Chapter 7
Improving Tracking Efficiency of Two-Axis Sun Tracking Systems

Fevzi Kentli and Musa Yilmaz

Abstract Due to both reduction and insufficient of fossil fuel to supply current growing energy needs, investigation and employing of renewable resources has been accelerated. Besides, using fossil fuel affected the environment negatively. Therefore, renewable energy resources in the most studies are solar, wind and geothermal. In this study, electrical energy production methods from solar energy have been examined, a fixed and a two axis tracking system have been designed. Both systems are compared each other regarding to several factors by performing annual measurements. Energy consumption of the system is minimized by employing actuator motor in two axis solar tracking system. According to the efficiency of two-axis tracking system, the annual average has been calculated as 31.67% more. This efficiency has been calculated as 70% in winter, 11% in summer. As a result of these measurements several graphics of a year empirically daily, monthly and annual data have been contributed to the literature for Diyarbakir, one of the prominent cities of Southern east, having the most solar energy of Turkey. In the first section, literature review will be indicated. In the second section, solar angles, photovoltaic panels and systems, sample designs and solar tracking systems are examined. In the third section, photovoltaic two-axis solar tracking system and qualifications, work and advantages of fixed system which we designed are stated. In following section, obtained results will be given and in last section, financial analysis of fixed and tracking photovoltaic systems has been performed. Also, recommendations for increasing their efficiency have been noted.

Keywords Solar energy · Photovoltaic · Two-axis sun tracking

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7.1 Introduction

Importance of energy needed today in every area of life becomes increasing. Energy is the main input for our civilization and its production and consumption is one of the reliable merits to measure the improvement and development of the country.

Studies on finding and developing alternative energy resources have been accelerated as a result of insufficiency of existing resources to provide constantly increasing energy need. Yet, traditional energy production and consumption methods, especially fossil fuel based ones, lead to unrecoverable environmental damages. Saving the living environment on earth and decreasing the environmental damage caused by energy production and consumption beneath the damage caused by climate change give responsibility to all humankind. As a result of this responsibility; preparing national and international legal regulations, prioritizing the environmental effects in selection of energy production technology and resources and giving maximum effort in efficiently using energy are gaining much more importance by the time.

As a consequence, instead of using traditional and fossil fuel based energy production systems which are causing worldwide environmental pollution and climate change, finding energy resources and developing new technologies providing sustainability and renewability and causing less environmental damage and climate change became necessary. Both of the facts that fossil fuel resources are limited and their production and consumption systems cause environmental damage led to investigate renewable, unlimited and environmental friendly energy resources and technologies. So, renewable energy resources including solar energy gained importance [1, 2].

Solar energy with the characteristics such as its potential, cleanliness, renewability, easy-to-use and being environmental friendly features has much more probability to become widespread when compared with other renewable energy resources. Overcoming it limitations such as having higher setup cost, having less efficiency and capacity will make it more attractive at the future. Unfortunately, Turkey could not use today all its potential even though it has a favorable position from solar energy perspective.

Solar energy is vast and also does not damage environment. This makes it a good choice in this consumption era as most known energy sources have becoming exhausted and some complications are occurred such as corrosion in living world and climate changes. However, there are different opportunities which allow us fix the situation. One of these opportunities and also the most convenient one is to find out the new and clean energy sources. Another opportunity is to reduce the amount of consumed energy.

Nuclear energy has first considered as sharp cut solution but having high hazard risk and changing nearby habitat made it less preferable. On the other hand, sun has much more potential as it has not such kind of disadvantages. Available energy on
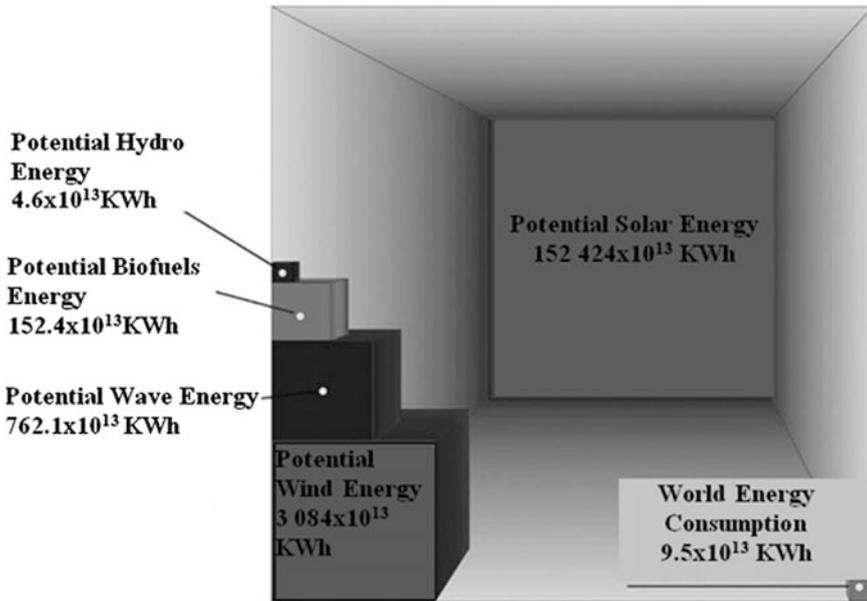
Fig. 7.1 World energy consumption and production status

the world produced by sun is in $152{,}424 \times 10^{13}$ kWh while total energy produced by power plants is 100 thousand times less and produced solar energy on earth is 15 thousand times less as seen in Fig. 7.1. Thus, today solar energy systems have begun to be used in every part of life even though solar energy is intended to use after the second half of our century [1–12].

At the present time, utilization of solar energy becomes significant in almost every country as there are many different application areas. It is used in providing hot water or heating house. Also, it is converted into electrical energy and then used in lighting of buildings, for propulsion of cars and even for assisting to grow crops by the help of solar water pumps. In last 20 years, new technologies are improved on solar panels and studies are focused on making them cheaper [2, 3].

Optimal usage of photovoltaic (PV) panels for different cases is an important problem because the efficiency of the panels is changing as the weather changes. To solve this problem, panels are used in rural area or away from city centers where there are plenty of empty spaces letting get much more sunlight onto panel surface. But even in these conditions it is needed to maximize obtained solar energy by determining appropriate declination angle. That is why so many studies on declination angle have been done [1, 2].

Output power of any photovoltaic system depends on amount of obtained solar irradiance. To provide more sunlight as an input to system, it is required to track the sun. Main concern of these systems is first cost of system and cost of consumed

energy during sun tracking. In this study, consumed energy of the system during sun tracking is minimized and it is compared with the other studies [11–15]. Applications brought out different sun tracking systems [16–20].

7.2 Maximizing Sunlight on Panels

Easiest way to maximize sunlight in most system is to mount panels onto a horizontal tracking system. Sun takes highest place in sky according to horizontal axis at noon, so it is the time that sun has minimum distance in atmosphere and air has the minimum density during day. At other times, incident radiation flux becomes less since mass density is increasing and the angle between sunlight and normal of panel surface is increasing. Consequently, tracking at two axes is needed to increase the efficiency by decreasing this angle.

In summer, even with a dry weather, approximately 12% more energy could be produced by using dynamic photovoltaic panels. During winter, 70% more energy and as an annual average 31% more energy could be produced. Figure 7.2 shows the comparison of stationary and dynamic photovoltaic panels at different months [2].

To select the type of PV system (single axis or two axes) is a difficult decision as two-axis systems are much more expensive even though they are much more efficient. Slope will be changed during the year if it is decided to use one-axis tracking system. Inclination of panel changes depending one semester. For example, inclination of the system used during summer is different than others (Fig. 7.2).
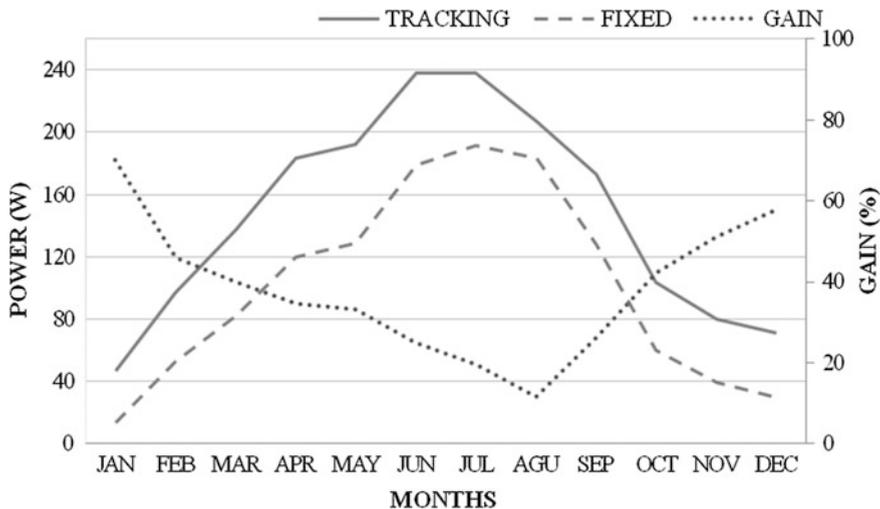

Fig. 7.2 Comparison of fixed and dynamic photovoltaic panels at different months for Diyarbakır (Turkey) in 2012 [2] [Gain = (Power$_{tracking}$ − Power$_{fixed}$) * 100/Power$_{tracking}$]

7.3 Sun Tracking Systems

Solar cells produce electrical energy using photon energy of sunlight. Output electrical energy is directly related with the amount of sunlight hitting onto the panel surface. Sunlight reaches earth with different angles during the day. So, to obtain maximum electrical energy by solar cells, PV systems should track the sun. This system aiming to maximize sunlight by tracking sun is called Sun Tracking System. Sun tracking systems are designed to track through West-East direction (one axis), West-East and North-South directions (two-axis) [3, 4]. Main aim of the all studies on photovoltaics is to decrease payback time of the system. It becomes possible only by increasing its efficiency. And efficiency could only be increased by increasing amount of solar radiation hitting on to the panel surface (Fig. 7.3).

Amount of radiation hitting on to panel surface is related with cosine of the angle between the sunlight and the normal of the surface. It means that efficiency is maximized when sunlight goes through the normal of the panel surface. This situation brings the need of a system to provide sunlight always normal to the panel surface by tracking the sun.

Finsten has developed the first tracker in 1962. Later Saavedra has added an automatic control unit to this mechanical system in 1963. This unit inspired to build Eppley pyrheliometer. Maldonado designed and constructed a sun tracker system at Technical University Federico Santa Maria [5, 6].

Main function of all tracking systems is to provide 1 or 2 degree of freedom to motion. In other words, main function is to supply sunlight at desired direction. There are many applications of single (one) axis tracking systems (SAT) as they provide power gain: Horizontal (HSAT), Vertical (VSAT), Tilted (TSAT) and Polar Aligned (PASAT). But studies on these systems are seen rarely in literature except one study which has concerned these systems. It is mentioned in this study that TSAT with 5 has collected 10% more radiation than HSAT where HSAT 15% more than VSAT. Also, it is found that PASAT collected 10% more than HSAT [3, 4].

Sun tracking systems are classified considering number of degree of freedom, position of turning axis or the systematic for sun tracking.
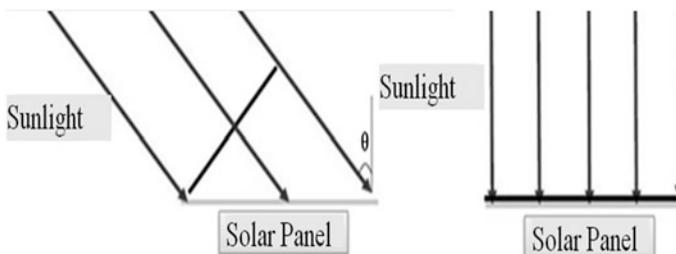

Fig. 7.3 Radiation hitting on to the panel (To provide maximum sunlight, θ should be equal to zero)

Fig. 7.4 One axis tracker
system

7.3.1 Classification Considering Number of Degree of Freedom

One Axis Sun Tracking, Two Axis Sun Tracking.

One axis sun tracking systems: One axis tracking systems performs movement in either azimuth or vertical axis (Fig. 7.4). Reason to prefer single axis tracking system is to have free area where it is mounted [11]. For example, parabolic trough systems tracks using azimuth and most of the roof application of photovoltaic systems track using only height angle due to limited space. SAT is direct and cheaper way to get better efficiency. By using a simpler system, efficiency is increased. RayTracker, a tracking system manufacturer, implied that they improved the performance 23 and 38% when compared respectively with fixed angle modules and outer flat modules.

Two axis tracking systems: Two-axis tracking systems let movement in two axes (vertical and azimuth) which maximizes the efficiency of the tracking process. But SAT developers are questioning the efficiency as two axis tracking systems have additional installation, permitting and ongoing maintenance costs. Also higher defect risk related to having more moving parts compared to SATs is another concern. Moreover, two-axis systems need bigger spaces to place and consequently, to receive planning permits is much more difficult for them [3, 4].

7.3.2 Classification Considering Position of Turning Axis

Sun tracking systems are also classified considering joint axis. One axis tracking systems are classified as polar (Fig. 7.5), azimuth (Fig. 7.6) and horizontal (Fig. 7.7). On the other hand, two axis tracking systems are divided into two groups: azimuth and polar (Fig. 7.8).

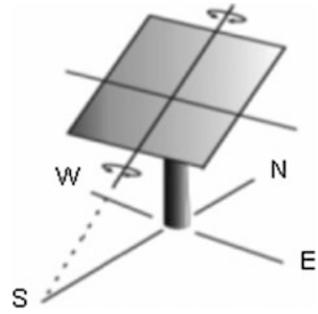**Fig. 7.5** Polar one axis
tracking system

Fig. 7.6 Azimuth one axis
tracking system

Panel surface of polar one axis tracking systems is tilted through south direction
and azimuth angle is tracked by turning around the axis goes through weight center
of panel surface. While panel is tracking azimuth angle, it also tracks height angle
in the meantime due to its geometry. Thus, polar one axis tracking systems have
higher performance values when compared with other one axis tracking systems
from energy production perspective. Azimuth one axis tracking systems (Fig. 7.6),
turns on a structure with tilted panels around the axis normal to ground. This kind
of one axis tracking systems are preferred when there are big areas for the panels.

Horizontal one axis tracking systems turns on an axis parallel to ground
(Fig. 7.7). This kind of tracking systems is generally used where height angle is
approximately 90° like equatorial region (0°–±30°). Structure is compatible to
move as groups. One motor could run many photovoltaic arrays at the same time.
On the other hand, two axis systems are separated as polar and azimuth angles.
Polar two axis systems only completes turning around its axis in a day. During the
year it moves complying with sun movements and the issuing the commands comes
from control system or sensor by the time.

On the other hand, two axis azimuth moves both around its axis and along two
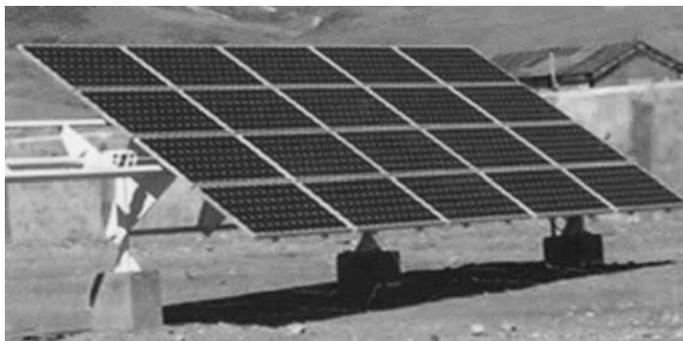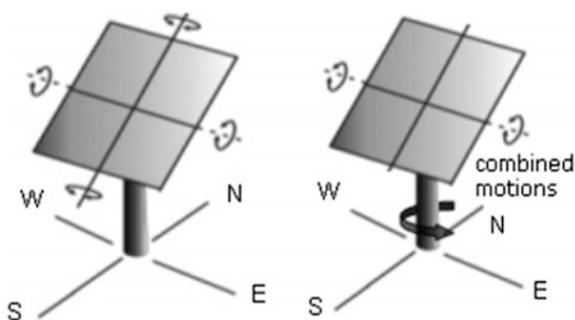axis during a day and so its control is much more complex (Fig. 7.8).

Fig. 7.7 Horizontal one axis tracking system

Fig. 7.8 Polar and Azimuth
two axis tracking system

Setup and maintenance costs of sun tracking systems are higher than the fixed
systems having certain angle. Thus, this kind of systems needs being robust, less
maintenance required and high capacity to redeem their costs in long term. Also,
this kind of systems should be built at rural areas and at the places where sunlight
will be present from sunrise to sunset as the performance of sun tracking systems
will be lowered in city centers and in the places where intense building shadows
occurred (Fig. 7.9). At these places, costs related with sun tracking system and its
sensors will be decreased as sun tracking will be able to be accomplished from one
center for whole system. Any battery will not be needed as the system will be on
grid and its cost will be removed.

7.3.3 Classification Considering Sun Tracking Systematic

Generally control circuits consisting of electronic sensor systems, controller,
microprocessor and GPS are used to position the system to where it is required to be.

Fig. 7.9 A high capacity solar farm tracking sun in two axes

Passive sensor tracking: Some companies have tried to develop more energy efficient and cheaper tracking systems. For example, Portasol tracking systems—Australia—developed a hydraulic passive tracking system working according to thermal changes during the day to track the sun. Company states that electrical energy is not needed as tracking system does not include any electronic equipment, motor or gearbox. Figure 7.10 shows (a) panel stopped at night through west, at morning sun heats more the bottom part of tube and liquid expands through top, (b) panel turns until sun heats both tube equally, (c) panel tracks the sun with a certain angle by the time sun moves, (d) as a last step panel stopped at night through west [3, 4].

First decision that should be taken is to choose whether passive or active tracking system will be used. While low boiling point of compressed gas is used to move in passive tracking systems, motor, gearbox or hydraulic components are used in active tracking systems and they consume energy. Passive systems using gas pressure produced by sun does not consume energy but they are more insufficient to track the sun [3, 4].

Active sensor tracking: Two photoresistances and photovoltaic cell are used as a sensor for one axis tracking systems. These sensors place next to each other. So, both sensors are at same conditions. Sensor are directly connected to motor, generally direct current (DC) motors are used. The angle between panel surface and sunlight changes when sun moves. This leads to occur a difference between sensor outputs. Control circuit runs the motor and turns the system considering where more sunlight has come. Control circuit adjusts as panel surface is always normal to sunlight using this difference. The example by Poulek and Libra claimed their system was able to collect 95% of the energy with a $\pm5°$ tolerance. Figure 7.11 shows a sample structure [3, 4].

Chronological tracking: Systematic of chronological tracking is based on determining the movement positions before for every day during the year. Calculations are done for the related geographical region. System includes a pressor
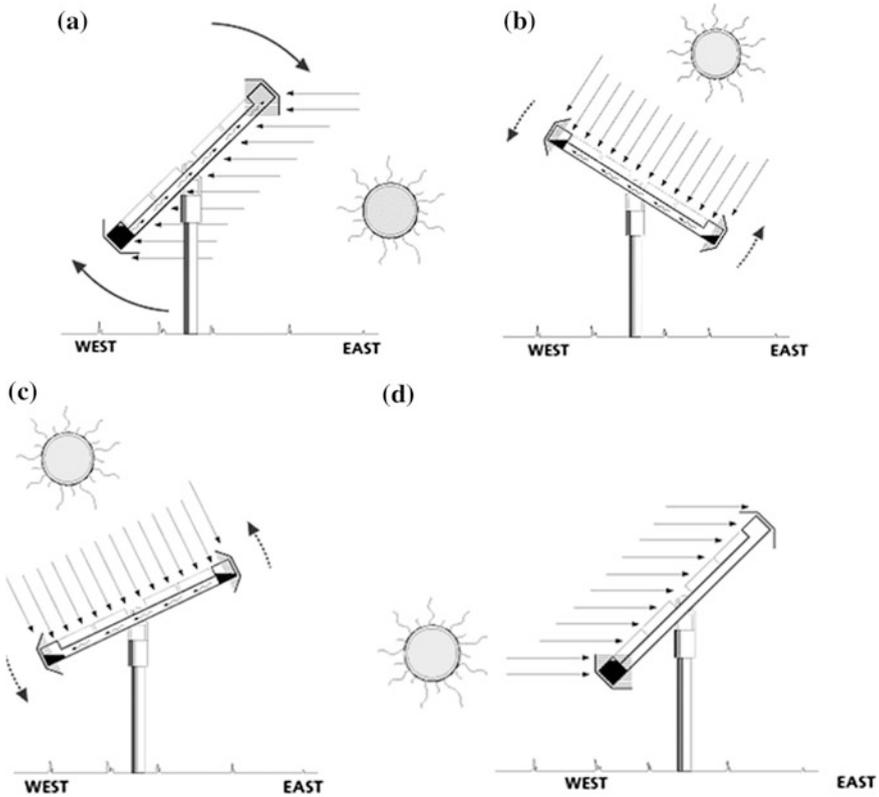
Fig. 7.10 Running of passive sensor tracking system. **a** Morning **b** Before noon **c** After noon **d** Night
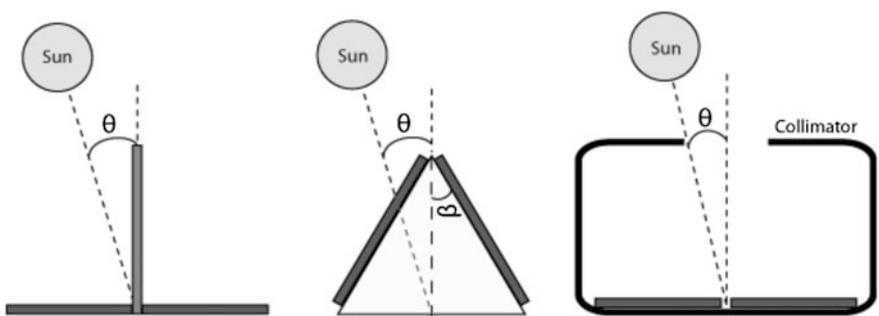

Fig. 7.11 Tracker sensor setups from *left* to *right*: divider, tilted mount, and collimator [4]

(microprocessor, PLC, computer etc.) making calculations. Latitude and longitude values of the region are given as constant input to the processor. Variable time value is taken from Real Time Clock. For the current date and time, position of sun

is calculated and system is turned as panel surface is normal to sunlight. Disadvantage of this system is that system continues to track and consume energy even during overcast sky.

7.4 Application

In this section, design and comparison of fixed and two axis photovoltaic panel system applications are given. Energy consumption is an important factor in two axis systems differing from one axis systems. It affects the system efficiency. To minimize this effect, literature is investigated and a low energy consumed DC motor having gearbox (Damper motor) is selected to use. Both used motors are identical. To be able to compare rightfully, both systems are used in same circumstances and panels having same trademark and model are used. Also, disturbing environmental factors (shadows, reflections etc.) are minimized as much as possible. Thus, a location where sunlight reached the panel all day during the whole year is chosen.

7.4.1 Fixed Photovoltaic Panel Systems

Widely used systems are fixed panel systems having low efficiency. Block scheme of fixed system is shown in Fig. 7.12 and picture of the used system is shown in Fig. 7.13. This system contains panel, measurement system, battery, inverter and load. Photovoltaic panel is placed as fixed considering geographical and meteorological data. Obtained power from panels are stored in batteries optimally.
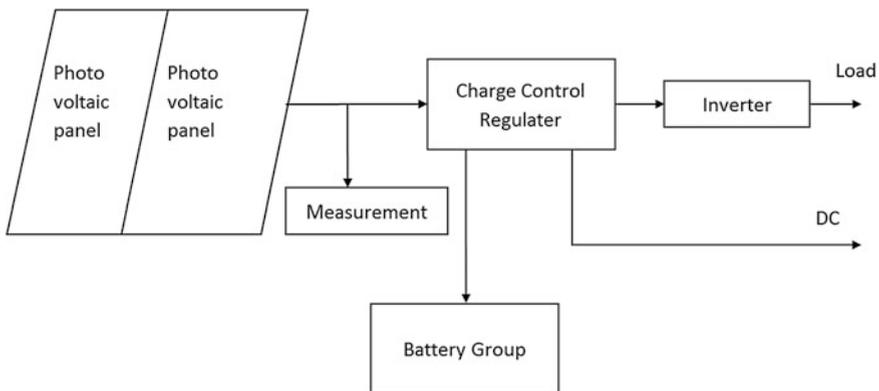
Fig. 7.12 Block scheme of fixed photovoltaic panel system

**Fig. 7.13** Picture of the fixed photovoltaic panel system

Fig. 7.14 Picture of the used two-axis dynamic system [2]

7.4.2 Two Axis Photovoltaic Panel System (Sun Tracking System)

In this section, proposed two axis PV (sun tracking) system will be detailed. Consumed energy by the system has a higher priority in designing dynamic systems as it is related with the system performance. To minimize the consumed energy, literature is investigated and a new motor type (DC motor with gear unit) is found as a solution. Figure 7.14 shows the application of proposed system.

This dynamic system moves in two axes. East-West direction is defined as horizontal axis and North-South direction is defined as vertical axis. System is able to move in both axes at the same time as shown in Figs. 7.14 and 7.15. Two roller bearings are used as supports in the system. Wind load data of the last 10 years for

Fig. 7.15 Improved two-axis sun tracking system [2]
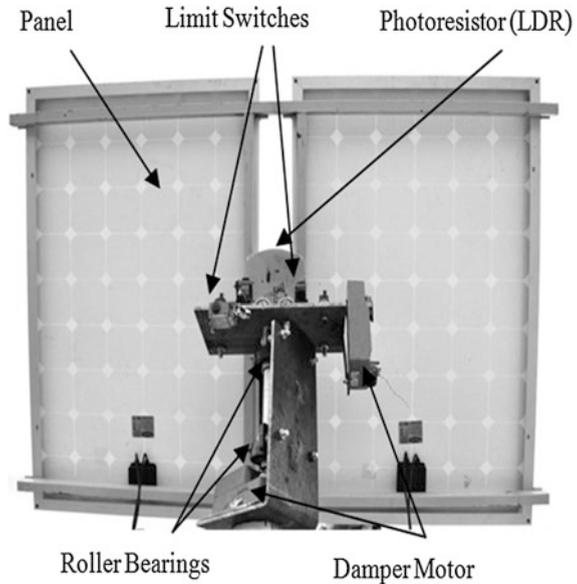
the application area is acquired from meteorology are so low that no need to be taken into account in design stage eventhough system is capable of resisting the loads over average [1].

Designed system consists of 2 Damper Motor (DM), 4 gel batteries (12 V– 100 Ah), 2 PV panel (120 W), power inverter, solar battery charger, Maximum Power Point Tracker (MPPT), data acquisition card, Light-Dependent Resistors (LDR)s and mechanical system (Fig. 7.16).

Required energy to track the sun is provided from batteries. System tracks sun continuously at vertical and horizontal axis in sunny weather conditions. System is stopped by a LDR in cloudy weather conditions and at nights. Produced energy just after sun rise is enough to start the motor even if all energy in batteries is consumed. Because total need power for panels is 240 W while it is only 12 W for motors.

Two axes photovoltaic system contains solar panel moving through North-South and East-West directions. Solar panel is moved by the help of motor tracking sun by photoresistances (LDRs) and control system. So, it is profited from sun efficiently. Efficiency of photovoltaic panel is maximized when sunlight comes normal to panel surface. For this reason, control circuits need to command motor at certain points to provide panel angle as 90° to sunlight. This task is accomplished by control circuit by the help of photoresistances. Control system has electronic and electrome-chanical components. Suns movement is determined by 5 LDRs in control circuit to provide being normal to surface (Fig. 7.17). Also, time delay relays arranged with 3 s time difference are used to prevent PCBs work at the same time. 2 LDRs are used to measure movement in horizontal axis (East-West). 2 LDRs are used to measure movement in vertical axis (North-South) and one is to know whether being
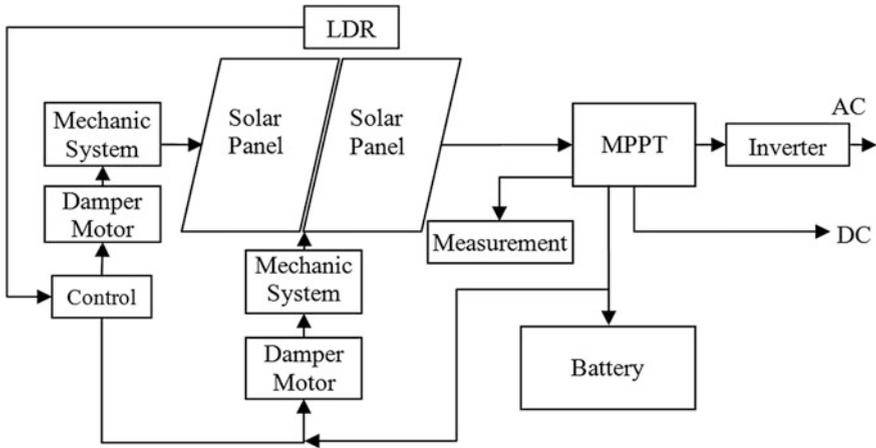
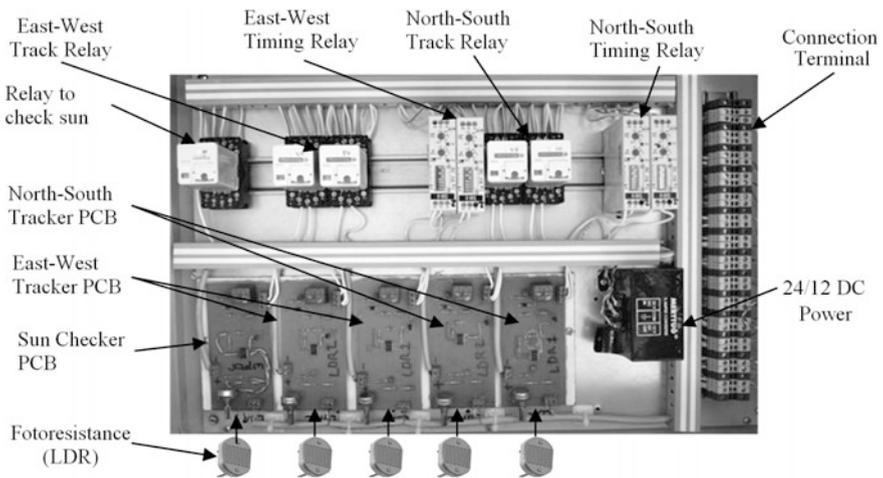**Fig. 7.16** Schematic view of two axis photovoltaic system (sun tracking system)

Fig. 7.17 Picture of the used control unit

sunny or not. Scheme of the sun checker PCB is shown in Fig. 7.18. So, damper motors are able to move panel to provide being normal to surface [1]. To determine the position of sun, several variables (irradiance, declination angle, azimuth angle, zenith angle etc.) should be defined or calculated. Control unit calculates these variables and then adjust the position of the system. Calculation of some important variables will be given in next sections.
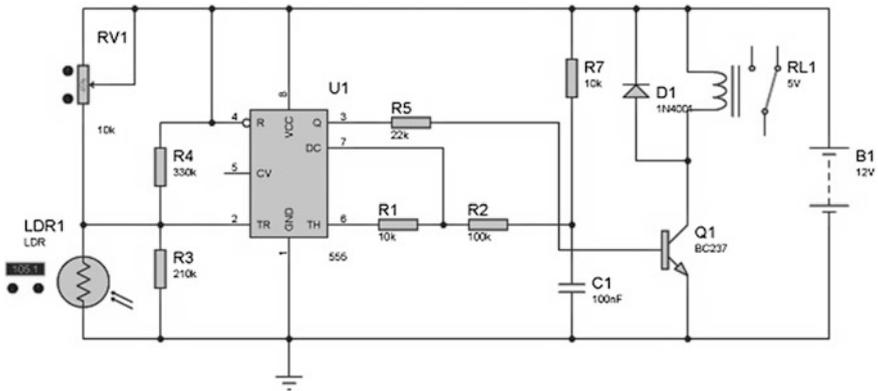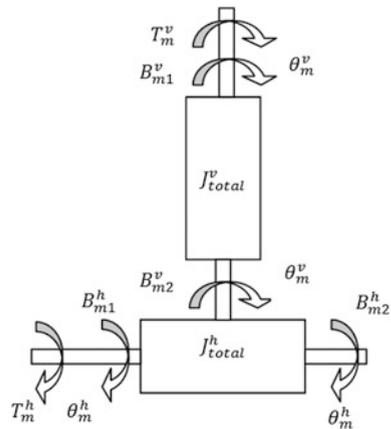
Fig. 7.18 Control circuit of sun checker PCB

Fig. 7.19 Mechanical model
of two-axis dynamic system
[2, 10]

7.4.3 Mathematical Modeling of Two Axis Photovoltaic System

This system tracks in two axis. Even horizontal (East-west) and vertical (North-south) axis seems together, they are moving independently. System freely moves in horizontal and vertical as shown in Fig. 7.19. Two roller bearings ease movement in both axes. Wind load is omitted as it is seen low in Diyarbakır's last 10 year data (<3.5 m/s). But system is designed for overloads. Mathematical modelling of system for horizontal and vertical axis is done as seen below [2, 10].

In modeling the system, Eqs. (7.1)–(7.5) (derived for system shown in Fig. 7.20) are used for horizontal (East-West) and vertical (North-South) axis [2, 10].

Fig. 7.20 Electric circuit of DC motor for horizontal and vertical axis [2, 10]
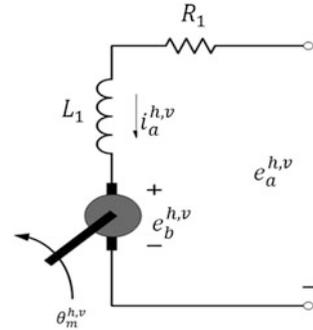
For vertical (North-South) axis of the system;

$$e_a^{vertical} = i_a^v R_1 + L_1 \frac{di_a^v}{dt} + e_b^v \tag{7.1}$$

$$e_b^{vertical} = K_b^v \frac{d\theta_m^v}{dt} \tag{7.2}$$

Torque constant $\rightarrow K_T^v$
Electromotive force constant $\rightarrow K_b^v$

$$e_a^v = i_a^v R_1 + L_1 \frac{di_a^v}{dt} + K_b^v \frac{d\theta_m^v}{dt} \tag{7.3}$$

Mathematical modeling of vertical axis of mechanical systems is (Fig. 7.19);
$B_t^v = B_{m1}^v + B_{m2}^v \rightarrow$ Viscous damper coefficient of bearing

$$T_m^v = J_t^v \frac{d^2\theta_m^2}{dt^2} + B_t^v \frac{d\theta_m^v}{dt} \tag{7.4}$$

$$T_m^v = K_T^v \cdot i_a^v \tag{7.5}$$

$J_t^v = 1$. Equivalent moment of inertia for torque of motors (kg · mm^2)

$$K_T^v \cdot i_a^v = J_t^v \frac{d^2\theta_m^2}{dt^2} + B_t^v \frac{d\theta_m^v}{dt} \tag{7.6}$$

Laplace transform of equation;

$$E_a^v(s) = I_a^v(s)R_1 + L_1 s I_a^v(s) + K_b^v s \theta_m^v(s) \tag{7.7}$$

$$K_T^v I_a^v(s) = J_t^v s^2 \theta_m^v + B_t^v s \theta_m^v(s) \tag{7.8}$$

Equation (7.7) is shortened as;

$$I_a^v(s) = \frac{E_a^v(s) - K_b^v s \theta_m^v(s)}{R_1 + L_1 s} \tag{7.9}$$

When Eq. (7.9) is substituted into Eq. (7.8);

$$K_T^v \left(\frac{E_a^v(s) - K_b^v s \theta_m^v(s)}{R_1 + L_1 s} \right) = J_t^v s^2 \theta_m^v(s) + B_t^v s \theta_m^v(s) \tag{7.10}$$

$$K_T^v E_a^v(s) - K_T^v K_b^v s \theta_m^v(s) = [J_t^v s^2 \theta_m^v(s) + B_t^v s \theta_m^v(s)](R_1 + L_1 s) \tag{7.11}$$

$$\begin{aligned} K_T^v E_a^v(s) = J_t^v s^2 \theta_m^v(s) R_1 + J_t^v s^3 L_1 \theta_m^v(s) + B_t^v s R_1 \theta_m^v(s) \\ + B_t^v s^2 L_1 \theta_m^v(s) + K_T^v K_b^v s \theta_m^v(s) \end{aligned} \tag{7.12}$$

$$K_T^v E_a^v(s) = \theta_m^v(s)[J_t^v s^3 L_1 + (J_t^v R_1 + B_t^v L_1)s^2 + (B_t^v R_1 + K_T^v K_b^v)s] \tag{7.13}$$

$$\frac{\theta_m^v(s)}{E_a^v(s)} = \frac{K_T^v}{J_t^v L_1 s^3 (J_t^v R_1 + B_t^v L_1)s^2 + (B_t^v R_1 + K_T^v K_b^v)s} \tag{7.14}$$

It is not needed to derive the equations for horizontal axis because both axes have same situation [2–10].

7.5 Modeling of Sun Tracking

As same principles are valid for both axes, modelling for one axis will be enough in designing system. Working principle of system is shown in Fig. 7.21. Four LDRs helped to direct panel into the right direction by giving correct angle (between normal and coming sunlight). Location of LDRs are adjusted as every LDR has the same amount of sunlight when sunlight comes as normal to panel surface. The current produced by LDRs are amplified by an operational amplifier and measured change in current is accepted as error which shows that sunlight doesn't come to surface normal. Then control unit drives the motor to turn the system into position here error value becomes zero.

Coordinate System: Center of coordinate system is assumed to be on output gear. When reference axis is accepted as the stationary body of DC motor, all rotations are measured around this axis. Sun axis (line connecting center of output gear with sun) states $\theta_r(t)$ reference angle (Fig. 7.22). Purpose of control system is to minimize the angle difference, $\alpha(t)$, between B_t^v and $\theta_0(t)$ where $\theta_0(t)$ represents the angle between reference axis and tracking axis [10].
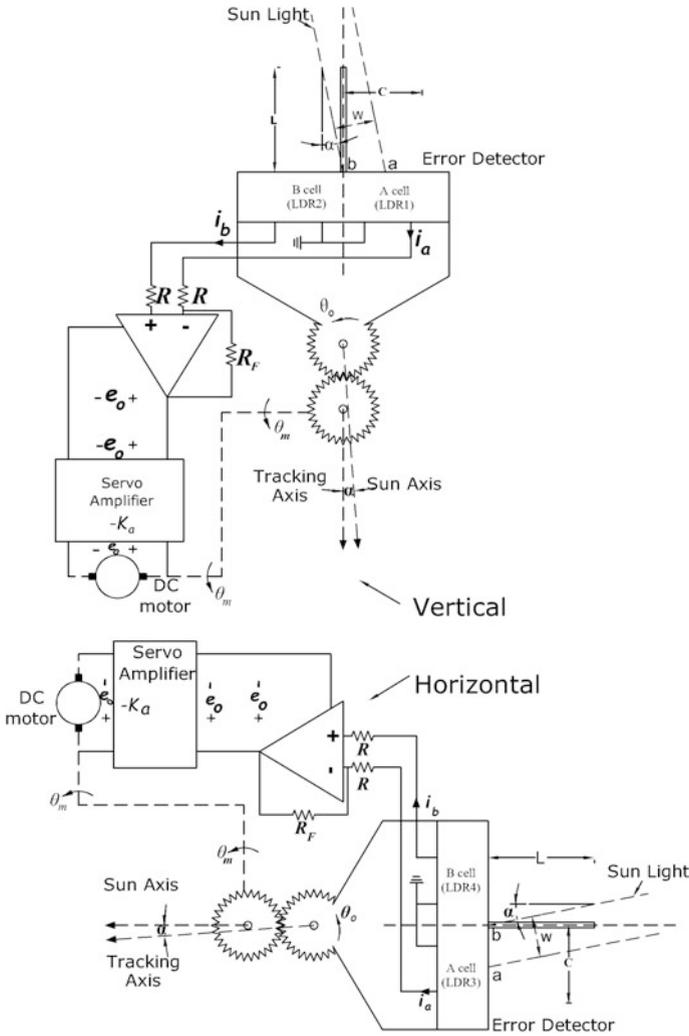
Fig. 7.21 Working principle scheme of improved two-axis solar tracking system [2, 10]

$$\alpha(t) = \theta_r(t) - \theta_0(t) \tag{7.15}$$

Error Detector: When tracking axis overlaps with sun axis: $\alpha(t) = 0$ and $i_a(t) = i_b(t) = I$ or $i_a(t) - i_b(t) = 0$. As shown in Fig. 7.21, sunlight having W width reaches at certain α angle to A cell with oa width and to B cell with ob width [10].

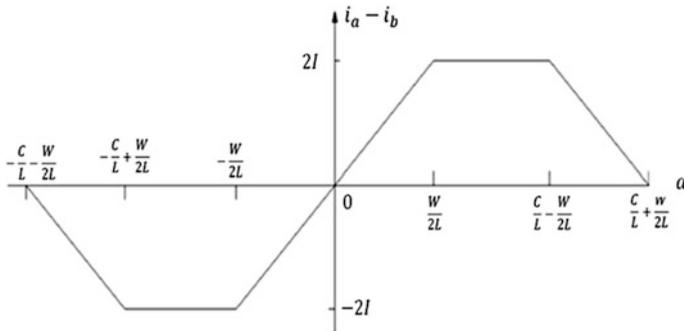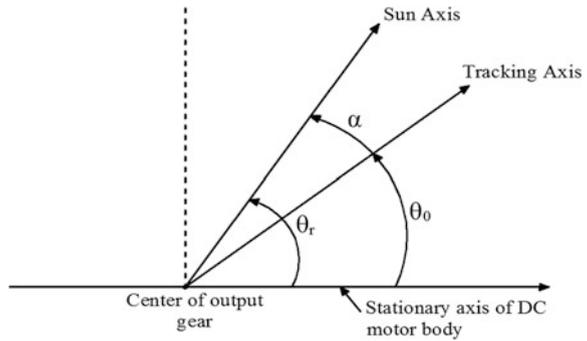**Fig. 7.22** Coordinate system of sun tracking system

Fig. 7.23 Nonlinear characteristic of error detector

$$oa = \frac{W}{2} L \tan \alpha(t) \tag{7.16}$$

$$ob = \frac{W}{2} - L \tan \alpha(t) \tag{7.17}$$

On the other hand, when 2I is the maximum current of a LDR and $0 \leq \tan \alpha(t) \leq W/2L$ as $i_a(t)$ current is related with oa and $i_b(t)$ current is related with ob;

$$i_a(t) = I + \frac{2LI}{W} + \tan \alpha(t) \tag{7.18}$$

$$i_b(t) = I - \frac{2LI}{W} + \tan \alpha(t) \tag{7.19}$$

Sunlight goes only onto A cell (LDR1) and $i_a(t) = 2I$, $i_b(t) = 0$ when $W/2L \leq \tan \alpha(t) \leq (C - W/2)L$. When $(C - W/2)L \leq \tan \alpha(t) \leq (C + W/2)L$, $i_a(t)$ current goes through zero from 2I. When $\tan \alpha(t) \leq (C + W/2)L$, $i_a(t) - i_b(t) = 0$. Nonlinear characteristic shown in Fig. 7.23 can be used to define error detector. As $\alpha(t)$ angle is very small, $\alpha(t)$ is used instead of $\tan \alpha(t)$ [10].

Operational Amplifier: There is following relation between $i_a(t)$ and $i_b(t)$ and operational amplifier:

$$e_o(t) = -R_F[i_a(t) - i_b(t)] \tag{7.20}$$

Servo Amplifier: Gain of servo amplifier is –K. Output of servo amplifier as shown in Fig. 7.21 could be written as;

$$e_a(t) = -Ke_o(t) \tag{7.21}$$

Damper Motor: The systems using solar panels produce DC power and it is preferred to use DC motors and devices working with DC power in the system. As a matter of fact that an inverter will be needed for alternative current (AC) systems and both cost of inverter and losses of inverter will decrease the efficiency of system.

Damper motors are the AC motor types which can easily control under varying loads. Easiness to control and to start running at desired speed makes DC motors preferred in tracking systems. Moment could be changed by changing armature current and speed could be changed by changing voltage in motors by the help of electronic circuits. The motor used in the system is a brushed permanent magnet DC motor. DM consists of DC motor and a coupled gear unit (having 15 gears). Moment of DM is increased by the help of gearbox (16 Nm). For both axes, same motor is used. Movements through North-South and East-West of panels in the system are performed slowly considering movement of sun. Selected DC motor with a gear unit is shown in Fig. 7.24 and its specifications are given in Table 7.1 [1, 2].

Damper motor consists of two components. First is gear unit and second is DC motor. Angular position θ_0 of output gear is related with angular position of motor θ_m and 1/n gear ratio.

$$\theta_o = \frac{1}{n}\theta_m \tag{7.22}$$

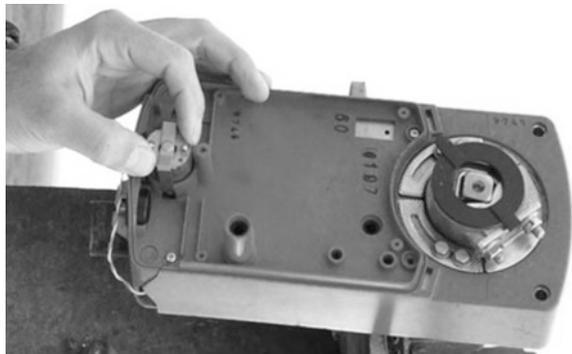**Fig. 7.24** Picture of used DC motor with gearbox (Damper motor)

Table 7.1 Specification of the motor used in the study

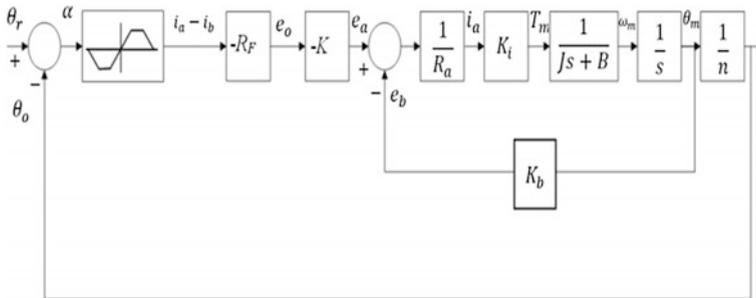| Parameter	Unit	Value
Voltage	V	24 DA/220 AA
Current	A	0, 5
Power	VA	12
Moment	Nm	16
Rotation angle	°	360
Rotation time	s	320
Weight	g	1200

Fig. 7.25 Block diagram of sun tracking system [2, 10]

While J and B represents inertia and friction coefficient of motor shaft of DC motor;

$$e_a(t) = R_a i_a(t) + e_b(t) \qquad (7.23)$$

$$e_b(t) = K_b \omega_m(t) \qquad (7.24)$$

$$T_m(t) = K_i i_a(t) \qquad (7.25)$$

$$T_m(t) = J \frac{d\omega_m(t)}{dt} + B\omega_m(t) \qquad (7.26)$$

Block diagram showing functional relations of system is given in Fig. 7.25. It is not needed to derive equations for vertical axis as both axes has same situation.

7.6 Experimental Results

In this section, data obtained from fixed and two axis systems are compared. Diyarbakır is chosen as the location where the area of highest solar radiation potential in Turkey is and experiments are run on the roof of Engineering Faculty of Dicle University in this city. Efficiency of the designed sun tracking system is observed
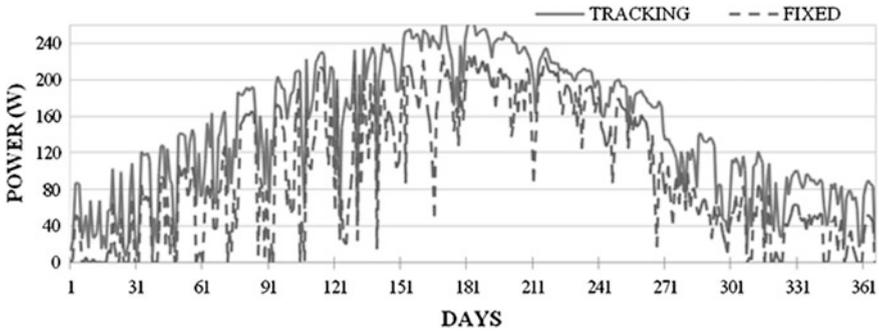
Fig. 7.26 Obtained output power of fixed and two axis systems during 2012 in Diyarbakır [2]
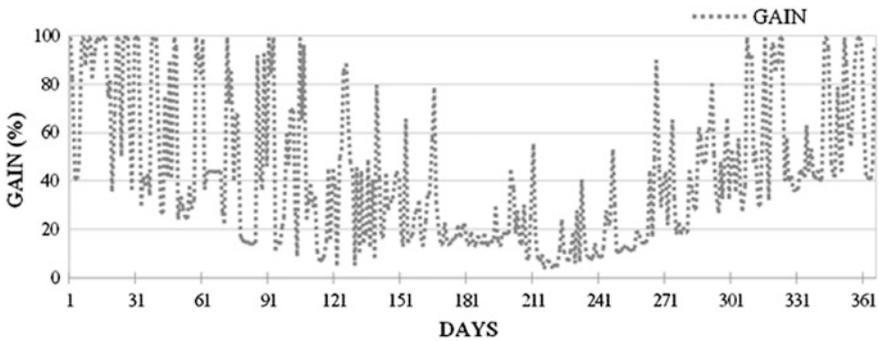

Fig. 7.27 Gain of two axis system during 2012 in Diyarbakır compared to fixed system [2] [Gain = (Power$_{tracking}$ − Power$_{fixed}$) * 100/Power$_{tracking}$]

under different weather conditions during the year [2]. To be able to compare the designed tracking system with the fixed system placed at the same location, panels having same trademark and model are used under same conditions. Comparison is done for the whole year data. Also, measurements are compared with the meteorological data. These data belong to the interval between 01.01.2012 and 30.12.2012. Measurements are done at each 10 min daily. Then, hourly and daily data are calculated using minute measurement data and also monthly and annual data are derived from daily data. Obtained data are shown in Figs. 7.26 and 7.27.

Energy consumption of two-axis sun tracking system is seen as low as not to take into consideration to calculate. As seen in Fig. 7.28, the permanent magnet DC motor of 12 W has a small structure and total consumed power during a day doesn't exceed 3 Wh. As sun tracking system stop at west position at sunset, at sunrise system turns to east for 3 min and most of the energy consumption occurs at this stage (0.6 Wh) as shown in Fig. 7.28. Then, until sunset energy is consumed at small values (as an average 0.1 Wh) according to movement of sun at horizontal and vertical axis.
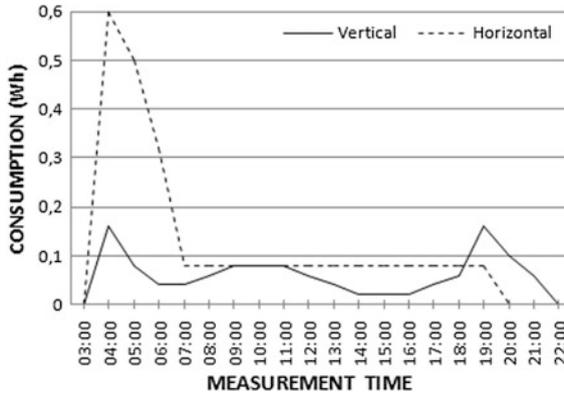
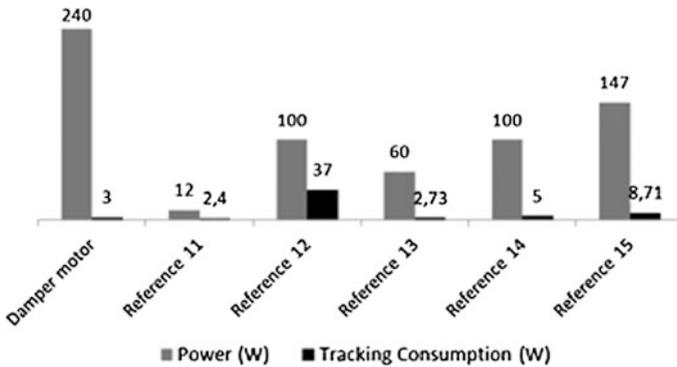**Fig. 7.28** Daily energy consumption of the used motor

Fig. 7.29 Comparison of produced and consumed energies of tracking systems [2, 11–15]

Disadvantage of sun tracking systems is its cost and consumed energy during tracking. Damper motor, used firstly in this system, has decreased both cost and also the consumed energy during tracking. Power of used motor is equal to 12 W. Daily power consumption even for the longest day (21 June) didn't exceed 3 Wh. DC motor is generally used in sun tracking system. Asynchronous motor is also used in several studies [1–3]. Obtained power is converted to AC by the help of an inverter in these studies. In this case, inverter losses decrease energy efficiency. Comparison with previous studies has shown that the system using damper motor consumed less energy as shown in Fig. 7.29 [1–4]. There are two reasons that damper motor consumes less energy. First reason is to have less power (12 W) and second reason is to have many gears (15 gears). To use these motors is recommended in tracking systems as sun moves slowly.

7.7 Conclusions

Energy production from sun by using panels is related with their cost and efficiency. Having high cost (1 W = 1$) and low efficiency (10–25%) of panels led to develop sun tracking systems. The feasible way to reduce the cost and produce more energy in a unit panel area is to use sun tracking systems. Even setup cost is higher than fixed systems; they are more advantageous when produced energy and occupied area is considered. Today it is inevitable to use these systems.

Efficiency of photovoltaic systems used to produce electrical energy directly from sun energy is still low. Most difficult task for sun tracking system which is one of the methods applied to increase efficiency is to minimize the consumed energy and cost. Panel cost is much higher than design and consume energy costs of tracking system. Also, need surface area will be low as power obtained from a unit panel area is higher [2, 17].

Disadvantages of the sun tracking systems are setup cost and the consumed energy during tracking. Using damper motor, contrary to general application, in designed system and having more basic control circuit made possible to decrease both cost and consumed energy during tracking. In the mentioned study 12 W damper motor is used and daily consumed power is not reaching even 3 W/h during the longest day (21 June). Design of control circuit is critical as it provides tracking at both horizontal (West-East) and vertical (North-South) direction during the day. Developed circuit stops the system at cloudy weather and night and so it helps saving energy.

Obtained data showed that efficiency of newly designed two axis sun tracking system is 70% higher during winter, 11% higher during summer and 31.67% higher as an average during the year when compared with fixed system. Figure 7.2 shows that fixed system is also producing high power during summer where sun is generous even two axis system is given better results. So, power difference is becoming low during summer. But this difference changes during winter and efficiency of two axis system becomes higher.

Another important factor for tracking system is how much cheaper and light mechanical components are built. This factor affects directly payback time. New studies on minimizing its effect will make tracking system cheaper and advantageous and sun as a clean and renewable energy resource will continue to heat and give energy to next generations.

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