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Impact of steam generator start-up limitations on the performance of a parabolic trough solar power plant

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ABSTRACT

Concentrating solar power plants are an attractive option in the renewable energy generation market. The possibility of integrating relatively cheap forms of energy storage makes them a desirable solution when power generation must be readily available at any time of the day. Solar power plants typically start-up and shut down every day, so in order to maximize their profitability, it is necessary to increase their flexibility in transient operation and to initiate power generation as rapidly as possible. Two of the key components are the steam generator and steam turbine and the rates at which they can reach operational speed are limited by thermo-mechanical constraints. This paper presents an analysis of the effects of the thermal stress limitations of the steam generator and steam turbine on the power plant start-up, and quantifies their impact on the economy of the system. A dynamic model of a parabolic trough power plant was developed and integrated with a logic controller to identify start-up limitations, and subsequently the dynamic model was integrated in a techno-economic tool previously developed by the authors. The plant was analysed under two different operating strategies, namely solar-driven and peak-load. The results indicate that for steam generator hot start-ups, a 1.5% increase in peak-load electricity production would be achieved by doubling the maximum allowable heating rate of the evaporator. No useful increase would be achieved by increasing the rates beyond a limit of 7–8 K/min, as the turbine would then be the main limiting component during start-up. Similar conclusions can be drawn for the solar-driven case, for which the solar field and the energy source availability would pose the major constraint when starting up the steam generator system.

1. Introduction

Concentrated solar power plants (CSPPs) are becoming more common in the renewable energy market. This trend is expected to rise in the upcoming years due to their key capability of being integrated with relatively cheap thermal energy storage (International Energy Agency, 2014). This feature makes it possible to decouple the energy generation from the solar input, making the power they can generate available at any time (Guedez et al., 2017). However, despite this characteristic feature, CSPPs are not currently designed for continuous operation, therefore they still experience daily start-ups and shut-downs. In order to maximize their performance from both technical and economical standpoints, increasing the flexibility of their dynamic performance is an important aspect which must be addressed (Topel et al., 2017). The rate at which a power plant can start up is limited by thermo-mechanical constraints, which may increase the time to reach the nominal load of the power plant. The receiver, the steam turbine and the steam generator system (SGS) are usually the most limiting components in this regard. While the receiver (Samanes and Garcia-Barberena, 2014) and steam turbine (Topel et al., 2017) have been examined in the literature, the steam generator has not been the focus of many studies .

Many CSPPs in use today have steam generators which were typically designed as conventional heat exchangers, not optimised for transient applications (Vant-Hull, 2012). As the industry mainly used designs from conventional power plants, their SGS responded inefficiently to sudden changes in incident solar radiation and equally poorly to repeated morning start-ups. This can cause failures in the component due to excessive thermal stresses, which may compromise the economic viability of the power plants. Although the industry is interested in optimising SGS designs for CSPPs (Pelagotti et al., 2014), there is little information on optimal heating rate requirements. In order to maximize the flexibility (i.e. to increase the responsiveness of the power plant to a change in the power load or in insolation), and both the peak and the baseline rate of electric power production, it is essential that all the components are able to start as quickly as possible

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Nomenclature

ACC	air cooled condenser
CSPP	concentrating solar power plant
CT	cold tank
D	deaerator
ECO	economizer
EVA	evaporator
HP	high pressure
HT	hot tank
HTF	heat transfer fluid
HX	heat exchanger
IHX	indirect heat exchanger
LCF	low cycle fatigue
LP	low pressure
PB	power block
PI	proportional-integral
PTPP	parabolic trough power plant
RH	re-heater
SF	solar field
SGS	steam generator system
SH	super-heater
SM	solar multiple
ST	steam turbine
TES	thermal energy storage

Symbols

ITD	inlet temperature difference [°C]
$\dot{m}$	mass flow [kg/s]
p	pressure [bar]
T	temperature [°C]
t	time [s]
v_T	allowable ramp-up rate/heating rate [K/min]

Subscripts

f	fluid
max	maximum
min	minimum

and enable the CSPPs to quickly start harvesting the incoming solar radiation. On the other hand, there might be limiting factors for one component, which might reduce the required heating rate for another. For example, if the receiver or solar field are the limiting factors, there is no need for the SGS to be able to start up at a faster rate than that of the solar field (Ferruzza et al., 2017).

The SGS and steam turbine both start up at a rate that is governed by the need to limit thermal stresses and low-cycle fatigue (LCF) (Pelagotti et al., 2014; Topel et al., 2017). Thick-walled components, material properties and temperature gradients are the limiting factors. In the case of the steam generator, the main constraining factors are the maximum allowable stresses in thick walled components such as the steam drum, super-heater headers and T or Y junctions in the steam pipelines (Dzierwa and Taler, 2014; Taler et al., 2015). Typically, the limiting component is the evaporator drum, which is designed as a large diameter high pressure vessel, which must consequently have thick walls. The start-up procedure of the component is intended to reach nominal conditions for temperature, pressure and mass flow rates as rapidly as possible. In the case of the steam turbine, the shaft seal and blading clearances determine the maximum allowable thermal expansion of the components, while the shaft thickness is the limiting factor for thermal stress. As a general rule, the starting procedure of a steam turbine can be considered to have three different phases: pre start-up heating, rolling up and loading up. During this procedure, the key parameter which limits the heating rate is the difference in temperature between the incoming steam and the metal of the turbine. In order to avoid excessive thermal stresses in this component it is desirable to keep the temperature difference as low as possible (Spelling et al., 2012).

In previous studies, much attention is given to the thermal stress that limits the maximum heating rates of these components, but little information is available about their impact on the performance of the overall power plant. For instance, González-Gómez et al. (2017) analysed the thermo-mechanical stress in the case of SGS for solar applications, but the study was performed at component level, without considering the impact of such limitations on the performance of the power plant. The author also focused on design and cost-based optimization of such components without considering the system perspective.

The abovementioned studies considered the limitation regarding either the steam generator or the turbine, without addressing the interaction between the two (Dzierwa et al., 2016; Dzierwa and Taler, 2014; Taler et al., 2015). It is of crucial importance to evaluate how much different constraints on the start-up procedures of CSPPs affect their electric power production and whether significant differences occur under different conditions. This information will indicate where to improve the operation of the power plant and the design specifications for the components, from a thermo-mechanical point of view. Lastly, the operational strategy of the power plant determines the number of start-ups and their typology (hot, warm or cold start-ups) (Guedez et al., 2017; Spelling et al., 2012). For instance, if a CSPP operates purely in solar-driven without fuel back-up, its start-up would mainly occur in the morning when the sun is still rising. On the other hand, if a power plant is designed to work in peak load during a particular time of the day (e.g. during evening hours, when the price of electricity is higher), the start-up would occur when solar radiation or heat from the storage are readily available. From a start-up perspective (in the absence of back-up fuels), this would mean different availability of heat input, hence different start-up constraints.

The dynamic performance of parabolic trough power plants has been analysed previously (Almasabi et al., 2015; Blanco et al., 2011; Conrado et al., 2017; Luo et al., 2015), although the models proposed deal only with validation of the detailed component modelling of the solar field. Blanco et al. (2011) presented a model of a parabolic trough power plant (PTPP) and validated it against experimental data, but in this case the model of the power block was developed with a simplified correlation. Another approach was presented by Abed et al. (2016), in which a detailed dynamic model in APROS (Advanced Process Simulation Software) was validated against the operational data of Andasol II. The focus of the study was to develop a detailed control strategy of the power plant by means of PI (Proportional-Integral) controllers. The model presented did not focus on yearly performance but on daily control. None of these studies considered start-up constraints due to thermo-mechanical limitations. In previous works such constraints were usually analysed from a component perspective. For instance, Pelagotti et al. (2014) described in detail a dynamic model of a steam generator, and carried out a low-cycle fatigue analysis. The authors predicted the impact on the annual electricity production of PTPPs. Their calculations did not take into account start-up schedules of steam turbines or rates of heat availability, nor yearly performance evaluation of such power plants. A previous work by the authors (Topel et al., 2015) considered the impact of the start-up rate of the steam turbine for solar tower direct steam generation; however, in this work the start-up constraints of the steam turbine were not coupled with SGS constraints.

This paper presents an analysis of the effects of the thermal stress limitations of the steam generator and steam turbine on the power plant