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Comparison of constant and sliding pressure operation strategies for a 1 MW$_e$ multi-field concentrated solar power plant[#]

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ABSTRACT

A 1 MW$_e$ multi-field solar thermal power plant comprising parabolic trough collectors and linear Fresnel reflectors was proposed and studied in the literature for Jodhpur, India. This power plant runs without a fossil fuel backup and thermal energy storage. It operates at part-load due to daily and seasonal variations of the direct normal irradiance, causing a reduction in annual power generation and capacity factor. The steam turbine usually operates at a constant pressure. The present study simulates the power plant using a sliding pressure operation strategy and compares the annual performance with a constant pressure strategy. The simulations were performed in TRNSYS for the 1 MW$_e$ multi-field power plant proposed at Jodhpur, India. The simulation showed an improvement of 3.83 % in annual electricity production using sliding pressure compared to the constant pressure operation strategy.

Keywords: Multi-field, concentrated solar power plant, linear Fresnel reflector, parabolic trough collector, TRNSYS

NOMENCLATURE

Abbreviations	
CSP	concentrated solar power
DNI	direct normal irradiance
HTF	heat transfer fluid
LFR	linear Fresnel reflector
PTC	parabolic trough collector

1. INTRODUCTION

The concentrated solar power (CSP) plant is among many viable renewable energy technologies that have gained researchers' attention in the past few decades. It can convert the incident solar radiation into useful heat for running a turbine and generating electricity. A CSP plant can be based on point-focused technologies like heliostats and parabolic dishes or line-focused technologies like a parabolic trough or linear Fresnel reflector. The steam turbine usually operates at a constant inlet pressure and flow rate. However, the turbine inlet temperature varies due to daily and seasonal variations in the direct normal irradiance (DNI), resulting in the part-load operation of the power plant.

Several studies are available in the literature on improving the performance and reducing the power generation cost of CSP plants. The economics of a CSP plant is typically assessed in terms of the levelized cost of electricity (LCOE) (IRENA, 2018). Many researchers have performed a cost comparison study among the line focusing solar collectors on achieving cost parity between the two (Morin et al., 2012). The parabolic trough collector (PTC) is the most mature CSP power generation technology with the highest installed capacity of 6192 MW (Achkari & El Fadar, 2020). Compared to PTC collectors, linear Fresnel reflectors (LFR) are less costly due to their simple installation and tracking arrangements (Desai & Bandyopadhyay, 2017). However, LFR is less optically efficient than PTC collectors (Khajepour & Ameri, 2020).

A 1 MW$_e$ multi-field solar thermal power plant without thermal energy storage has been studied and optimized to achieve synergy and exploit the low-cost potential of the LFR collectors integrated with a high-cost PTC collector (Desai & Bandyopadhyay, 2015). A similar techno-economic study was carried out on a multi-field solar thermal power plant using a central receiver solar tower and LFR with high-temperature molten salt thermal energy storage and low-temperature latent heat enhanced steam accumulator to assess the potential of LCOE reduction (Karandikar et al., 2021).

At constant pressure, the governing and control over the steam turbine operation is achieved through the turbine inlet pressure using nozzle–governing valves to

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keep the volumetric flow rate constant. It is achieved by changing the operating pressure at the turbine inlet and different stages or sliding the pump's operating pressure with the change in the generated steam mass flow rate. Biencinto et al. (2017) performed a simulation study based on a sliding pressure operation strategy suitable for direct steam generation power plants. Franchini et al. (2013) performed a simulation study using a sliding pressure strategy for an indirect steam generation to compare the performance using PTC and solar tower collector technologies.

The present study simulates a 1 MW$_e$ multi-field CSP plant comprising PTC and LFR using a sliding pressure operation strategy and compares the monthly and annual performance with a constant pressure strategy. The simulations were performed in TRNSYS for the 1 MW$_e$ plant proposed at Jodhpur, India. Our TRNSYS numerical model of a multi-field solar thermal power plant is in good agreement with Desai & Bandyopadhyay (2015), with a -3.9 % deviation in LCOE.

The remainder of the paper is divided into the following sections: Section 2 briefly describes the power plant. Section 3 describes the detail of modelling and simulation adopted in TRNSYS. Section 4 summarizes the results and discussion, and Section 5 concludes the present work.

2. DESCRIPTION OF THE SOLAR POWER PLANT

A schematic of a 1 MW$_e$ multi-field solar thermal power plant employing a PTC and LFR solar fields is shown in Fig.1. It consists of a PTC and LFR solar fields of collector areas of 3500 m^2 and 9500 m^2, respectively. An optical efficiency of 70 % and an overall heat loss coefficient of 0.1 W/(m^2 K) have been considered for the PTC collector, whereas an optical efficiency of 65 % and an overall heat loss coefficient of 0.1 W/(m^2 K) have been considered for the LFR collector in this study. Table. 1 shows the properties of heat transfer fluid (HTF) at various points in the power plant shown in Fig. 1. The PTC solar field operates at 390 °C collector outlet temperature. The LFR field operates at an inlet pressure of 45 bar pressure and outlet pressure of 40 bar, and 250 °C outlet temperature. It is assumed that there is no pressure loss within the stream flow at the steam side of the power block.

The operation strategy of the PTC collector is to vary the HTF mass flow rate to maintain the desired collector outlet temperature. The HTF used in the PTC collector is Therminol VP 1(Therminol® heat transfer fluids, 2019). At the same time, the LFR solar field is designed to generate wet steam of 50 % vapour quality at the exit of the LFR collector.

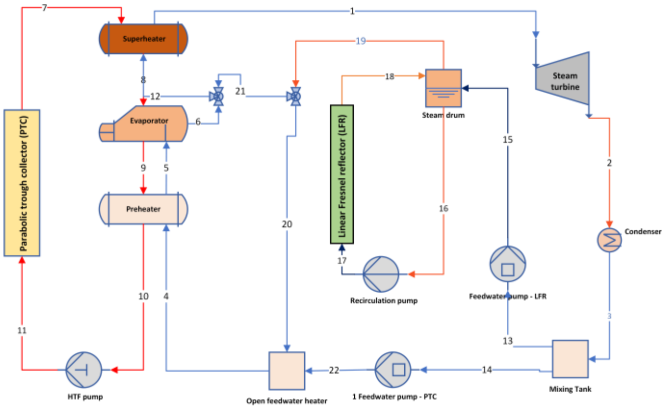

Fig. 1 Multi-field STPP configuration diagram

Table. 1 State point properties

	Enthalpy	Pressure	Entropy	Temperature	Mass flow rate
State points	P	T	h	s	$\dot{m}$
	[bar]	[°C]	[kJ/kg]	[kJ/kg K]	[kg/s]
1	40.0	350.2	3092	6.58	1.57
2	0.1	46.0	2437	7.69	1.57
3	0.1	46.2	193	0.65	1.57
4	40.0	46.9	199	0.66	0.58
5	40.0	250.5	1087	2.80	0.58
6	40.0	250.5	2801	6.07	0.58
7	13.0	390.2	0	0.00	4.68
8	12.0	351.3	0	0.00	4.68
9	10.0	260.5	0	0.00	4.68
10	8.5	209.2	0	0.00	4.68
11	13.4	209.6	0	0.00	4.68
12	40.0	250.5	2801	6.07	1.57
13	0.1	46.0	193	0.65	0.99
14	0.1	46.0	193	0.65	0.58
15	40.0	46.9	199	0.66	0.99
16	40.0	250.5	1087	2.80	3.03
17	45.0	250.8	1088	2.80	3.03
18	40.0	250.5	1944	4.43	3.03
19	40.0	250.5	2801	6.07	0.99

A constant mass flow rate of the feed-water is supplied through the LFR receiver tubes to cause a change in exit quality and maintain the desired outlet temperature of 250 °C. The power block consists of a single-stage steam turbine with exit steam pressure at 0.1 bar and is designed to operate at 65 % isentropic efficiency with turbine inlet conditions of 40 bar and 350 °C. The minimum pinch point temperature difference in the condenser is 5 °C. All the pumps in the plant are assumed to operate with an isentropic efficiency of 60 %. A pinch point temperature of 10 °C is considered to be located at the entry of the steam generator with vapour quality $x = 0$. It is assumed that the exit state of the steam generator is saturated vapour. The parasitic power consumption for such a plant is typically 10 % of the gross power production (Biencinto et al., 2017).

3. MODELLING AND SIMULATION

A quasi-steady time-dependent simulation of the multi-field solar thermal power plant is performed in a TRNSYS 18.0 simulation environment (TRANSSOLAR Energietechnik GmbH, 2017). The part-load mathematical models of all the desired components are accessible from the TRNSYS component library. These mathematical models were validated qualitatively or quantitively and are referred to as 'Types' in TRNSYS. The component types of TESS libraries (Thornton et al., 2014) and the STEC library (Zentrum, 2006) were used to implement the power plant model. A weather processing model has been used for implementing a weather data file of the Jodhpur location.

The integrated efficiency equation of a PTC is based on the model of Lippke (Lippke, 1995). The HTF's heat demanded mass flow rate has been calculated with a desired collector outlet temperature. The mass flow rate of the collector field HTF varies to meet the set temperature requirement. The details quasi-steady efficiency equation of the solar field models can be referred to from the STEC library for the PTC solar field. A TRNSYS Type 397 has been implemented for PTC solar field, and TRNSYS Type 1287 has been implemented to model LFR solar field from the TESS library. The details of these quasi-steady efficiency equations can be referred to from TESS libraries of the TRNSYS.

A flow following steam turbine (Type 592a) has been employed to model the electric power generation for constant pressure operation, whereas the Type 318 turbine model of STEC library has been used to model sliding pressure operation. The turbine model calculates the inlet pressure of the turbine from turbine outlet pressure, mass flow rate of steam and the design values of the mass flow rate of steam, turbine inlet and outlet pressure using Stodola's law of ellipse. The off-design isentropic efficiency of the turbine was evaluated using the equation given by Shang (2000). A water-cooled condenser Type 383, assuming a constant condenser pressure, has been implemented to model the heat rejection of the power cycle. A superheater and pre-heater Type 315 and steam generator Type 316 of STEC library have been used to model the steam generation process to power the Rankine cycle. A pump model Type 597, 618 was implemented to model the feed water and recirculation pumps for the LFR solar field, whereas Type 390 is used for a feed-water pump to the PTC heat exchanger circuit.

4. RESULTS AND DISCUSSION

A weather data file of the Jodhpur location was taken from the Center for Study of Science, Technology and Policy (CSTEP). The weather file consists of month, day, hour of the day, ambient temperature and DNI. The average hourly DNI in (W/m^2) has been published in the CSTEP report (Ramaswamy et al., 2013). It is to be noted that the HTF recirculates within the PTC until the outlet temperature reaches 390 °C, after which it is sent to the power block heat exchangers.

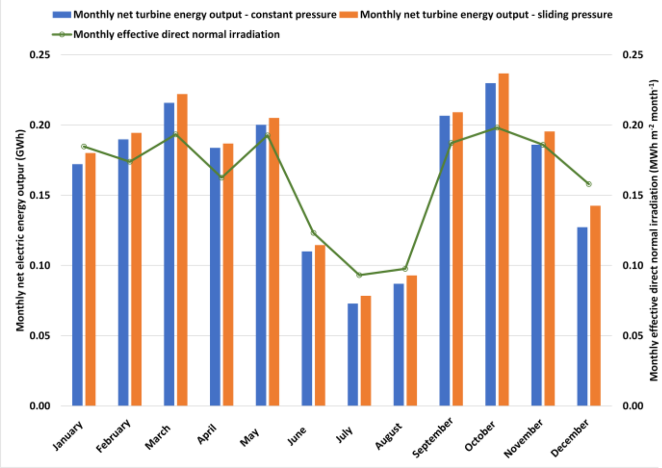

Fig. 2 Comparison of monthly turbine electric energy output for constant pressure (Blue bars) and sliding pressure operation strategy (Orange bars) and monthly effective direct normal irradiation (Green line)

A solution methodology based on successive substitution has been implemented to solve the model using a convergence criterion of 10^{-3}. The hourly values of the turbine power, PTC useful thermal power, and LFR useful thermal power were calculated during the simulation. These values have been integrated to obtain the annual performance of the power plant during a typical operation year. A capacity factor is defined as the ratio of the turbine's total electric energy output (MWh) to that of the electric energy output of the power plant when operated at the nameplate capacity for the entire year.

Fig. 2 compares the monthly turbine energy output for constant pressure and sliding pressure operation strategies. The highest energy output achieved was 0.237 GWh in October with sliding pressure. It is due to the highest monthly DNI of 0.198 MWh/m^2. The least energy output of 0.073 GWh was observed with the constant pressure in July due to the least monthly DNI of 0.093 MWh/m^2. It is due to the monsoon season causing cloud covers of the rain. Energy output with sliding pressure than constant pressure in July, August, November and December prevails due to higher solar collector efficiency of the LFR compared to PTC solar field. The present study predicted a net annual electricity output of 2.058 GWh for sliding pressure and 1.982 GWh for constant pressure. It indicates a marginal rise of 3.83 % in the performance using the sliding pressure operation strategy for the studied 1 MW$_e$ multi-field solar thermal power plant.

5. CONCLUSION

It can be concluded from the simulation study that there is no significant improvement, i.e., only 3.83 % in the annual electricity output of a 1 MW$_e$ multi-field solar thermal power plant when operated at a sliding pressure compared to constant pressure for the Jodhpur location. It also shows that monthly electricity output of sliding pressure is better for a few months of low DNI input. Further research needs to be carried out for higher megawatt-scale multi-field power plants to assess the conclusive output of the effects of the sliding pressure operation strategy.

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