Recursive Tuning of Intelligent Controllers of Solar Collector Fields in Changing Operating Conditions

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Abstract: Solar power plants should be designed to collect all the available thermal energy in a usable form within a desired temperature range. In cloudy conditions, the collector field is maintained in a standby mode ready for full-scale operation when the intensity of the sunlight rises again. Control is achieved by means of varying the flow of oil pumped through the pipes during the plant operation. The multilevel control system consists of a nonlinear linguistic equation (LE) controller with predefined adaptation models, some smart features for avoiding difficult operating conditions, and a cascade controller for obtaining smooth operation. The whole system can be tuned recursively with specialised dynamic LE models developed with generalised norms and moments. The parameters of the dynamic models and the controllers are closely connected. Hazardous operating conditions are avoided. Fast start-up and efficient energy collection in variable operating conditions extend considerably the operating time of the collector field.

Keywords: Solar energy, intelligent control, nonlinear systems, adaptation, efficiency, linguistic equations, modelling, simulation

1. INTRODUCTION

Solar power plants should collect any available thermal energy in a usable form at the desired temperature range, which improves the overall system efficiency and reduces the demands placed on auxiliary equipments. In cloudy conditions, the collector field is maintained in a state of readiness for the resumption of full-scale operation when the intensity of the sunlight rises once again.

Solar collector field is good test platform for various control methodologies (Camacho et al., 1997; Juuso, 1999). An overview of possible control strategies presented in (Camacho et al., 1997) include basic feedforward and PID schemes, adaptive control, model-based predictive control, frequency domain and robust optimal control and fuzzy logic control. A comparison of several intelligent controllers was presented in (Juuso, 1999).

Models have been integrated to various control schemes. Feedforward approaches based directly on the steady state energy balance relationships can use measurements of solar irradiation and inlet temperature (Camacho et al., 1992). Lumped parameter models taking into account the sun position, the field geometry, the mirror reflectivity, the solar irradiation and the inlet oil temperature have been developed for a solar collector field (Camacho et al., 1997). A feedforward controller has been combined with different feedback controllers, even PID controllers operate for this purpose (Valenzuela and Balsa, 1998). The classical internal model control (IMC) can operate efficiently in varying time delay conditions (Farkas and Vajk, 2002).

Linguistic equations have been used in various industrial applications (Juuso, 1999, 2004b). Modelling and control activities with the LE methodology started by the first LE controllers implemented in 1996 (Juuso et al., 1997) and the first dynamic LE models developed in 1999 (Juuso et al., 2000). The robust dynamic simulator based on linguistic equations is an essential tool in fine-tuning of these controllers (Juuso, 2003, 2004a, 2005). The LE controllers also use model-based adaptation and feedforward features, which are aimed for preventing overheating, and the controller takes also care of the actual set points of the temperature Juuso and Valenzuela (2003). Genetic algorithms with binary coding combined with simulation and model-based predictive control have further reduced temperature differences between collector loops (Juuso, 2006).

Parameters of the LE controllers were first defined manually, and later tuned with neural networks and genetic algorithms. Data analysis methods based on generalised norms, which were recently developed for condition monitoring (Juuso and Lahdelma, 2010), provide new data-driven tools for modelling (Juuso, 2010). A recursive version of the scaling approach is needed in this application where the variations of operating conditions can be drastic.

This paper extends the scaling approach to a recursive tuning method for LE controllers used for flow control in thermal energy collection. All the experiments have been carried out in the Acurex Solar Collectors Field of the Plataforma Solar de Almeria in Spain.
2. SOLAR COLLECTOR FIELD

The aim of solar thermal power plants is to provide thermal energy for use in an industrial process such as seawater desalination or electricity generation. In addition to seasonal and daily cyclic variations, the intensity depends also on atmospheric conditions such as cloud cover, humidity, and air transparency. Unnecessary shutdowns and start-ups of the collector field are both wasteful and time consuming. Finally if the control is fast and well damped, the plant can be operated close to the design limits thereby improving the productivity of the plant (Juuso et al., 1998).

The Acurex field supplies thermal energy (1 MW) in form of hot oil to an electricity generation system or a Multi-Effect Desalination Plant. The solar field consists of parabolic–trough collectors, see (Juuso et al., 1997). Control is achieved by means of varying the flow pumped through the pipes in the collector field (Fig. 1) during the plant operation. In addition to this, the collector field status must be monitored to prevent potentially hazards situations, e.g. oil temperatures greater than 300 °C. The temperature increase in the field may rise up to 110 degrees. In the beginning of the daily operation, the oil is circulated in the field, and the flow is turned to the storage system (Fig. 1) when an appropriate outlet temperature is achieved. The valves are used only for open-close operation, and the overall flow \( F \) to the collector field is controlled by the pump.

The lumped parameter energy balance of the collector field presented in (Valenzuela and Balsa, 1998) can be written as a feedforward controller for the flow rate of the oil (m³s⁻¹):

\[
 F = \frac{A_{eff}}{1 - \eta_p} \rho c \frac{T_{out} - T_{in}}{T_{diff}}
\]

where \( I_{eff} \) is effective irradiation (Wm⁻²), and the difference of the inlet and the outlet temperature \( T_{diff} = T_{out} - T_{in} \) (°C) define the operating point. The effective irradiation is the direct irradiation modified by taking into account the solar time, declination and azimuth. The field is represented with the oil characteristics and geometrical parameters: \( A_{eff} \) effective collector area (m²), \( \rho \) oil density kgm⁻³, \( c \) specific heat of oil (Jkg⁻¹K⁻¹), and \( \eta_p \) a general loss factor.

Distributed parameter model can be based on the energy balance: energy stored = irradiance - energy transferred - heat loss. For a unit volume of the pipe this can be represented by

\[
\rho c A \frac{\partial T}{\partial t} = I_{eff} W \eta_0 - \rho c F \frac{\partial T}{\partial x} - h D(T - T_{amb})
\]

where \( A \) is cross section of the pipe line (m²), \( D \) pipe diameter (m), \( h \) heat transfer coefficient (Wm⁻²K⁻¹), \( T \) oil temperature (°C), \( T_{amb} \) ambient temperature (°C), \( x \) length coordinate (m), \( W \) width of the mirror (m), \( \eta_0 \) optical efficiency, and \( t \) time (s). Oil properties depend drastically on temperature, and therefore operating conditions change considerably during the working day, e.g. during the start-up stage, the oil flow is limited by the high viscosity. These distributed parameter models are discussed in (Juuso, 2004a).

3. DATA ANALYSIS

Data analysis is based on generalised norms and moments.

3.1 Generalised norms

The generalised norm is defined by

\[
||^\tau M_j^p||_p = (M_j^p)^{1/p} = \left[ \frac{1}{N} \sum_{i=1}^{N} |x_j|^p \right]^{1/p}, \quad (3)
\]

where the order of the moment \( p \in R \) is non-zero, and \( N \) is the number of data values obtained in each sample time \( \tau \). The norm (3) calculated for variables \( x_j \), \( j = 1, \ldots, n \), have same dimensions as the corresponding variables. The norm \( ||^\tau M_j^p||_p \) can be used as a central tendency value if all values \( x_j \) > 0, i.e. \( ||^\tau M_j^p||_p \) ∈ R. This norm combines two trends: a strong increase caused by the power \( p \) and a decrease with the power 1/p. The norm (3), which is a Hölder mean, also known as a power mean, was introduced for signal analysis in (Lahdelma and Juuso, 2008).

The norm values increase with increasing order, and the increase is monotous if all the signals are not equal.

The mean, the harmonic mean and the root mean square for signal analysis in (Lahdelma and Juuso, 2008).

For variables with only negative values, the norm is the opposite of the norm obtained for the absolute values. If a variable has both positive and negative values, each norms is an average of two norms:

\[
||^\tau M_j^p||_p = \frac{1}{2} \left\{ \left[ \frac{1}{N} \sum_{i=1}^{N} (|x_j|_i)^p \right]^{1/p} + x_L \right\} - \left\{ \frac{1}{N} \sum_{i=1}^{N} (|x_j|_i - x_H)^p \right\}^{1/p} + x_H, \quad (4)
\]

where the data sets are made positive and negative by subtracting a value \( x_L < \min(|x_j|) \) and a value \( x_H > \max(|x_j|) \), respectively.
The computation of the norms can be divided into the computation of equal sized sub-blocks, i.e., the norm for several samples can be obtained as the norm for the norms of individual samples. The same result is obtained using the moments:

\[ \|M_f^{\tau}\|_p = (K\cdot\tau M_f^{\tau})^{1/p} = \left\{ \frac{1}{K_\tau} \sum_{i=1}^{K_\tau} \tau(M_j)^{\tau}\right\}^{1/p}, \]

where \(K_\tau\) is the number of samples. Each sample has \(N\) variable values.

3.2 Generalised moments

The normalised moments are generalised by replacing the expectation with the norm (3) as the central value:

\[ (\gamma_p^k) = \frac{1}{N\sigma_j^p} \sum_{i=1}^{N} (|x_i| - |\tau M_j|)^k \]

where \(\sigma_j\) is calculated about the origin, and \(k\) is a positive integer. Dimensionless features are obtained by normalising the moments by standard deviation \(\sigma_j\), which is the norm (3) with the order \(p = 2\). (Juuso, 2010) The feature \(\gamma_p^k\) is the generalised coefficient of skewness, or here briefly skewness, and the feature \(\gamma_3^p\) as the generalised coefficient of kurtosis. The skewness is a measure of asymmetry: \(\gamma_3^p = 0\) for a symmetric distribution. If \(\gamma_3^p > 0\), the skewness is called positive skewness and the distribution has a long tail to the right, and vice versa if \(\gamma_3^p < 0\).

3.3 Scaling functions

Membership definitions provide nonlinear mappings from the operation area of the (sub)system to the linguistic values represented inside a real-valued interval \([-2, 2]\), denoted as the linguistic range, see (Juuso, 2004b). In current systems, the membership definitions consist of two second order polynomials: one for negative values, \(X \in [-2, 0)\), and one for positive values, \(X \in [0, 2]\):

\[ f^-_j = a^-_j x_j^2 + b^-_j x_j + c^-_j, \quad X_j \in [-2, 0), \]
\[ f^+_j = a^+_j x_j^2 + b^+_j x_j + c^+_j, \quad X_j \in [0, 2]. \]

The values \(X_j\) are called linguistic values because the scaling idea is based on the membership functions of fuzzy set systems. The coefficients of the polynomials are defined by the corner points of the feasible range: \(\{\min(x_j), (c^-_j), (c^+_j), \max(x_j)\}\).

As the membership definitions are used in a continuous form, the functions \(f^-_j(X_j)\) and \(f^+_j(X_j)\) should be monotonous, increasing functions in order to produce realisable systems. In order to keep the functions monotonous and increasing, the derivatives of the functions \(f^-_j\) and \(f^+_j\) should always be positive (Fig. 2). This is satisfied if the ratios

\[ \alpha^-_j = \frac{(c^-_j) - \min(x_j)}{c^-_j - (c^-_j)}, \]
\[ \alpha^+_j = \frac{\max(x_j) - (c^+_j)}{(c^+_j) - c^-_j}, \]

are both in the range \([\frac{1}{3}, 3]\), see (Juuso, 2009). Corrections are done by changing the borders of the core area, the borders of the support area or the centre point. Additional constraints for derivatives can also be taken into account. The coefficients of the polynomials can be represented by

\[ a^-_j = \frac{1}{3} (1 - a^-_j) \Delta c^-_j, \]
\[ b^-_j = \frac{1}{3} (3 - a^-_j) \Delta c^-_j, \]
\[ a^+_j = \frac{1}{3} (a^+_j - 1) \Delta c^+_j, \]
\[ b^+_j = \frac{1}{3} (3 - a^+_j) \Delta c^+_j, \]

where \(\Delta c^-_j = c_j - (c^-_j)\) and \(\Delta c^+_j = (c^+_j) - c_j\). Membership definitions may contain linear parts if some coefficients \(a^-_j\) or \(a^+_j\) equals to one (Fig. 2).

The best way to tune the system is to first define the working point and the core \([(c^-_j), (c^+_j)]\), then the ratios \(\alpha^-_j\) and \(\alpha^+_j\) from the range \(\frac{1}{3}, \ldots, 3\), and finally to calculate the support \([\min(x_j), \max(x_j)]\). The membership definitions of each variable are configured with five parameters, including the centre point \(c_j\) and three consistent sets: the corner points \(\{\min(x_j), (c^-_j), (c^+_j), \max(x_j)\}\) good for visualisation (Juuso, 2004b); the parameters \{\(\alpha^-_j, \Delta c^-_j, \alpha^+_j, \Delta c^+_j\}\) are suitable for tuning (Juuso, 2009); and the coefficients \{\(a^-_j, b^-_j, a^+_j, b^+_j\}\} are used in the calculations (Juuso, 2004b). The upper and the lower parts of the scaling functions can be convex or concave, independent of each other. Simplified functions can also be used: a linear membership definition only requires two parameters: \(c_j\) and \(b_j\) \(=\) \(b^-_j\) or \(\Delta c_j = \Delta c^-_j = \Delta c^+_j\), since \(a^-_j = a^+_j = 1\) and \(a^-_j = a^+_j = 0\); an asymmetrical linear definition has \(\Delta c^-_j \neq \Delta c^+_j\) and \(b^-_j \neq b^+_j\). Additional constraints can be taken into account for derivatives, e.g., locally linear function results if continuous derivative is chosen in the centre point. The continuity requirement limits the ranges of the ratios \(\alpha^-_j\) and \(\alpha^+_j\) if the functions are adjusted by moving the centre point (Juuso, 2010).
3.4 Corner points with generalised moments and norms

The value range of \( x_j \) is divided into two parts by the central tendency value \( c_j \) and the core area, \([c_j - a_j, c_j + a_j]\), is limited by the central tendency values of the lower and upper part. There are problems when the value range is very wide or the distribution is very concentrated. The central tendency value is chosen by the point where the skewness changes from negative to positive, i.e., \( \gamma^2_j = 0 \). Then the data set is divided into two parts: a lower part and an upper part. The same analysis is done for these two data sets. The estimates of the corner points, \((c_l)_j\) and \((c_u)_j\), are the points where \( \gamma^2_j = 0 \). The iteration is performed with generalized norms. Then the ratio \( \alpha_j \) is restricted to the range \([\frac{1}{3}, 3]\) moving the corner points \((c_l)_j\) and \((c_u)_j\) or the upper and lower limits \( x_j \) and/or \( \text{max} \{x_j\} \). The linearity requirement is taken into account, if possible.

The nonlinear scaling methodology based on generalised norms and skewness provides good results for the automatic generation of scaling functions when all values \( x_j \) are positive. Sensitivity to small faults and anomalies was increased considerably. The approach was tested with normal, Poisson and Weibull distributions and with two applications of condition monitoring. Absolute values were used in (Junso and Lahdelma, 2010). This study extends the method to positive and negative values.

4. MULTILEVEL CONTROL

The multilevel control system consists of a nonlinear LE controller with predefined adaptation models, some smart features for avoiding difficult operating conditions and a cascade controller for obtaining smooth operation. For the solar collector field, the goal is to reach the nominal operating temperature 180–295 °C and keep it in changing operating conditions (Fig. 3).

4.1 Linguistic equation controller

General feedback linguistic equation (LE) controllers use error \( e_j(k) \), derivative of the error \( \Delta e_j(k) \), and sum of errors \( \delta e_j(k) \), where \( k \) is the discrete time index. These can be obtained for any variable \( x_j \), \( j = 1, \ldots, m \) and mapped to the linguistic range \([-2, 2]\) by nonlinear scaling with variable specific membership definitions \( f(x)_j \), \( f(u)_j \) and \( f(\delta e)_j \), respectively. As all these functions consist of two second order polynomials, the corresponding inverse functions consist of square root functions. The linguistic values of the inputs, \( e_j(k) \), \( \Delta e_j(k) \), and \( \delta e_j(k) \), are limited to the range \([-2, 2]\) by using the functions only in the operating range: outside the scaled values are -2 and 2 for low and high values, respectively.

A PI-type LE controller is represented by

\[
\Delta u_{ij}(k) = K_p(i,j) \Delta e_{ij}(k) + K_i(i,j) \frac{e_{ij}(k)}{\Delta u_{ij}(k)}
\]

which contains coefficients \( K_p(i,j) \) and \( K_i(i,j) \), and variables \( [\hat{e}_{ij} \ \Delta e_{ij} \ \Delta u_{ij}]^T \). The linguistic value of the change of control, denoted as \( \Delta u_{ij} \), is obtained by (10) and limited to the range \([-2, 2]\), and the scaled to the real values \( \Delta u_{ij}(k) \) by the membership definitions of the change of error denoted as \( f(\Delta u) \):

\[
\Delta u_{ij}(k) = (f(\Delta u))(\Delta u_{ij}(k)).
\]

The output \( i \) of a single input single output (SISO) controller is calculated by adding the effect of the controlled variable \( j \) to the manipulated variable \( i \):

\[
u_i(k) = u_i(k-1) + \Delta u_{ij}(k).
\]

In the solar collector field, the feedback controller is a PI-type LE controller with one manipulated variable and one controlled variable. The error is the deviation of the outlet temperature, \( T_{out} \), from the set point, and the controlled variable is oil flow, \( F \). High irradiation allows higher temperatures (Fig. 3). The inlet temperature and the solar irradiation are taken into account in the adaptation part. (Junso, 2006).

The scaling function for the error \( e_j(k) \) and the change of control \( \Delta u_{ij} \) can be generated for different operating conditions by using the scaling function of the corresponding variable. The derivative of the error \( \Delta e_j(k) \) and the sum of errors \( \delta e_j(k) \) are defined in the controller tuning.

4.2 Predefined adaptation

Oscillations are considerably reduced by modifying the operation of the controller by adaptive scaling of the manipulating variable \( i \) based on the working point

\[
wp_i(k) = \sum_{j=1}^{m} w_{ij} \hat{x}_j(k) + b_i^{W},
\]

where \( \hat{x}_j(k) \) and \( w_{ij} \) are the linguistic values of the variable \( j \), \( j = 1, \ldots, m \), and the corresponding weight factors. The bias term \( b_i^{W} \) is specific to the manipulating variable. The working point, \( wp_i(k) \in [-2, 2] \), is a deviation from the normal operation. The change of control is multiplied by a scaling factor \( s_{c_i}(k) \), which is obtained from the \( wp_i(k) \) by membership definitions of \( s_{c_i}(k) \).

In this application, the manipulating variable \( i \) is the oil flow. The working point variables are the effective solar irradiation, \( I_{eff} \), the temperature difference between inlet and outlet temperatures, \( T_{diff} \), and the ambient temperature \( T_{amb} \). For the other variables \( w_{ij} = 0 \). In the normal working point \( wp = 0 \), the irradiation \( I_{eff} \) and the temperature difference, \( T_{diff} \), are on the same level. High working point \( wp > 0 \) means low \( T_{diff} \) compared to the irradiation level \( I_{eff} \). Correspondingly, low working point \( wp < 0 \) means high \( T_{diff} \) compared to the irradiation level \( I_{eff} \). The ambient temperature has a minor effect. On a clear day the working point is normal \( wp = 0 \) during the start-up phase and high \( wp = 1 \) in the afternoon. On a cloudy day, the working point should be kept normal throughout the day. To avoid oscillations the working point should be kept positive. (Junso, 2005)

The adaptive part contains additional braking and asymmetrical actions (Junso, 1999). The predictive braking action (PBA) is used to ensure smooth recovery after severe disturbances or smooth change to a considerably
4.3 Smart and cascade control

The predefined adaption is not enough in fast changes of operating conditions. Too high temperatures are usually results of following cases:

- The inlet temperature changes considerably from the average level corresponding to case known to the controller;
- Temperature is rising so fast that the controller cannot handle efficiently the evolving situation;
- The temperature difference between the inlet and the outlet is too high compared to acceptable level corresponding to the recent average of the corrected irradiation.

Additional change of control is introduced if at least one of these cases is active. The main purpose of these additional control actions is to avoid oscillatory conditions as delays make it difficult to damp oscillations with feedback control. The first two actions are predictive, and the third one is corrective. These smart control actions are beneficial in smooth compensation of load disturbances without exceeding the safety limits of the collector system. Their tuning can be improved by distributed parameter models. These situations are tackled by changing the set point as well: the set point is reduced if the irradiation or the inlet temperature is staying on a lower level long time (Juuso and Valenzuela, 2003). Cascade control is used in the start-up to facilitate fast temperature increase without oscillatory behaviour. Similar reduction of the set point is activated for load disturbances. In cloudy conditions the cascade control reduces considerably the overshoot after clouds. (Juuso, 2005)

4.4 Recursive tuning

The parameters of the scaling functions can be recursively updated with (5) by including new samples into calculations. The number of samples $K_s$ can be increasing or fixed with some forgetting, and weighting of the individual samples can be used in the analysis. The order of the corresponding norms are re-analysed if the distribution is changing considerably with new measurements. The process operation during the start-up is very different from the normal operation. Specialised models for different working conditions can be constructed with the data analysis by using separate sets of samples.
Nonlinear scaling functions are analysed for the effective irradiation $I_{eff}$ and the ambient temperature $T_{amb}$ from long term data, and for the outlet temperature $T_{out}$ from cases of good operation. The resulting temperature differences $T_{diff}$ depends on economical factors and properties of the collector field, e.g. how much the temperature is allowed to increase. Operating range of the oil flow is defined, and the operating point $c_j$ is chosen in such a way that the field operation is good when both $I_{eff}$, $T_{diff}$ and $T_{amb}$ are all normal. The levels -1 and +1 are chosen by comparing the alternative combinations. The scaling functions used in LE controller are constructed from the functions of the corresponding variables: error $e_j$, derivative of the error $\Delta e_j$ and initial error $e_j^0$ from $T_{out}$, and change of control $\Delta u_{ij}$ from the oil flow.

5. ENERGY COLLECTION

According to the test results the solar collector field operates well also in less favourable conditions if the multilevel LE controller is used. Start-up is very fast in good weather conditions: effective energy collection starts in less than 30 minutes (Fig. 3(a)), and the increase of irradiation is utilised efficiently (Fig. 3(b)). Short irradiation disturbances (two points in Fig. 3(b)) do not have any effect on the outlet temperature. The highest allowed temperatures were achieved (Fig. 3(a)) even though the irradiation did not reach high levels above 1 kW m$^{-2}$. Temperatures were lowered in the end of the day when a large load disturbance took place. Fast start-up and recovery from the load disturbances are clear benefits resulting from the predefined adaptation and the cascade control.

On a cloudy day, the operation time is shorter (Fig. 3(c)), but also quite high temperatures are achieved. Start-up was very fast and fairly good operating conditions were kept for whole day in spite of drastic changes in irradiation (Fig. 3(d)). The multilevel LE controller was necessary in this case: all the special features described in Section 4 were used.

In good weather conditions, the thermal power was most of the time close to 1 MW (Fig. 4(a)). Higher power levels were reached only for a very short period since these levels normally require very high irradiation (Fig. 4(b)). In this case, the high power levels lead to temperature differences, which are slightly above the limit (Fig. 4(c)). These periods belong to good operation when the irradiation is in this level. The start-up period has lower efficiencies, and higher efficiencies are achieved when the field is in the high operation limit. In the beginning of the start-up, the oil temperature decreases in the field, i.e. $T_{diff}$ < 0, leading to negative power and efficiency values.

In cloudy conditions, irradiation is fluctuating and there are periods of very low irradiation. Naturally, the efficiency decreases, but even short sunny spells are utilised quite well (Fig. 4(e)). The thermal power almost reaches 1 MW (Fig. 4(d)). The temperature difference is kept rather low for safety reasons (Fig. 4(f)). Although the efficiencies are almost on the same level as in good weather conditions, the total collected thermal energy reduces with about 30% (Fig. 5), since there is less solar energy available. However, all this energy was collected with the aid of the advanced LE controller, since the collector field would have kept closed on that day.
Fig. 5. Results of the energy collection in different weather conditions.

6. CONCLUSION

Multilevel LE control system is adapted to changing operating conditions with predefined adaptation techniques. Special features are activated when needed. The new data-based methodology improves tuning possibilities. The whole system can be tuned recursively with specialised dynamic LE models developed with generalised norms and moments. The parameters of the dynamic models and the controllers are closely connected. Fast start-up, smooth operation and efficient energy collection is achieved even in variable operating condition.

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