

Application Research of Sliding Mode Predictive Control Based on Feedforward Compensation in Solar Thermal Power Generation Heat Collecting System

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Abstract

For solar thermal power generation system with fast time-varying, strong interference and uncertainty characteristics, combined with compensatory of the feedforward compensation to measurable disturbance, strong robustness of sliding mode control and the advantages of predictive control to handle obvious constraints effectively a method of feedforward sliding mode predictive controller is put forward to apply in solar thermal power generation heat collecting system. First of all, ignoring the heat loss in heat transfer process mathematical model of solar thermal power generation heat collecting system is established as prediction model of controller design. Progressive stable sliding surface was designed through the pole placement method, which effectively overcame the chattering phenomenon and reduced interference caused by uncertainty at the same time. Feedforward compensator was designed to compensate the effect of measured interference signal which is solar radiation to collector output. Simulation results show that feedforward sliding mode predictive control has strong anti-interference ability and improves the control accuracy compared with sliding mode predictive control.

Keywords: *Solar Thermal Power Generation, Feedforward Compensation, Sliding Mode Predictive Control*

1. Introduction

Linear Fresnel solar thermal power generation technology has the advantages of compact arrangement, high rate of land utilization, small wind resistance, weak wind resistance, strong wind resistant ability, flexible installation and other advantages. In the past 30 years, various control strategies have been applied to thermal control of solar energy, including PID controller, feed-forward control, adaptive control and generalized predictive control technology [1]. The plant dynamics also can be approximated by an affine state-space neural network, of which the complexity is depend on the cardinality of dominant singular values associated with a subspace oblique projection of data-driven Hankel matrix [2]. The use of Nonlinear Model Predictive Controller (NMPC) can manipulate the oil flow rate to maintain the field outlet temperature in the desired reference value and attenuate the disturbances effects [3]. Through the application of a robust nonlinear predictive controller into the distributed collector field of a solar desalination plant, and using a robust dead-time compensation structure and a nonlinear model predictive control, time delay uncertainties and system nonlinearities were dealt with [4]. Adaptive model predictive control using an unscented Kalman filter (UKF) was presented [5]. The literature [6] used the sliding mode predictive control (SMPC) method. Non-linear optimal feedforward control of solar collector plants is not easy because of non-linear disturbance effects and long input-dependent transport delays. So as to obtain an accurate model of feedforward controller design, measured data were used in a black-

box recursive prediction error identification algorithm. Through the simulation accurate feedforward control was obtained [7]. Feedback linearization (FL) has been used to control the temperature in a solar field; however, undesirable control signal oscillation is caused by a delay uncertainty. Filtered Smith predictor (FSP) as the control strategy dealing with dead-time errors and including control signal saturation caused by flow rate constraints was an effective method [8]. As can be seen from applications above, model Predictive control algorithms or sliding mode predictive control (SMPC) can improve the control accuracy of system but for strong random interference signal control effect is poor. The literature [7, 8] used the feedforward compensate the Interference of solar radiation. Therefore, this paper proposes strategy of feedforward sliding mode predictive control (FFSMPC) applied to the control of linear Fresnel collector system.

2. Dynamic Model of Solar Thermal Power System

Light focusing and heat collecting subsystem is the core of linear Fresnel thermal power generation system. The solar radiation is focused into the Fresnel collector to heat the heat conducting oil in heat collector, which realizes that solar energy is converted to heat energy. Using heat conducting oil after heated Heats the water to generate high-temperature steam to drive generator. Figure 1 is a linear Fresnel collector field which has been put into use.



Figure 1. Linear Fresnel Collector Field

In 1985 the Spanish scholar Carmona, R. initially use mathematical models (1) and (2) in his doctoral thesis[9]to describe the heat change of solar collector field, then literature[4-6] cited the model analyzed and simulated heat collecting system.

$$\rho_f C_f A_f \frac{\partial T_f}{\partial t}(x,t) + \rho_f C_f u(t) \frac{\partial T_f}{\partial x}(x,t) = \eta_0 GI(t) \quad (1)$$

Equation (1) can be expressed as (2):

$$\rho_f C_f A_f \frac{dT_n(t)}{dt} = n_0 GI - \rho_f C_f u(t) \frac{T_n(t) - T_{n-1}(t)}{\Delta x} \quad n = 1 \dots N \quad (2)$$

Table 1 lists the physical quantities of formula (1) and (2).

Table 1. Solar Power Plant Model Variables and Parameters

symbol	description	units
t	Time	s
x	Space	m
ρ_f	Density	kg m^{-3}
C_f	Specific heat capacity	$\text{JK}^{-1}\text{kg}^{-1}$
A_f	Cross-sectional area	m^2
$u(t)$	Oil pump volumetric flow rate	l/s
$I(t)$	Solar irradiance	W m^{-2}
η_0	Mirror optical efficiency	
G	Mirror optical aperture	m
$T_n(t)$	corresponding Oil outlet of $\square x$	$\text{K}, ^\circ\text{C}$
$T_{n-1}(t)$	corresponding Oil inlet of $\square x$	$\text{K}, ^\circ\text{C}$
L	The total length of collector tube	m

Let $\square x = L$, the formula (2) is:

$$\rho_f C_f A_f \frac{dT_n(t)}{dt} = \eta_0 G I(t) - \rho_f C_f u(t) \frac{T_n(t) - T_0(t)}{L} \quad n = 1 \dots N \quad (3)$$

Where $T_n(t)$ and $T_0(t)$ are the outlet temperature and the entrance temperature of the whole collector field at t moment.

According to the measured actual data, the temperature change range of outlet temperature and entrance oil temperature at the same time is $20^\circ\text{C} \square 25^\circ\text{C}$. When the sampling period is T and $a = \frac{T_n(t) - T_0(t)}{L}$, $y(t) = T_n(t)$, formula (3) after discretization is expressed as:

$$\rho_f C_f A_f \frac{[y(k+1)T] - y(kT)}{T} = \eta_0 G I(k) - \rho_f C_f a u(k) \quad (4)$$

Where $u(t)$ is input, $y(t)$ is output and $I(t)$ is disturbance. So formula (4) is:

$$y(k+1) = y(k) + \left(-\frac{Ta}{\rho_f C_f A_f}\right)u(k) + \frac{\eta_0 GT}{\rho_f C_f A_f} I(k) \quad (5)$$

3. Structure of Feedforward Model with Predictive Control

Structure of feedforward model with predictive control diagram is shown in Figure 2.

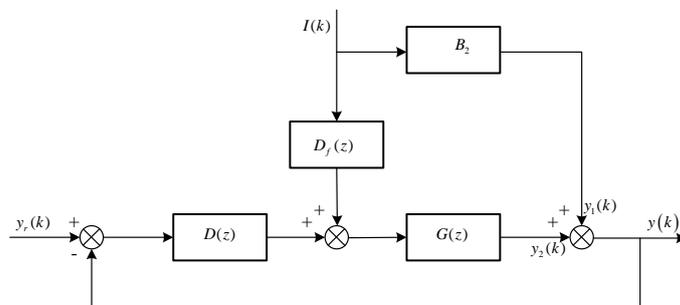


Figure 2. Structure of Feedforward Model with Predictive Control

In the Figure 2, $D(z)$ represents model predictive controller, $G(z)$ represents heat collecting field model, $I(k)$ represents solar radiation, $D_f(z)$ represents feedforward compensator, $y_1(k)$ is output parts of the system caused by solar radiation, $y_2(k)$ is the output caused by feedforward compensation, $y_r(k)$ is the expected outlet oil temperature and $y(k)$ is the future predict output.

Consider the following uncertain discrete linear system [10]:

$$\mathbf{y}(k+1) = (\mathbf{A} + \Delta\mathbf{A})\mathbf{y}(k) + (\mathbf{B} + \Delta\mathbf{B})\mathbf{u}(k) + \xi(k) \quad (6)$$

where $\mathbf{y}(k)$ is output vector, $\mathbf{u}(k) \in R$ is the control input, \mathbf{A} and \mathbf{B} are the matrix with suitable dimension, $\Delta\mathbf{A}$, $\Delta\mathbf{B}$ represent the component caused by parameter uncertainty and $\xi(k)$ represents the external interference obtained from feedward compensation, so the design of sliding mode predictive control only consider the following uncertain systems(7).

$$\mathbf{y}(k+1) = (\mathbf{A} + \Delta\mathbf{A})\mathbf{y}(k) + (\mathbf{B} + \Delta\mathbf{B})\mathbf{u}(k) \quad (7)$$

3.1 Feedforward Compensator Design

The last item of the mathematical model of solar thermal power generation system (5) is solar radiation signal which is measured and random interference signal. In order to eliminate the feedforward disturbance [11].

$$y_1(k) + y_2(k) = 0 \quad (8)$$

Let

$$F_1 = -\frac{Ta}{\rho_f C_f A_f}, \quad F_2 = \frac{\eta_0 GT}{\rho_f C_f A_f},$$

so the controlled object is

$$G(z) = F_1 \times \frac{1}{1-z} \quad (9)$$

and feedforward compensator is

$$D_f(z) = -\frac{F_2}{G(z)} \quad (10)$$

3.2 Sliding Mode Predictive Control Algorithm

3.2.1 Sliding-Mode Surface Design: Definition of switching function [12-14].

Let the reference command signal be $\mathbf{y}_r(k)$ and the tracking error be:

$$\mathbf{e}(k) = \mathbf{y}(k) - \mathbf{y}_r(k) \quad (11)$$

Define the linear sliding mode function

$$s(k) = \boldsymbol{\sigma}^T \mathbf{e}(k) \quad (12)$$

where, $\boldsymbol{\sigma}^T = [\sigma_1, \dots, \sigma_n]$, σ_i is obtained through the method of pole placement which can guarantee the stability and dynamic performance of the ideal sliding mode. Construct following sliding mode prediction model

$$s(k+1) = \boldsymbol{\sigma}^T \mathbf{e}(k+1) \quad (13)$$

Prediction sliding-mode surface is $S_m = \{\mathbf{e}(k) | s(\mathbf{e}(k)) = 0\}$.

Ahead predictor of p step is

$$s(k+p) = \sum_{i=1}^p \boldsymbol{\sigma}^T \mathbf{A}^{i-1} \bar{\mathbf{y}}_r(k+p-i) \quad (14)$$

Using the the error between the actual output value of the switching function $s(k)$ and the predicted value in advance of p step at $k-p$ moment makes feedback correction of

output value $s_p(k+p)$ of sliding mode prediction model. So output $\tilde{s}_p(k+p)$ of closed loop sliding mode prediction model can be expressed:

$$\tilde{s}_p(k+p) = s(k+p) + \zeta_p[s(k) - s_p(k|k-p)] \quad (15)$$

where, $\zeta_p \in R$ is Feedback correction coefficient, namely the weighted feedback correction. From the view of engineering application, usually make $\zeta_1 = 1, 0 < \zeta_p < 1(p=1)$ and the effect of feedback correction will decrease along with ζ_p .

3.2.2 Sliding Mode Reference Trajectory: Take the current commonly used approach law as a reference trajectory.

$$\begin{cases} s_r(k+p) = \mu s_r(k+p-1) + \eta \operatorname{sgn}(s_r(k+p-1)) \\ s_r(k) = s(k) \end{cases} \quad (16)$$

where, $0 < \mu < 1, \eta > 0$. when μ is bigger, approach speed is slower and the switching control force is smaller. The control objective is to make the error states $e(k)$ reach the sliding surface, namely $s(e(k)) = 0$.

3.2.3 Design of Control Law: Define the index of performance:

$$J = \sum_{i=1}^N (s_r(k+i) - \tilde{s}(k+i))^2 + \sum_{j=0}^{M-1} \lambda_j u^2(k+j) \quad (17)$$

where, N and M are positive integers respectively represent prediction time domain and control time domain. M needs satisfy $0 < M \leq N$ and $u(k+j) = u(k+M-1), M \leq j < N$. λ_j is the weight coefficient, which is used to measure the degree of attention of tracking error and control quantity in index of performance.

$$\begin{aligned} \mathbf{S} &= [s(k+1), \dots, s(k+N)]^T, \quad \mathbf{S}_r = [s_r(k+1), \dots, s_r(k+N)]^T, \\ \tilde{\mathbf{S}} &= [\tilde{s}(k+1), \dots, \tilde{s}(k+N)]^T, \\ \bar{\mathbf{S}} &= [s(k) - s_p(k|k-1), \dots, s(k) - s_p(k|k-N)]^T = [\bar{\mathbf{S}}(1), \dots, \bar{\mathbf{S}}(N)]^T \\ \mathbf{U} &= [u(k), \dots, u(k+M-1)]^T, \quad \mathbf{F} = [\sigma^T \mathbf{A}, \dots, \sigma^T \mathbf{A}^N]^T \\ \Xi &= \operatorname{diag}\{\zeta_1, \dots, \zeta_N\}, \quad \Lambda = \operatorname{diag}\{\lambda_1, \dots, \lambda_M\}, \\ \tilde{\mathbf{Y}}_r &= [\tilde{y}_r(k), \dots, \tilde{y}_r(k+N-1)]^T, \end{aligned}$$

$$\mathbf{G} = \begin{bmatrix} \sigma^T \mathbf{b} & 0 & \dots & \dots & 0 \\ \sigma^T \mathbf{A} \mathbf{b} & \sigma^T \mathbf{b} & \dots & \dots & 0 \\ \vdots & \vdots & \dots & \dots & \sigma^T \mathbf{b} \\ \vdots & \vdots & \dots & \dots & \vdots \\ \sigma^T \mathbf{A}^{N-2} \mathbf{b} & \sigma^T \mathbf{A}^{N-3} \mathbf{b} & \dots & \sigma^T \mathbf{A}^{N-M} \mathbf{b} & \sum_{i=0}^{N-M-1} \sigma^T \mathbf{A}^i \mathbf{b} \\ \sigma^T \mathbf{A}^{N-1} \mathbf{b} & \sigma^T \mathbf{A}^{N-2} \mathbf{b} & \dots & \sigma^T \mathbf{A}^{N-M+1} \mathbf{b} & \sum_{i=0}^{N-M} \sigma^T \mathbf{A}^i \mathbf{b} \end{bmatrix}$$

$$P = \begin{bmatrix} \sigma^T & 0 & \dots & 0 \\ \sigma^T A & \sigma^T & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ \sigma^T A^{N-1} & \sigma^T A^{N-2} & \dots & \sigma^T \end{bmatrix}, \quad \tilde{P} = \begin{bmatrix} \sigma^T & 0 & \dots & 0 \\ \sigma^T & \sigma^T A & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ \sigma^T & \sigma^T A & \dots & \sigma^T A^{N-1} \end{bmatrix}$$

So formula(14), (15) can be separately expressed as a vector form, namely (18), (19) .

$$S = Fe(k) + GU + PY_r \tag{18}$$

$$\tilde{S} = S + \Xi \bar{S} \tag{19}$$

Formula(16) can be written as vector form expressed by (20).

$$J = (H - GU)^T (H - GU) + \Lambda U^T U \tag{20}$$

Where, $H = (L_1 \alpha^k + L_2 \beta^k) s(0) - Fe(k) + PY_d - \Xi \bar{S}$.

Minimization of J can be analytically obtained U .Let $\frac{\partial J(U)}{\partial U} = 0$ and solve the corresponding equation, U can be obtained.

$$U = (G^T G + \Lambda)^{-1} G^T H \tag{21}$$

4. Simulation Analysis

This paper selects the model represented by formula (5) as the simulation object. Flow rate range of heat conducting oil is 3l/s ~ 12l/s. The actual values of other parameters are respectively $\eta_0 = 0.60$, $T = 20s$, $L = 220m$, $A_f = 0.65m^2$, $\rho_f = 800kg/m^3$, $C_f = 2600J \cdot /kg \cdot ^\circ C$, $G = 0.80m$. Take the data of June 6th,2014, the expected output of outlet temperature ranged from 220⁰C to 240⁰C. SMPC algorithm and FFSMPC algorithm was used to simulate and Comparison of the results was shown in Figure 3 to Figure 8.

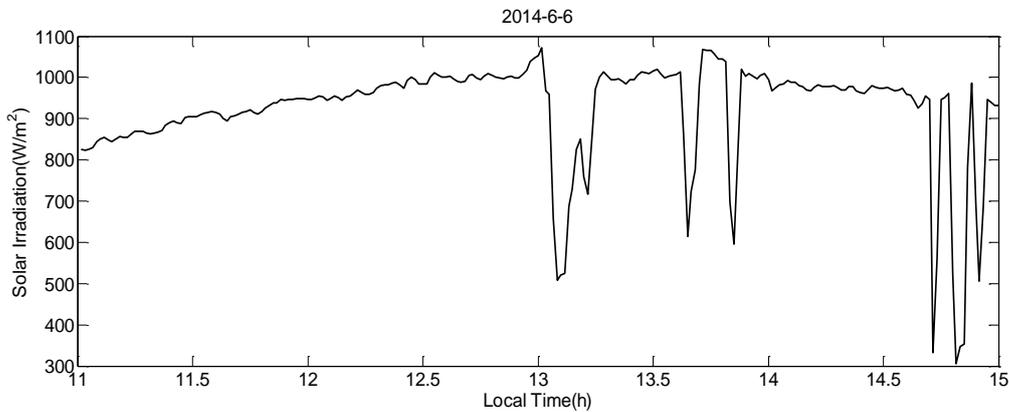


Figure 3. The Measured Actual Intensity of Solar Radiation

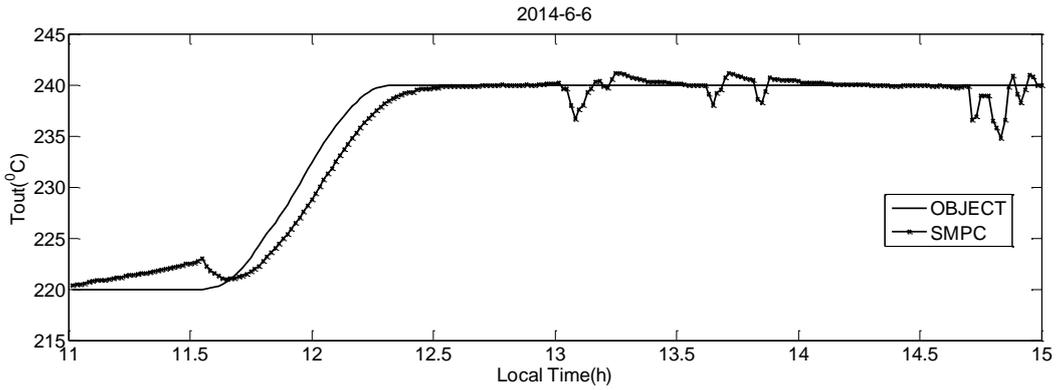


Figure 4. The Following Curve of Outlet Temperature of SMPC

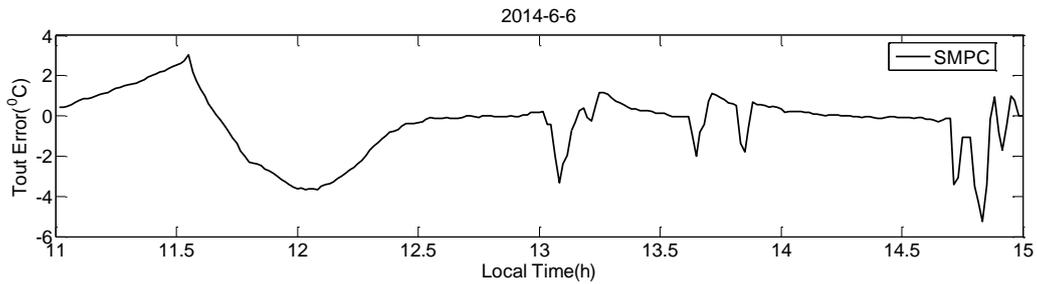


Figure 5. The Following Error Curve of Outlet Temperature of SMPC

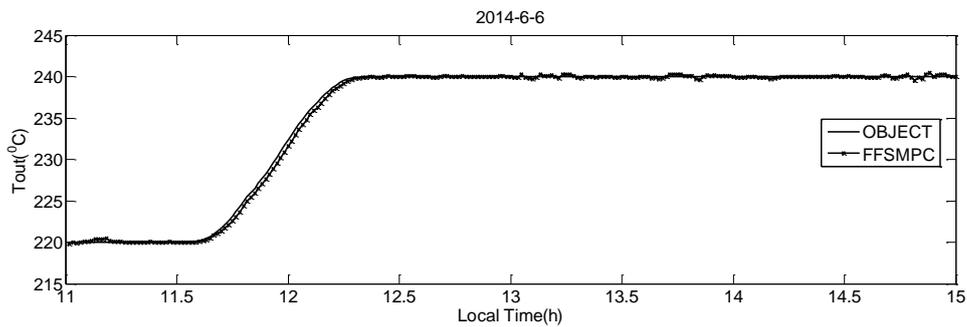


Figure 6. The Following Curve of Outlet Temperature of FFSMPC

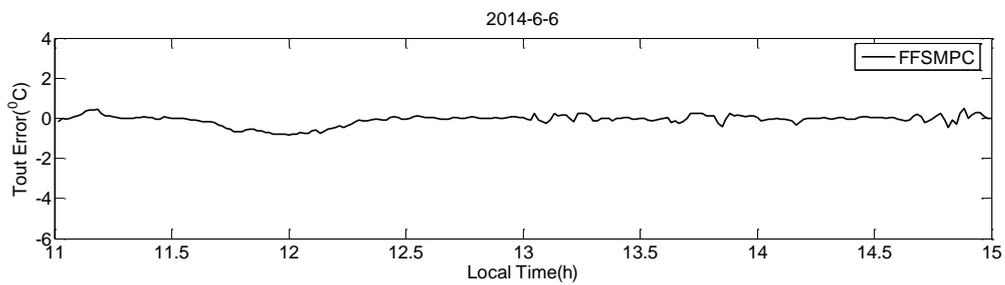


Figure 7. The Following Error Curve of Outlet Temperature of FFSMPC

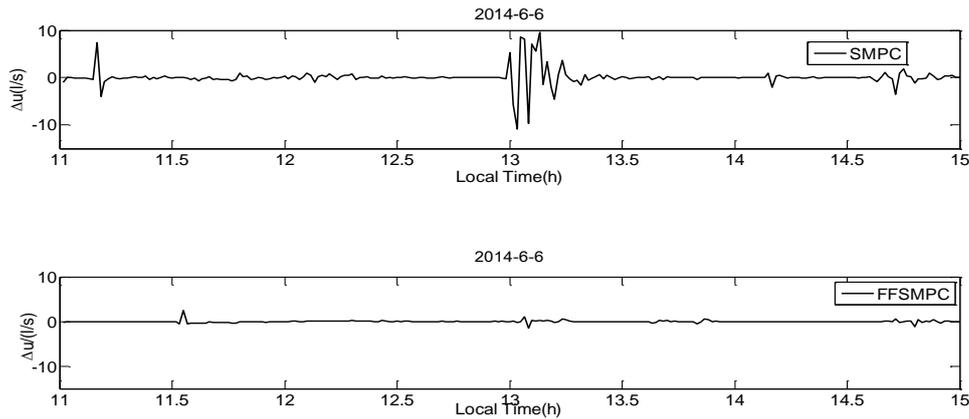


Figure 8. Comparison of the Changes of Control Increment

As can be seen from simulation results above, using FFSMPC obviously reduced the tracking error. In figure8, when FFSMPC algorithm was used, the velocity change of heat conducting oil was more stable compared with SMPC. Calculate the mean squared error (MSE), then MSE of Figure 4 is 1.490 and figure6 is 0.262. Therefore, when the FFSMPC strategy was applied to the control of linear Fresnel collector system, the tracking effect is better.

5. Conclusion

In order to improve the stability of power generation of solar thermal power generation system, sliding mode predictive controller based on feedforward compensation was designed in which the tracking error of outlet oil temperature of heating system was considered as control objective. SMPC and FFSMPC were respectively applied to the linear Fresnel thermal power generation system which has been put into use in western china. The measured actual data was used to simulated and verified, and the results show that the control effect of FFSMP was obviously better than that of SMPC. Using the feedforward control reduced the interference caused by measured random large signal on the output. Sliding mode model predictive control has good robustness to random system. The FFSMPC strategy makes the control increment, MSE and tracking error smaller and has the very good application and popularization value.

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