Technical and Economic Evaluation of Concentrated Solar Power Plant

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Abstract: - Concentrated Solar Power (CSP) are systems that use lenses or mirrors to concentrate a large area of sunlight onto a small area. Variable nature for such technologies affects mainly on active power and frequency behavior of power system grid. In this paper, the frequency responses of these plants are investigated. The effect of both CSP grid-connected technologies on the system's frequency stability are presented and discussed for the IEEE 9-bus benchmark system. The analyses are performed at the transmission system level and from the system operator's perspective. This study summarizes the main features of concentrated solar technologies frequency behavior. Typical case is studied economically for different concentrated solar technologies. An economic evaluation of concentrated solar technologies is summarized for one of Sunbelt countries. According to this study, concentrated solar thermal technologies has more technical and economic benefits than concentrated photovoltaic one.

Key-Words: - CPV, CSP, CST, Smart Grid's Generation Technologies, and VRES.

1 Introduction

Variable renewable energy (VRE) is a renewable energy source that is non-dispatchable due to its fluctuating nature, like wind power and solar power. VRESs have two basic characteristics; variability and uncertainty.

Solar variability is generation changes according to the availability of the primary fuel, i.e. solar irradiation, resulting in swings of the plant output. And uncertainty is magnitude and time of the generation output is unpredictable [1, 2].

There are two different concentrated solar technologies, which convert solar irradiation into electric energy. First, concentrated solar thermal plant (CST) where a thermodynamic cycle is used to generate electrical power. Second, Concentrated photovoltaic plants (CPV), where the sunlight is directly converted into electric energy.

However, both of CST and CPV use solar direct normal irradiation (DNI) [3, 4]. Thus, and according to the weather conditions, any variation in DNI will affect the output power.

Traditional power systems are designed to handle the variable nature of loads. Uncontrolled additional supply-side variability and uncertainty will pose new challenges for utilities and system operators. One of these challenges is maintaining frequency stability, which will be greatly affected by any power deficiency events.

This paper investigates the effect of different CST or CPV plant on power grid frequency behavior. In addition to comparing between CST plant and CPV plant economically.

The following sections are divided as follow: section 2, CPV and CST technologies are presented. In section 3, different frequency response of grid connected CST and CPV plants are investigated. Section 4 presents economical comparison for CST and CPV in one Sunbelt MENA countries. Finally, the main conclusion and recommendations are presented in section 5.

2 Concentrated Solar Power Market

2.1 CPV

Concentrating Photovoltaic (CPV) technology uses mirrors or lenses to concentrate sunlight onto a relatively small area of photovoltaic cells that generate electricity.

The CPV systems are commonly classified according to the concentration ratio of the solar radiation incident onto the cell. This ratio indicates the number of times that the solar light is concentrated. And it is usually known as 'Suns' [5].

It can be defined three different CPV systems:

Low Concentration (LCPV): it refers to those systems that concentrate the light between 1 and 40

times (1–40x), so the LCPV systems have a concentration factor between 1 and 40 suns.
Medium Concentration (MCPV): these are the systems that concentrate the sunlight between 40 and 300 times (4–300x).
High Concentration (HCPV): the concentration level of these systems varies between 300 and 2000 suns (300–2000x).
It should be noted that more than 90% of the capacity documented to be installed through end July 2015 is in the form of high concentration PV (HCPV) with two-axis tracking [3].
A key reason for the increasing number of large-scale power plants using HCPV is the significant increase in the efficiency of individual modules, which also leads to a reduction of area-related system costs. And efficiencies of commercially available CPV modules exceed 30%.
In addition to using high efficiency CPV modules, tracking allows CPV systems to produce a larger amount of energy throughout the day in sunny regions, notably during late part of the day when electricity demand peaks.
CPV technology has recently entered the market as a utility-scale option for the generation of solar electricity. Figure 1 presents the total installed capacity of CPV plants in different countries. Golmud 2 project is the largest CPV installation worldwide of 80 MW_p capacity [7]. The typical structure of a grid connected CPV plant is shown in figure 2. Its main subsystems are the photo-voltaic array, the DC/DC and DC/AC converters and the associated controls (converter and overall system). A storage system is in general absent in large grid-connected SPVG installations, except for small critical loads of the plant such as start-up controls.
HCPV directly competes with CST as both technologies are suited best for areas with high DNI, which are also known as the Sun Belt region.

2.1 CST

Concentrating Solar Thermal power (CST) technologies are based on the concept of using mirrors to concentrate solar irradiation onto a receiver, which collects and transfers the solar energy to a heat transfer fluid (HTF) used to generate electricity through traditional steam turbines. Large CST plants can be provided with a heat storage system to allow electricity generation at night or when the sky is cloudy [6].
At present, there are four available CST technologies which differ depending on the design, configuration of mirrors and receivers, heat transfer fluid used and whether or not heat storage is involved.

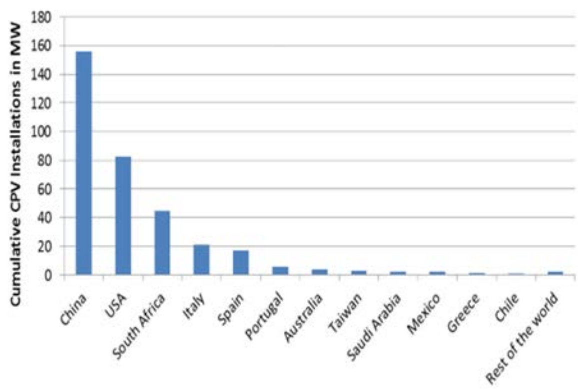

Fig. 1 Grid-connected CPV capacity by country through end of July 2015 [3].

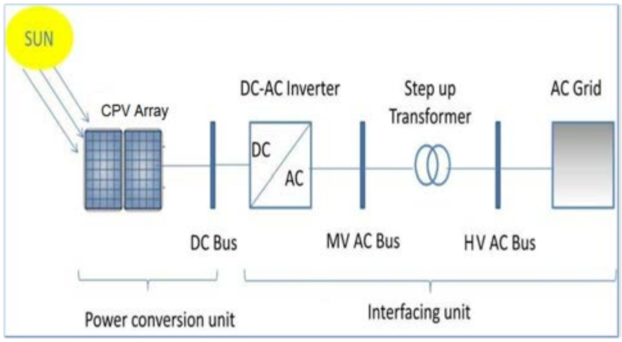

Fig. 2 The typical structure of a grid connected CPV plant.

They can be classified to solar power towers, parabolic trough collectors (PTC), linear Fresnel reflectors, and parabolic dish collectors, according to focusing solar irradiation configuration and the receiver technology.
The first three types are used mostly for power plants in centralized electricity generation, with the PTC system being the most commercially mature technology.
Grid-connected CST plants essentially consist of three independent but interrelated components that can be seized differently: the power block, the solar field, and the thermal energy storage system.
A schematic diagram of CST parabolic trough grid-connected plant with thermal energy storage system (TESS) is shown in fig 3.
A CST plant with TESS can shift electricity production to periods of highest prices. Second, TESS may provide firm capacity to the power system, replacing conventional power plants as opposed to just supplementing their output. Finally, the dispatchability of a CSP plant with TESS can provide high-value ancillary services such as spinning reserves.
In the absence of storage capacity, on the sunniest hours, plant operators defocus some unneeded solar collectors to avoid overheating the HTF. Storage avoids losing the daytime surplus energy while extending the production after sunset.

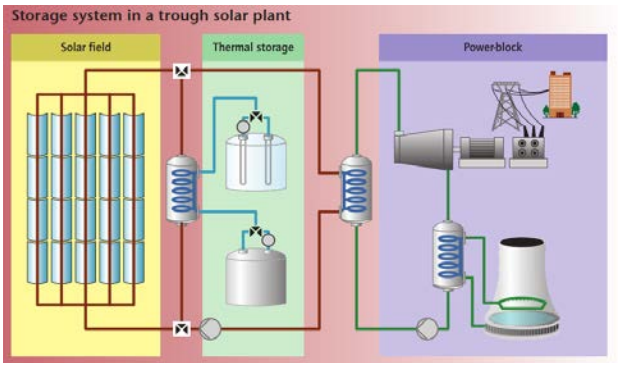

Fig. 3 Schematic diagram of CST parabolic trough grid connected plant with thermal storage system [2].

In 2014, four new projects totaling over 0.9 GW increased total global capacity by 27% to nearly 4.4 GW [7]. Although parabolic trough collector technology is the most mature CSP design, solar tower technology occupies the second place and is of increasing importance as a result of its advantages.

3 Frequency response study.

The frequency responses of both CST plant and CPV plant are examined when they are connected with electric power system. A multi machine system IEEE 9-bus test power system described in [8] is tested.

In the study, generation at bus 3 will be replaced once by a CPV plant of the same rating to allow a realistic modeling of the effect of adding a CPV plant to an existent system. In another case, the generation will be replaced by a CST plant.

The examination is based on studying the frequency behavior during several cases, as follows:

1) Active loads varying from 10 to 25% of the total loading are connected at time = 1 sec.
2) To investigate the sharing effect of solar plant on frequency response, different sharing levels varying from 10% to 30% of the total generated power are simulated.
3) The synchronous generator's inertia constant equals 6 sec.

The most severe case is 25% overload level of the total system load, and solar plant shares by 30% of the total system generated power. This case will be discussed in details.

Due to the inertia effect, the traditional plant and CSP plant have the same frequency response. Their frequency decays from 60 Hz to 57.31 Hz over 4 sec after the over load event. While, the frequency decays to 56.75 Hz in the inertia less CPV case after the same period, as shown in fig. 4.

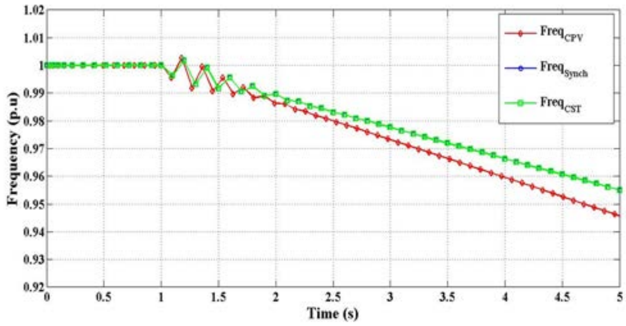

Fig. 4 Frequency response of CPV, CST and traditional plants.

Traditional grids are powered by synchronous generators which respond to frequency and voltage disturbances according to many factors.

After the over load event, Synchronous generators is releasing part of their stored kinetic energy immediately. This released energy damps frequency variation and eliminate power mismatch between generated power and demand power as shown in figure 5. While at all different cases, the total active generated power is nearly constant and equals to the total load in addition to the over load level which is presented in figure 6.

When a frequency disturbance occurs, the synchronous machines will inject or absorb kinetic energy into or from the grid to counteract the frequency deviation. The lower this system inertia, the more jumpy the grid frequency reacts on unexpected changes in generation and load patterns.

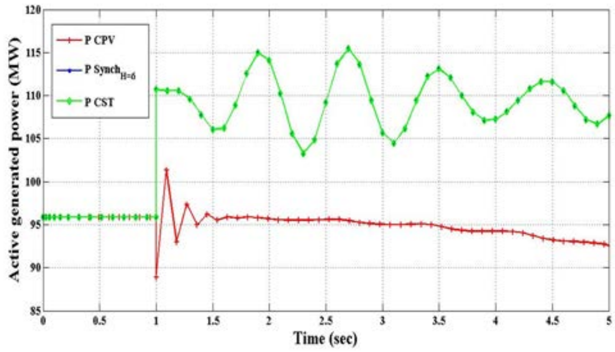

Fig. 5 The active output power of CPV, CST and traditional plants during frequency decaying period.

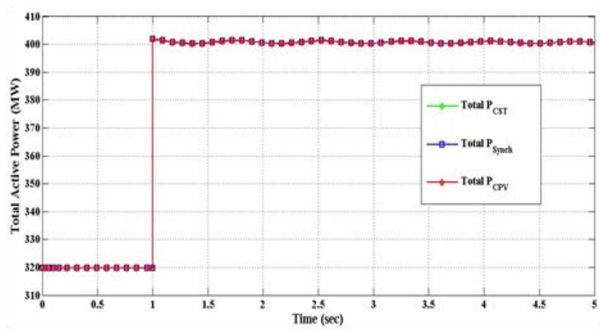

Fig. 6 Total active generated power of CPV, CST and traditional plants.

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CST plant's power block consists of the same components as used in the traditional power plants.

In case of CPV plant, no moving parts are employed in the process of converting solar irradiation to electric power, CPV plants do not provide any form of energy storage. Consequently, CPV plants are inertia-less systems.

The CPV plant's frequency response has higher decaying rate than CST plant. Thus, integrating CST plants would be preferable than CPV plant from technical point of view.

4 Economic Evaluation

One standard that is used to compare different energy generation technologies or systems is the levelized cost of energy (LCOE). LCOE index is often cited as a suitable summary measure of the overall competiveness of different generating technologies. It represents the per-kilowatt-hour cost of building and operating a generating plant over an assumed financial life and duty cycle [9].

Key inputs to calculating LCOE include capital costs, fuel costs, fixed and variable operations and maintenance (O&M) costs, financing costs, and an assumed utilization rate for each plant type. The importance of the factors varies among the technologies.

For technologies such as solar and wind generation that have no fuel costs and relatively small variable O&M costs, LCOE changes in rough proportion to the estimated capital cost of generation capacity.

Utility-scale LCOE is calculated based on the required revenues over the project life and is described as nominal according to:

$$nominal\ LCOE = \frac{\sum_{n=1}^{N} \frac{R_n}{(1+DR_{nominal})^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+DR_{nominal})^n}} \quad (1)$$

Where Q_n is the electricity generated in year n, R_n is the required revenue from electricity sales in year n, and $DR_{nominal}$ is the nominal discount rate (with inflation). Hidden within Q and R are numerous factors such as degradation rate, weather data, price escalation rate, etc. [10].

SAM is a system performance model incorporating financing options ranging from residential to utility scale, has developed by the National Renewable Energy Laboratory (NREL), Sandia National Laboratory and the U.S. Department of Energy [11]. This software is used in this study, to analyze solar technologies for specific locations. It also provides users with the capability to probe the relative influence of input parameters on both the energy production and financial aspects.

For CST technology, Solar Multiple (SM) is considered as one of the most factors which affects the economic analysis. The solar multiple can be defined as the ratio of the actual size of a CST plant's solar field compared to the field size needed to feed the turbine at design capacity when solar irradiance is at its maximum.

In this study, two cases of CST with TESS are investigated. First case, CST plant with TESS has SM equals to 1, i.e. there is no much excess solar field specified for thermal energy stored in TESS.

In second case, SM equals to 2, i.e. the size of solar field is doubled to make the most benefits of TESS.

Egypt is a one of Sun Belt countries, have high DNI, which makes the concentrating technologies preferable. Egypt is going to install a 100 MW grid-connected CSP plant in Kom Ombo, Aswan.

Kom Ombo proposed plant is analyzed economically for both CPV and CST technologies, to examine the economic benefits under typical condition of temperature and DNI data.

The economic comparison is done among CPV, CST w/o TESS, and CST with TESS plants under the following conditions:

1- The rated output active power of each plant is 100 MW_{ele}.
2- The same weather conditions (Kom Ombo typical data).
3- HCPV system is used.
4- CST parabolic trough collectors is used.
5- The 25 MWh_{th} TESS can supply full load energy for 6 hours.
6- Estimated CPV module efficiency is 29.8%.
7- The same financial conditions.
8- The same life time i.e. 25 years.

Table 1 summaries the economical comparison among these plants. The CST technology is more economic than CPV technology. The CST plant with TESS and of SM = 2 has the lowest LCOE, but has the largest net capital cost.

Table 1 summary of economic analyses.

	CPV plant	CST w/o TESS SM=1	CST with TESS SM=1	CST with TESS SM=2
Annual energy (kWh)	179,278,352	182,309,328	184,217,712	376,237,056
Capacity factor	19.8%	20.8%	21.1%	43%
Nominal LCOE (¢/kWh)	25.36	18.01	24.48	16.12
Net capital cost ($)	588,715,712	371,003,712	560,889,280	787,378,496

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As discussed Tables 1, although, studied CPV plant capital cost is more than 150% of CST without TESS plant one, annual generated energy of CPV is slightly less than CST w/o TESS one . On the other hand, CST with TESS, without any increase in solar field area, increase LOCE by 36% of CST without TESS. Therefore, solar field area should be studied economically beside necessary technical studies.

5 Conclusion

CSP has increased potential in the world day by another. Therefore, CST parabolic trough plant with 6 hours thermal storage system and CPV plant have been technical and economic evaluated. From technical point of view, the CST plant is more stable than CPV plant and behaves in power deficiency events as traditional plant.

CPV plant doesn't store in energy by its technical nature. Therefore, it needs additional energy storage to react with appropriate behavior in power deficiency cases.

From economic point of view, studied CST cases has lower LCOE than the CPV plant for the same technical and financial conditions.

More technical and environmental studies should be studied for different regions, to cover all features of both technologies.

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