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Performance evaluation of a multi-degree of freedom hybrid controlled dual axis solar tracking system

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ABSTRACT

Solar energy represents a clean and sustainable energy resource for many countries around the world. A solar tracking system (STS) can significantly improve the collection of solar energy by reducing the solar incidence angle. The present research presents the design, modeling, and simulation of a two-axis STS with a hybrid controlled tracking system. The present hybrid control system implements a Multi-Degree of Freedom Simplified Universal Intelligent Proportional Integral Differential controller (MDOF SUI PID). The MDOF controller integrates an open-loop astronomical algorithm and a closed-loop strategy based on a simplified and intelligent controller. The impact of the hybrid control strategy using the MDOF SUI PID controller on the sun tracking system accuracy was evaluated in the present work. Modeling and simulation of the proposed control strategy were performed using the MATLAB/Simulink package. The results show a sun tracking pointing error of ± 0.18° and a typical tracking accuracy of ± 0.12°. The present hybrid STS provides a uniform Performance ratio of about 97% for a 60 W PV panel from sunrise to sunset.

1. Introduction

The solar energy is currently among the most important clean and sustainable energy resources. Therefore, many investigations have been attempted to improve the sun trackers' performance using effective mechanical drives and efficient control systems. The sun tracking mechanisms can be classified into active and passive trackers (Luque-Heredia et al., 2007). Active solar trackers may be classified according to their control type into open-loop, closed-loop, and hybrid controlled solar trackers. Open-loop controlled solar tracking systems (STS) are based on a fixed control algorithm that depends only on a date, time, and geographical location. An open-loop STS has the sun tracking capability regardless of the weather conditions. However, it requires a precise timing source and an accurate definition of the geographical location. It also requires an accurate system setup and initialization. Meanwhile, closed-loop controlled STSs have a dynamic tracking control algorithm. They depend on a feedback signal from a sun position sensor. A closed-loop STS could be simpler in the implementation compared to the open-loop one (Luque-Heredia et al., 2007). However, its reliability may be affected by drifts in the utilized analog electronics due to the cleanliness requirements or bad weather conditions and wear of mechanical components (Luque-Heredia et al., 2007). The hybrid controlled STSs integrate the open-loop and the closed-loop sun tracking strategies. A typical hybrid sun tracking strategy switches between an open-loop algorithm and a closed-loop algorithm (Prinsloo and Dobson, 2014).

Authors have implemented different techniques in order to increase the accuracy of the solar tracking systems. Chao et al. (2017) designed a single axis solar tracking system with an adaptive hybrid calibration algorithm that reduces the accumulated error due to the inaccuracy of the sun position model and the servo system error. This hybrid algorithm calibrates the system error once a day. Chao et al. (2017) reported a maximum tracking pointing error of ± 1.5°. Skouri et al. (2016) designed and constructed three dual-axes STSs with different mechanical structures based on a microprocessor controller. They concluded that the most efficient and cost-effective one achieved a tracking error of ± 0.2° using a gear reduction unit. Garrido and Diaz (2016) developed a high concentration PV system for concentrator photovoltaic modules (CPV). They developed a cascade PID controller that follows a double loop topology. In this double loop topology, the inner loop compensates for the disturbances in the motors before implementing the sun tracking outer loop. The performance of this controller was evaluated using an experimental prototype and showed a tracking error of ± 0.014° (Garrido and Diaz, 2016). Kittiphot et al.

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Nomenclature

A_p	surface area of the PV panel [m^2]
a	diode ideality factor [-]
Alt	sun altitude/elevation angle [°]
Az	sun azimuth angle [°]
C_1	wide-range controller output
C_2	fine tuning controller output
E_{AZ}	sun sensor azimuth angle error [°]
E_{Alt}	sun sensor altitude/elevation angle error [°]
E_g	semiconductor energy band-gap [eV]
e	actual system error [°]
e_{norm}	normalized system error [-]
e_{max}	maximum actual error [°]
e_{min}	minimum actual error [°]
G	solar irradiance [W/m^2]
G_{ref}	reference solar irradiance (STC irradiance) [W/m^2]
I	load current [A]
I_{bat}	battery current [A]
I_B	effective incident irradiance on the solar panel [W/m^2]
I_o	PV cell reverse saturation current [A]
$I_{o\ ref}$	PV cell nominal reverse saturation current [A]
I_{SC}	PV cell short circuit current/photocurrent [A]
I_{SCref}	PV cell reference short-circuit current/photocurrent [A]
K_b	Boltzmann's constant [1.38×10^{-23} J/K]
K_d	differential controller gain
K_i	integral controller gain
k_i	PV cell current temperature coefficient [A/K]
K_p	proportional controller gain
N_s	number of PV series cells
N_p	number of PV parallel cells
NOCT	nominal operating cell temperature [K]
P_m	maximum power of the PV panel [W]
q	electron charge [1.602×10^{-19} C]
R_s	PV cell series resistance [Ω]
R_p	PV cell parallel resistance [Ω]
T	PV cell operating temperature [°C]
T_{amb}	ambient temperature [°C]
T_{ref}	reference temperature [°C]
V	PV panel operating voltage [V]
V_{mp}	PV panel voltage at maximum power point [V]
V_{OC}	PV cell open circuit voltage [V]
V_{th}	thermal voltage [V]
η_{STC}	PV module efficiency under Standard Test Conditions

(2016) designed and constructed a hybrid solar tracking system with tolerances of the azimuth and altitude angles of less than ± 2°.

In most reviewed hybrid control literature, the switching between the open-loop and the closed-loop control strategies is managed by decision parameters. These switching parameters may cause frequent oscillations between both strategies and result in high variations in the sun tracking accuracy. Moreover, it may cause higher power consumption of the STS (Bortolini et al., 2012). Accordingly, the objective of the present work is to improve the tracking accuracy of the STSs using a general, simple, and intelligent hybrid controller. The proposed hybrid control system can be utilized with flat PV panels as well as with concentrator solar power systems. It is investigated in the present work with flat PV panels. The present work implements a multi-degree of freedom (MDOF) simplified universal intelligent (SUI) PID controller for the hybrid control of the STSs. This controller offers simplicity in design, modeling, and implementation. Moreover, it has the ability of self-adaptation with changes in the system parameters and it is faster in response compared to the Fuzzy logic controller (FLC). Therefore, the ability of the MDOF SUI PID controller to satisfy a high tracking accuracy of the STSs is investigated in the present work. Moreover, the MDOF controller is investigated for the hybrid control of the sun tracker in lieu of the switching techniques. The MDOF controller simultaneously activates the open loop and the closed-loop control strategies with different adaptive weights instead of switching between the two controllers.

2. Solar tracking system modeling

The present hybrid control strategy implements the Sun Position Algorithm (SPA) of the National Renewable Energy Laboratory (NREL) (Reda and Andreas, 2004) as an open loop tracking algorithm and a sun-tracking sensor for the closed-loop control. The SPA algorithm was used for the open loop control because it has the least uncertainty. The utilized sun-tracking sensor comprises an array of four photodiodes. A MDOF controller performs the required hybrid control. The performance of the hybrid controlled STS was evaluated using the tracker accuracy and the maximum power generated by the solar tracker (Sabry and Raichle, 2014). The proposed STS experimental set-up is shown in Fig. 1. The present STS consists of three main subsystems; the mechanical system, the electrical system, and the control system. The mechanical system consists of a two degree of freedom solar tracker coupled with a timing belt transmission system. Meanwhile, the electrical system consists of a PV system and two stepper motors. Finally, the control system consists of a controller, motors, and a sensory system.

The PV system consists of a PV solar panel, a battery, and a 12 V DC and 6 A/10 A charging controller. The present work concerns with the modeling, simulation, and verification of the proposed tracking system while its experimental investigation will be considered in a future work.

The PV module was modeled using a generalized PV cell equivalent

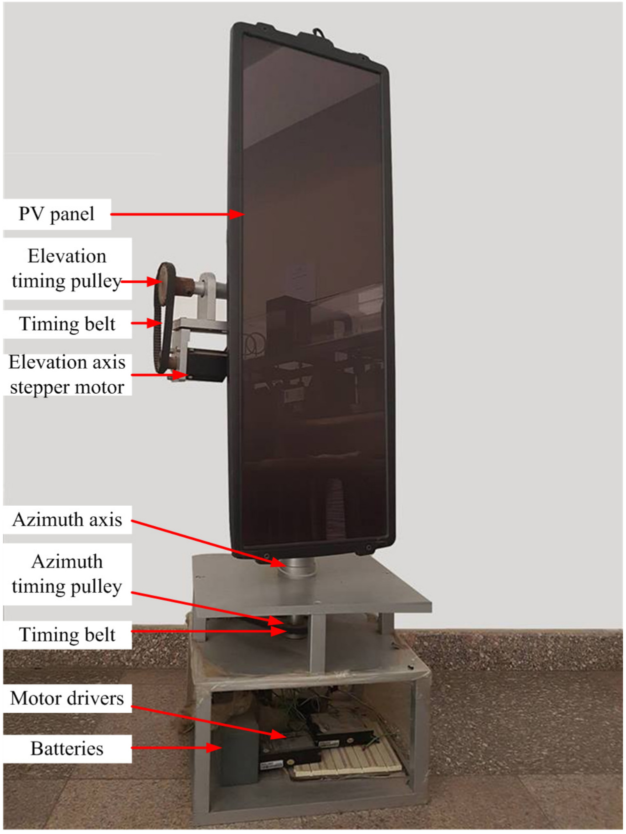

Fig. 1. Designed solar tracking system.