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Simulation of 1MWe Solar Thermal Power Plant

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Abstract

A grid-connected solar thermal power plant, with a gross capacity of 1 MWe at direct normal irradiance (DNI) of 600 W/m^2, has been designed and is being commissioned at Gurgaon near New Delhi in India. The unique feature of the plant is the integration of two different solar fields (parabolic trough collectors and linear Fresnel reflectors) without a fossil fuel backup. The hot oil (Therminol VP1) from parabolic trough collectors and saturated steam from linear Fresnel reflectors are integrated to produce superheated steam at 350°C, 42 bar to run a turbine-generator to produce electricity. A simulation package has also been developed as a part of the project. This paper outlines the salient features of this package and presents simulation studies of the power plant under the climatic conditions of New Delhi. A detailed performance model of the actual plant is created in the simulator using its libraries. Diurnal simulation of the plant has been done to see the daily variations of the collector heat gain and plant power output. The plant will produce about 1365 MWh of annual energy at a capacity factor of 15.6%; the annual DNI at New Delhi being 1273 kWh/m^2-year. These results can be used to plan the operation and device the appropriate control strategy of the power plant. The simulation results will be validated with actual plant data, after commissioning.

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Keywords: Linear Fresnel reflector; Parabolic trough collector; Solar thermal power; Solar thermal simulator

1. Introduction

The global demand for energy and more specifically clean energy is growing rapidly. With growing energy demand and green-house gas emission, concentrating solar power (CSP) is considered as one of the promising options and has invited wide attention. There are a large number of CSP plants installed in the world [1] and also detailed studies on economic aspects have been reported in the literature (for an example, Krishnamurthy et al. (2012) [2]). Among the CSP technologies, the plants with parabolic trough collectors (PTC) using oil as heat transfer fluid (HTF) are found to be more attractive commercially.

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Nomenclature

A_p	aperture area of the collector (m^2)
h	enthalpy (J/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (MPa)
Q_{gain}	collector heat gain (W)
T	temperature (°C)
Greek symbols	
η	efficiency
θ	incidence angle
Subscripts	
a	ambient
in	inlet
m	mean
out	outlet

Several investigators have also proposed the direct steam generation (DSG) in PTC field as a viable option economically [3,4]. Also the linear Fresnel reflector (LFR) for direct steam generation has been reported as cheaper design due to the use of flat mirrors and structural advantages, though with a lower optical efficiency [5-7]. Manzolini et al. (2011) [8] presented an innovative solar field layout named "Milan configuration". The main concept is the division of the solar field into two sections: one generates saturated steam like in DSG process and the second heats up a conventional HTF which is used for superheating and reheating the steam. In this configuration, the pre-heated feed-water directly enters the DSG solar field for steam generation. At the outlet of the collectors a two-phase mixture is obtained. The mixture enters a drum, where the saturated steam is directed to the superheater and the liquid is re-circulated to the DSG solar field inlet. The superheating and reheating sections adopt the HTF as the heat source in dedicated heat exchangers. Giostri et al. (2012) [9] compared HTF based, molten salt based, DSG-HTF based and DSG-salt based plant, in terms of both performance at design conditions and annual energy production. However, no plant in MW-range has been built using PTC with HTF and LFR for DSG. Under the initiative of Indian Institute of Technology Bombay (IIT Bombay), such a plant is being commissioned in India.

Simulation of a solar thermal power plant allows to study the performance of the entire power plant prior to its actual construction. The simulation results can be successfully applied to optimise the plant configuration, to devise the overall control strategy and to determine the start-up procedures. IIT Bombay has developed a solar-thermal-simulation package to predict the performance of each equipment of the plant, annual power generation, capital cost and cost of energy for a given configuration. The package can be used for preliminary sizing, heat balance design, off-design simulations and performance evaluation of a small subset of a complete plant or a complete plant. Parametric study can be done changing the system parameters, such as, control variable, place, working fluid and equipment model parameters. The comparison of solar thermal simulator of IIT Bombay with different widely used software, like System Advisor Model, TRNSYS and Thermoflex, for solar thermal application has been reported by Desai and Bandyopadhyay (2012) [10]. The capabilities and advantages of the package developed are presented.

This paper outlines the salient features of the package and presents simulation studies of the 1 MWe solar thermal power plant under the climatic conditions of New Delhi.

2. Models and Features of the Simulator

The main features of the simulator include graphical user interface for data input and output, simulation of user defined process flow diagram (PFD), library of climatic and equipment parameters or facility for manual entries, provision for overall optimisation through multiple simulations, user defined time step and time horizon for the simulation, etc. The interface of the simulator is self-describing hence very user friendly and easy to use. The results can be displayed in tabular form or graphical form and also can be exported as MS Excel file. The different equipment used in solar thermal power plant such as solar collector, heat exchanger, pump, storage vessel, turbine, auxiliary boiler, etc., are incorporated into the simulator library.

2.1 Solar collector

The collector heat gain (Q_{gain}) and efficiency ($\eta_{Collector}$) are given as follows:

$$Q_{gain} = \dot{m} \cdot (h_{out} - h_{in}) = \eta_{Collector} \cdot DNI \cdot Cos\theta \cdot A_p \tag{1}$$

$$\eta_{Collector} = A - B \cdot \left(\frac{T_m - T_a}{DNI \cdot Cos\theta} \right) - C \cdot \left(\frac{(T_m - T_a)^2}{DNI \cdot Cos\theta} \right) \tag{2}$$

where, $\dot{m}$ = mass flow rate (kg/s), h = enthalpy (J/kg), DNI = direct normal irradiance (W/m^2), θ = incidence angle (for LFR $\theta = \theta_{mean}$, which is the mean/average incidence angle calculated from incidence angle of each reflector rows), A_p = aperture area of the collector (m^2), T_m = mean temperature (°C) = $(T_{in}+T_{out})/2$, T_a = ambient temperature (°C), A = optical efficiency, B = first order loss co-efficient based on aperture area (W/m^2-K), C = second order loss co-efficient based on aperture area (W/m^2-K^2).

The user has to specify thermo-optical properties to predict the performance of the solar collector. To study the overall plant performance, various controls are also incorporated in the equipment. The user can select the fixed flow rate or the option of controlling the outlet temperature or outlet dryness fraction with manipulating variable such as mass flow rate through the collector. It may be mentioned that the current version of the simulator includes PTC, LFR and paraboloid dish.

2.2 Turbine

The user can predict the performance either selecting a model which uses isentropic efficiency or a model which uses Willan's line equation. The isentropic efficiency of the turbine is given as follows:

$$\eta_{isentropic} = A' + B' \cdot \dot{m} + C' \cdot \dot{m}^2 \tag{3}$$

where, $\dot{m}$ = mass flow rate (kg/s), *A'*, *B'* and *C'* = efficiency parameters.
The Willan's line equation is given as follows:

$$Power(MWe) = a + b \cdot \dot{m} + c \cdot \dot{m}^2 \tag{4}$$

where, $\dot{m}$ = mass flow rate (kg/s), *a*, *b* and *c* = parameters of Willan's line equation.

Thus, the actual power output is given by

$$Power_{actual}(MWe) = Power \cdot X_P \cdot X_T \quad (5)$$

where, X_P and X_T are respectively pressure and temperature correction factors and are given by

$$X_P = d + e \cdot P + f \cdot P^2 \quad \text{and} \quad X_T = g + h \cdot T + i \cdot T^2 \quad (6)$$

and P = pressure (MPa), d, e and f = pressure correction factors, T = superheat temperature (ºC), g, h and i = temperature correction factors.

2.3 Other equipment

In case of heat exchanger, user can predict the performance specifying any one of the following parameter: temperature driving force, heat duty, hot or cold fluid outlet temperature, hot or cold fluid temperature change, product of heat transfer coefficient and area. Splitter and Mixer can be used to arrange equipment in series and parallel combinations. Pressure drop and heat loss through the piping are evaluated using piping element. Storage vessel is modeled as a well-mixed tank. The detailed description of all the equipment models is given in the user manual of the simulator [11].

2.4 Fluids

The library for property models includes properties of water (all phases). The vapor pressure of the water is calculated based on Antoine vapor pressure equation [12], empirical equations are developed for saturation properties, subcooled properties and thermophysical properties (viscosity, surface tension etc.) of the water and superheated properties are calculated following Garland and Hand (1989) [13]. Apart from these, property equations of heat transfer fluid – Therminol VP-1 [14] are also incorporated.

3. Simulation of 1 MWe plant

A grid-connected solar thermal power plant, with a gross capacity of 1 MWe at direct normal irradiance (DNI) of 600 W/m^2, has been designed and is being commissioned at Gurgaon near New Delhi by IIT Bombay as a part of the project titled 'Development of a Megawatt-scale Solar Thermal Power Testing, Simulation and Research Facility', sponsored by the Ministry of New and Renewable Energy, Government of India. The Ministry has given its own land for the plant in the campus of Solar Energy Centre. Based on site DNI condition, 600 W/m^2 has been chosen as the design point. The unique feature of the plant is the integration of two different solar fields (parabolic trough collectors and linear Fresnel reflectors) without a fossil fuel backup. The plant intends to combine the advantages of synthetic oil based parabolic trough collector (PTC) field and direct steam generation (DSG) of linear Fresnel reflector (LFR) field. The hot oil (Therminol VP1) from PTC field and saturated steam from LFR field are integrated to produce superheated steam at 350°C, 42 bar to run a turbine-generator to produce electricity. The simplified PFD of the plant is shown in Fig. 1.

The heat supplied for generation of steam is received from two different solar fields. The PTC field (aperture area of 8175 m^2) supplies about 60% of the required heat, while the LFR field (aperture area of 7020 m^2) supplies the balance about 40% of the required heat at design condition. The PTC field uses concentrated solar radiation incident on it to generate high temperature oil at 390ºC, which is fed into the heat exchanger. Simultaneously, the LFR field generates saturated steam at 44 bar and 256.1°C which is added to the steam generator. At the outlet of the LFR field a two-phase mixture is obtained. The mixture enters a drum, where the saturated steam is directed for superheating and the liquid is re-circulated to the

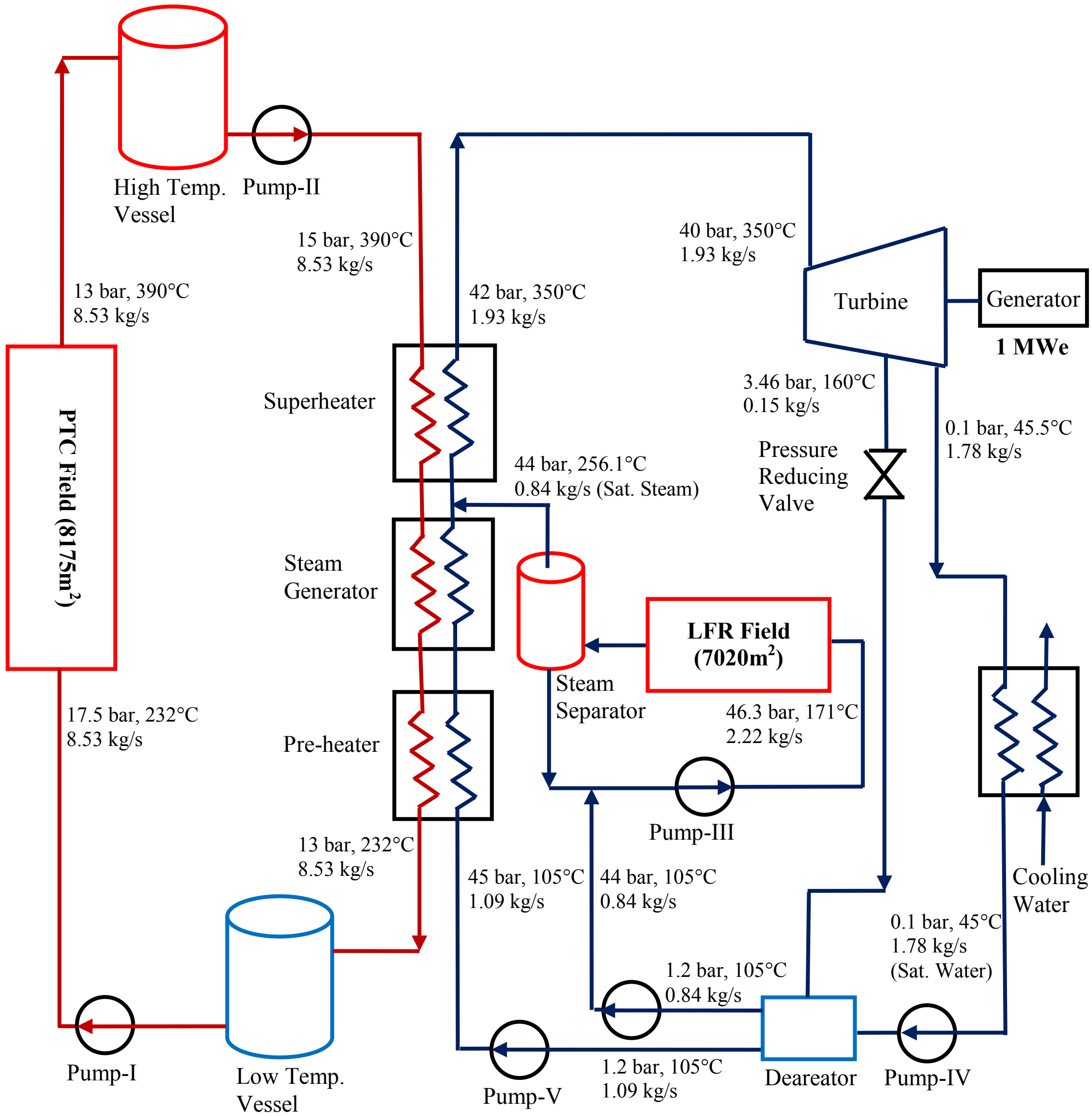


Fig. 1. Simplified process flow diagram of 1 MWe solar thermal power plant

LFR field inlet. The combined heat generated by these two fields is fed into the heat exchanger to produce the required steam to generate power of 1MWe at a design DNI of 600 W/m^2. The steam mass flow rate, pressure and temperature at the inlet of the turbine are 1.93 kg/s, 40 bar and 350ºC respectively.

The plant is designed without any fossil fuel or biomass based auxiliary heater. The inherent variation and discontinuity in the output of solar fields, such as cloud cover and sudden changes in radiation level, can cause disruptions in smooth running of the turbine and also can cause shutdowns within a day's operation affecting the turbine life. To tackle this issues, a thermal storage in the form of an additional oil tank, is provided between the parabolic trough solar field and the steam system of the plant.

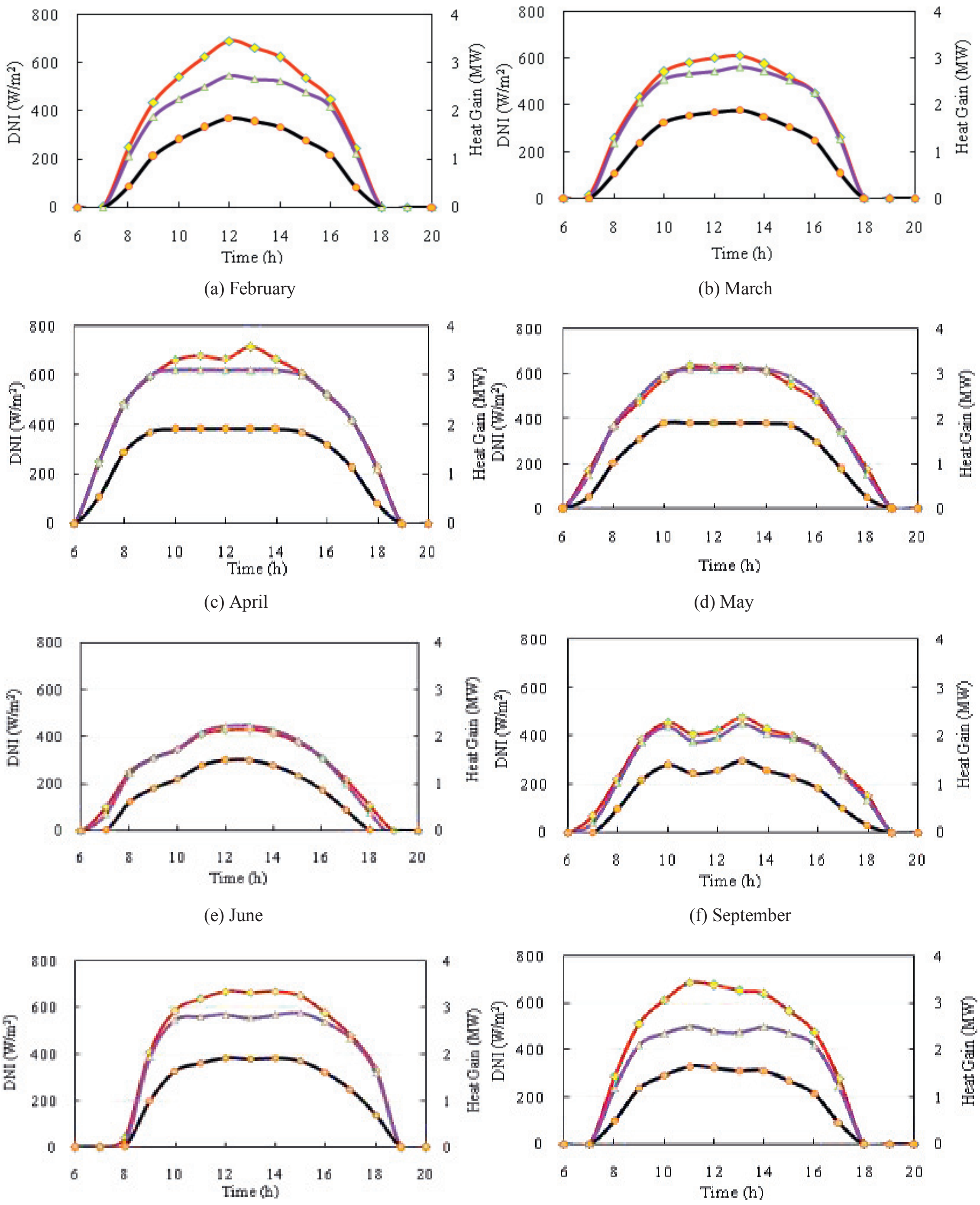
3.1 Results and discussion

A detailed model of the actual plant is created in the simulator using the model library. Essentially, the solar thermal simulator solves energy and mass balance equations for user defined plant configurations. The input parameters of PTC field, LFR field, turbine, storage vessels and heat exchanger used for the simulation are given in Table 1. Diurnal simulation of the plant, based on monthly average hourly DNI, has been done to see the daily variations of collector heat gain and plant power output. For these calculations, the monthly average hourly DNI and ambient temperature data are taken from Ramaswamy et al. (2013) [16] and Tyagi et al. (2009) [17] respectively. It is observed that the plant will remain almost nonoperational due to low DNI condition in the month of January, July, August and December. Figure 2 presents the monthly average of hourly heat gain from PTC and LFR fields of the remaining eight months. It is seen that the DNI is relatively higher in the month of April and May. During these months at New Delhi, the sun's altitude is such that the cosine effect is quite less resulting in higher collector heat gain. On the other hand, the DNI is the least in June (among these eight months) due to cloud covers and the cosine effect is the highest in the month of November causing lower collector heat gain. Figure 3 presents monthly average of hourly plant output of eight months. It may be mentioned that the minimum turbine output is 0.25 MWe as per the manufacturer's specifications.

In the month of November compared to May, the decrease in DNI is 4.7% and the reduction in the heat gain of both collector fields is 26.2% resulting in a decrease in the plant output by 30.1%. This is mainly due to the cosine effect in the month of November. On the other hand in June compared to May, the decrease in DNI is 34.8% and the corresponding reduction in the heat gain of collectors is 34.7% and that of energy output is 48.7%. The higher decrease in energy output is mainly due to the part load effect

Table 1. Input parameters of PTC field, LFR field and turbine used for the simulation

Equipment	Input Parameters
PTC Field	Aperture area: 8175 m^2; Efficiency model parameters: A = 0.7, B = 0.1, C = 0
	Tracking mode: Focal axis N-S horizontal and E-W tracking; Control Option: T_{out} = 390ºC
LFR Field	Aperture area: 7020 m^2; Efficiency model parameters: A = 0.6, B = 0.2, C = 0
	Tracking mode: Focal axis N-S horizontal and E-W tracking
	Receiver height = 13 m, No. of reflectors in each loop = 8, Distance between two reflectors = 2.378 m
Turbine	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
	Maximum and Minimum mass flow rate: 2.05 kg/s and 0.73 kg/s
High Temp. Vessel	Volume: 18 m^3; Higher level limit: 80%; Lower level limit: 20%; Loss co-efficient: 0.0076 kW/K
Low Temp. Vessel	Volume: 16 m^3; Higher level limit: 80%; Lower level limit: 20%; Loss co-efficient: 0.0076 kW/K
Super Heater	Product of heat transfer coefficient and area: 8.748 kW/K; Heat exchanger type: Shell and tube
Steam Generator	Product of heat transfer coefficient and area: 58 kW/K; Heat exchanger type: Shell and tube
Preheater	Product of heat transfer coefficient and area: 16.05 kW/K; Heat exchanger type: Shell and tube



(a) February (b) March

(c) April (d) May

(e) June (f) September

(g) October (h) November

Fig. 2. Monthly average of hourly heat gain in both collector fields

(DNI PTC Field LFR Field)

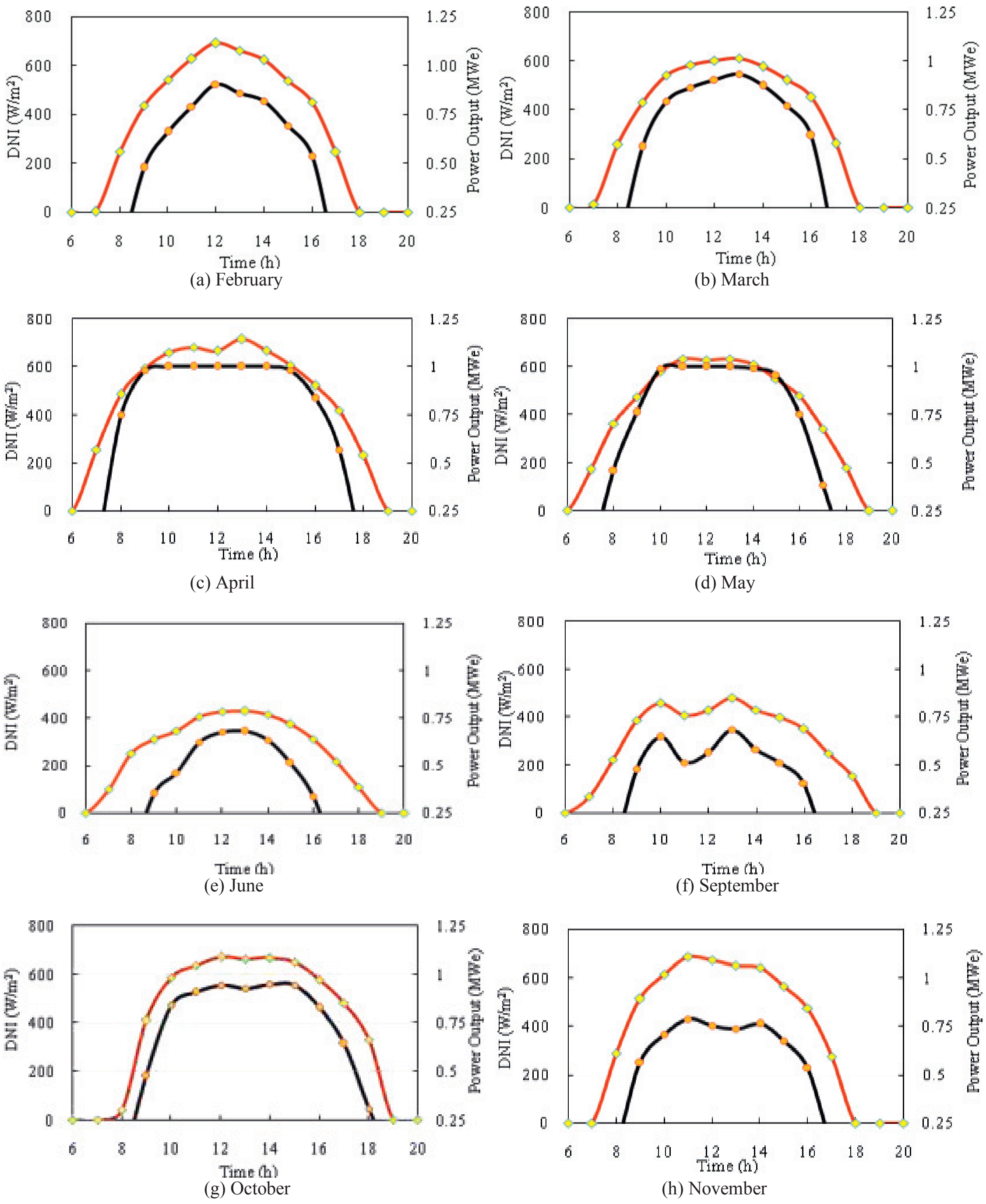


Fig. 3. Monthly average of hourly power output.

(DNI Power Output)

of the turbine. It may be mentioned that such predictions from the simulation package can be used for planning the operation of the plant. From hourly simulation, the monthly energy output of the plant can be estimated and is shown in Fig.4; the gross annual energy output is 1365 MWh. It may be mentioned that the annual DNI value at New Delhi is 1273 kWh/m^2-year resulting in a capacity factor of 15.6%. The plant can deliver a maximum output of 232.2 MWh in the month of April (DNI = 641.4 MJ/m^2-month) and a minimum output of 122.5 MWh in the month of June (DNI = 364.8 MJ/m^2-month).

The simulator can be used to determine the operational strategy under various conditions. To demonstrate this, an example of plant operation under low DNI is considered. The plant incorporates HTF storage as a buffer to handle low solar radiation and cloud cover. The control philosophy of the plant incorporates the combined effect of the two solar fields under given solar radiation and ambient conditions to effect continuous power generation from the turbine-generator unit during the sunshine hours of the day. Storage system operation is naturally a time-dependent process. The modelling of plant operation with storage is done with a quasi-steady state approach. The storage system's state at the end of a time step is fed as the initial condition for the next time step. The performance of the plant under low solar radiation or cloud cover is shown in Fig. 5. As mentioned earlier, the minimum power level at which the turbine should be operated is 250 kW. For safety, the control logic is framed keeping 320 kW as the minimum power level. When the radiation drops to a level which is too low to generate about 320 kW power output, the oil will be expelled from the high temperature (HT) vessel until the higher radiation level is achieved or the oil level in the HT vessel reaches the minimum (20%) value. If the HT vessel level reaches minimum and the radiation is not enough to run the plant at a minimum rating, then the shutdown will be initiated.

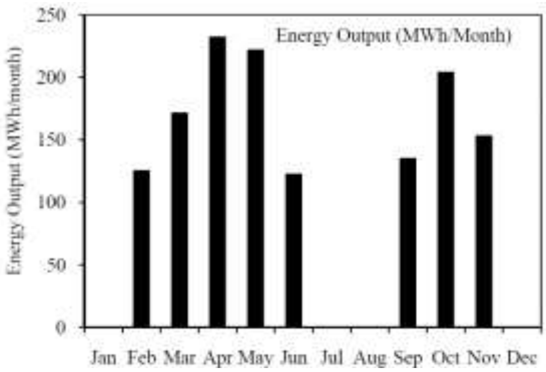


Fig. 4. Monthly energy output of the plant

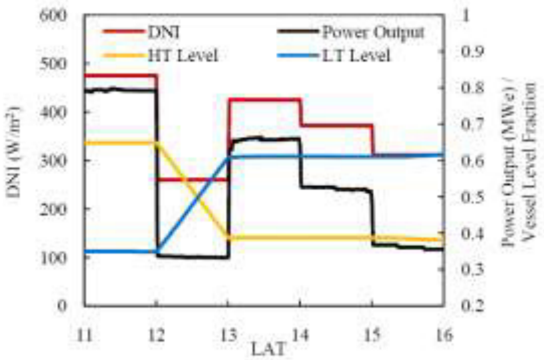


Fig. 5. Performance of the plant during low solar radiation or cloud cover

4. Conclusions

A solar thermal power plant that intends to combine the advantages of synthetic oil based PTC field and DSG of LFR field has been designed and built. The PTC solar field supplies about 60% of the required heat, while the LFR solar field supplies the balance 40% of the required heat at design condition. The control philosophy of the plant incorporates the combined effect of the two solar fields under given solar radiation and ambient conditions to effect a continuous power generation from the turbine-generator unit during the sunshine hours of the day using HTF storage. These would be checked and validated after the plant is commissioned. Quasi-steady-state solar thermal simulator developed as a part of the project can be used for preliminary sizing, heat balance design, off-design simulations and performance evaluation of a small subset of a complete plant or a complete plant. The difference between DNI and power output is higher in the month of November due to cosine effect and that in the month of June is due to part load effect of the turbine. The plant will produce about 1365 MWh of annual energy output at a capacity factor of 15.6%. The plant can deliver a maximum output of 232.2 MWh in the month of April and a minimum output of 122.5 MWh in the month of June. Such results can be used to plan the operation and devise the appropriate control strategy of the power plant. The simulation results will be validated with actual plant data, after commissioning.

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