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Research On Control Methods for Solar Heliostat Systems

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ABSTRACT
The optimization of green energy sources for practical applications and academic research has attracted widespread interest. Improving the efficiency of emerging energy technologies, particularly solar energy harvesting systems, represents a critical high-tech domain of significant concern both in Vietnam and worldwide. A core challenge in these systems is the development of control mechanisms that maximize energy collection through precise solar tracking. The implementation of advanced control strategies, characterized by high scientific rigor and practical viability, offers promising prospects for real-world deployment.
KEYWORDS: Solar heliostat, solar tracking, parabolic trough collector, fuzzy logic control, hedge algebra control.

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I. INTRODUCTION

Solar energy is a resource that humans have utilized since ancient times; however, deploying it in industrial manufacturing and on a large scale remains a highly novel challenge and currently stands as a primary focus for scientists worldwide. The fundamental barrier to the commercialization of solar-powered devices and technologies lies in several major unresolved limitations, which include:

- High equipment costs: Most developing and least developed nations possess immense solar energy potential; however, researching and implementing solar technologies require substantial capital investment. In particular, the research and development of solar-powered cooling and air conditioning systems incur prohibitive costs relative to the average income in low-income countries.
- Low equipment efficiency: This is particularly evident in solar collectors designed to provide high-temperature heat for absorption chillers. Conventional fixed flat-plate collectors exhibit very low efficiency under these conditions, resulting in bulky installations that fail to meet spatial and aesthetic requirements.

Despite the immense potential of solar energy, its share in global total energy consumption remains modest. Consequently, researching methods to enhance the efficiency of solar energy devices and deploying them in practical applications are highly topical issues. Current widespread applications of solar energy primarily span the following areas: photovoltaic cells, solar thermal power plants, solar drying systems, solar-powered refrigeration and air conditioning systems, solar PV power supply systems, solar cooking systems with reflectors, and notably, hot water supply systems using flat-plate or finned-tube collectors.

Generally, however, these devices still suffer from high manufacturing costs and low efficiency, which hinder their widespread adoption. While collectors utilizing parabolic dishes or parabolic troughs can achieve high temperatures, the solar tracking and orientation mechanism is highly complex, creating substantial operational difficulties

II. SOLAR ENERGY HARVESTING SYSTEM

2.1. System Overview

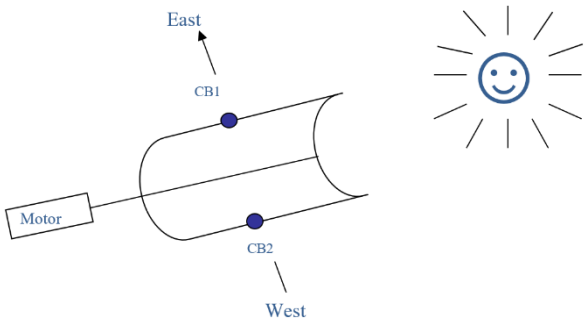


Figure 2.1. Schematic diagram of the system

The solar energy harvesting system utilizes parabolic trough collectors to concentrate solar radiation onto a receiver tube positioned along the focal line of the trough. Due to the parabolic geometry, the trough can focus sunlight onto these tubes with an intensity of 30 to 60 times. This concentrated energy heats a heat transfer fluid (HTF) typically thermal oil circulating through the piping network. The thermal energy from the fluid flowing through the receiver tube is then utilized for various applications. Collector efficiency depends on numerous variables, among which solar tracking accuracy is paramount. The drive system is responsible for precisely orienting the mirror surface to follow the sun's trajectory as it moves from East to West.

2.2. The Solar Tracking Control Problem for Heliostat Systems.

The output signal of each sensor and the sensor pair (CB1 - CB2) are connected to a differential amplifier. The resulting output voltages correspond to the deviations from the reference voltage. These voltages determine the feedback responses used as input variables for the controller to generate the desired control inputs. Consequently, the speed and direction of the corresponding DC motor are controlled.

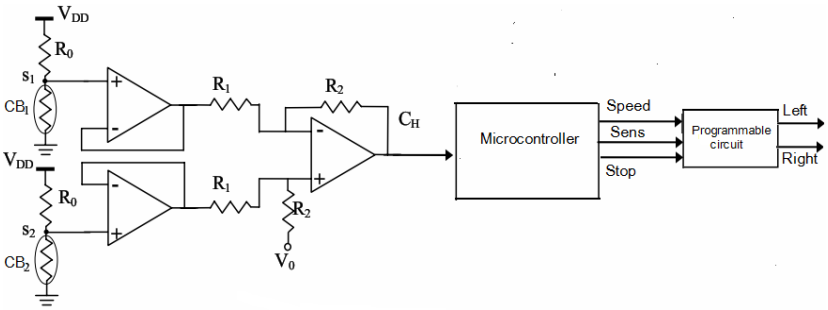


Figure 2.2. Schematic diagram of the drive system control

- Determination of the Reference Signal

Fundamentally, the heliostat system operates as a continuous sun-tracking servomechanism (servo system). The electromotive force (EMF) generated by each sensor (photovoltaic cell) depends on the luminous flux of the solar beam and its angle of incidence. Sensors CB1 and CB2 are interfaced with a differential amplifier; the resulting output voltage applied to the motor drives the mirror to rotate in a direction that eliminates the tracking error between the mirror's optical axis and the direction of the sun's rays. When sunlight is weak (e.g., due to cloud cover), the reduction in deviation causes the voltage applied to the motor to decrease. Conversely, under intense sunlight, the applied voltage increases, leading to a higher motor rotational speed. The gain of the entire system:

$$K=KcbKkdK\Sigma$$

In there: Kcb Sensor conversion coefficient

Kkd Electronic amplifier gain

K_Σ Other gains within the system, including the motor gain and the transmission coefficient of the speed reducer, remain practically constant

To determine the value of x(t), two alternative approaches can be employed:

Based on trajectory calculation software: This method computes the sun's orbital trajectory to drive the system to track this specific reference value. First, the geographical coordinates of the heliostat installation site (latitude, longitude, and real-time data) must be defined. Once these coordinates are established, the solar trajectory at the designated location can be calculated.

Based on sensor feedback: Alternatively, x(t) can be interpreted as the differential value measured between the two sensors, CB1 and CB2. The value x(t) represents a time-varying function that changes very slowly, corresponding to the sun's trajectory. Under the assumption that the sun's displacement is evaluated every 10 minutes,

if $\Delta u=Us1+Us2 > \zeta$ then the controller will actuate the drive system to rotate

if $\Delta u=Us1+Us2 \leq \zeta$ hen the system will remain stationary

Speed	Sens	Stop	Left	Right	Motor
SPEED	X	0	0	0	STOP
	0	1	0	1	Turn Right
	1	1	1	0	Turn Left

Therefore, during each movement interval, the reference signal can be considered constant (modeled as a step function, (1(t)). The resulting output voltage Ch is utilized as the input variable for the controller to generate the desired control inputs. Based on these signals, the speed and direction of the corresponding DC motor are precisely regulated $C_h = \frac{R_2}{R_1} (U_{s2} - U_{s1}) + U_0$ Where: Ch is computed from the microcontroller's input circuit. The reference voltage U_0 is injected to comply with the microprocessor's operating levels.

Table 2.1 illustrates the representation of the variables derived from the solar receiver structure.

Table 2.1. Different states of the heliostat

	Ch > U0	Ch < U0	Ch = U0
Adjust the rotational direction of the heliostat	From West to East	From East to West	Maintain position

- Drive Motor Control

The concentrated energy heats a heat transfer fluid (HTF) typically thermal oil circulating through the piping network. The solar receiver is positioned above the trough along the East-West axis and rotates with the sun to optimize the collection of thermal energy from the receiver tubes. The optical efficiency of the collector is a function of five parameters: surface mirror reflectivity, mirror surface coating transmittance, thermal absorptance, the angle of incidence modifier (IAM), and the intercept factor:

$$\eta o = f(\rho, \tau, \alpha, K, \gamma) \qquad (2.1)$$

Under normal operating conditions, the angle of incidence modifier is equal to unity (K = 1); therefore:

$$\eta o = [\tau \alpha \rho] \gamma \qquad (2.2)$$

The coefficients τ, α, ρ are intrinsic physical properties of the specific materials composing the collector and are therefore considered constant. The intercept factor γ which is independent of variations in solar irradiance and fluid temperature is a function of both geometric parameters and tracking alignment error characteristics. These errors, which tend to accumulate throughout the construction and operational phases of the system, include:

- Collector misalignment

- Reflector displacement (Reflector error)
- Solar tracking error
- Mirror geometric error (Specular error)
- Receiver spillage (Error due to rays falling outside the absorber zone)

Consequently, the thermal efficiency is expressed as a function of γ and by extension, as a function of the tracking error, which directly impacts the collector's thermal performance. To maximize the efficiency of the thermal collector, it is imperative to minimize the tracking error as much as possible, which requires adjusting the mirror assembly and the control system so that the parabolic mirror surface precisely faces the sun at all times. Numerous solar tracking control systems have been investigated and implemented over recent decades. The control system investigated in this study utilizes a single motor to adjust the rotational direction of the mirror, as illustrated in Figure 2.3.

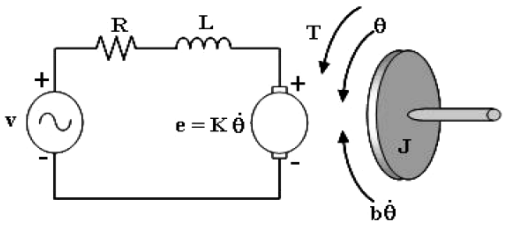


Figure 2.3. Actuation motor

III. CONTROL METHODS

3.1. Fixed-Rate Control

Assuming that the sun rotates across the sky at a constant speed of 0.25°/min, this tracking system employs a continuous drive method. These drive systems utilize ON/OFF switching at a specific ratio to ensure the collector tracks the solar movement. The system uses a specific time unit for the sun's incremental steps with a minor error margin, while the mirror remains centered within the adjustment angle. The initiation point for the drive mechanism is defined as the instance when the tracking error exceeds the allowable threshold.

3.2. PSA Algorithm-Based Control

This model determines the solar position utilizing the Almería algorithm (from the Plataforma Solar de Almería). The parameters used are the geographical coordinates (latitude and longitude) of the mirror's location, while the variable is the real-time clock calculated by the microprocessor. Feedback signals are obtained from a position encoder to compare the computed solar position with the actual position of the mirror.

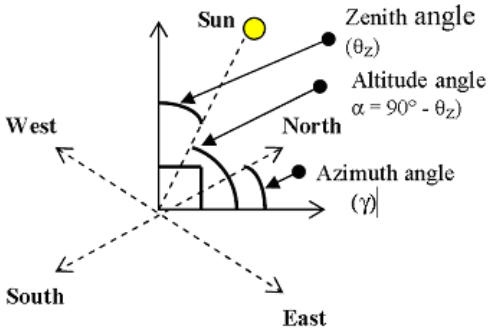


Figure 2.4. Solar position determination

By utilizing a PLC, a control program can be developed to calculate the solar position in real time.

3.3. Fuzzy Logic Control (FLC)

The model utilizes a fuzzy logic controller based on an intelligent control algorithm to determine the output signals for the drive motor speed. This control model is constructed with three inputs: the mirror (trough) position, the fluid inlet temperature, and the wind speed. Consequently, the three input variables are fluid temperature, wind speed, and [trough position], while the single output variable is the motor speed

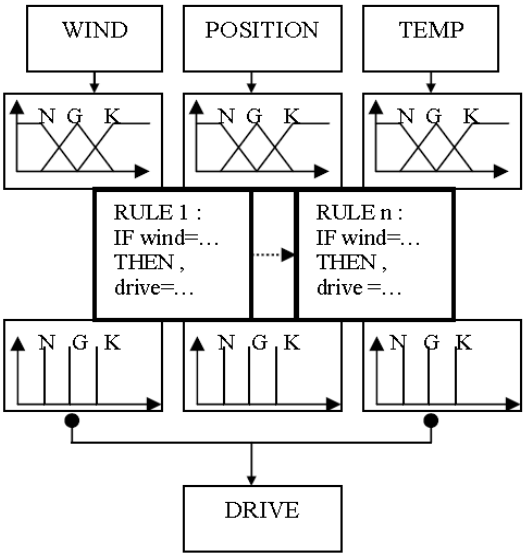


Figure 2.5. Architecture of the controller

After naming the input and output variables, the membership functions for each input and output are defined. Trapezoidal membership functions are employed for the input variables, while singleton membership functions are used for the output variable. These membership functions are constructed based on the system variables, which include wind speed, parabolic trough position, fluid temperature, and drive motor speed. The fuzzy control rules are developed based on data acquired from the anemometer, the trough position encoder, the temperature sensor, and the variations in motor speed.

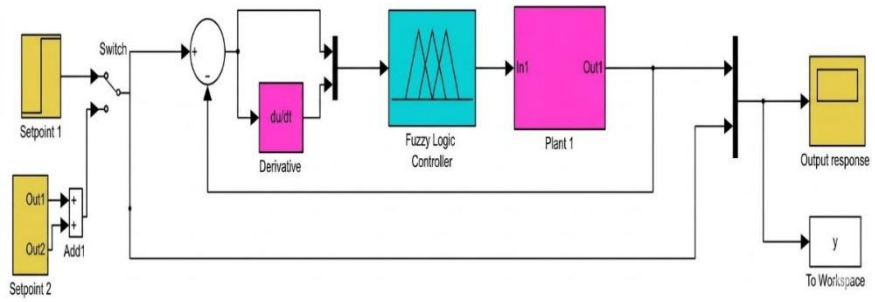


Figure 2.6. Simulation with the fuzzy logic controller

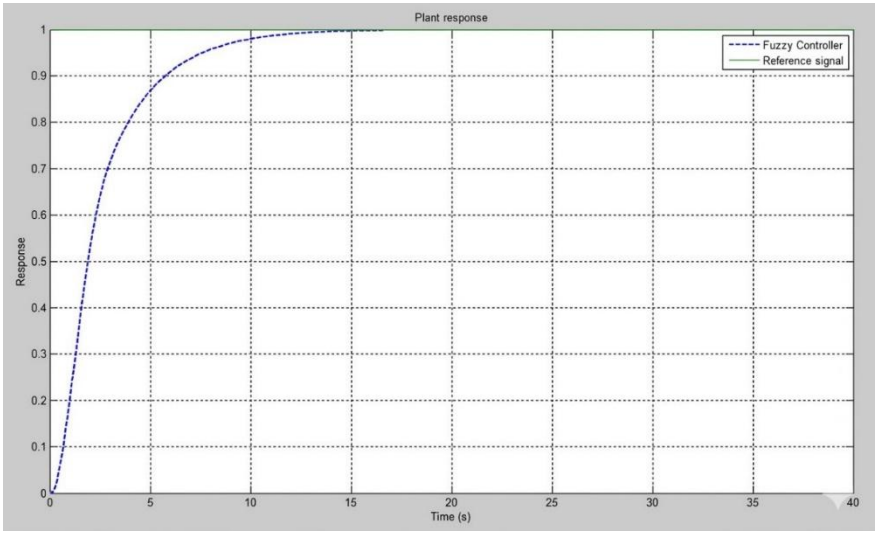


Figure 2.7. Simulation results with the fuzzy logic controller

3.4. Hedge Algebra Control (HAC)

Selection of Calculation Parameters:

G = { 0, Small, W, Large, 1}

H– = { Little} = {h–1}; q = 1;

H+ = {Very} = { h1}; p = 1;

fm(Small) = θ = 0.5;

μ(Very) = 0.5; μ(Little) = 0.5.

so: α = 0.4;

β = 0.6;

μ(h1) = 0.6; μ(h–1) = 0.4.

fm(Small) = θ = 0.5;

fm(Large) = 1 – fm(Small) = 1 – 0.5 = 0.5.

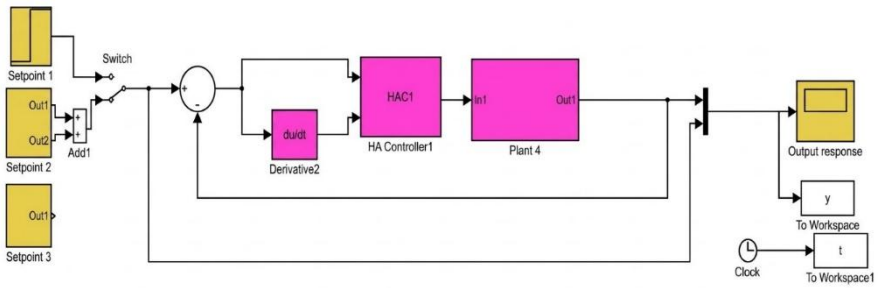


Figure 2.8. Simulation with the hedge algebra controller (α≠β)

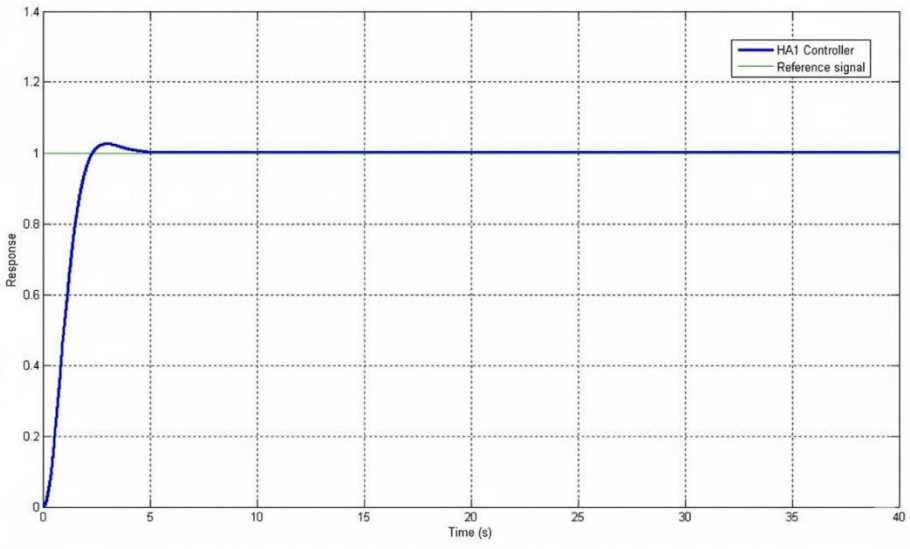


Figure 2.9. Simulation results with the hedge algebra controller (α≠β)

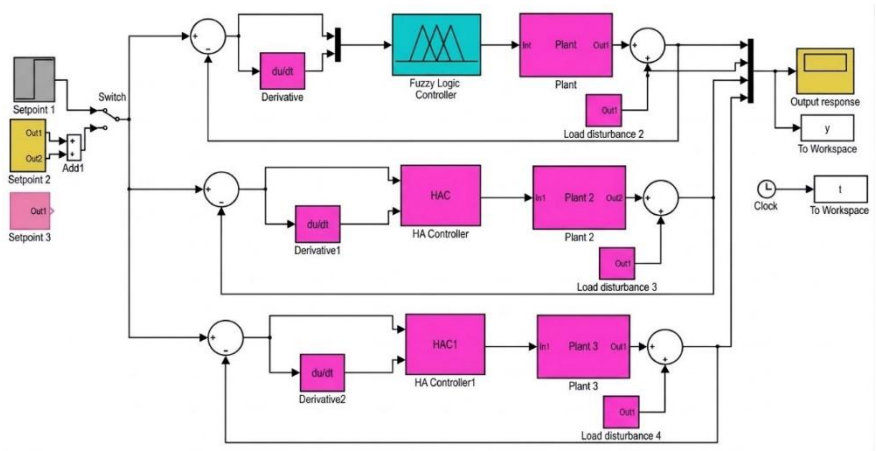


Figure 2.10. Simulation diagram with load disturbance using the fuzzy controller and two hedge algebra controllers

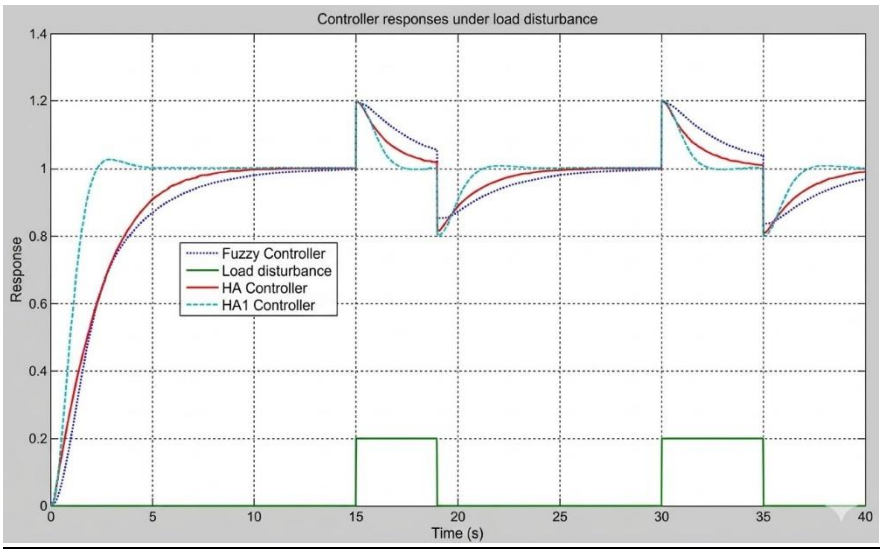


Figure 2.11. Controller responses under a step reference input and load disturbance

Remarks: In the event of a load disturbance occurring due to certain factors as simulated in the figure, it can be observed that:

All controllers exhibit smooth response curves and achieve rapid stabilization upon the application of the load disturbance.

The fuzzy controller demonstrates a sub-optimal response and a slow disturbance rejection time (approximately 19 seconds).

When a 20% load disturbance is applied for a duration of 4 seconds, the HA controller 1 ($\alpha \neq \beta$) yields the best response with a settling time of approximately 7 seconds. Therefore, in the presence of load disturbances under a step reference input, the use of HA controller 1 is highly recommended ($\alpha \neq \beta$).

IV. CONCLUSION

Solar tracking control plays a vital role in solar energy harvesting systems. The thermal efficiency of the energy collector is expressed as a function of the intercept factor, which strictly depends on the precision of the solar tracking operation. Accurate collector control is therefore crucial to maximizing the overall thermal efficiency of the solar energy harvesting system.

Most existing heliostat control systems operate on an open-loop framework. In the fixed-rate control method, the speed variable is programmed to rotate the reflector at a constant rate corresponding to the sun's movement. In the PSA control method, the algorithm is defined by mathematical equations based on the solar position. In both approaches, position feedback is merely utilized as a sampling parameter and is not strictly required for the execution of the control law. Conversely, for intelligent controllers (such as fuzzy logic and hedge algebra controllers), position feedback sensors, wind speed anemometers, and heat transfer fluid temperature sensors are essential to precisely determine the mirror position.

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