Analysis of transmission losses of Very Large-Scale Photovoltaic power generation systems (VLS-PV) in world desert

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ABSTRACT

VLS-PV systems in desert area are promising in view of rich irradiation and huge land area. But its desert situation, transmission loss may be barrier to realize. This paper is described about estimation of transmission loss without detail irradiation data. Based on power current is in proportion to irradiance, transmission loss is calculated considering change in day, month and year. And rise in temperature is also considered because desert situation. Transmission loss is not so big if it is compared with corrector loss. This result will help preliminary survey of VLS-PV systems in desert areas.

BACKGROUND AND OBJECTIVE

Nowadays, world energy demand has been rapidly expanding due to the world economic growth and population increase, especially in developing countries. While world energy demands continue to increase, the fossil fuel will dry up in this century. In addition, too much energy consumption causes a variety of serious environmental problem such as global warming, acid rain and so on. On the other hand, renewable energies are expected to resolve both the energy problem and the environmental problem. Photovoltaic power generation system is one of promising renewables. Because it need no fuel, no maintenance and no emission when it's generating. Although the solar energy is of low density by nature, it has a large potential by assuming that world deserts can be utilized. Therefore the authors have been investigating very large-scale photovoltaic power generation (VLS-PV) systems on deserts. Even the Gobi desert that locates on high latitude has higher irradiation (4.7kWh/m²/d) than Tokyo (3.5kWh/m²/d). Furthermore, the Sahara desert has more irradiation as 7.4kWh/m²/d. Theoretically, PV systems installed in the Gobi desert with 50% space factor, has potential to generate energy as much as recent world energy supply (384EJ in 2000).

Considering arid or semi arid land area, large parts of the area may be far from existing power grid line. So, if the VLS-PV systems are installed in such kind of area, transmission cost has to be discussed. Economic and environmental discussions of VLS-PV systems were done in view of LCA. It is written in paper [1] or book [2]. They were including transmission equipment cost, but they were not including transmission losses. Therefore, this paper is described about transmission losses, if the MW or GW scale VLS-PV systems are installed in desert areas. And we investigate feasibility of the system.

SYSTEM CONFIGURATION

Geographic information is shown in Table 1. VLS-PV systems are assumed to be installed in six deserts which are Sahara, Negev, Thar, Sonoran, Great Sandy and Gobi. Performance ratio is considered operating

<table>
<thead>
<tr>
<th>Desert</th>
<th>Sahara</th>
<th>Sahara</th>
<th>Negev</th>
<th>Thar</th>
<th>Sonoran</th>
<th>Great Sandy</th>
<th>Gobi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Nema</td>
<td>Ouazazat</td>
<td>Betdagan</td>
<td>Jodhpur</td>
<td>Chihuahan</td>
<td>Portheadland</td>
<td>Hohhot</td>
</tr>
<tr>
<td>Performance ratio</td>
<td>0.69</td>
<td>0.73</td>
<td>0.70</td>
<td>0.70</td>
<td>0.73</td>
<td>0.70</td>
<td>0.78</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>30.2°C</td>
<td>19.2</td>
<td>18.9</td>
<td>26.9</td>
<td>18.4</td>
<td>26.1</td>
<td>5.8</td>
</tr>
<tr>
<td>In-plane irradiation</td>
<td>Global</td>
<td>2688</td>
<td>2042</td>
<td>1943</td>
<td>2173</td>
<td>1998</td>
<td>2345</td>
</tr>
<tr>
<td>Tilt angle=10°</td>
<td>2750</td>
<td>2159</td>
<td>2042</td>
<td>2301</td>
<td>2100</td>
<td>2418</td>
<td>1848</td>
</tr>
<tr>
<td>Tilt angle=20°</td>
<td>2769</td>
<td>2235</td>
<td>2104</td>
<td>2381</td>
<td>2170</td>
<td>2451</td>
<td>1958</td>
</tr>
<tr>
<td>Tilt angle=30°</td>
<td>2721</td>
<td>2254</td>
<td>2115</td>
<td>2407</td>
<td>2184</td>
<td>2422</td>
<td>2020</td>
</tr>
<tr>
<td>Tilt angle=40°</td>
<td>2604</td>
<td>2221</td>
<td>2075</td>
<td>2374</td>
<td>2148</td>
<td>2334</td>
<td>2031</td>
</tr>
<tr>
<td>[kWh·m⁻²·yr⁻¹]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
temperature, degradation, load matching factor, efficiency factor, inverter officiating and so on.

Figure 1 is thematic circuit diagram of 100 MW VLS-PV system. 200 500 kW units, 208 6.6kV circuit breaker, 5 30 MVA transformer, 18 110kV GIS, 10 110kV disconnecting SW, 2 SVC (Static Var Compensator) and common power board are installed in 100 MW unit Table 3 is shown detail information. Table 2 shows assumptions of efficiency.

Figure 1. Thematic circuit diagram of 100 MW VLS-PV

Table 2. Assumptions of efficiency

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>110kV/6.6kV transformer</td>
<td>99.21</td>
</tr>
<tr>
<td>SVC (Static Var Compensator)</td>
<td>99.5</td>
</tr>
<tr>
<td>Power factor</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 3. System required materials (30° tilt angle case)

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Sahara</th>
<th>Gobi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material requirement</td>
<td>piece</td>
<td>848,500</td>
<td>848,500</td>
</tr>
<tr>
<td>Capacity</td>
<td>MW</td>
<td>101.8</td>
<td>101.8</td>
</tr>
<tr>
<td>Array support structure</td>
<td>ton</td>
<td>9,755</td>
<td>9,755</td>
</tr>
<tr>
<td>Foundation</td>
<td>m³</td>
<td>59,578</td>
<td>59,578</td>
</tr>
<tr>
<td>Cable</td>
<td>km</td>
<td>1,434</td>
<td>1,434</td>
</tr>
<tr>
<td>600 V CV 2 mm²</td>
<td>km</td>
<td>173</td>
<td>173</td>
</tr>
<tr>
<td>600 V CV 8 mm² double core</td>
<td>km</td>
<td>87</td>
<td>109</td>
</tr>
<tr>
<td>6,6 kV CV-T 22 mm²</td>
<td>km</td>
<td>27</td>
<td>33</td>
</tr>
<tr>
<td>6,6 kV CV 200 mm²</td>
<td>km</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>110 kV CV 150 mm²</td>
<td>km</td>
<td>26</td>
<td>29</td>
</tr>
<tr>
<td>Trough</td>
<td>m³</td>
<td>32,000</td>
<td>34,000</td>
</tr>
<tr>
<td>Common apparatus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inverter (with transformer)</td>
<td>set</td>
<td>202</td>
<td>202</td>
</tr>
<tr>
<td>6,6 kV circuit breaker</td>
<td>set</td>
<td>208</td>
<td>208</td>
</tr>
<tr>
<td>110 kV/6.6kV transformer</td>
<td>set</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>110 kV disconnecting SW</td>
<td>set</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>110 kV GIS</td>
<td>set</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>SVC</td>
<td>set</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Common power board</td>
<td>set</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy oil consumption</td>
<td>ton</td>
<td>148</td>
<td>150</td>
</tr>
<tr>
<td>Transmission</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Transmission line

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Unit</th>
<th>Sahara</th>
<th>Gobi</th>
</tr>
</thead>
<tbody>
<tr>
<td>110 kV TACSR 410 mm²</td>
<td>km</td>
<td>1,202</td>
<td>1,202</td>
</tr>
<tr>
<td>AC 70 mm²</td>
<td>km</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Pylon (steel)*</td>
<td>ton</td>
<td>7,348</td>
<td>7,348</td>
</tr>
<tr>
<td>Foundation*</td>
<td>ton</td>
<td>16,977</td>
<td>16,977</td>
</tr>
<tr>
<td>Construction*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel oil consumption</td>
<td>kl</td>
<td>167</td>
<td>212</td>
</tr>
<tr>
<td>Labour requirement</td>
<td>Man-yr.</td>
<td>2,300</td>
<td>3,700</td>
</tr>
</tbody>
</table>

*Transmission is assumed 330 MW capacity. One third data is used for calculating cost.

**APPROACH**

Irradiation and power current

Basically, transmission loss is calculated by equation (1). In case of photovoltaic system, irradiation is changing in a day time, so power current is also changing. And so, we assume power current is in proportion to irradiance and we estimate power current from irradiation data. There are strong and low irradiation in a day time such as noon and morning. Because of transmission loss is calculated by equation (1), average of a day is not suitable, but RMS (root-mean-square) should be applied. And differences of monthly averages are also considered. In case of desert area, it is difficult to get the detail data. So, dairy irradiation curve is calculated by Berlage model from monthly average irradiation data of Japan whether association (JWA).

Transmission loss = \( I^2 \cdot R \) \[\text{(1)}\]

For calculating transmission losses, we follow these steps below.

1. Calculate dairy irradiation curve for 12 months by Berlage model [3] (equation (2)), which is for making theoretical clear day’s curve.

\[
E_{gh} = \tau \cdot I_{\text{on}} \cdot \cos \theta_z + 0.5 \left(1 - \tau \cdot I_{\text{on}} \cdot \cos \theta_z\right) \left(1 - 1.4 \ln(t)\right) \text{[equation (2)]}
\]

\( H_{gh} \) : Global horizontal irradiance [kW/m²]
\( \tau \) : Atmospheric transmissivity
\( AM \) : Air mass
\( \theta_z \) : Zenith angle [deg]
\( I_{\text{on}} \) : Direct component of horizontal irradiance (AM=0) [kW/m²]

2. Divide sunny day and cloudy day of monthly day’s irradiation by Rate of sunshine. Sunny day’s curve is assumed same as theoretical curve. Cloudy day’s curve is assumed condensed curve of Berlage model, and total irradiation in the month is same as original. So, average irradiation from JWA and calculated irradiation by RMS are different. For the detail calculations, in-plain irradiations are also calculated by rb model, Hey model and isotropic model.

\[
G_{avg} \approx \frac{G_s^2 \times 31 \times r + G_c^2 \times 31 \times (1 - r)}{31} = \sqrt{G_s^2 r + G_c^2 (1 - r)} = G_{avg} \text{[equation (3)]}
\]
3. Calculate RMS of day’s irradiation from RMS of each month. This is final of calculating RMS.

\[
\text{RMS of monthly day irradiation} = \sqrt{G_{\text{ave1}}^2 \times 31 + G_{\text{ave2}}^2 \times 28.25 + G_{\text{ave3}}^2 \times 31 + \Lambda + G_{\text{ave12}}^2 \times 31}\]

\[
= \frac{365.25}{31} \quad \text{........(4)}
\]

4. Calculate a day’s curve from Berlage model and scale up it to be same irradiation as RMS which is calculated in section 3.

5. Finally, each cable loses and transmission losses of VLS-PV system are calculated.

**Resistances of cable and transmission line**

The VLS-PV systems installed in desert area are assumed. In kind of hot Sahara area and cold Gobi area, temperature characteristics of resistances of cable and transmission line should be considered. Basic resistances of electric cable/line are referred from Fujikura electric wire manual [4].

1. Calculate daily average irradiance by using above method. And calculate current of the irradiance.

2. Estimate rise in temperature when sending the current. Equation (5) is used for calculating permissible current. It is assumed that transmission loss is same as heat dissipation because of convection and wind.

\[
I^2 R = \pi dlK_t \quad \text{........(5)}
\]

Where:
- \(I\) : Permitted current [A]
- \(d\) : Outside diameter [cm]
- \(l\) : Length of transmission line [cm]
- \(K\) : Ratio of heat dissipation [W/({°C} \cdot \text{cm}^2)]
- \(t\) : Rise in temperature [°C]
- \(R\) : Resistance of final temp. and length / [Ω]

\[
K = \left( h_r \frac{W}{\pi t} \right) + h_w \quad \text{........(6)}
\]

Where:
- \(W\) : Irradiance [W/cm²]
- \(\eta\) : Radiative coefficient of full black
- \(h_r\) : Ratio of heat dissipation by heat emission

\[
h_r = 0.000567 \left( \frac{273 + T + t}{100} \right)^4 - \left( \frac{273 + T}{100} \right)^4 \quad \text{........(7)}
\]

\[
h_w = 0.00572 \left( \frac{273 + T + \frac{t}{2}}{0.125 \pi \sqrt{d}} \right) \quad \text{........(8)}
\]

Where:
- \(T\) : Ambient temp. [°C]
- \(v\) : Wind speed [m/s]

3. Ambient temperature is assumed to be average ambient temperature plus 10 [°C]. Because it is day time, when system is generating.

4. Considering permitted current, 200 MW per line is assumed.

5. Calculate resistance by using the ambient temperature and rise in temperature. This resistance is used for estimation of cable loss and transmission loss.

**Cable loss and transmission loss**

Cable and transmission resistance are calculated above method. Equation (9) is applied for calculating for short distance. Equation (10) is suitable for estimating long distance transmission loss. It is considering charging current of transmission line.

\[
P_L = 3I^2Rl \quad \text{.........(9)}
\]

\[
P_L : \text{Total resistance of 3 phase 3line} \quad \text{[W]}
\]

\[
I : \text{Power current} \quad \text{[A]}
\]

\[
R : \text{Resistance of line} \quad \text{[Ω/km]}
\]

\[
l : \text{Length of transmission line} \quad \text{[km]}
\]

\[
P_L = 3RI^2(1 - I_c \cos \phi + \frac{1}{3} I_c^2) \quad \text{.........(10)}
\]

\[
I_{c} : \text{Charging current at sending end} \quad \text{[A]}
\]

\[
\cos \phi : \text{Power factor (assumed to be 0.9)}
\]

\[
I_c = 2\pi CIE \times 10^{-6} \quad \text{.........(11)}
\]

\[
C : \text{Electric capacity of one line} \quad \text{[µF/km]}
\]

\[
f : \text{Frequency} \quad \text{[Hz]}
\]

\[
E : \text{Voltage at sending end} \quad \text{[V]}
\]

\[
C = \frac{0.02413}{\log_{10} D_{rz}} \quad \text{.........(12)}
\]

Where:
- \(\cos \phi\) is power factor and 0.9 is assumed; \(E\) is voltage at sending end, it is calculated by line voltage times \(1/\sqrt{3}\); Equation (12) is assumed 3 phase 2 channels with earth wire; \(D_{rz}\) is distance of two lines when lines are fully coordinated.

**RESULTS**

Figure 2 shows annual average day’s losses curve which is estimated by above three steps, which are considering RMS of power current, resistance considered rise temperature, and cable and transmission loss. Transmission loss is considered charging current. Transmission loss is first majority of losses, and half part of total losses.
Cable and transmission losses in the other deserts are shown in Figure 3. Strong irradiation and high temperature causes big loss in Nema in Sahara desert. Loss ratio in Nema is obtained 8.2% which is the highest in six deserts as shown in Table 4. And it is obtained lowest cable and transmission losses in Gobi desert in China. It is 5.8% of power generation.

Sensitivity analysis

Transmission loss is depends on residence of transmission line. TACSR 240sq and 680sq are also estimated transmission loss as shown in Figure 4.

Transmission loss of TACSR 680sq in Nema in Sahara is 60% of TACSR 410sq. The reduction is 1.4% of generation power. But in case of Gobi desert, the reduction is 0.9%. Transmission line should be considered area where VLS-PV system is installed.

CONCLUSION

Transmission and each cable losses are obtained. First majority is power transmission line. It is much larger than other cable losses. A VLS-PV system in Sahara desert generates big power, but losses become big. It is about 13 GWh/year and 8.2% of inverter output, (Annual power generation is 194 GWh/year with 30° tilt angle). In Gobi desert case, a VLS-PV system generates 160 GWh/year, which is lowest in six deserts. But transmission loss is also lowest, which is 7 GWh/year and 5.8%. In other words, Gobi desert is effective area.

Transmission loss is high in strong irradiation area, and low in not so strong irradiation area. A power generation decrease about 5-8% by 100 km TACSR/AC 410sq transmission, cable, transformer and SVC. If power transmission line is changed to TACSR/AC 680 sq, transmission loss becomes 60%. But its effect is different in areas. However, analysis of power losses will help to preliminary survey of VLS-PV systems in desert areas.

REFERENCES