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Cascade closed-loop control of solar trackers applied to HCPV systems

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ABSTRACT

High concentration photovoltaic (HCPV) modules require a high precision tracking system for reaching their highest conversion efficiency. One way to accomplish this goal is by using a closed-loop mechanism and a sun sensor to track the sunlight. This paper proposes a cascade control algorithm capable of achieving a sun tracking error of 1′ for its application in high concentration photovoltaic systems. The algorithm follows an inner loop-outer loop topology. The inner loop employs a Nonlinear Proportional-Proportional Integral (NP-PI) controller and the outer loop resorts on a Proportional Integral (PI) controller. A tuning procedure for setting up the cascade controller is also described. Experiments on a laboratory prototype compare the performance of the proposed cascade controller with a PI controller not resorting on an inner loop. These outcomes show that the proposed control law provides improved tracking accuracy with less actuator wear.

1. Introduction

Solar energy is a key renewable resource that has been increasingly harnessed through the use of photovoltaic technologies in the last years. In this regard, concentrator photovoltaics (CPV) has several advantages over conventional photovoltaics including higher efficiency, smaller space, ease of recycling and reduced use of toxic substances [1]. Note that concentrator photovoltaic modules require a tracking system to maintain high efficiency. Two factors have influence on maintaining the deviation below the acceptance angle. The first one is related to assembly, mounting, alignment and stiffness of the concentrator system. The second factor corresponds to the precision of the tracking system that is related to the quality of the sun sensor and to mechanical factors including backlash and friction.

Tracking algorithms are classified as open-loop and closed-loop. An open-loop algorithm employs the sun ephemeris, the date and time to compute the desired angles of the tracking mechanism [2–7], or alternatively a Maximum Power Point Tracking algorithm [8]. Advantages of open-loop systems include low cost, insensitivity to changing weather conditions, and cloudy sky. Moreover, a properly designed feedback loop applied to the motors driving the solar tracker may counteract the effects of mechanical disturbances including the solar tracking system itself as it is shown in Ref. [5] for standard photovoltaic panels. However, they need recalibration if the solar tracker is relocated in a new geographic coordinate. Closed-loop approaches depend on a feedback mechanism that uses an optical sensor to measure sunlight and require tuning of the controller closing the loop. Besides, optical sensors are prone to diffuse light, which translates into noisy measurements, and are affected by cloudy sky. Although the use of sun sensors raises the cost of a photovoltaic systems, closed-loop approaches are able to track the apparent movement of the sun without regard on the geographical location of the solar tracker and exhibit robustness against external disturbances. Furthermore, they do not require frequent calibration thus reducing maintenance costs. The advantages of both algorithms are exploited in hybrid tracking algorithms [9–12].

There exist in the literature a variety of closed-loop control techniques for concentrator photovoltaic systems. The approach described in Ref. [11] resorts on an ON-OFF controller with hysteresis. Luque et al. [13] compare the performance of a Proportional Integral (PI) controller with the EUCLIDES algorithm. Ref. [9] employ an inner-loop outer loop cascade topology where a PI controller closes the outer loop; the tuning of the cascade controller is not addressed. Yung et al. [14] propose a sun tracking algorithm designed using pole placement technique and tested through numerical simulations. An interesting approach [15] employs a vision

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system as a sun sensor. A solar parabolic concentrator is controlled using a switching logic relay scheme in Ref. [16]. In the case of tracking systems applied to heliostats, the quality of the tracking error has been studied in several works using theoretical and empirical statistical distributions [17,18].

The main contribution of this work is to propose a closed-loop control algorithm for tracking systems aimed to drive high concentration photovoltaic (HCPV) modules. The algorithm is based on an inner-outer loop cascade design. The inner-loop resorts on a Nonlinear Proportional-Proportional Integral (NP-PI) controller that regulates the angular position of a DC motor driving the concentrator photovoltaic modules. The outer loop is closed through a Proportional Integral (PI) controller and a photo-diode-based sun sensor. Unlike previous approaches using inner-outer loop topologies, this work proposes a tuning procedure in which the inner loop compensates for disturbances and adds damping to the tracking system and the outer loop tracks a light source. Experiments on a one-axis tracking system show that the proposed cascade controller improves the tracking accuracy compared with a PI controller functioning without an inner position loop. After giving a detailed mathematical model of the one-axis solar tracking system in Section 2, Section 3 exposes the proposed cascade control algorithm and its tuning. Section 4 is devoted to experiments using a laboratory prototype. The paper ends with some concluding remarks.

2. Modeling issues

2.1. Solar tracker model

Fig. 1 shows a one-axis solar tracker that corresponds to the elevation movement of an equatorial dual-axis solar tracker [5]. It is composed of a DC motor and a sun sensor without HCPV modules. Fig. 2 depicts a schematic of the solar tracker. A base supporting the sun sensor is driven by the DC motor through a gearbox. A model for the solar tracker without the DC motor is derived using Newton's second law

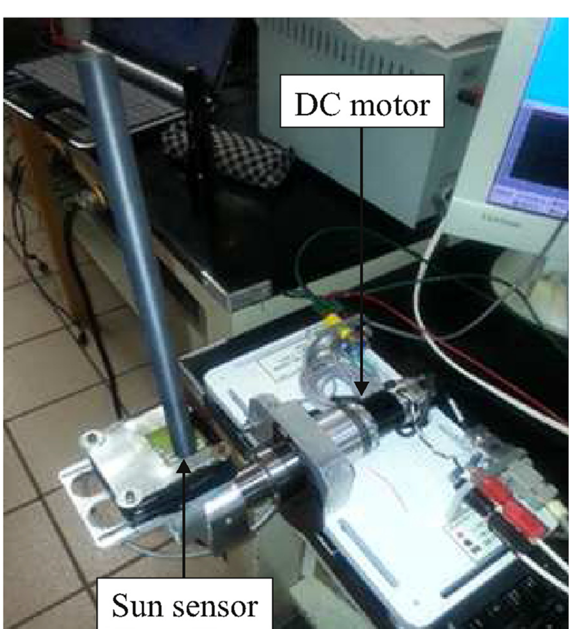

Fig. 1. One-axis solar tracker composed of a DC motor and a sun sensor.

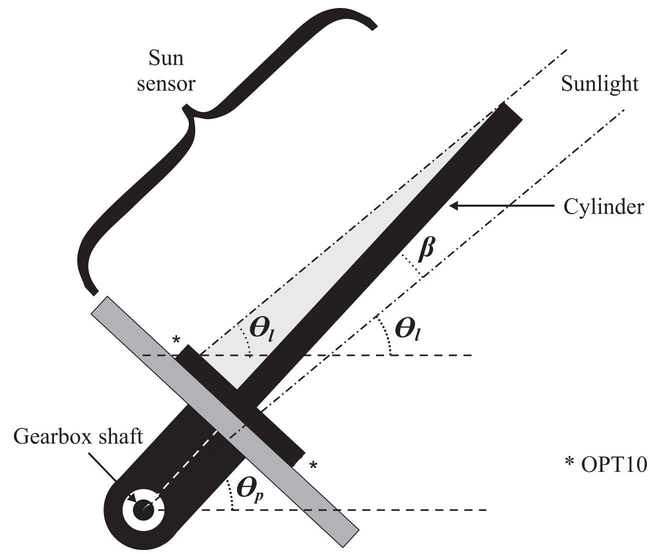

Fig. 2. One-axis solar tracker schematic.

$$J_p\ddot{\theta}_p + B_p\dot{\theta}_p + C_p\sin(\theta_p) + d_e = \tau \tag{1}$$

where θ_p, $\dot{\theta}_p$, and $\ddot{\theta}_p$ are the gearbox output shaft angular position, velocity and acceleration. The term J_p corresponds to the base and the sun sensor inertias, B_p is the viscous friction associated to the gearbox, the term $C_p\sin(\theta_p)$ is the torque produced by the gravitational forces acting on the platform, d_e accounts for external mechanical disturbances including wind loads, and τ is the torque provided by the DC motor through the gearbox. The terms J_p and $C_p\sin(\theta_p)$ may also account for the HCPV modules inertia and the gravitational torques if they are driven by a solar tracker. The DC motor dynamics are described by

$$J_m\ddot{\theta}_m + B_m\dot{\theta}_m = \tau_e - \tau_m + d_m \tag{2}$$

The terms θ_m, $\dot{\theta}_m$, $\ddot{\theta}_m$ are the motor angular position, velocity and acceleration respectively. The term J_m models the motor and gearbox inertias, the coefficient B_m corresponds to the motor and gearbox viscous frictions. The term τ_m is the load torque acting on the motor and corresponds to the solar tracker. Constant disturbances produced by mechanical static friction in the motor and the parasitic voltages produced inside the power amplifier, are modeled by d_m. Finally, the term τ_e is the electromagnetic torque provided by the motor. A current power amplifier drives the DC motor and produces a proportional relationship $\tau_e = Kv$ where v is the control voltage and K is a constant depending on the motor torque constant, the power amplifier gain, and the gain of the controller regulating the amplifier current. A single model from (1) and (2) follows by noting that $\theta_p = r\theta_m$ where r is the gearbox reduction ratio. Note also that $\tau = \tau_m/r$, which means that the mechanical load due to the solar tracker acts on the DC motor through the motor gearbox. Substituting θ_p and τ given by the aforementioned equalities into (1) produces

$$r^2J_p\ddot{\theta}_m + r^2B_p\dot{\theta}_m + rC_p\sin(r\theta_m) + rd_e = \tau_m \tag{3}$$

Substituting τ_m given by the above equation into (2) and rearranging terms yields