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Characterization of cadmium sulfide light dependent resistors sensors for optical solar trackers

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ABSTRACT

The aim of this paper is to study the effect of dissimilarity of the intrinsic characteristics of the light dependent resistor (LDRs) on optical sun tracking systems, designed for solar power concentration applications such as parabolic trough collectors, Fresnel mirrors concentrators, and concentrated photovoltaic, a comparative study was done between a sun tracker based on LDRs chosen randomly with and without an initial calibration of the offsets, and a sun tracker based on LDRs selected meticulously thanks to a black box test bench, developed especially for this purpose. By choosing two light dependent resistors randomly, the dissimilarity between them can reach 23.2%, which cause a bad sun tracking even with initial offset calibration, in the other hand, and by the use of selected LDRs using the test bench, the dissimilarity drops to 0.06%, which meets requirements of solar power concentration systems.

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1. INTRODUCTION

Nowadays all climate scientists have agreed that the planet earth is facing huge environmental catastrophe, like the melting of the polar glaciers, rising sea levels, drought and desertification, all these phenomena are directly linked to global warming caused by the increase of greenhouse gas emissions due to the increase in polluting industrial activities since the industrial revolution [1]. Depending on climate specifications of each geographic area, many clean sources of energy solutions can be advised [2], [3], with the aim of solving the energy crisis, climate change, and global warming, the most abundant renewable sources of energy is solar energy [4], it can be exploited to produce electricity by using photovoltaic solar panel or concentrated photovoltaic, or to produce thermal energy by using solar concentrators such as Fresnel mirrors concentrators [5], parabolic trough collectors [6]. Solar trackers systems are required in the cases of solar concentration systems such as Fresnel mirrors concentrators, parabolic trough collectors and concentrated photovoltaic, while in the case of photovoltaic panels, the sun trackers are not mandatory, but allows better performances that can reach 40 to 60% [7], [8] in comparison to a static photovoltaic panel, depending on weather conditions.

It exists two types of automatic sun tracking systems [9], [10], the first one is called passive, because it don't use any electric or electronic components, it is based on elementary and simple mechanisms, such as movement of fluids [11], thermal expansion effect of some materials [12], bimetallic strips [13] in the other hand, the second type of sun tracking systems, is based on electric and electronic components (comparators, microcontrollers, microprocessors) and hydraulic/electric motors or actuators, to drive the metallic structure to the correct azimuth and elevation angles in order to face the sun rays.

The active sun trackers are divided into three other systems:

- Sensorless sun trackers: this type of sun trackers uses astronomic equations that can predicts the position of the sun depending on date-time and geographic location, it have the advantage of being independent of weather conditions, but it requires feedback from motor's encoders in order to know its position, and needs an initial precise installation and calibration with Nord pole axis [14].
- Sensored sun trackers: this type of sun trackers is based exclusively on sensors, it usually use electro-optical sensors such as light dependent resistors [15], [16], photodiodes [17], cameras [18]–[20], it have the advantages of do not needs a feedback from motors, don't needs an initial alignment with the Nord pole and it is totally independent of the date–time and the geographic location of the system, but it is weather sensitive and miss easily the sun position during cloudy days.
- Hybrid sun trackers: These kind of sun trackers is a combination of the two previous types; it mixes their advantages in order to track the sun roughly using the astronomic equations, then it switch to the optical sensors to refine the final exact position, if the sky is cloudy, then, the sun tracker uses just the sensorless mode to keep at least an approximate position, better than stop sun tracking in the case of sun trackers based on sensors [21].

The aim of this paper is to study the effect of the dissimilarity of intrinsic characteristics of cadmium sulfide light dependent resistor [22], [23] sensors on sun tracking accuracy, and propose a solution to avoid the caused side effects, applied to a Fresnel mirrors concentrator.

2. METHOD AND TOOLS

2.1. Light dependent resistor (LDR) test bench

In order to study and compare the intrinsic characteristics of the light dependent resistors. It was necessary to build a black box test bench that allows to select two couples of light dependent resistors accordingly to their illuminance-resistance characteristics. One couple for azimuthal tracking and the other one for the elevation tracking, then install them on a 3D printed holder assembly, in order to test them on a dual axis Fresnel mirrors solar tracker system, built especially to test the accuracy of the selected LDR by focusing the sunlight on an evacuated tube collector. By measuring the temperature at the evacuated tube collector surface, it can be approved that there is or no an effect on the accuracy of the sun tracking system.

2.1.1. Mechanical part

The test bench setup is based on an opaque 3D printed box as shown in Figures 1 and 2, composed of two compartments, the internal walls of the first compartment is painted with a matte black color and contains a halogen bulb lamp, in front of it, there is a placement that holds the LDR to be able to illuminate it using the bulb lamp. The second compartment is reserved to the electric and electronic circuitry needed to perform the data collection. The box has a sliding door that allows the user to install the desired LDR to test, and to block any out coming light that can interfere with the internal light source and may alter the experiment, and also allows access to the electric and electronic circuitry in order to maintain it, in addition to that the box have an input power socket, an output universal serial bus (USB) port to connect it with a personal computer (PC), in order to record generated data thanks to a developed software.

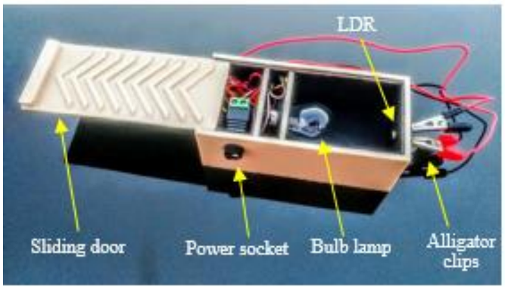

Figure 1. Overview of the black box test bench with open slide door

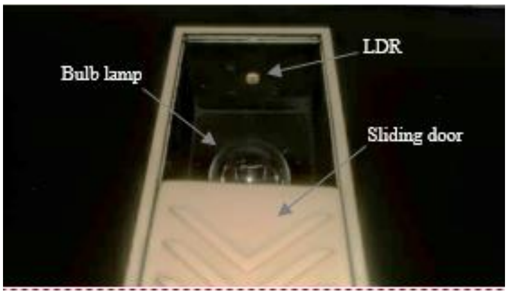

Figure 2. A view inside the black box, with the incandescent bulb lamp facing the LDR

2.1.2. Electric and electronic part

The aim of the electric and electronic part, is to create a dimmer circuit to vary the light intensity of the incandescent bulb lamp, in order to pass overall light intensities starting from darkness to maximum brightness, for this, a microcontroller is used to drive a power metal oxide semiconductor field effect transistor (MOSFET) using a pulse width modulation (PWM) signal, a 12 v DC 3 A power supply is used to power the microcontroller AtMega328p, and the incandescent bulb lamp P21 w 12 v via the MOSFET IRFB4110, the microcontroller starts with a PWM duty cycle of 0% and goes to 100%, during the variation the microcontroller read the returned values sent by the LDR through the microcontroller's 10 bits analog to digital converter (ADC), and record it into a file in order to process all collected data later, the LDR is connected to the electronic circuit thanks to two alligator clips, and the whole electronic circuit is connected to a computer via a USB cable. The reason for choosing an incandescent bulb lamp is to have a light source that most approach and cover the solar spectrum, in comparison with other indoor light sources that have a spiny and discontinued spectrum.

2.1.3. Software part

The used software is developed with python 3.9, and consists on once the LDR is connected to the circuit, the start button is then pressed, the microcontroller's PWM output pin start generating a signal with the lowest duty cycle in order to drive the MOSFET at its lower power mode, to have a low light intensity, then the program stops for 500 ms to let the light be stable, then the microcontroller read the returned light intensity value by the LDR, and send it to the software in order to store it with the correspondent PWM value, after that, the microcontroller increases the PWM duty cycle to its next level and reads the return value and so on. Once all desired LDRs are tested, then collected data is inserted in a spreadsheet software in order to have a better organization and to analyze it.

2.2. Dual axis solar tracker

2.2.1. Mechanical part

Figure 3 shows the metallic structure that allows the Fresnel mirrors to track the sun on its azimuth and elevation axis thanks to two electric motors, each one is driven accordingly to its two corresponding LDRs, as shown in Figure 4 the LDRs holder is 3D printed using a high precision resin 3D printer, the holder is crossed by two walls in order to create shadows on the LDRs when they are facing the sun rays, each wall have on its opposite sides an LDR, that send measured illuminance value to a microcontroller, then a software processes all received data and decides in which direction motors should turn. The LRDs holder assembly is fixed at the highest available point of the metallic structure in order to avoid any shadows or reflections.

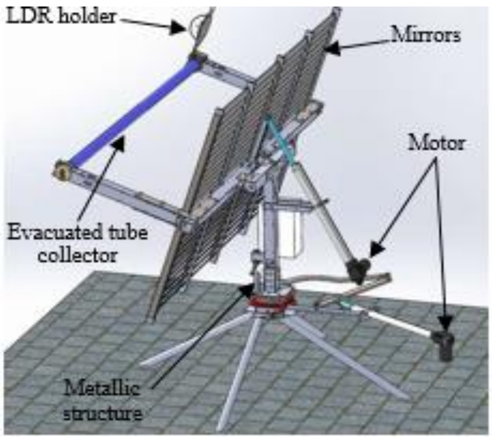

Figure 3. A 3D model of the metallic structure supporting the Fresnel mirrors and the absorber

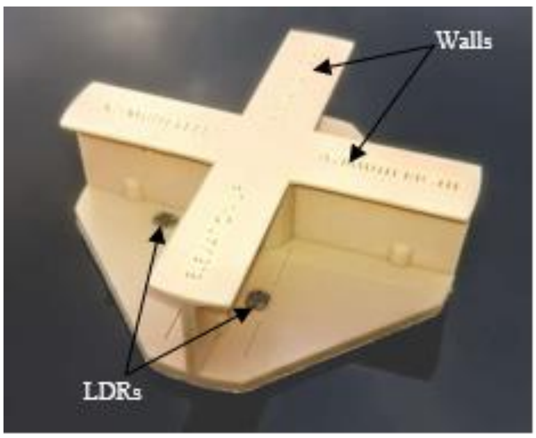

Figure 4. The 3D printed LDR holder

2.2.2. Electric and electronic part

The LDRs holder is screwed to a printed circuit board (PCB) that contains four voltage divider bridges, and have a RJ45 output socket that allows it to send LDRs values to the motherboard PCB via a network cable, the motherboard is based on a microcontroller chip AtMega328p, that reads the returned values from the LDRs and take the decision to energize a H-bridge relay set, in order to turn the azimuth and elevation motors into the right directions, in addition to that, a power MOSFET is used as an electronic speed controller (ESC) in order to control the motor speed to have smooth acceleration and motions.

2.2.3. Software part

The microcontroller has an embedded program that allows it to be autonomous to track the sun without any external intervention, thanks to the implemented sun tracking algorithm that is based on optical sensors only and don't need any other information like GPS coordinates, date and time, and even encoders or any feedback sensors on the motors, which means that the solar tracker can be positioned without taking care of the north pole alignment or any other geometric parameter. During the first run of a new assembled sun tracker, a software calibration is needed due to the fact that any electronic components have some small imperfections on their internal characteristics which differentiate each one from the others, in order to remedy to these dissimilarities, two offset constants was added to the program, the first one for the azimuth LDR couple and the second one for the elevation LDR couple, then the tracking system is started and let it track the sun until it reaches its equilibrium point, once it is done, the user check visually if the shadows are covering the same area on both sides of the vertical 3D printed support wall with the help of a printed line on its surface, if not the offset value is increased or decreased by the user, depending on which direction it should be shifted, then a new sun tracking test cycle is performed to see the effect of the new offset parameter, the same process is repeated until we get the same shadows on both sides on the vertical wall, then the same calibration method is performed to the elevation axis. Figure 5 shows the control flow diagram of the sun tracker system, the algorithm can be divided into three main part: initialization, sun tracking, and night mode.

- Initialization: After powering on the sun tracker, an initialization procedure is executed which allows to the algorithm to reads the values of the sun illuminance power measured by the four LDRs, in order to know if it is night or day period, if it is night, the program execute the night mode procedure by driving motors to the sunrise position, the Fresnel mirrors are then positional vertically, and turned to the extreme east, to be ready to detect the sunrise of the next morning, the algorithm stays in this state during night period, and checks every 15 minutes if there is any increase in the sun illuminance power measured by the four LDRs, when the sun illuminance power exceeds a preset threshold, which means that the sun is rising, then the algorithm starts the sun tracking procedure.
- Sun tracking: Once the program detects that the sunrises, it starts the sun tracking routine, by first tracking sun roughly on its azimuth axis, at this step, the tracker drives motors continuously at a low speed to reach the optimal equilibrium point as fast as possible, then passes to the second step that consists of a fine tracking by moving motor step by step in order to have better control on the motion, between each step, the program wait 2 seconds in order to give enough time to the metallic structure to stabilizes before reading the new returned LDR values, the same cycle is repeated until the left and right LDRs return the same value, then the program stops the azimuth motor, and starts the elevation tracking that is based on the same logic as the azimuth tracking. Once both azimuth and elevation tracking are performed successfully, the program enters to a preset pause time period, under which the Fresnel mirrors focal line is concentrated perfectly on the absorber, when the pause time is elapsed, the program starts for the beginning by checking if it still on the day period or not and then repeat the same routine, again and again, all day long, until the four LDR return values smaller than a preset threshold.
- Night mode: Once the program detects that the four LDRs sun illuminance power is bellow a preset threshold, which means that the sun is setting; the algorithm gives the order to the motor drivers to rotate the Fresnel mirrors on its azimuth axis to the extreme east, and put the mirrors on a vertical position facing the horizon, in order to be ready to detect the first sunrays of the next morning sunrise, this sleeping position also allows to minimize the quantity of dirt and mist that can be deposited on the surface of Fresnel mirrors during the night.

2.3. Experimentation

This study was done on a sunny weather with some passing clouds (cumulus clouds), the ambient temperature was between 22 and 37 °C, all test was performed during 5 hours between 11:00:00 and 16:00:00 GMT in order to avoid morning clouds and have stable weather. Four tests were performed during this study, i) the first one is to take two LDRs couples randomly and track sun without calibration, ii) the second test is to test with the same previous LDRs couples and adjust the offsets before starting sun tracking, iii) the third test is done by using LDRs couple issued from the test bench setup in order to have LDRs couples as similar as possible without performing calibration, and iv) the fourth test is to use the same LDR and adjusting the offsets before starting sun tracking.

In order to have a way to control the sun tracking efficiency, an isolated K-type thermocouple [24], [25] is placed at the middle of the absorber that have a 40 mm width, the thermocouple is connected to a data recorder to measure the temperature every 90 seconds, an efficient sun tracking system should keep the sun rays concentrated on the absorber surface, which means that the thermocouple should indicate a stable and a high temperature during all test period. A pyranometer was installed at the highest available point to avoid shadows and surrounding reflections, and minutely leveled. The pyranometer assure that the tests were done approximately under the same conditions, and there were no clouds during the test periods.

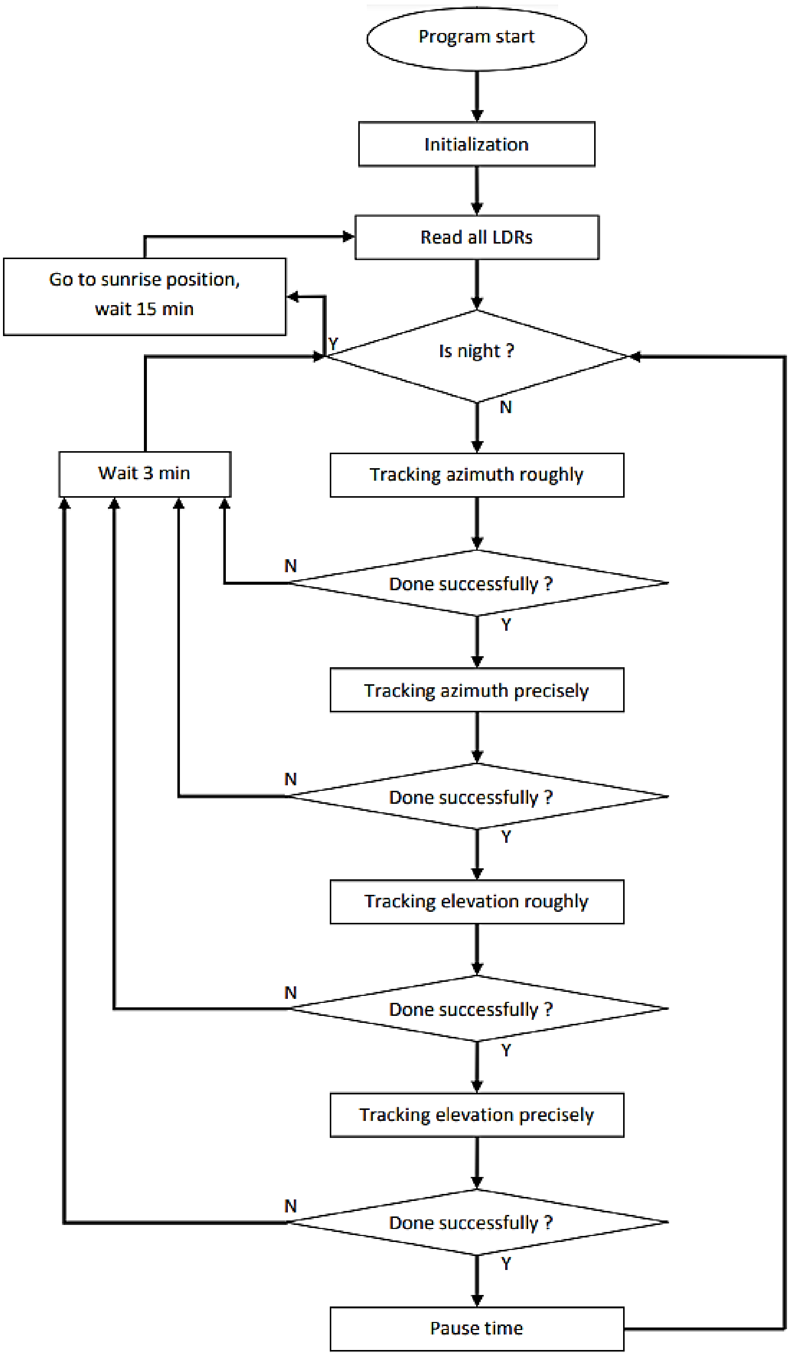

Figure 5. Control flow diagram of sun tracking system

3. RESULTS AND DISCUSSION

3.1. Random LDRs without calibration

This test was done on 20 July 2021, Figure 6 shows that during the morning at approximately 08:00:00 there was some clouds, while during the test period and rest of the journey the sky was clear, and the peak of solar power was 1,026 watt at 12:47:00. During the experiment, we can visually notice that the Fresnel mirrors are facing the sun, but in reality, they are focusing sunlight somewhere else near the desired area, Figure 7 shows that choosing random LDRs without calibration do not guarantee precise sun tracking for solar concentration applications, the thermocouple temperature stays at approximately the ambient temperature all along the experience.

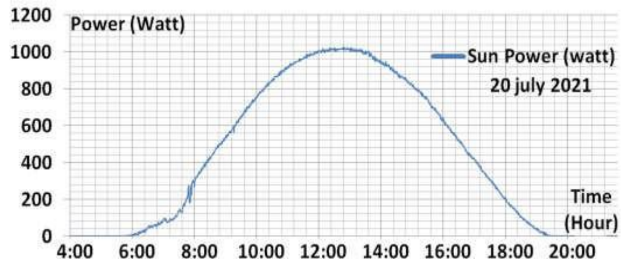

Figure 6. Sun irradiance curve of the 20 July 2021

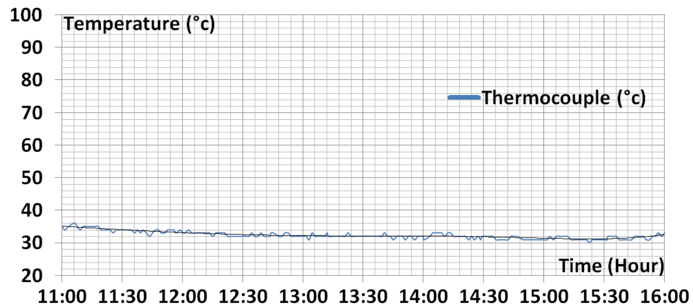

Figure 7. Thermocouple data recorder curve during the test of random LDRs without performing a calibration

3.2. Random LDRs with calibration

This test was done on 23 July 2021, Figure 8 shows that during the morning from sunrise to 10:25:00 there was some clouds, while during the test period and the rest of the journey the sky was clear, and the peak of solar power was 1006 watt at 12:39:00. By adjusting the offset between the random LDRs, the sun tracker was able to track sun accurately, Figure 9 shows that the average thermocouple temperature was between 80 and 90 °C during an hour and a half, after that the temperature starts decreasing faster and faster, while the solar power is increasing to reach its peak power, thing that is not logical.

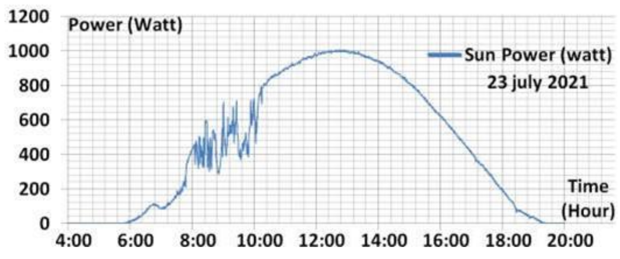

Figure 8. Sun irradiance curve of the 23 July 2021

Figure 10 explain the reason why the sun tracking starts well but a little bit later, the sun tracker drifts away. The reason is due to the fact that the LDR couple's offset is not constant, but vary depending on sunlight, which means that when the calibration was performed at the beginning of the experiment, the offset was correctly adjusted for the sun irradiance at this moment, but after the sun irradiance increased the offset also changed, in addition to that, the offset change dynamically in function of the sun irradiance, which is difficult to predict using ordinary methods. For this reason, and during the next experiment, the test bench black box is used in order to sort LDRs depending on their illuminance-resistance characteristics, and use for each axis two LDRs with the minimum dissimilarity, to prevent the sun tracker from drifting due to the offset.

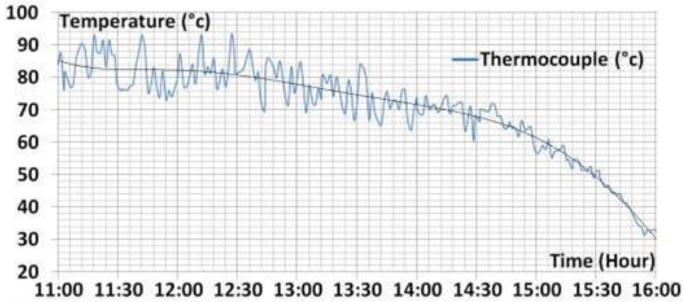

Figure 9. Thermocouple data recorder curve during the test of random LDRs with performing a calibration

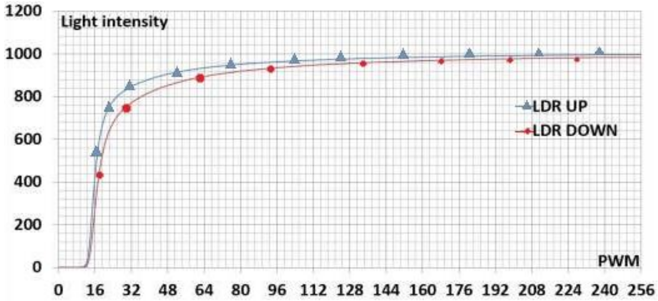

Figure 10. Characteristic curves of two random LDRs, obtained by using the black box test bench, the offset change dynamically depending on the light intensity, and have an average dissimilarity of 5.52%

3.3. Selecting LDRs couples

Thanks to the black box test bench, a set of 26 LDR chosen randomly among a lot of 300 LDRs, were tested in order to select the most similar LDRs, Figure 11 shows the result of all tested LDRs, we can conclude that there is a huge offset between some LDRs while there is some LDRs that are closer characteristic curves. By calculating the difference between each LDR with the rest of the set and calculating the standard deviation with each one of them, then apply a threshold based on the average difference and the standard deviation, we get only the LDRs with the minimum offset. The average dissimilarity between a random lot of LDRs is 3.7% while dissimilarity can reach 23.2%. It is also possible to get similar LDRs geometrically by eliminating the most distant curves, and then keep only the superposed curves, but this is a time-consuming technique in comparison with the analytic one. Figures 12 and 13 shows two separate curves of two selected LDRs, with a dissimilarity less than 0.06%, while Figure 14 shows the two curves superposed in the same graphic

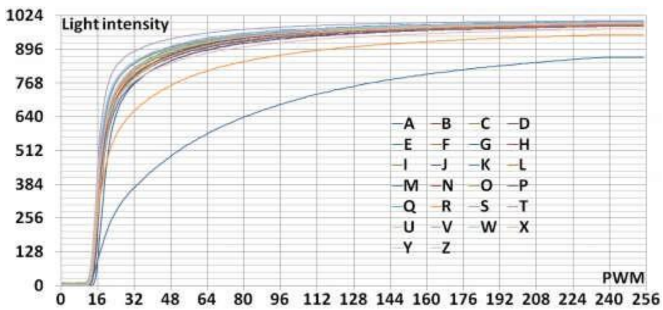

Figure 11. Characteristic curves of 26 LDRs chosen randomly

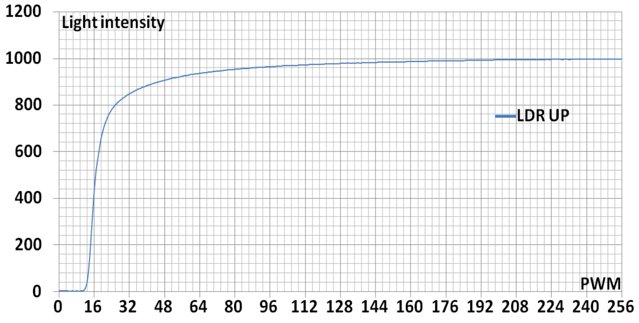

Figure 12. The characteristic curve of the selected LDR used for sensing the coming sunrays from the top

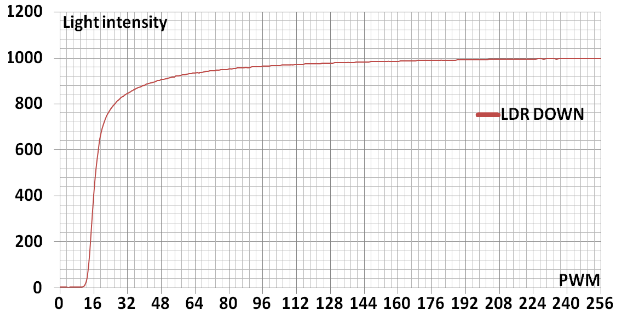

Figure 13. The characteristic curve of the selected LDR used for sensing the coming sunrays from down

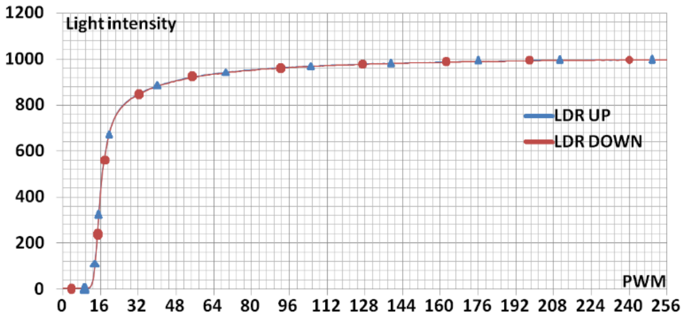

Figure 14. Superposed characteristic curves of selected LDR used for the elevation axis tracking to sense coming sunrays from top and down

3.4. Selected LDRs without calibration

This test was done on 27 July 2021, Figure 15 shows that during the morning from sunrise to 08:45:00 there was some clouds while during the test period and rest of the journey the sky was clear, and the peak of solar power was 1,036 watt at 12:27:00. By using the previously selected LDRs using the black box test bench, Figure 16 shows that the accuracy and the efficiency of the sun tracker is significantly improved, we can notice that the thermocouple measure a stable temperature depending on sun power during all the test period.

3.5. Selected LDRs with calibration

This test was done on 31 July 2021, Figure 17 shows that during the morning from sunrise to 08:50:00 there was some clouds while during the test period and rest of the journey the sky was clear, and the peak of solar power was 1,011 watt at 12:53:00. Figure 18 shows that the temperature was maintained stable depending on sun power during all the period of the test, and we can also notice that there is no significant improvement in efficiency after performing calibration for selected LDR, knowing that the offsets are negligible.

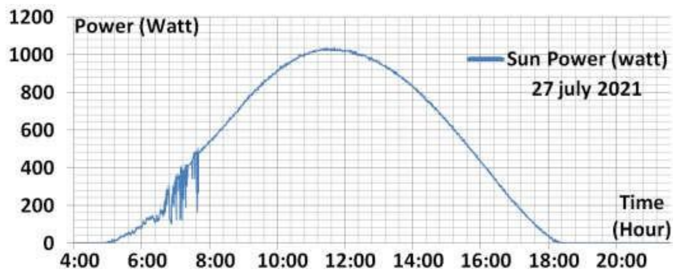

Figure 15. Sun irradiance curve of the 27 July 2021

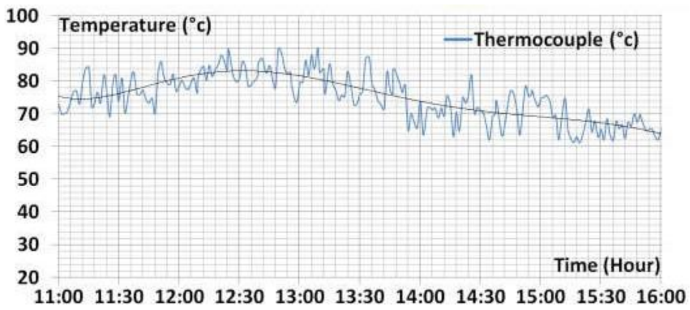

Figure 16. Thermocouple data recorder curve during the test of Selected LDRs without performing calibration

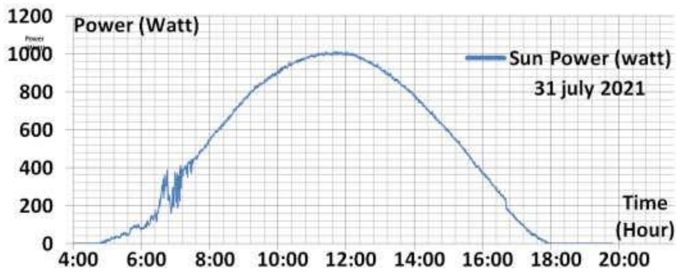

Figure 17. Sun irradiance curve of the 31 July 2021

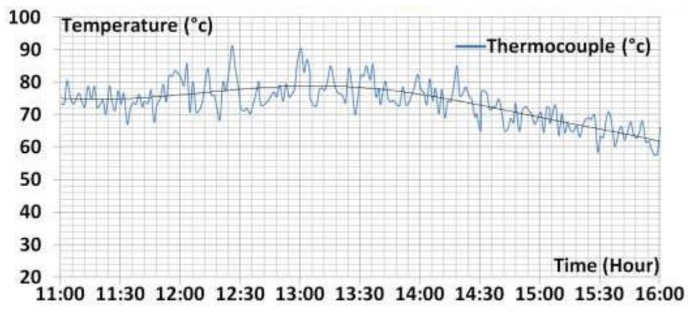

Figure 18. Thermocouple data recorder curve during the test of Selected LDRs with performing calibration

4. CONCLUSION

This study allowed us to know the effects of the dissimilarity between the intrinsic characteristics of LDRs, and proposes a solution to better choose LDRs, in order to meet the requirements of solar concentration systems, the verdict is, there is a huge dissimilarity between two LDR chosen randomly, this difference can reach 23.2%, what results in a bad sun tracking for solar concentration systems, even if an offset calibration is performed at the beginning of the experiment. Thanks to the use of the black box test bench, which allows to sort LDR depending on their intrinsic characteristics, this technique results on obtaining 2 LDRs with a dissimilarity less than 0.06%, which means that at any moment of the day, the two LDR measure the same value, with 0.06% of reading error, which allows to track sun during all the day without any drift, and also without need of an initial offset calibration.

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