. Designed PCB for Contol of Heliostat Power Production System

V. Sensor less Tracking Methodology

A. Tracking Equations

Derivation work is already done on tracking equations. Tracking equations are used in reference from the work done by Peter-Duffett Smith [11].

B. Tracking Algorithm

D-A-M ALGORITHM ( )
1) INITIALIZE-SERIAL-TRANSMISSION ( )
2) $\Theta_E \leftarrow$ Elevation Angle
3) $\Theta_A \leftarrow$ Azimuth Angle
4) $\Theta_{ACK} \leftarrow$ Acknowledgement
5) $\Theta_{AD} \leftarrow$ Angle Data
6) $\Theta_{Eo} \leftarrow \emptyset$
7) $\Theta_{Ao} \leftarrow \emptyset$
8) **Wait** for Serial Interrupt
9) **while** DAY
10) **if** Θ_{AD} request from slave controller
11) SEND-SERIAL Θ_{AD}
12) **Wait** until Θ_{ACK}
13) **do** $\Theta_E \leftarrow$ Sun-POSITION ( )
14) $\Theta_A \leftarrow$ SUN-POSITION ( )
15) **while** $\Theta_A \neq \Theta_{Ao}$
16) **do**
17) $\Theta_{Ao} \leftarrow \Theta_A$
18) $\Theta_{CA} \leftarrow$ Current Azimuth Angle
19) **do**
20) $\Theta_{CA} \leftarrow$ Sensor-POSITION ( )
21) **while** $\Theta_{CA} \neq \Theta_{Ao}$
22) **do**
23) DRIVE-Azimuth-MOTOR ( )
24) $\Theta_{CA} \leftarrow$ Sensor-POSITION ( )
25) **while** $\Theta_E \neq \Theta_{Eo}$
26) do
27) $\Theta_{Eo} \leftarrow \Theta_E$
28) $\Theta_{CE} \leftarrow$ Current Elevation Angle
29) do
30) $\Theta_{CE} \leftarrow$ Sensor-POSITION ( )
31) **while** $\Theta_{CE} \neq \Theta_{Eo}$
32) **do**
33) DRIVE-Elevation-MOTOR ( )
34) $\Theta_{CE} \leftarrow$ Sensor-Position ( )

C. Controller Flow Charts

The flow charts for master and slave controllers are shown in Fig. 14 and 15 respectively.

D. Slave Controller Algorithm

S-C ALGORITHM ( )
1) INITIALIZE-SERIAL-TRANSMISSION ( )
2) INITIALIZE-LCD ( )
3) INITIALIZE-RTC ( )
4) $\Theta_E \leftarrow$ Elevation Angle
5) $\Theta_A \leftarrow$ Azimuth Angle
6) $\Theta_T \leftarrow$ Time
7) $\Theta_{ACK} \leftarrow$ Acknowledgement
8) $\Theta_{AD} \leftarrow$ Angle Data
9) **while** DAY
10) $\Theta_{AD} \leftarrow \emptyset$
11) $\Theta_T \leftarrow$ READ-RTC ( )
12) DISPLAY-LCD (Θ_T)
13) **if** $\Theta_T >$ 10 SEC
14) **then**
15) SEND-TIME-DATA ( )
16) **Wait** until Θ_{ACK}
17) $\Theta_{AD} \leftarrow$ REQUEST-ANGLE-DATA ( )
18) **if** $\Theta_{AD} \neq \emptyset$
19) then
20) SEND Θ_{ACK} for received data
21) DISPLAY-LCD (Θ_E)
22) DISPLAY-LCD (Θ_A)
23) **else**
24) $\Theta_{AD} \leftarrow$ REQUEST-ANGLE-DATA ( )
25) **else**
26) **Wait** for 500ms

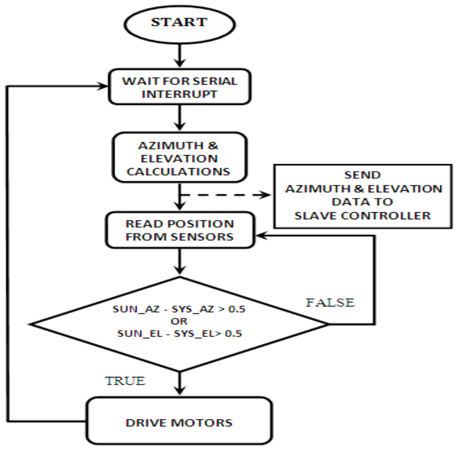


Fig. 14. Master Controller Flow Chart

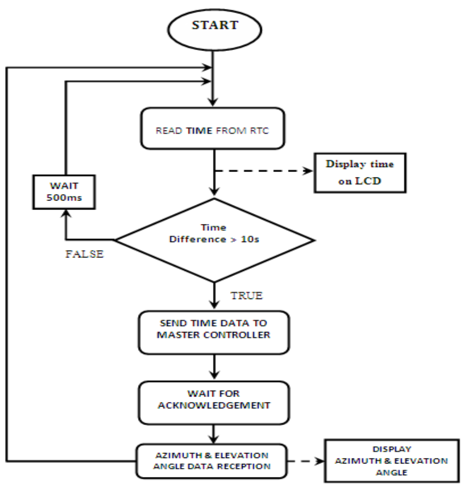


Fig. 15. Slave Controller Flow Chart

VI. System Analysis & Optimization

A. System Stability

For every system, stability is the parameter on which the operation of whole system relies. The primary function of the system is directly affected by the system stability which in this case is power production.

Counter weights are used to achieve higher rank of stability of the system mechanical structure. Two counter weights are used to make both the axis of elevation and azimuth stable. The elevation counter weights support the weight of the power production assembly and introduce a counter-torque to support the fork assembly which in turn enhances the system stability in great deal.

Feedback control system is implemented to make the software part aware of the mechanical system position at all times. This information then helps the software to make decisions to achieve better stability in the tracking system.

Stability of the system ensures the better working of system and make it desirable disturbance tolerable. Noise introduced during tracking such that a push or pull through any undesired source is firstly mitigated by the system mechanical and then in turn stability is further enhanced by the efficient algorithm implementation.

It can be concluded that the system is stable in terms of operating mechanism. This is due to the fact that the positions of the mechanical parts are fixed and therefore not much affected by parameter changes other than the intensity of the sunlight and surrounding effects.

B. System Accuracy

System accuracy gives the measure of the ability of the system to perform the primary function according to the desired specification without any erroneous working. As the system tracks the sun without any sensors using complex astronomical equations, so a high level of accuracy is required.

The system has a tolerance of around 2^o-3^o i.e. the power production capability is not affected by this much error. Yet the system achieved an accuracy of $\pm$ 0.25^o regardless of the atmospheric conditions and change of seasons.

C. System Sensitivity

System sensitivity is the measure of the change in output of the system when the input is varied by a small amount. In this system, the input is the position of the sun in the sky in form of two angles and output is the movement of the mechanical assembly of the system which tracks the sun. The system showed high sensitivity as it responded to very small changes in the angles characterizing the position of the sun. The Output i.e. the movement of mechanical system was observed to follow the position of the sun according to the changes in the characterizing parameters. The system is found to be so sensitive that it detects and mitigate any undesirable angles changes in the output of the system to stop the system to do erroneous tracking of the sun.

D. Sensitivity & Stability under Severe Atmospheric Conditions

Severe atmospheric conditions force the system to deviate from its normal operating characteristics. To mitigate these effects, feedback control system is made efficient enough to tackle these conditions to some extent.

If the external forces are small and under a certain threshold, the system mechanical gear assemblies together with the efficiently implemented algorithms ensure the normal operation of the system. On the other hand, if these external forces are greater enough to do harm to the system while it is in operation, a special detection system is installed to move the system in sleep mode. In sleep mode, the system becomes compact enough by facing downward to become more robust and tackle these severe conditions. Also, in heavy rains and extreme windy environments the system electrical supplies are cut-off to prevent any sparking or hazardous damage to the system.

E. Speed of Reaction

While tracking, the speed of reaction of heliostat is considered fast as it responds almost instantaneously when the angles characterizing the position of sun are changed. Also, when the system is restored from sleep mode, it tracks the sun instantly. The system reacts very fast to move the system back to its original position when external forces cause it to deviate from its desired position.

F. System Efficiency

System efficiency is the ratio of the power produced to the input power. In this case, the input is the power received from the sun and the output is the electrical power produced.

The system produced the peak power of 40W during operation when the temperature difference of 150^oC was achieved. The experimental results are shown in Table 1.

TABLE I: Output Results

Temperature Difference (^oC)	Voltage (Volts)	Current (Amps.)	Power (Watts)
75	8.4	2.28	19.2
100	10.04	2.82	28.31
150	12.84	3.16	40.57

The system received maximum input solar power of approximately 1KW. The system produced electrical power of 40 watt at maximum input. Thus, the system achieved an accuracy of 4%. The efficiency of the system can be increased by using better cooling solution for the TEGs. The system has the capability to improve power production to 100 watts by minor changes in the design.

VII. Conclusions

The design and implementation of a low cost dual axis heliostat mirror system for power production is presented. The goal of designing this system was to make a low cost system which can achieve lower cost per watt. The system achieved a cost of Rs. 750/watt which is very low for a prototype systems where as past prototypes cost Rs.1320/watt (11€/watt). Also the cost of the system can be greatly reduced by mass production making it competitive and suitable for commercial purposes.

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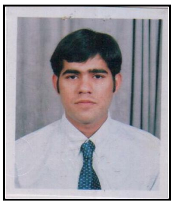

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Hafiz Muhammad Ishtiaq Awan, was born on DEC 1985. After doing intermediate from Government College University, Lahore in 2006, he entered in the field of engineering with a passion and high rank of interests in power systems control and stability. He received his B.Sc. Electrical Engineering degree in 2010 from University of the Punjab, Lahore. He has a deep interest in renewable energy resources and started research in CSP Technologies.

Muzzamil Janjua, was born on September 18, 1988. He completed his Electrical Engineering degree from University of The Punjab Lahore in 2010. His core research interests include renewable energy, power transmission and distribution. Currently he is focusing on production of power using renewable energy resources and interfacing the developed system to grid.