Supplementary Material: Plantwide Decentralized Controller Design for Hybrid Solar Thermal Power Plant

1 STEP TEST FOR HSTP

In single input and single output control systems most of the algorithms for controller tuning are based on empirical models. These empirical models are typically obtained through step tests of dynamic models (representing plant) at specific operating points. Based on a similar approach, Table S1 shows values of operating variables maintained during step test for Hybrid Solar Thermal Power Plant (HSTP).

2 DIGITAL PID CONTROLLER DESIGN

The velocity form of the PID controller has been used in this work. The velocity form of PID controller has the advantage of no integral windup problems. Moreover, the controller output stays at its previous value itself in case of failure in the hardware device (Stephanopoulos, 1984). The general continuous-time form of PID controller is given as:

$$u(t) = K_c\left[e(t) + \frac{1}{\tau_i}\int e(t)dt + \tau_d\frac{de(t)}{dt}\right] \tag{S1}$$

The velocity form of PID controller is obtained from the difference equation, $\Delta u(kT_o) = u(kT_o) - u((k-1)T_o)$, where T_o is the sampling interval. Thus,

$$\Delta u(k) = q_o e(k) + q_1 e(k-1) + q_2 e(k-2) \tag{S2}$$

$$\text{where, } q_0 = K_c\left(1 + \frac{\tau_d}{T_o} + \frac{T_o}{\tau_i}\right); \qquad q_1 = -K_c\left(1 + 2\frac{\tau_d}{T_o}\right);\ q_2 = K_c\left(\frac{\tau_d}{T_o}\right)$$

Table S2 shows list of tuning rules involved in design of decentralized controller design for HSTP. Consolidated list of disturbance variables, manipulated variables and their limits and controlled variables for decentralized control of HSTP are shown in Table S3.

3 ELECTRIC POWER GENERATION OF HSTP

The Electric power generated from the turbine and generator is computed using Willan's line equation (Desai et al., 2014) given as:

$$P_{(MWe)} = a + b\dot{m}_{(st,i,Tur)} + c\dot{m}^2_{(st,i,Tur)} \tag{S3}$$

where $\dot{m}_{(st,i,Tur)}$ represents the mass flow rate of steam to turbine (kgs^{-1}), which has contribution from both SG and SD ($\dot{m}_{(st,i,Tur)} = \dot{m}_{(st,o,SD)} + \dot{m}_{(st,o,SG)}$) and a, b and c parameters of Willan's line equation. The actual power output is given as Desai et al. (2014):

$$POW_{act,Mwe} = P_{(MWe)} X_{Pc} X_{Tc} \tag{S4}$$

where X_{Pc} and X_{Tc} represent the correction factor for pressure and temperature respectively, and are given as

$$X_{Pc} = d + eP + fP^2; \qquad X_{Tc} = g + hT + iT^2 \tag{S5}$$

The parameters used in Equations (S3)-(S5) are listed in Table S4. In these equations, P and T represent pressure (bar) and temperature (^{o}C) of superheated steam entering the turbine. It can be noted from Table S4 that the coefficients of the quadratic terms in Equations (S3)-(S5) are 0.

The final electric power generated from HSTP is obtained as:

$$POW_{ele} = MAX(0, POW_{act,Mwe}) \tag{S6}$$

In the above equation, the max operator is considered since power computed by Willan's equation can be negative (coefficient a in Equation (S3) is negative).

4 CASE STUDY-I:QUADRATIC SOLAR RADIATION

In this section PH and its temperature profile of water and oil, SH temperature profile of oil and steam is discussed.

- The temperature profile of oil and steam can be rationalized from the solar radiation pattern. The temperature of oil and water of PH is affected primarily by the mass flow rate of water flowing into PH ($\dot{m}_{(w,i,PH)}$) which is a manipulated variable for the SG level controller.
- Temperature of the steam outlet of SH $(T_{(st,o,SH)})$ oscillates in the range of 299 to 269°C while the variation in the SH oil outlet temperature $(T_{(o,o,SH)})$ is in the range from 310 to 281°C in the 4 hrs to 5 hrs 26 mins duration. Variation of the flow rate of oil through SH varies significantly (2 to 12 kg/s) during this duration due to the interaction between the override and regulatory control although the temperature of oil flowing through SH ($\dot{m}_{(o,i,SH)}$) is nearly constant. During the cloud cover episode (drop and rise period), the temperature of oil drops from 313 to 283°C and rises from 283 to 310°C as shown in Figure 16 (main manuscript). The temperature of steam flow out of SH drops from 304 to 286°C and rise from 286 to 309°C as shown in Figure 17 (main manuscript).
- In Figure 17 (main manuscript), Temperature of water outlet of PH $(T_{(w,o,PH)})$, oscillates in the range 229 to 215°C while temperature of PH oil outlet $(T_{(o,o,PH)})$ (Figure 16, main manuscript) oscillates in the range 209 to 225°C during period of 4 hrs to 5 hrs 26 mins duration. The variation temperature of oil out of SG ($T_{(o,o,SG)}$) has low variation even though flow rate of oil through PH is varied. During the cloud cover episode, the temperature of oil out of PH varies 226 to 205°C and again rises to 225°C as shown in Figure 16 (main manuscript).

The temperatures, generated steam, and pressure variables at peak solar radiation and at shut down for the quadratic solar radiation case study are shown in Table S5.

5 CASE STUDY-II: TWO DAYS SOLAR RADIATION

In this section, observations related to performance of HSTP with plantwide decentralized control scheme for two days solar radiation case study are discussed.
Open-Loop (OL) operations with cold startup and shutdown and hot startup and shutdown conditions are discussed in detail in our previous research work (Kannaiyan et al., 2019). Mass flow rates of oil and water in all the sections are maintained constant at start of operation on day one of cold startup. Once a steady pressure of 40 bar is attained in SG and SD, Closed–Loop (CL) control action is initiated in PTC, LFR, SD, SG and HX+turbine of HSTP. Once shutdown occurs in HSTP during evening, the system cools down.

But, the oil in high temperature storage tank (which is insulated) remains at a higher temperature at start of day two as compared to start of day one. Thus, the second day's start of operation is termed as hot startup. Once the solar radiation reaches a value of 250 W/m^2, OL operation on second day starts. Similar to day one, the OL operation leads to CL operation after attainment of 40 bar pressure in SG and SD along with temperature of oil outlet of PTC ($T_{(o,o,PTC)}$) reaching a value of 300^{o}C. Duration of OL and CL operations on both the days (cold startup, and warm startup) are shown in Table S6.

During Night Time Cooling (NTC) operation, mass and thermal energy variables and their transient values are shown the Table S7. In the two days simulation study, CL control operation is initiated once the pressure in Steam Generator (SG) reaches 40 bar. Maintaining the steam pressure is an essential requirement in thermal power generation. The pressure of SG depends on steam generation, steam leaving out of SG and mass flow rate of water flowing into SG. Once CL operation starts, level of water in the SG is maintained by level PI controller. However, the mass of water in SG oscillates in the range of 3122 to 3128 kg and accordingly, the pressure in SG also oscillates between 40.72 to 40.8 bar.

The shutdown condition occurs when the volume of oil in HT tank is lesser than a threshold 1.5m^3 for a duration of 10 minutes. During night cooling, pressure drops in SG and SD are shown in Table S7. Second day OL operation starts with pressure in SG at 42.9 bar and SD at 1 bar.

Due to override control action of HT, mass flow rate of oil out of HT ($\dot{m}_{(o,o,HT)}$) oscillates in range 12 to 2 kg/s. This in turn causes generated steam flow to oscillate in range 1.5 to 0.8 kg/s for CL control operation on both the days. During this oscillation stage, mass flow rate of water flow into SG ($\dot{m}_{(w,i,SG)}$) also oscillates in range 0.9 to 0.13 kg/s to control the height of water in SG.

Mass of oil present in HT and LT decides duration of CL control operation. Once CL operation starts on the first day, mass flow rate of oil out of LT depends on setpoint PTC temperature setpoint. Mass flow rate of oil out of HT depends on the override control action. Mass of oil in HT oscillates in range 7866 to 7093 kg on both the days. Once control action starts, mass of oil in LT oscillates in range 1931 to 1184 kg on both the days.

Mass of steam present in SG ($M_{(st,SG)}$) reaches the constant level of 2469 kg on both days of operation before CL operation start. In CL operation, $M_{(st,SG)}$ reach the constant value of 2424 kg on day one and 2370 kg on day two operation. Mass of steam present at SD on the first day of operation (after cold startup) reaches a value of 49 kg at the end of OL operation, and it increases to 56 kg during CL operation end for cold startup. On day two (starting with a warm startup), during CL operation, mass of steam in SD is maintained at 46 kg during peak hour of electric production to shutdown condition of warm startup.

Electrical power energy generation through decentralized controller of HSTP on cold startup (day one) and hot startup (day two) operation duration is increased by 2 hrs 43 mins and 1 hrs 46 mins respectively compared to OL operation. Accordingly, electrical power generation also increases by 17% and 25%, for cold startup and hot startup days, respectively.

REFERENCES

Bequette, B. W. (2003). *Process control: modeling, design, and simulation* (Prentice Hall Professional)

Desai, N. B., Bandyopadhyay, S., Nayak, J. K., Banerjee, R., and Kedare, S. B. (2014). Simulation of 1MWe solar thermal power plant. *Energy Procedia* 57, 507–516. doi:10.1016/j.egypro.2014.10.204

Kannaiyan, S., Bhartiya, S., and Bhushan, M. (2019). Dynamic modeling and simulation of a hybrid solar thermal power plant. *Industrial & Engineering Chemistry Research* 58, 7531–7550

Nayak, J. K., Kedare, S. B., Banerjee, R., Bandyopadhyay, S., Desai, N. B., Paul, S., et al. (2015). A 1 MW national solar thermal research cum demonstration facility at Gwalpahari, Haryana, India. *Current Science* 109, 1445–1457. doi:10.18520/v109/i8/1445-1457

Rivera, D. E. (1999). Internal model control: a comprehensive view. *Arizona State University, Tempe, Arizona* , 85287–6006

Stephanopoulos, G. (1984). *Chemical process control*, vol. 2 (Prentice hall New Jersey)

Table S1. Step test for system identification of HSTP

HSTP Component	Input during step test
PTC: Oil outlet temperature	$I = 600$ W/m^2, $\eta_{(opt,PTC)} = 0.6$, $\dot{m}_{(o,i,PTC)} = 3$ to 4 kg/s
SG: Water level	$T_{(o,i,HX)} = 390$°C, $T_{(w,i,HX)} = 105^oC$, $\dot{m}_{(o,i,HX)} = 8$ kg/s, $\dot{m}_{(w,i,HX)} = 2$ to 1 kg/s
LFR: Steam quality	$T_{(w,i,SD)} = 35^oC$, $I = 700$ W/m^2, $\eta_{(opt,LFR)} = 0.22$, $\dot{m}_{(w,i,LFR)} = 2.4$ to 3.4 kg/s
SD: Level of water	$M_{(w,SD)} = 3500$ kg, $P_{(i,LFR)} = 45$ bar, $\eta_{(opt,LFR)} = 0.22$, $\dot{m}_{(w,i,SD)} = 0.65$ to 0.8 kg/s
HX-SG: Electrical power	$\dot{m}_{(o,i,HX)} = 8$ to 9 kg/s, $T_{(o,i,HX)} = 330$ °C, $M_{(W,SG)} = 3500$ kg, $\dot{m}_{(w,i,HX)} = 0.5$ kg/s

Table S2. IMC- PID controller tuning rules

G_P	G_{CL}	K_C	τ_i	τ_d
$\frac{K_P}{\tau s+1}$ (Bequette, 2003)	$\frac{1}{\lambda s+1}$	$\frac{\tau}{K_P\lambda}$	τ	-
$\frac{K_P(-\beta s+1)}{\tau^2 s^2+2\zeta\tau s+1}; \beta > 0$ (Rivera, 1999)	$\frac{1}{(\lambda s+1)}$	$\frac{2\zeta\tau}{K_P(\beta+\lambda)}$	$2\zeta\tau$	$\frac{\tau}{2\zeta}$
$\frac{K_P}{s}$ (Bequette, 2003)	$\frac{2\lambda s+1}{(\lambda s+1)^2}$	$\frac{2}{K_P\lambda}$	2λ	-
$\frac{K_P(\tau_z s+1)}{(\tau_p s+1)}$ (Rivera, 1999)	$\frac{1}{(\lambda s+1)}$	$\frac{\tau_p}{K_P\lambda}$	τ_p	-
$\frac{K_P}{s(\tau s+1)}$ (Rivera, 1999)	$\frac{2\lambda s+1}{(\lambda s+1)^2}$	$\frac{2\lambda+\tau}{K_p\lambda^2}$	$2\lambda+\tau$	-

Table S3. HSTP closed-loop variables

Parameters/ System	PTC	HX		LFR	SD
		Electric Power	water level		
Manipulated Variable (MV)	$\dot{m}_{(o,i,PTC)}$	$\dot{m}_{(o,i,HX)}$	$\dot{m}_{(w,i,HX)}$	$\dot{m}_{(w,i,LFR)}$	$\dot{m}_{(w,i,SD)}$
MV (Minimum to Maximum)	0.5 to 7	2 to 12	0 to 2	0.8 to 2.4	0 to 2
Controlled Variable (CV)	$T_{(o,o,PTC-500m)}$	Pow_{ele}	$he_{(w,SG)}$	$\dot{m}_{(2\phi,o,LFR)}$	$he_{(w,SD)}$
Disturbance	$\eta_{(opt,PTC)}$, $T_{(o,i,PTC)}$, I	$\dot{m}_{(w,i,HX)}$	$T_{(o,i,HX)}$, $T_{(w,i,HX)}$	$T_{(w,i,LFR)}$, I,$\eta_{(opt,LFR)}$	$\dot{m}_{(st,o,SD)}$
Equations of continous and discrete form of controller respectively	S1 and S2	S1 and S2	S1 and S2	S1 and S2	S1 and S2
Tuning of controller, λ	Table S2 (Bequette, 2003), 79.5	Table S2 (Bequette, 2003), 6.2	Table S2 (Bequette, 2003), 20	Table S2 (Rivera, 1999),7.98	Table S2 (Bequette, 2003), 100

Table S4. Turbine parameters Desai et al. (2014) Nayak et al. (2015)

Willan's line equation parameters	$a = -0.263, b = 0.668, c = 0$
Pressure correction factor parameters	$d = 0.4, e = 0.15, f = 0$
Temperature correction factor parameters	$g = 0.125, h = 0.0025, i = 0$

Table S5. Case study I: HSTP variables comparison for closed and open-loop operation

	Peak solar radiation (2 hrs 45 mins)		At shut down	
STP component variable	Open-loop	Closed-loop	Open-loop (4 hrs 17 mins)	Closed-loop (6 hrs 02 mins)
$T_{(o,o,PTC)}$ (^{o}C)	357	307	283	304
$T_{(o,o,HT)}$ (^{o}C)	351	323	295	315
$T_{(o,o,SH)}$ (^{o}C)	313	309	283	280
$T_{(o,o,SG)}$ (^{o}C)	252	252	252	251
$T_{(o,o,PH)}$ (^{o}C)	220	224	231	206
$T_{(o,o,LT)}$ (^{o}C)	227	228	228	215
$T_{(st,o,SH)}$ (^{o}C)	309	298	285	291
$T_{(st,o,SG)}$ (^{o}C)	250	250	250	250
$T_{(w,o,PH)}$ (^{o}C)	206	206	236	225
$\dot{m}_{(st,gen,SG)}$ (kg/s)	0.83	0.71	0.34	0.071
$\dot{m}_{(st,o,SD)}$ (kg/s)	0.80	0.72	0.25	0
P_{SG} (bar)	40	40	40	39.99
P_{SD} (bar)	72	66	43	40.93

Table S6. Case study II: Duration of loop operation for Case study

	CstO	HstT
OL	8 hrs 04 mins to 11 hrs 09 mins	8 hrs 04 mins to 9 hrs 05 mins
CL	11 hrs 10 mins to 18 hrs 18 mins	9 hrs 06 min to 18 hrs 28 mins
NTC	18 hrs 19 mins to 8 hrs 04 mins	18 hrs 29 mins to 8 hrs 04 mins

CL- Closed-Loop (control) operation, OL - Open-Loop operation
NTC- Night time cooling operation
CstO- Cold startup day one operation, HstT - Hot startup day two operation

Table S7. Case study II: Night time cooling variables

Component	Night time cooling (18 hrs 19 min to 8 hrs 04 min)
SH ($T_{(o,SH)}$ (^{o}C))	313 to 305
PH ($T_{(o,PH)}$ (^{o}C))	231 to 224
HT ($T_{(o,HT)}$ (^{o}C))	333 to 331
LT ($T_{(o,LT)}$ (^{o}C))	232 to 231
SG (P_{SG} (bar))	40.82 to 39.04
SG ($M_{(w,SG)}$(kg))	3125 to 3286
SG ($M_{(st,SG)}$(kg))	2469 to 2308
SG ($T_{(w,SG)}$(^{o}C))	257 to 254
SD (P_{SD}(bar))	43.6 to 30.16
SD ($M_{(w,SD)}$(kg))	3507 to 3544
SD ($M_{(st,SD)}$(kg))	37 to 1
SD ($T_{(w,SD)}$(^{o}C))	234 to 228