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An adaptive Fuzzy logic-based approach to PID control of steam turbines in solar applications☆

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HIGHLIGHTS

- An adaptive Fuzzy Logic PID approach is proposed to control steam turbines.
- A CSPP has been modeled focusing on power loop with variable steam conditions.
- Design of FPID controller through the knowledge acquired during simulation phase.
- FL allows to control steam turbines in off-design points with optimal performance.
- Control algorithm with reduced design and implementation time on PLC platforms.

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ABSTRACT

In Concentrated Solar Power Plants, steam turbines controlled with standard Proportional Integrative Derivative (PID) methods may suffer from performance downgrading in power generation when the steam conditions deviate from nominal ones. An enhancement of standard steam turbine controller can be the key to achieve optimal performance also in non-nominal steam conditions. This paper presents the improvement of the PID control concept by exploiting Fuzzy Logic, an artificial intelligence technique that allows taking into account the human experience and knowledge on the system behavior. A real Concentrated Solar Power Plant has been modeled focusing on generated power control loop, its stability and performance analysis, knowledge useful to design a Fuzzy Inference System. A fuzzy logic controller is proposed to continuously adapt the PID parameters, to improve the steam turbine governor action. Its performance is compared to the classical PID tuned according to three different approaches. The fuzzy logic PID controller extends the simplicity of PID and adapts the control action to actual operating condition by providing the system with a sort of "decision-making skill". The possibility to design implementable algorithms on a Programmable Logic Controller, which have stringent computational speed and memory requirements, has been explicitly taken into account in the developed work, through the minimization of the controller complexity with a reduced number of fuzzy sets and fuzzy rules within the fuzzy inference system.

1. Introduction

In the last decade, Concentrated Solar Power Plants (CSPP) showed an 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 [3]. In particular in the European Union, the CSPP power capacity installed is about 2312 MWe in the 2014, with more than 1 billion euros worth of projects expected in Italy, currently in the commissioning phase, for a total of 361.3 MWe to be installed [4].

A CSPP generates electrical power by using different kind of technologies [5] (e.g. parabolic trough, solar towers, etc.) and uses solar thermal energy to generate steam, normally exploited by steam turbines in a Rankine cycle, or integrated with other fossils combined cycles in cogeneration power plants, such as in [6], with the possibility to reduce the cost of solar electricity by 35–40% as pointed out in [7]. The available solar energy changes during the day, due to the daily cycle of irradiation and to the weather conditions. This implies a daily start-up and shut down cycle in the power generation unit and quite sensitive

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Nomenclature

Abbreviations

AI	Artificial Intelligence
COA	Center of Area
CSPP	Concentrated Solar Power Plant
EG	Electric Generator
FIS	Fuzzy Inference System
FL	Fuzzy Logic
GB	Gearbox
HP	High Pressure
IAE	Integral Absolute Error
LP	Low Pressure
MF	Membership Function
MPC	Model Predictive Control
PI	Proportional Integrative
PID	Proportional Integrative Derivative
PLC	Programmable Logic Controller
PM	Power Measure
SP	Set Point
ST	Steam Turbine

Parameters and variables

K_{steam}	steam gain
P_{rated}	rated power
f_{rated}	maximum steam mass flow
K_{actual}	actual power of the steam
f_{inlet}	inlet steam mass flow
P_{out}	useful power output
P_m	turbine mechanical power
P_{Tfric}	turbine friction power losses
J	moment of inertia
P_{RatedF}	power losses at synchronism speed
ω_s	synchronism rotational speed
τ	torque
τ_{bw}	bearing and windage friction torque
P_{GBLoss}	gearbox power losses
P_{EGLoss}	electric generator mechanical losses
τ_{load}	gearbox full load power losses
P_{Rbw}	bearing and windage rated power losses
P_{Rl}	power losses at rated shaft load
e	error
Δe	derivative error
$\bar{e}$	conditioned error
$\overline{\Delta e}$	conditioned derivative error
K_p	correction of proportional gain
K_i	correction of integral gain

Subscript

i	i-th time step

variations in the steam production, with the possibility to continuously operate by incorporating thermal energy storage or backup system in the plant, such as discussed by Zhang et al. in [8]. The continuity of energy production of a CSPP is also one of the main factors that may result effective in the thermal conversion of solar energy with respect to the photovoltaic, as highlighted by Desideri et al. in [9]. This approach can be coupled to non-standard control techniques, which allow to face the complexity of CSPP systems, by exploiting, for instance, a Model Predictive Control (MPC) approach, such as proposed by Vassallo and Bravo in [10], or adaptive control approaches and Artificial Intelligence (AI) techniques, such as highlighted by Camacho et al. in [11].

The Steam Turbine (ST) has been originally designed for energy production from fossil fuels, thus both their mechanics and their control systems have been designed to face a quite stable steam production and very rare start-up and shut down cycles. As a consequence, in the context of CSPP, the standard PID control techniques currently applied to turbo-machinery are often not effective in the automatic adaptation to changing operating conditions of the machine [12]. Control system parameters are determined on the brand-new machine during the commissioning phase, with time consuming and effort-intensive procedures. In addition, these parameters are only occasionally re-adjusted on the basis of semi-heuristic procedures. This forces the machine to work in non-optimal efficiency conditions during its lifetime.

On the other hand, the control procedures need to allow correct and efficient machine operation in transient conditions without compromising its integrity, in particular focusing on variable operating conditions where steam turbines are subjected to continuous thermal stresses, premature aging and consequent lowering of efficiency. The turbine control problem with variable steam conditions can be addressed by looking for applicability of innovative control strategy. Adaptive Control approaches, which allow to adapt gains in different loading conditions and uncertainties are known. An example of this kind of strategy is described in [13], where the turbine speed control is adapted as a function of the load, as well as Model Based Control schemes, such as the Feedback Linearization and linear quadratic regulator described in [14], or Feedback Linearization combined with a PI controller designed by means of a H_∞ loop-shaping robust method as in [15], or internal model control techniques for the design of a robust Proportional Integrative Derivative (PID) controller in a speed control application as in [16]. Predictive control approaches have been investigated in [17], where the General Predictive Control and Constrained Receding-Horizon Predictive Control have been exploited for the control of large steam turbines during load variations and in [18], where an Exponential Auto-Regressive eXogenous (ARX) model-based multistep predictive control algorithm is applied to control a thermal power plant. An interesting MPC application for the design of fault tolerant control systems is presented by Salahshoor et al. in [19], where a Generalized Predictive Control, combined with support vector machine and adaptive neuro-fuzzy inference system, allows to recover the normal operation also in different fault scenarios. A complex control scheme, presented in [20], exploits a combined action of a feedforward controller based on nonlinear programming and a feedback controller designed with robust methods involving turbine governor valve and others control inputs, in order to control a fossil power plant in different load conditions.

In the field of AI, Fuzzy Logic (FL) and Evolutionary Algorithms (EA) have sometimes been exploited to control steam turbines. For instance, in [21] FL is used in order to adjust the parameters of a PID controller during speed control, while PID controllers whose parameters are tuned through different EA methods are proposed in [22] and in [23]. However, none of the above-mentioned approaches definitely proved to overcome the other ones in any operating scenarios.

The main purpose of the work proposed here is to optimize the current control concept based on PID or Proportional Integral (PI) controllers by exploiting human knowledge and experience on the system behavior, with a focus on CSPP application and typical power loading profiles. The main goals have been achieved by using FL, an AI approach very close to human reasoning, which allows to formalize an effective control strategy that takes into account large operating point variations, large variations of steam features or other non-linear effects in a simpler way with respect to other approaches, such as MPC. Although FL in general allows to balance design and implementation