Factors Influencing the Performance of a Photovoltaic Power Plant

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Abstract—The performance of a photovoltaic power plant depends on many design parameters. An efficient design must optimize each parameter in order to achieve the greatest possible amount of energy. A good planning and design can boost the system performance as well as poor one can compromise it. To obtain the best performance from any photovoltaic power system, the system design must address all pertinent factors. These include weather data (sun stroke levels), factors for expected soiling, factors for expected shading (trees, adjacent structures, installation hardware), performance characteristics of photovoltaic technology used, tilt angle and azimuth, seasonal snow cover, array mismatch, distribution losses, inverter efficiency. This paper presents an overview of the most representative of these factors and their influence in determining the performance of a photovoltaic power plant. The degree of influence was determined by analyzing the losses they cause to the system, during their variation. Finally, the paper presents the performance variation of a photovoltaic power plan simulated by a computer program, when two of the key system factors change their value. The analysis will refer only to the direct-current part of the power plant.

Index Terms—PV systems; performance parameters; temperature; installing angles; spectral distribution; mismatch; soil and dirt; snow; photovoltaic analysis software programs.

I. INTRODUCTION

There is no substitute for experience when it comes to designing a PV power system and as a result, there is a real need for outdoor performance evaluation and monitoring of PV technologies, especially for new technologies with no field experience, in order to establish their performance and the deviations observed from the STC conditions. However, a good knowledge of how fundamentals design parameters affects the performance of a PV power system is essential in order to predict and achieve a higher efficiency from a PV plant.

The performance of PV technologies is typically predicted under standard laboratory conditions, STC, of solar irradiance 1000 W/m², air mass of 1.5 and temperature of 25 °C. In outdoor installations, PV systems rarely experience these conditions.

There appears to be no “standard” way of predicting system performance. The key is a good understanding of the PV technology, how it performs under a range of conditions, and how each of the factors affects the particular system in a particular location [1].

II. DEFINITION OF PHOTOVOLTAIC SYSTEM PERFORMANCE

The performance of PV system results from the performance of its components which are in turn affected by climatic factors and associated losses.

Almost all system requirements are unique in some way so the ability to anticipate the on-site challenges and design the system accordingly can help ensure an optimum system performance.

The efficiency of an installed Photovoltaic (PV) system is the most significant parameter that provides a realistic view of the overall system output expectations under the pronounced climatologically circumstances and variable weather conditions found at different locations. Paper [2] concludes that the different technologies exhibit different efficiency performances under the different climatic and seasonal conditions.

Parameters describing energy quantities for the PV system and its components have been established by the International Energy Agency (IEA) Photovoltaic Power Systems Program and are described in the IEC standard 61724 [3].

III. CRITICAL DESIGN PARAMETERS THAT INFLUENCE PERFORMANCE

It is important for designers and planners of PV systems to have an idea about which parameters are critical for system performance, and which may be relaxed on without significant consequences.

Many studies have quantified the relative importance of this parameters and Table I [4] provides a summary of the secondary effects in PV arrays, with an estimate of their effect on monthly energy production.

Several performance models and software have been developed and utilized to assess the performance of PV systems [5]. One of the main aspects that differentiate PV system performance models is the extent to which these factors are taken into account and the approach taken to calculate the operating temperature of the PV array and the incident irradiance falling on the surface of the array.
TABLE I

<table>
<thead>
<tr>
<th>Effect</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>1 % to 10 %</td>
</tr>
<tr>
<td>Angle of incidence</td>
<td>1 % to 5 %</td>
</tr>
<tr>
<td>Spectral distribution</td>
<td>0 % to –3 %</td>
</tr>
<tr>
<td>Uncertainty in manufacturer's rating</td>
<td>0 to 5% or more</td>
</tr>
<tr>
<td>Ageing</td>
<td>5 % over lifetime</td>
</tr>
<tr>
<td>Mismatch</td>
<td>2 %</td>
</tr>
<tr>
<td>Soil and dirt</td>
<td>0 to 15 %</td>
</tr>
<tr>
<td>Snow</td>
<td>Location dependent</td>
</tr>
<tr>
<td>Partial shading</td>
<td>Location dependent</td>
</tr>
<tr>
<td>Diodes and Wiring</td>
<td>3 %</td>
</tr>
</tbody>
</table>

A. Temperature

The operating temperature plays a central role in the photovoltaic conversion process. PV current output is relatively stable at higher temperature; however, the voltage is reduced, leading to a reduction of solar or electrical conversion efficiency as the cell temperature is increased.

The temperature effect on cell operation is shown in Fig. 1.

![Fig. 1. Temperature effect on cell operation [6]](image)

The pronounced effect the operating temperature of a photovoltaic (PV) cell/module has upon its electrical efficiency is well documented [7], [8], [9], [10] and [11]. There are many correlations expressing the PV cell temperature as a function of weather variables such as the ambient temperature and the local wind speed, as well as the solar radiation flux/irradiance, with material and system-dependent properties as parameters.

The various correlations that have been proposed in the literature represent simplified working equations which apply to PV modules or PV arrays mounted on free-standing frames, to PV/Thermal collectors, and to BIPV arrays, respectively.

Understanding temperature effects on PV systems performance is important in order to maximize the output of the system in different climate zones.

Fig 2. show the operating temperature influence on efficiency for double junction amorphous silicon technology in different climate zones.

![Fig. 2. Influence of operating temperature on efficiency [12]](image)

B. Installing angles

The best tilt angle for any PV array is the one that produces the highest annual energy output for that particular location. The primary reference point is the latitude but, other factors are involved as well. The arc of the sun varies with time of year so, typically, the shallow tilt angles produce more energy in the summer months while the steeper angles produce more energy in the winter months.

Tilt angle is especially important with crystalline PV technology, which is much more sensitive to the angle of the incident light as well as dust and dirt accumulations than amorphous silicon PV.

Different methods are available to obtain optimum tilt of a PV system based on the latitude, local climates, insolation conditions and energy demand, and specific measurements have been reported on the seasonal dependence of PV system performance [13].

Paper [14] presents the effects of the solar module installing angles on the output power and the relationship between the sunlight incident angle and the sunlight radiation intensity on the solar-cell panel surface.

Artificial intelligence techniques are also used to determine the suitable tilt angle and power output [15].

C. Spectral distribution

It is commonly recognized among people familiar to photovoltaic technology that electrical current, generated by photovoltaic devices, is influenced by the spectral distribution (spectrum) of sunlight. Also, it is commonly understood that spectral distribution of sunlight varies during a day. The magnitude of the influence the changing spectrum has on performance can vary significantly, depending on the photovoltaic technology.

The effect of the solar spectrum on PV performance is difficult to estimate since it depends on local meteorological conditions, the position of the sun, module mounting type and the physical properties of the modules.

Actual solar spectrum is usually quantified by using so called air mass (AM) factor which unfortunately is a
parameter which describes the shape of solar spectrum only in approximate way and does not reflect complex character of the actual atmosphere condition which filters and scatters solar radiation reaching the Earth’s surface [16].

As the solar spectrum for arbitrary meteorological conditions is so poorly known, a number of authors have suggested models the overall effect of the spectrum in different ways. An interesting model is proposed by the paper [17] authors. They propose a simple empirical model for the influence of the solar spectrum on the performance of PV modules. The model is based on measurements on modules performed outdoors during extended time periods and it is applied to data from crystalline silicon and Cadmium Telluride modules. The final goal for the model is to estimate the overall influence of the spectral effects on the long-term energy output of the modules.

In conclusion what is well known about this loss factor is that amorphous silicon technology has the highest sensitivity to this effect, but the observed changes usually remain under 3%.

**D. Mismatch**

The maximum power output of the total PV array is always less than the sum of the maximum output of the individual modules. This difference is a result of slight inconsistencies in performance from one module to the next and is called module mismatch and amounts to at least a 2% loss in system power. Power is also lost to resistance in the system wiring. These losses should be kept to a minimum but it is difficult to keep these losses below 3% for the system. A reasonable reduction factor for these losses is 95% or 0.95.

Mismatch loss is due to either current mismatch or voltage mismatch. Current mismatch occurs when low current modules are present in a series string or when a portion of the array is shaded; if the current and voltage of the modules are not matched, modules providing low output determine the overall array output. Voltage mismatch arises when cells are shorted. Cells connected in series or parallel operate at the same current or voltage resulting in significant energy loss when the operation of cells is limited by the cell power with the lowest peak output.

The mismatch losses in solar PV arrays can be due to a variety of reasons:
- Manufacturer’s tolerances in cell characteristics;
- Environmental stresses;
- Shadow problem.

An interesting approach is made by the authors of paper [18]. They investigate the aging effect of solar cells on the reduction in available power. This investigation is based on real-life data of ensemble of fresh and aging solar cells and is intended to enable the sizing of solar PV system in such a way that it can deliver the power to the given load without failure for longer duration.

Fig. 3 shows the variation of fractional power loss as a function of cell’s lumped characteristic parameter, C, which is cell characteristic parameter related to fill factor.

**E. Soil and dirt**

The energy lost to soiling of PV systems is of great interest to system owners and operators, but there is little information currently available regarding it. Much of the information available is applicable only to the specific location in which the testing was conducted, and there is a need to characterize soiling at a more general level.

Dirt and dust can accumulate on the solar module surface, blocking some of the sunlight and reducing output. Although typical dirt and dust is cleaned off during every rainy season, it is more realistic to estimate system output taking into account the reduction due to dust buildup in the dry part of the seasons. Soiling may account for up to a 10% of reduction of the annual energy production [19].

Most existing PV system simulation programs assume a PV module soiling loss that is constant through time. A new model has been developed by a group of researchers for the prediction of the energy loss of photovoltaic systems from the accumulation of dirt and particulate matter on PV modules [20]. They found that photovoltaic system efficiency declines by an average of 0.2% per day without rainfall in dry climates. This daily loss finding equates to an annual energy loss between 1.5-6.2% depending on system location.

Fig. 4 shows the average annual soiling loss predicted with this new model for typical year weather.
F. Snow

For northern locations in winter, snow reduces the amount of PV energy produced, with the severity of the reduction a function of the amount of snow received and how long it remains on the PV modules. Snow remains the longest on PV modules when sub-freezing temperatures prevail, small PV array tilt angles prevent snow from sliding, the PV array is closely integrated into the roof, and the roof or other structure in the vicinity facilitates snow drifting onto the PV modules.

Presently, there is little information pertaining to predicting performance losses from snow, but it has been identified for some locations as a serious loss factor [21].

Paper [22] describes two instruments useful for evaluating PV system performance losses from the presence of snow: (1) a pyranometer with a heater to prevent buildup of ice and snow, and (2) a digital camera for remote retrieval of images to determine the presence of snow on the PV array. Application of the instruments and their use for analysis was demonstrated for a snowfall occurring on January 26, 2009 and subsequent losses in PV system performance were determined. Most of the PV systems analyzed lost 1 to 2 days of energy production. But the BIPV system, with a smaller tilt angle, lost 4 days of energy production.

A group of German researchers have carried out a study on the operational performance under snow condition for a 1 MW PV plant in Munich [23]. The values for the proportional annual yield decrease by snow lie between 0.3 and 2.7 %. This value is confirmed by operational experiences of others plants. This work shows interesting approaches, but for universally valid results more detailed measuring campaigns are required.

Further research will be made in order to find an additional simulation parameter for PV simulation programs to consider the average impact of snow on the yield.

IV. CASE STUDY

Performance variation of a PV system was studied using two photovoltaic analysis software programs. The study was done considering Romanian climate conditions, and its purpose is to confirm the theoretical aspects listed above. The two software programs used are PVSOL and PVSYST.

**PVSol** is a photovoltaic system analysis software program developed by Valentin Energy Software in Germany with an English language version distributed by the Solar Design Company based in the UK. The first version of PVSol was released in 1998. The Expert edition has the most features, including a 3-D shading program. For POA radiation, it uses the Hay and Davies (Davies and Hay, 1980) anisotropic sky model. Array performance is calculated as a function of incoming irradiance, module voltage at STC and an efficiency characteristic curve. PVSol can use either a linear or dynamic shading and other voltage losses due to wiring, and soiling. Other useful features include an incident angle modifier and an air mass spectral correction for thin-film modules, as well as the ability for the user to input known parameters and coefficients if measured data is available for both PV modules and inverters.

**PVSYST** is a photovoltaic system analysis software program developed by the Energy Group at the University of Geneva in Switzerland and can be used at any location that has meteorological and solar insolation data. It is widely used due to the many parameters available for the user to modify. The complexity of the input parameters makes it suitable for expert users. For POA radiation, the default is the Hay (1979) model, however the user can also specify the Perez et al. (1987, 1988) model. PVSYST uses the one-diode equivalent circuit model for calculating performance in cSi and HIT modules, and a modified version for what they consider “stabilized” thin film modules, such as aSi, CiS and CdTe. The program allows input from many different weather and solar insolation datasets, including Meteonorm, Satellight, TMY2/3, ISM-EMPA, Helioclim-1 and -3, NASA-SSE, WRDC, PVGIS-ESRA and RETScreen. There is also a custom input option that allows for importing the required data from a comma-separated value (.csv) file format.

Other interesting features include a 3-D shading tool that allows a user to draw a structure with PV arrays and see potential shading impacts from simulated obstructions. There is an option to analyze array mismatch to determine more specific Isc and Voc parameters, as well as look at cell/module shading and other voltage losses due to wiring, and soiling. Other useful features include an incident angle modifier and an air mass spectral correction for thin-film modules, as well as the ability for the user to input known parameters and coefficients if measured data is available for both PV modules and inverters.

The main features of the simulated photovoltaic system are:

- **Location Bucharest**
- **PV Output 23.10 kWp**
- **Performance Ratio 75.9 %**
- **Specific Annual Yield 1100 kWh/kWp**
- **Technology Used MonoCrystalline Si**

Graphics from Fig. 5 and Fig. 6 show the PV Module behavior according to temperature and incident irradiation. Fig. 7 shows arrays losses for Ginc= 1000 W/m².

![Fig. 5. PV Module behavior according to Temperature, [source: PVSYST]](image-url)
Fig. 6. PV Module behavior according to incident irradiance, [source: PVSYST]

Fig. 7. Array losses for Ginc=1000 W/m², [source: PVSYST]

It may be noted that the influence parameters are considered within the range analyzed in the literature.

Finally, PVSYST software is used to analyze the Performance Ratio variation of the simulated photovoltaic power plan, when two of the key system factors change their value. The analysis will refer only to the direct-current part of the power plant.

PR variations when inclination and orientation values are changing are shown in Table II. When one parameter was modified the other was kept constant at optimum value.

<table>
<thead>
<tr>
<th>Inclination (Tilt angle)</th>
<th>PR (%)</th>
<th>Orientation (Azimuth)</th>
<th>PR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>75.1</td>
<td>0</td>
<td>75.9</td>
</tr>
<tr>
<td>10</td>
<td>75.1</td>
<td>5</td>
<td>75.9</td>
</tr>
<tr>
<td>20</td>
<td>75.5</td>
<td>10</td>
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<td>60</td>
<td>75.8</td>
<td>30</td>
<td>75.8</td>
</tr>
<tr>
<td>90</td>
<td>74.1</td>
<td>35</td>
<td>75.6</td>
</tr>
</tbody>
</table>

V. CONCLUSIONS

The performance of a photovoltaic power plant depends on many design parameters. An efficient design must optimize each parameter in order to achieve the greatest possible amount of energy. A good planning and design can boost the system performance as well as a poor one can compromise it.

Different technologies exhibit different efficiency performances under the different climatic and seasonal conditions. Future studies are required in order to obtain maximum performance from the PV technology and outdoor performance evaluation and monitoring are the keys from obtaining it.

However, specialized software can predict the performance of a PV power plant and the results are mostly closed to outdoor measured values.

VI. REFERENCES


