Solar Energy 165 (2018) 10–18

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Improving concentrating solar power plant performance by increasing steam turbine flexibility at start-up

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ARTICLE INFO

Keywords:
Flexibility
Start-up
Steam turbine
Techno-economic analysis
Optimization

ABSTRACT

Among concentrating solar power technologies, solar tower power plants currently represent one of the most promising ones. Direct steam generation systems, in particular, eliminate the usage of heat transfer fluids allowing for the power block to be run at greater operating temperatures and therefore further increasing the thermal efficiency of the power cycle. On the other hand, the current state of the art of these systems does not comprise thermal energy storage. The lack of storage adds to the already existing variability of operating conditions that all concentrating power plants endure due to the fluctuating nature of the solar supply. One way of improving this situation is increasing the operating flexibility of power block components to better adapt to the varying levels of solar irradiance.

In particular, it is desirable for the plant to achieve fast start-up times in order to be available to harness as much solar energy as possible. However, the start-up speed of the whole plant is limited by the thermal inertia of certain key components, one of which is the steam turbine. This paper studies the potential for power plant performance improvement through the increase of steam turbine flexibility at the time of start-up. This has been quantified by carrying out power plant techno-economic studies in connection with steam turbine thermo-mechanic behavior analysis. Different turbine flexibility investigations involving the use of retrofitting measures to keep the turbine warmer during offline periods or changing the operating map of the turbine have been tested through multi-objective optimization considering annual power performance and operating costs. Results show that reductions of up to 11% on the levelized cost of electricity are possible through the implementation of these measures.

1. Introduction

Solar tower systems currently account for 4% of the global installed share of concentrating solar power (CSP) and recent market trends indicate that this technology is set to play an increasingly prominent role within the CSP landscape (Groupe Reaction Inc., 2014). However, it is also a fact that the development of new CSP plants is threatened by the relative high costs of the technology, which are not yet competitive with other means of power generation, including other renewables such as solar photovoltaics and wind (IRENA, 2012). Only in certain markets, such as Chile and Dubai, has CSP been able to compete with the other technologies. Since the readiness level of CSP technologies will continue to mature in the same measure as new power plants are deployed worldwide, it is crucial to reduce the previously mentioned threat for the future generations of CSP. In addition, currently installed CSP plants are built for over 30 years of operation, period during which revenues can be increased significantly by means of operational improvements. Therefore, it becomes relevant to investigate technology improvement opportunities of currently deployed systems.

In solar tower power plants, the highest impact on the annual electricity generation is given by the varying levels of solar irradiance (Sattler et al., 2013). This is related to the variation in power plant operating conditions induced by the inherent fluctuations of the solar resource and weather. The impact of such fluctuations is aggravated for systems that do not incorporate thermal energy storage as is the case of direct steam generation (DSG) solar tower power plants (STPPs). However, previous studies have shown (Guedez et al., 2016) that in the search of increasing profitability with respect to electricity prices, a peaking dispatch strategy of the storage is more suitable. This meaning that configurations with storage are not immune to operational variations either.

Among the proposed improvement opportunities for solar tower systems (Groupe Reaction Inc., 2014; IRENA, 2012; Kolb et al., 2011) a significant focus of the industry relies on the solar components due to a high potential for cost reductions. Nevertheless, the consideration of rapid temperature changes in the design and operation of the power

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https://doi.org/10.1016/j.solener.2018.02.036
Received 20 July 2017; Received in revised form 22 January 2018; Accepted 12 February 2018

Nomenclature

Abbreviations

ACC	Air cooled condenser
CSP	Concentrating Solar Power
DSG	Direct Steam Generation
EOH	Equivalent Operating Hours
EV	Evaporator
HPT	High Pressure Turbine
LCOE	Levelized Cost of Electricity
LPT	Low Pressure Turbine
NOH	Normal Operating Hours
OPEX	Operational Expenditures
RH	Reheater
SH	Superheater
STPP	Solar Tower Power Plant

Symbols

C_{ref}	reference cost [USD]
$C_{SERVICE}^{OPEX}$	total service costs [USD]
n_{start}	start schedule number [–]
P_{reqST}	required steam pressure [bar]
PP	Partial Power [MW h]
RD	Ramp Delay [min]
SD	Sync Delay [min]
t	time [s]
T_{reqST}	required steam temp. [°C]
T_0	initial temp. [°C]
T_{ss}	steady state temp. [°C]
T_{met}	metal temp. [°C]
τ	time constant [s]

block (Kolb et al., 2011) is also a highlighted need. Through improved operating flexibility, energy losses during transient operation can be mitigated, leading to an increase in the energy production of the CSP plant. This, in turn, improves its availability and the overall costs of the technology.

In the aim of increasing the thermal flexibility of the power block, it is desirable for the CSP plant to achieve fast start-up times to harness the solar energy as soon as needed in the operation of the plant. However, certain power plant components are constrained during this transient operating phase. The steam turbine (Leyzerovich, 2008) and the steam generator (Bozzuto, 2009) are typically highlighted as components with an intricate start-up operation. The challenge of boiler operation is to deliver the steam at the minimum allowed conditions for intake to the turbine while respecting the established permissible temperature and pressure ramp rates (ASME, 2013; European Standard EN 12952-3). Analogously, turbine start-up operation consists of controlling the ramp rates of rotational speed, load and admission steam conditions in a way such that the maximum stress does not exceed a life consumption related limit (Greis et al., 2012).

Considering that the disposition of the steam generator and the turbine in the power plant layout is sequential, so are their respective contributions to the overall start delay of the plant. One could argue which component is the most critical, when in fact they are both contributing to power production losses when not optimized for the solar fluctuations. From the perspective of a plant operator, their control over the plant start operation is overridden at the time of turbine start-up by the control system pre-defined by the turbine manufacturer, removing the notion that they have a choice over how to run their component. Previous experience has evidenced that the steam produced by the solar field was not fully utilized for power production (Jöcker et al., 2012). Also, at the Solar One power plant, the inability to quickly restart the turbine on days with intermittent radiation led to significant energy losses for the power plant (Kolb et al., 2011). Both of these support the idea that the steam turbine can limit the start-up of the whole power plant. It is therefore the objective of this work to concentrate on steam turbine operational flexibility through start-up time improvements.

Turbine start times are governed by curves which limit the speed at which the turbine can reach full load. The main purpose of these curves is to maintain temperature gradients in the turbine metal under allowable limits. There are different start-up curves depending on the thermal state of the turbine. The curves are designed by the turbine manufacturer and provided to the power plant operator as the set of instructions on how to operate their installed component. Essentially, a discrete number of curves that covers the thermal operating range of the turbine are provided. Commonly, the curves, and thus the turbine starts (Leyzerovich, 2008), are denominated within three categories: cold, warm and hot. However, there can be more than three curves within the operational design of a turbine.

In general, the warmer the turbine is before the start, the faster the start-up can be. Therefore, a potential area for increased turbine flexibility involves maintaining higher internal temperatures during idle periods. In previous works, temperature maintaining modifications have been studied on steam turbines operating in parabolic trough plants (Spelling et al., 2012a,b; Topel et al., 2015a,b). Results indicated a great potential for maintaining the turbine temperature when combining the application operational modifications, yielding increases in power output of up to 9.5% on the day following a long-cool down and 3.1% improvements in annual power plant performance. However, despite the positive results of such studies the impact on operating costs of the plant from including these modifications was not reflected.

In the context of conventional power generation, special focus has been given to the steam turbine start-up routine (Gülen, 2013). Other works have studied means of changing operating procedures to achieve faster start-up times (Emberger et al., 2005) or improve the operating conditions of the turbine (Guedez et al., 2013; Greis et al., 2012). In addition, methods for optimal turbine start-up time calculations have been developed (Beer et al., 2015). However, these studies have had a one-sided modeling approach, of either focusing only on the steam turbine component or on the power plant.

The present work aims to quantify the annual performance improvements that can be achieved on tower-based CSP plants through increased steam turbine flexibility. Addressing such question involves understanding both thermo-mechanical aspects at component level (turbine) and their interaction with techno-economic aspects at system level (power plant). As such, two separate models for this purpose were developed for a DSG-STPP and its corresponding steam turbine, representing a test-case based on the current state-of-the-art of that technology. In this regard, it is important to highlight that for the studies conducted, the two models were never solved within the same time step. Instead, they were linked with relevant parameters.

Once having set up the test-case, optimization studies were carried out in pursuit of the established aim. For this, three flexibility investigations were carried out. The first and second consisted on implementing temperature maintaining measures on the turbine during offline periods with different considerations on the related operating costs. The third involved varying the available start-up curves provided by the manufacturer in pursuit of an improved operating map of the turbine, this was done while keeping the same constraints with respect to turbine lifetime consumption.