INTRODUCTION

In recent years, photovoltaic (PV) technology has emerged as a credible alternative to fossil fuels for the generation of electrical energy. It avoids the environmental hazards associated with conventional energy sources and harnesses energy from an unlimited and readily available source. Photovoltaics is one of the fastest growing industries worldwide [1] and the total power generated by this technology is expected to increase tenfold by 2020 [2]. Yet, there are still some technical issues that should be addressed in order to improve the overall efficiency of PV cells. One major factor that compromises the output power of a PV cell is the angle $\theta$ at which the solar radiation is incident on it, as depicted in Fig. 1. The output current of a PV panel with respect to the angle of incidence of sunlight can be approximated by a cosine function at $\theta$ values ranging from 0° to 50° and falls rapidly for $\theta$ values beyond this range as shown in Fig. 2 [3]. Hence, maximum power is generated by the panel when sunlight is perpendicular to its surface. Although solar irradiation incident on a surface consists of indirect, diffused, and reflected radiations, the cosine approximation can be assumed as solar radiation is predominantly direct.

SOLAR TRACKING SYSTEMS

The diurnal and seasonal movement of the Earth causes the Sun to move across the sky during the day. To ensure maximum power output, a control system must be used to constantly adjust the position of the PV panel so that sunlight is incident normally to the panel at all times. Such control systems, known as solar tracking systems, are classified as either passive systems employing an open-loop approach or as active systems using a closed-loop methodology [4]. Passive tracking systems apply the principle of thermal expansion of matter to follow the Sun and do not use electronic control and motors. Active solar trackers are precision orientation systems based on either mathematical calculations or electro-optical sensors to find the exact position of the Sun in the sky. A controller then activates one or more actuators to adjust the panel to its optimum position. In single-axis trackers, the trajectory of the Sun is followed by changing only the azimuth angle to move from the East to the West. For more precise tracking, the system usually offsets changes in both the altitude and the azimuth angles of the Sun throughout the day. One actuator is used to adjust each angle so as to enable the PV panel with two axes of rotation. Several comparative studies conducted on the efficiency of PV systems in various geographical regions have reported that the annual energy output for the dual-axis solar tracker is better by 5 to 10% and up to 50% than the single-axis and the fixed PV systems respectively [5–8].

Fig. 1. Incidence angle of solar radiation to PV panel.
Considerable research efforts have been directed towards the development of innovative designs for dual-axis solar trackers. Generally, the trackers are driven by gear trains and motors that orient the PV panel as directed by an intelligent controller. The driving mechanism uses energy which is often drawn from PV panel output itself in order to ensure its autonomy. Since two-axis tracking systems have higher power requirements than their single-axis counterparts, it is not recommended to use them to track smaller solar panels. Studies have revealed that the power consumption of the tracking device account for 2 to 3% of the total power generated by the PV panel [9].

The aim of this paper is to present a dual-axis solar tracker that minimizes the power consumption of the system during operation so as to increase the efficiency of the PV panel. Basically, three strategies have been implemented to achieve this goal. Firstly, the motors are coupled with gearboxes to considerably decrease the speed of the output shaft and reduce the required torque. The combination of gears and bearings also helps to resist potentially high wind loading effects. Then, the drive power consumption of the dual-axis tracker is reduced at the expense of the tracking sensitivity of the system. Finally, a night-return algorithm is implemented to reposition the panel to its initial position at night before it switches into a “sleep” mode to further boost energy savings.

MATERIALS AND METHODS

The growing market of PV systems has resulted in a massive surge in the interest for solar tracking systems. Design considerations have become more stringent in terms of performance, robustness and cost. A dual-axis solar tracking system has been designed and implemented with the underlying principles being minimization of the drive power consumption and cost. The PV panel used is a 120 W mono-crystalline silicon type, with a weight of 12 kg and dimensions of $1061 \times 810 \times 35$ mm. The mechanical structure of the tracker must be resilient in order to support the weights of the panel, frame, actuators, shafts, gearing mechanisms and sunlight sensing devices. Moreover, wind flowing over the PV system can exert potentially destructive forces on the structure. It is therefore critical that the wind load be determined for the system. The present tracker has been designed to withstand wind speeds of 33.33 m/s to prevent risks of damage caused by mild cyclones that are common during summer in tropical regions. Assuming perpendicular wind flow on the panel area, an air density of 1.25 kg/m$^3$ and a drag coefficient of 2.0 for a flat surface, the wind load is calculated as 1193.4 N using the generic formula [10]. Thus, the structure should be able to resist a vertical force of about 1200 N. Due to its high tensile strength, mild steel would easily bear the effect of the calculated wind load along with the weight of the other components. Its low cost further supported its use as the main material in the fabrication of the structure.

The structural design of the dual-axis solar tracking system is depicted in Fig. 3. The primary axis of rotation is a vertical shaft that enables rotation of the panel to follow the azimuth angle of the Sun. It is mounted on an axial load ball bearing located in an appropriate housing on the base of the structure. At the other end, the vertical shaft is welded to a metal plate on the upper box frame structure. The other axis consists of a horizontal elevation shaft that allows the panel to tilt and follow the altitude angle of the Sun. It is supported by two radial load ball bearings that facilitate its rotation. The upper frame structure supports the PV panel through the horizontal shaft and accommodates the driving mechanism for the altitude angle tracking. The independent drive for each axis consists of a 1.8° high-torque hybrid stepper motor with holding torque, rated voltage and maximum phase current of 1.26 N m, 2.5 V and 2.8 A respectively, coupled to a reduction gear box. A K158 bipolar stepper motor driver board is used to actuate each motor using 5 V pulses generated by the system controller to regulate both the rotation angle and direction. The speed of rotation, which is determined by the number of pulses and their frequency, is kept constant for each axis. In order to pro-