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A fuzzy logic-based tuning approach of PID control for steam turbines for solar applications

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Abstract

This work aims at improving the control concept based on PID controller by jointly exploiting experience and knowledge on the system behaviour and artificial intelligence. A Concentrated Solar Power Plant (CSPP) system has been modelled and a stability and performance analysis has been carried out, focusing on power control loop, which is normally based on standard PID. A hybrid fuzzy PID approach is proposed to improve the steam turbine governor action and its performance are compared to the classical PID tuned according to three different approaches. Compared to the classic PID, the PID fuzzy logic controller extends the simplicity of PID and adapts the control action at actual operating condition by providing the system with a sort of "decision-making skill". The possibility to design implementable algorithms on PLC, which have stringent computational speed and memory requirements, has been explicitly taken into account in the developed work.

Keywords: CSPP; Steam turbine; PID; Tuning; Fuzzy Control.

1. Introduction

In the last decade, Concentrated Solar Power Plants (CSPP) show an ever-increasing diffusion worldwide [1], due, on one hand, to their increased efficiency and capacity of energy production [2], on the other hand, to the pressure toward an efficient exploitation of renewable energy sources in order to improve sustainable development of human activities.

A CSPP generates electrical power by using different kind of technologies [3] (e.g. parabolic trough, solar towers, etc.) and exploits solar thermal energy to generate steam. The available solar energy changes during the day, due to the daily cycle of irradiation and to the weather conditions. This implies a daily

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start-up and shut down cycle in the power generation unit and quite sensitive variations in the steam production. On the other hand, steam turbine mechanics and control systems were originally designed to face with a quite stable steam production and very rare start-up and shut down cycles. Therefore, in the context of CSPP the standard control techniques can be unable to adapt automatically to changing operating conditions of the machine, which works in non-optimal efficiency conditions during its lifetime hence. The control procedures need to allow correct and efficient machine operation in transient conditions without compromising its integrity.

The turbine control problem with variable steam conditions can be addressed by looking for applicability of innovative control strategy. Adaptive Control approaches able to adapt gains in different loading conditions and uncertainties are known [4][5], as well as Model Based Control schemes, such as Feedback Linearization or similar [6][7], internal model control [8] and Predictive control [9][10]. Intelligent Control approach has been also addressed through Fuzzy Logic and Neuro-Fuzzy Systems [11] and PID controllers with AI tuning [12][13] but none of the above-mentioned approaches definitely proved to overcome the other ones in any operating scenarios.

The main purpose of this work is to study the feasibility of optimizing the current PID-based control system using fuzzy logic, taking into account large operating point variations, large variations of steam features or other non-linear effects, with the simplicity of a closest approach to human reasoning, with respect to more complex approaches (e.g. model predictive control). The fuzzy logic allows implementing and upgrading a control algorithm with reduced design and implementation time on platforms such us algorithms on PLC, which have stringent memory requirements and computational speed. In particular, this work aims to optimize the current control concept based on PID or PI controllers by using knowledge and experience on the system behaviour, focusing on CSPP application and typical power loading profile. The PI initial gains are adjusted during the loading ramp using a Fuzzy inference engine.

The paper is organized as follows: Section 2 describes the main elements of a CSPP power loop and the model used to characterize their dynamics; Section 3 describes the proposed *Fuzzy logic-based PID gains adapter* named FPID; Section 4 presents the comparison between classical and fuzzy control approaches, while Section 5 provides some concluding remarks and hints for future work.

2. CSPP description and model

The power generation of the CSPP considered in this work is quite classical and is composed by a non-condensing high pressure (HP) steam turbine, coupled with a gearbox to a condensing low pressure (LP) steam turbine, an electric generator of 55 MW and a steam re-heater. The system is completed with two steam by-pass systems and a condensing system receiving the exhaust steam from the LP turbine outlet. An electro-hydraulic system controls the inlet valves of each turbine. The overall control system is a cascaded PI control. The outer loop follows a demand of power and gets a control signal demand from the inner loop. The inner loop controls the control oil pressure of the electro-hydraulic system and a demand of valve stroke.

The non-condensing high pressure (HP) steam turbine has an inlet rated steam pressure of about 106 bar, a temperature of 378 °C and an output power of about 18 MW. The condensing low pressure (LP) turbine has an inlet rated steam pressure of 18.3 bar, a temperature of 378 °C and an output power of about 40 MW.

The above depicted system has been modeled through a quite complex model developed in the Matlab/Simulink environment. Both the steam turbines models are composed by a block that computes the inlet steam mass flow as a function of control valve stroke, a steam gain K_{steam}, that gives the characteristics of flow rate and power of steam and a friction model, that evaluate the friction power losses P_{Tfric} in function of rotational speed ω. In particular, the inlet steam mass flow f_{inlet} is computed by

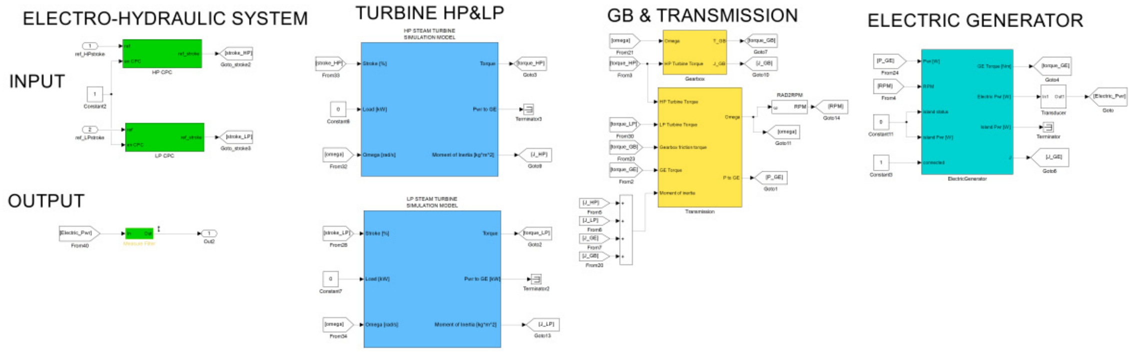


Fig. 1. CSPP Simulink Model

means of a simplified model with dynamics characterized by a transfer function of first order and a lookup table calibrated with a steam at rated conditions. K_{steam} is computed as function of a corrective factor that keeps into account the actual power of the steam k_{actual}, the rated power P_{rated} and the maximum steam mass flow f_{rated}. The turbine mechanical drive power is computed as follow:

$$P_m = \left(\frac{P_{rated}}{f_{rated}} k_{actual} \right) \cdot f_{inlet} \tag{1}$$

The useful power output P_{out} is computed as $P_{out}=P_m-P_{Tfric}$.

The gearbox model provides the balance of the power acting on the LP shaft.

The electric generator model computes the generated electric power P_e as the useful mechanical power at generator shafts minus the gearbox power losses P_{GBfric} and electrical and mechanical losses on the electric generator, namely as $P_e=P_{HPout}+P_{LPout}-P_{GBfric}-P_{GEloss}$.

The complex hydraulic parts of the electro-hydraulic actuator system and relative PI controller have been modelled by means of Simscape library of Matlab Simulink. For the scope of this study, the model has been linearized, identified and introduced as transfer function in the model.

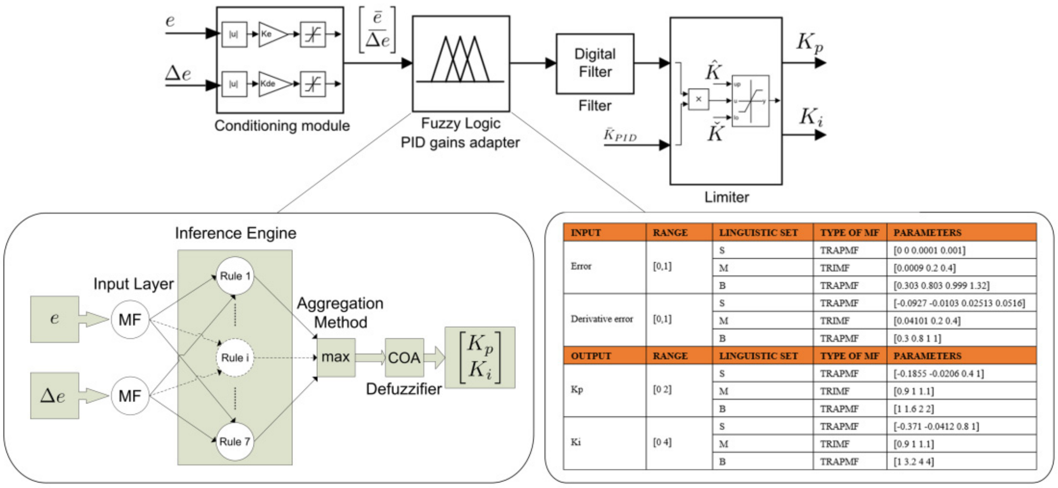
The outer loop controller is a PI controller with the task to follow a demand of power and to request a control signal demand to the actuators. The controller software is property of General Electric Oil & Gas.

3. Fuzzy logic-based PID gains adapter

In the field of industrial systems control, fuzzy logic is increasingly used, particularly in the case of complex nonlinear systems. The Fuzzy logic has been often juxtaposed with classical PID controllers [12], especially to find a trade-off between flexibility and simplicity.

The proposed control approach essentially aims to adapt the original PID proportional and integrative gains with weighting factors computed through a Fuzzy Inference System (FIS). Despite the actual power controller is a PI without derivative component, the study and the development of the FIS was based on a more general PID configuration, although here results are shown referring to a PI controller. The FIS, shown in Figure 2, takes as input the error at time *i*, $e(i)=[SP(i)-PM(i)]/(max_{PM}-min_{PM})$ and its derivative error $\Delta e=e(i)-e(i-1)$, where $SP(i)$ and $PM(i)$ are, respectively, the Power Set Point and the Power Measure at time *i* and outputs the PID gains correction parameters.

The FIS is composed of 4 modules: (i) a *conditioning module,* rescaling the inputs in the range [0, 1]; (ii) the *FPID*, the main component of the FIS, which modulates the default PID gains according to a set of rules and functions; (iii) a *filter*, a second order Butterworth digital filter which smooths the PID parame-



INPUT	RANGE	LINGUISTIC SET	TYPE OF MF	PARAMETERS
Error	[0,1]	S	TRAPMF	[0 0 0.0001 0.001]
		M	TRIMF	[0.0009 0.2 0.4]
		B	TRAPMF	[0.303 0.803 0.999 1.32]
Derivative error	[0,1]	S	TRAPMF	[-0.0927 -0.0103 0.02513 0.0516]
		M	TRIMF	[0.04101 0.2 0.4]
		B	TRAPMF	[0.3 0.8 1 1]
OUTPUT	RANGE	LINGUISTIC SET	TYPE OF MF	PARAMETERS
Kp	[0 2]	S	TRAPMF	[-0.1855 -0.0206 0.4 1]
		M	TRIMF	[0.9 1 1.1]
		B	TRAPMF	[1 1.6 2 2]
Ki	[0 4]	S	TRAPMF	[-0.371 -0.0412 0.8 1]
		M	TRIMF	[0.9 1 1.1]
		B	TRAPMF	[1 3.2 4 4]

Fig. 2. Schematic of the fuzzy logic PID gains adapter

ters variation in order to avoid the possibility of instability effects; (iv) a *threshold operator*, limiting the PID parameters value in a fixed range. The main components of the *FPID,* shown in Figure 2, are:

1) An input layer (*Fuzzifier*) that essentially converts the inputs into fuzzy variables determining their degree of membership to the fuzzy sets (Small S, Medium M, Big B) that are defined on the universe where they are defined by means of membership functions (MF). Both input and output MF are trapezoidal for the sets S and B, and triangular for M.
2) The *inference engine* enables of making decision by means of a series of rules;
3) The *aggregation method* that combines all the results of rules into a single fuzzy set, one for each output variable (K_p and K_i). In particular, in this implementation of the algorithm, the aggregation is obtained as the max of all rules result.
4) The *defuzzification layer*, where the final crisp values of the output variables are computed.

The rules, which are in the classical *"if-then"* form, are designed according to the behaviour of the system during the simulations. Such rules improve the operation of the PID for the analysed load ramp, which is often used in the power plant, but are not meant to be general and to give good results for similar systems or for different set point profiles. The number of rules is limited (7) in order to facilitate the implementation on PLC.

4. Numerical results

In order to assess the validity of the proposed approach, the performances of the Fuzzy approach have been evaluated on the tuning of a standard PI whose parameters are heuristically set and of the same PI after a tuning the well-known Relay auto-tuning method [14]. Among the different literature methods which were applied in a preliminary phase of the study (e.g. Ziegler-Nicholson and minimum error criteria of Integral Absolute Error), the Relay method provides the best results and is very similar to the practical method that can also be applied at site, therefore it is taken hereafter as reference for the optimal pre-tuning of the PI.

The developed tests are related to the loading ramp power control, with generator synchronized and connected with the Grid, when the by-pass valves are ramping to closure and the Governor must follow a demand of power ramp. The adopted performance indexes are *settling time* (time elapsed from ramp command start to actual power within ±5% of target value), *rise time* (time elapsed from ramp command start to 90% of target value), *overshoot* and *integral absolute error* (evaluated along the entire ramp) between set point and actual value. Two different trials were pursued: in the first one the nominal loading ramp is tested with the turbines train model, a nominal condition of steam at the inlet of turbines is assumed. In the second experiment, a reduced pressure steam on the inlet turbines is simulated, causing the reduction of 30% of the system static gain. In such case, the PI tuned in nominal condition has low gains for the actual steam condition and a slower control action.

Table 1 depicts the achieved results: in the first trial, the Fuzzy procedure for parameters tuning of the PI provide a very limited benefit. On the other hand, in the second trial, the Fuzzy approach substantially improves both the Relay PI and the Field PI, by achieving a good match between the Fuzzy PI and the Set Point. Comparing the Relay PI and the FPID, a little improvement is due to optimally tuned of original PI and so to have a quite fast control action. The benefit is more evident on the PI with field gains, where the overall performances of the control loop are recovered and comparable to the nominal steam pressure case. Figure 2 compares the response provided by the Field PI, the PI tuned with the Relay procedure and the PI tuned with the fuzzy procedure in the first trial.

Table 1. Performances of Relay PI, field PI and FPID applied in the trials

Trials	Indexes	Relay	Fuzzy	Field PI	Fuzzy
1	Overshoot (%)	0.1081	0.1556	0	0
	Settling Time	139.6400	139.5350	146.1650	141.3350
	Rise Time (s)	129.9700	129.8650	136.4100	131.3900
	IAE	2.6147e+04	2.1756e+04	4.6981e+05	1.6515e+05
2	Overshoot (%)	0.0361	0.1274	0	0
	Settling Time	139.9150	139.7200	154.8950	143.1050
	Rise Time (s)	130.1950	129.9800	139.2200	132.8350
	IAE	3.4055e+04	3.0209e+04	6.6299e+05	2.2842e+05

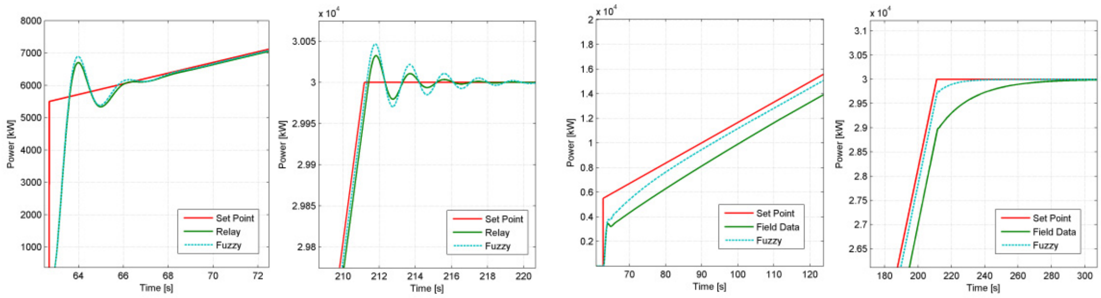


Fig. 2. From left to right, power response of steam turbines with PID gains tuned by Relay and Fuzzy, PID gains tuned with field setting and Fuzzy in the initial stage of the power ramp up to 30MW

5. Conclusion

The paper proposes an adaptive fuzzy approach to PID parameters tuning as an alternative to standard approaches. The various methods are applied on a modeled CSPP composed by a generator, two turbines and a gear. The results show that the fuzzy approach applied to an optimally tuned PID only slightly improve the system performance. On the other hand, when applied to the field tuned PID, which is result of standard site commissioning procedure, the benefit is more evident. The application of the fuzzy approach to the PID parameters tuning allows recovering on the field PID the performances of the optimally tuned PID. In particular, when actual boundary conditions are changing, the controller gains are adjusted in real time in order to obtain a good control loop response as well as is demonstrated even in case the steam pressure on turbine inlet is reduced of 30%.

In the present study, the fuzzy structure and rules set have been identified with the aim of optimizing the tracking of a loading ramp. Future work will deal with the identification of a set of rules that are more generally applicable to any PID control loop: for instance, additional rules can be included in order to consider gains scheduling based on the range of delivered power instead limiting the observation to the control error and its derivative.

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Biography

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