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

Masakazu Ito[1], Kazuhiko Kato[2], Keiichi Komoto[3], Tetsuo Kichimi[4], Kosuke Kurokawa[1]

1 Tokyo University of Agriculture and Technology (TUAT), 2-24-16 Naka-cho, Koganei, Tokyo, 184-8588, Japan,
Tel/Fax: +81-42-388-7445, E-mail: itomasa@cc.tuat.ac.jp
2 National Institute of Advanced Industrial Science and Technology (AIST),
Tsukuba Central 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8568, Japan
3 Fuji Research Institute Corp. (FRIC), 2-3 Nishiki-cho, Kanda, Chiyoda-ku, Tokyo, Japan
4 Resources Total System (RTS), Shinkawa, Chuo-ku, Tokyo, 104-0033, Japan

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.

100 km transmission loss is 8.2 % in Sahara and 5.8 % in Gobi desert. 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. If 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 1. Geographic information for world deserts

Desert		Sahara	Sahara	Negev	Thar	Sonoran	Great Sandy	Gobi
Location		Nema 16°N 7°W	Ouarzazate 31°N 6°W	Bet dagan 32°N 34°E	Jodhpur 26°N 73°E	Chihuahuan 28°N 106°W	Port headland 20°S 118°E	Hoh hot 40°N 111°E
Performance ratio		0.69	0.73	0.73	0.70	0.73	0.70	0.78
Ambient temperature		30.2 [°C]	19.2	18.9	26.9	18.4	26.1	5.8
In-plane irradiation	Global	2688	2042	1943	2173	1998	2345	1702
	Tilt angle=10°	2750	2159	2042	2301	2100	2418	1848
	Tilt angle=20°	2769	2235	2104	2381	2170	2451	1958
	Tilt angle=30°	2721	2254	2115	2407	2184	2422	2020
	Tilt angle=40°	2604	2221	2075	2374	2148	2334	2031
								[kWh·m^{-2}·yr^{-1}]

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.
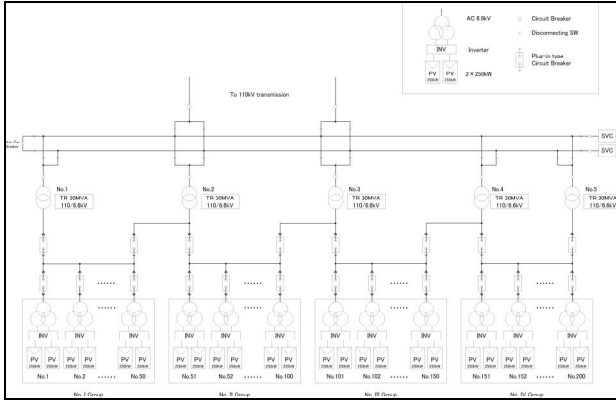

Figure 1. Thematic circuit diagram of 100 MW VLS-PV

Table 2. Assumptions of efficiency

Equipment	Efficiency [%]
110kV/6.6kV transformer	99.21
SVC (Static Var Compensator)	99.5
Power factor	90

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

Item	Unit	Sahara	Gobi
Material requirement			
PV module	piece	848,500	848,500
Capacity	MW	101.8	101.8
Array support structure	ton	9,755	9,755
Foundation	m^3	59,578	59,578
Cable			
600 V CV 2 mm^2	km	1,434	1,434
600 V CV 8 mm2 double core	km	173	173
600 V CV 60 mm^2	km	87	109
6,6 kV CV-T 22 mm^2	km	27	33
6,6 kV CV 200 mm^2	km	38	38
110 kV CV 150 mm^2	km	26	29
Trough	m^3	32,000	34,000
Common apparatus			
Inverter (with transformer)	set	202	202
6,6 kV circuit breaker	set	208	208
110 kV/6.6kV transformer	set	5	5
110 kV disconnecting SW	set	18	18
110 kV GIS	set	10	10
SVC	set	2	2
Common power board	set	1	1
Transportation			
Heavy oil consumption	ton	148	150
Transmission			
Transmission line 110 kV TACSR 410 mm^2	km	1,202	1,202
AC 70 mm^2	km	100	100
Pylon (steel)*	ton	7,348	7,348
Foundation*	ton	16,977	16,977
Construction*			
Diesel oil consumption	kl	167	212
Labour requirement	Man-yr.	2,300	3,700

*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).

$$\text{Transmission loss} = I^2 \bullet R \qquad \text{............ (1)}$$

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.

$$E_{gth} = t^{AM} \bullet I_{on} \cos q_z + 0.5 \frac{(1 - t^{AM}) \bullet I_{on} \bullet \cos q_z}{1 - 1.4 \ln(t)} \quad \text{........(2)}$$

H_{gth} : Global horizontal irradiance [kW/m^2]

t   : Atmospheric transmissivity

AM : Air mass

q_z : Zenith angle [deg]

I_{on} : Direct component of horizontal irradiance (AM=0) [kW/m^2]

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.

$$\sqrt{\frac{G_s^2 \times 31 \times r + G_c^2 \times 31 \times (1-r)}{31}} = \sqrt{Gs^2 r + Gc^2 (1-r)} = G_{ave1}$$

$$\text{............ (3)}$$

G_s : Sunny day's irradiation [kWh/day]

G_c : Cloudy day's irradiation [kWh/day]

$G_{ave\,n}$: RMS of monthly irradiation [kWh/day]

r : Rate of sunshine

n : Number of month

3. Calculate RMS of day's irradiation from RMS of each month. This is final of calculating RMS.

RMS of monthly day's irradiation=

$$\sqrt{\frac{G_{ave\,1}^{2} \times 31 + G_{ave\,2}^{2} \times 28.25 + G_{ave\,3}^{2} \times 31 + \Lambda + G_{ave\,12}^{2} \times 31}{365.25}}$$

.... (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 losses 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.

$$I^{2}R = \rho dlKt$$ .... (5)

I : Permitted current [A]

d : Outside diameter [cm]

l : Length of transmission line [cm]

K : Ratio of heat dissipation [W/(°C·cm²)]

t : Rise in temperature [°C]

R : Resistance of final temp. and length l [Ω]

$$K = \left(h_r - \frac{W}{\rho t}\right)h + h_w$$ .... (6)

W : Irradiance [W/cm²]

h : Radiative coefficient of full black

h_r : Ratio of heat dissipation by heat emission

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

$$h_w = \frac{0.00572}{\left(273 + T + \frac{t}{2}\right)^{0.123}} \bullet \sqrt{\frac{v}{d}}$$ .... (8)

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.

$$P_L = 3I^2 Rl$$ .... (9)

P_L : Total resistance of 3 phase 3line [W]

I : Power current [A]

R : Resistance of line [Ω/km]

l : Length of transmission line [km]

$$P_L = 3Rl(I^2 - II_C \cos f + \frac{1}{3}I_C^2)$$ .... (10)

I_C : Charging current at sending end [A]

$\cos f$: Power factor (assumed to be 0.9)

$$I_C = 2\pi f C l E \times 10^{-6}$$ .... (11)

C : Electric capacity of one line [μF/km]

f : Frequency [Hz]

E : Voltage at sending end [V]

$$C = \frac{0.02413}{\log_{10}\dfrac{D_e}{r}}$$ .... (12)

D_e : Distance of two lines

Where: $\cos f$ 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_e 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.
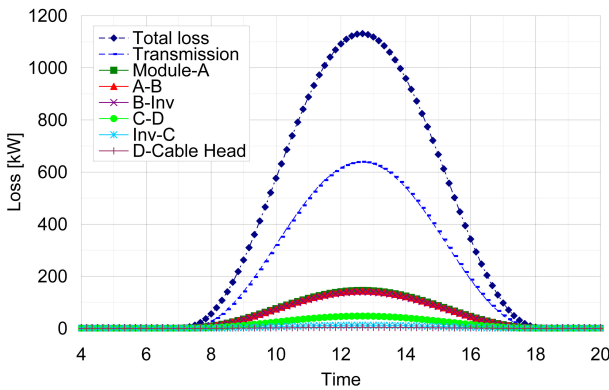

Figure 2. Estimated day's cable and transmission losses curve in annual average with 30° tilt angle in Sahara desert
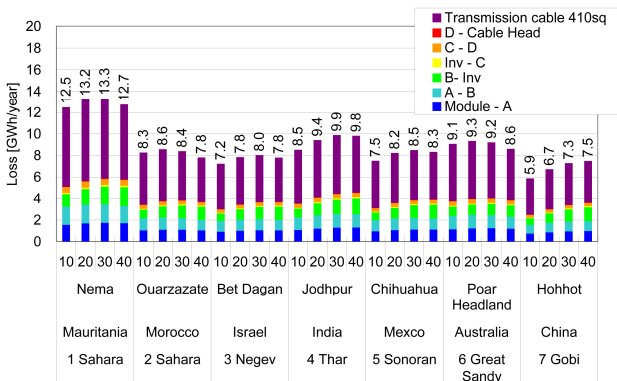

Figure 3. Cable and transmission losses in world desert

Table 4. losses ratio in six deserts with 30° tilt angle structure

	Correcto r loss* [GWh/y]	Transmi ssion loss [GWh/y]	Power Generat ion [GWh/y]	Loss ratio**
Sahara (Mauritania)	5.9	7.5	194	8.2
Sahara (Morocco)	3.8	4.6	166	6.3
Negev (Israel)	3.7	4.4	156	6.4
Thar (India)	4.4	5.4	170	7.1
Sonoran (Mexco)	3.9	4.6	162	6.5
Great Sandy (Australia)	4.0	5.2	175	6.5
Gobi (China)	3.4	3.9	160	5.8

* Corrector loss is including cable loss but transformer and SVC loss
** Including efficiency of transformer and SVC

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.
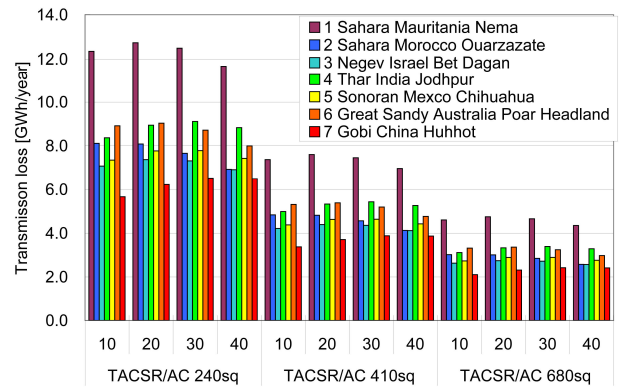

Figure 4. Transmission losses of TACSR 240sq, 410sq and 680sq

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.

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