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Temperature Effects on DC Cable Voltage Drop in Utility Scale Rooftop Solar PV Plant Based on Empirical Model

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Abstract

This paper discusses the effect of losses occurred due to rise in temperature in determining the optimal capacity of DC cable for a Solar Photovoltaic (PV) system application. An optimization is considered to address the existing trade-off between cost of losses due to the voltage drop and its investment cost. The main outcome of the model is the optimal DC cable capacity for a given PV system, as well as the relevant optimal DC cable sizing with respect to voltage drop. An experimental result of 250 kW Solar PV system installed at a latitude of 23.0290 N and longitude of 72.5770E is used to determine the effect of temperature rise on voltage drop of dc cable at outdoor conditions. This paper presents an empirical model to determine the effect of voltage drop by temperature through experimental data. In this work a focus is made on th effect of temperature on DC cable and its solution towards performance guarantee as well as improvement in generation forecasting. This study is carried out to find on site dc voltage prediction with minimum error and provides prediction based on empirical formula. The model results reveal that, by installing the dc cable in outdoor conditions of semi-arid placeslike Gujarat, and other arid regions, where average ambient temperature is about 30°C- 35°C and in summer maximum is above 40°C and there is an increment in voltage drop of about 12 to 18 % with respect to standard test condition. By choosing the proper cable size we can save 2400 kWh to 5400 kWh annually which reduces annually 1200kg to 3000 Kg Co2 and 300Kg to 700 Kg coal could be prevented annually. With optimal design of DC cable we can reduced the cable loss below 1 % which is at par and it generates 1.8 to 2.4 times more revenue.

Keywords—DC cable, losses, PV system, Rooftop, voltage drop, Temperature, Resistance.

INTRODUCTION

To meet the ever-increasing energy needs, it necessary to seek new and renewable energy sources as an alternative to fossil fuels considering environmental, social and economic factors. Recently, exhaustible fossil fuels are gradually replaced by renewable energy sources [1]. The most important feature of renewable energy sources is that they are permanent in nature. As renewable energy technologies have no negative effect on the environment, the interest in this energy sources has increased day by day.

Today, the production of electricity from renewable energy sources has gained even more importance. There are a number of advantages of solar energy over other types energy sources. One of the techniques for producing electrical energy from solar energy is the usage of photovoltaic (PV) systems. Electricity generation from PV systems is increasing every day. Environmental factors like solar radiation level, weather Conditions etc. and losses arise from the incorrect installation, which will affect the efficiency of PV systems have led to a reduction of the total energy efficiency. Hence, elements of PV system must be designed carefully in the installation stage to minimize system losses and maximize output energy. Measuring and

analyzing of the those losses due to dust, dirt, shading, inverters and cables used in the PV systems are of great importance. Detection of components, which cause the losses and be possible to correct technologically will increase the efficiency of the system by working in this area. Especially, the solar cables are needed to investigate and perform serious studies to show the direction to researchers working in this field. DC cables are integral part of any PV system or plant which must be taken with greater concern than the AC cables, as issues around their usage are still not understood very well unlike AC cables, which are used extensively across the power sector. Moreover, intense commercial pressure is forcing project developers and contractors to reduce capital cost resulting in the selection of inferior products and/or sub-optimal design. Losses in cables both cause a loss of energy in PV systems and also negatively affect the economic cost of the system[2]. The estimated system losses are all the losses in the system, which cause the power actually delivered to the electricity grid to be lower than the power produced by the PV modules. It is necessary to minimize the losses by eliminating the factors that cause the losses occurred in PV systems to get high energy yield. Factors that may cause losses in PV systems are environmental factors such as shade, dust, snow, rain, temperature and losses due to system components such as cables, inverters and batteries. PV systems should be installed taking into account the losses and the produced energy should be consumed in local areas where it was produced as much as possible. The power loss can vary between 10% to 70%. About 24%-25% of the produced energy by the PV system is lost due to some system losses as shown in the

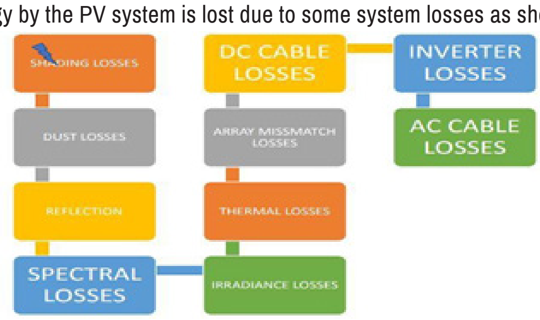

figure1[1-2].

Figure 1: PV system losses

In this study, it is aimed to give an idea to the scientists and companies working in this area of SPV power plant development by examining effects of solar cables on the whole PV system output which are generally selected by rough computations without considering both system efficiency with the effect of temperature and total system cost. This paper also aims to investigate the optimal solar DC cable capacity by trading off the investment cost against the cost of cable losses over the operational life-span of the asset. Therefore, an optimal trade-off between the cost of losses and the investment cost can be sought within a Life Cycle Assessment (LCA) framework [5,7].The following sections of this paper present the methodology and the relevant case study applications that illustrate the prominent role of losses in determining the optimal cable rating for Solar PV application[5].

METHODOLOGY

A. DC Cable optimization

DC cables are used in solar power plant between modules to combiner box and combiner box to inverter. So dc cables are one of the important parts of solar system and BOS. There are many losses occurred in pv plant but here we have focused on dc cable losses.

There are two types of DC cable used in the SPV plant

[1] String DC cable

[2] Main DC cable

[1] String DC cable

String dc cables are used to interconnect solar modules and to connect modules with string combiner boxes or an array combiner box. Cables for interconnecting modules come pre- connected with modules, whereas the cables required to interconnect strings and to connect with combiner boxes are procured separately. String DC cables carry current of only around 10 Ampere (A) and a small cross section (2.5 mm2 to 10 mm2) is sufficient for this purpose[6].

[2] Main DC cable

These cables are used to connect array combiner boxes with inverters. These cables carry higher current of around 200- 600 A in utility scale projects and require a larger cross section (95 mm2 to 400 mm2). DC cables, except for those pre- connected with modules, account for only around 2 per cent of solar project cost, but can have a significant impact on the power output. Improper design and/or poor cable selection can lead to safety hazards, reduced power output, and other performance issues[6].

Power output loss in DC cables can be as high as15 per cent but it is time consuming and arduous to empirically isolate and quantify the role of DC cables in poor performance. Further, a higher voltage drop typically leads to heating up of cables and fire accidents. Power loss in DC cables is measured in terms of voltage drop from module to inverter. As current in the cables remains the same, voltage drop implies proportionate loss of power[5-6].

B. DC Voltage Drop Calculation at STC condition

Voltage drop depends on various factors like Length of cable, cross-sectional area of cable, system current, and voltage of the system. According to change in above parameters results in change in voltage drop.

Standard Equation for the voltage drop is[3-5],

$$V_d = \frac{2*I*R*L}{V_m * No.of\ solar\ panels\ in\ string} * 100 \qquad (1)$$

Where,

V_d = Voltage Drop

I = Current of the string

R = Resistance of the cable for given cross sectional area

L = length of the cable

Vm = maximum voltage of the panels in STC condition

We can get the data of resistance from the cable manufacture accordingly, at the same length and same temperature, cable cross section area and resistance is inversely proportional. For low cross section area there is high resistance and for high cross sections are there is low resistance which is shown in Table 1. The relevant electrical data is retrieved from manufacturer datasheet and the associated solar cable price is obtained from solar cable manufacturer in India.

Table 1 Solar Cable Technical and Commercial data

Cable Size, mm²	Ampacity, A	Cost, INR/km	Resistance at 20 0 c in Ω/km
2.5	41	18,000	8.21
4	55	25,000	5.09
6	70	35,000	3.39
10	98	65,000	1.95
16	132	80,000	1.21

As per the table 1 the voltage drop considered on the STC condition which is validate the equation 1 which standard equation. But in actually there is variation of temperature from 20 to 70 on site which practically result in to higher voltage drop.

C. DC Voltage Drop Calculation at Real condition

Cable temperature on site is higher than the actual condition of cable testing. The resistance of all materials changes as their temperature changes. If the temperature is lowered, resistance (typically) declines. In fact, if cooled sufficiently, the material becomes a "superconductor" with no significant resistance. Increasing the temperature (typically) increases resistance. The temperature coefficient of resistance (TCR) of wire or a resistor relates the change in resistance to the change in temperature. It is usually expressed as "parts per million per degree Centigrade" (TCR = ppm/°C.) The temperature coefficient of resistance provides, how much the resistance changes (ppm) if the temperature changes one degree Centigrade.

For the Copper wire temperature coefficient is 0.004%/Degree Centigrade. New equation with consideration of temperature effect[3-5],

⊠

$$V_d = \frac{2*I*R0*\ 1+\alpha*\ T-T0\ \ *L}{V_m * no.of\ solar\ panels\ in\ string} * 100 \qquad (2)$$

Vd = Voltage Drop

I = Generated current in string R0 = Resistance at 20 degree T = cable temperature

T0 = cable temperature at STC L = Length of the cable

Vm = Maximum voltage of the solar panels

Base on Equation no 2. we can get the appropriate or nearby cable loss and voltage drop which is actually occurred site and result in to higher losses compared to theoretically consideration during the design of the Solar PV system.

There is a change in resistance with increment in temperature for the cable at 40 degree. The equation for the resistance with temperature effect shown below[3-5],

$R = R_0 *(1 + a*T - T_0\ )$

Where,

R_0 = Resistance at standard temperature ⊠= Temperature co-efficient of copper T = Cable temperature

T_0 = Standard temperature

Table 2 Comparison of the resistance of the cable at various temperatures

Cable Size (mm²)	Resistance(Ω/ km) 20 0 C	Resistance (Ω/ km) 40 0 C	Difference in Resistance
2.5	8.21	9.69	1.48
4	5.09	6.01	0.95
6	3.35	3.95	0.60
10	1.95	2.30	0.35
16	1.24	1.46	0.22

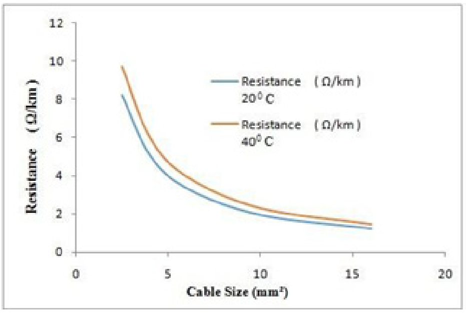

Figure 2. Comparison of the resistance of the cable at 20 0C and 40 0C.

From Table 1 and figure we can see the difference in the resistance at 20 0 C and 40 0 C. It is observed that there is increment in the cable resistance with increment temperature which directly leads to the cable loss.

RESULT AND DISCUSSION

There is an increase in voltage drop with increase in temperature as shown in the data and one can find outthe difference between STC and normal testing condition.

A. Voltage drop at different tempreture and different DC cable length for the DC cable size of 4 mm2, 6 mm2&10 mm2 diameter.

In this paper we have focused on DC cable losses occurred in utility scale Solar PV power plant which is mainly designed on 100 V DC voltage. In Utility scale solar PV plant considering from Solar PV Module cable to Inverter string cable generally 4 mm2, 6 mm2 and 10 mm2 size of cables commonly used. Apart from temperature Voltage drop is also depends on length of the cable. We have calculated the voltage drop at different lengths varies from 20 meter to 200 meter with respect to different temperature range between 200C STC to maximum field cable temperature 700C for the DC cable size of 4 mm2, 6 mm2&10 mm2 diameter.

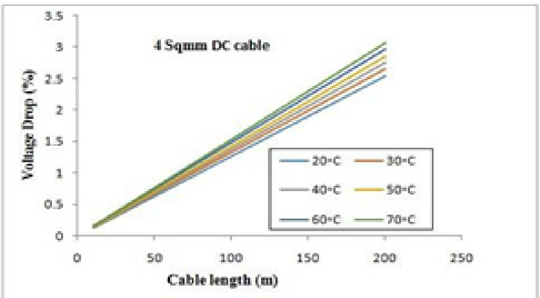

Figure 3 .4 mm2 Voltage drop at Different cable length

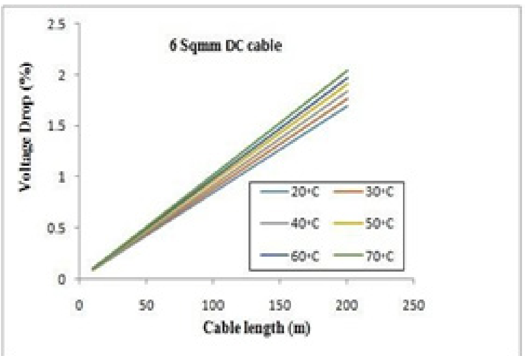

Figure 4. 6 mm2 Voltage drop at Different cable length

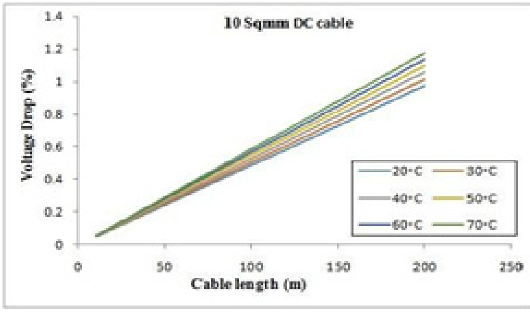

Figure 5. 10 mm2 Voltage drop at Different cable length

In Figure 3,4 and 5 shows the graph of Voltage drop at cable length between 20 meter to 200 meter calculated at 200C to 700C for the DC cable size of 4 mm2, 6 mm2 & 10 mm2 diameter. Results shows that If we increase the DC cable length from 20 meter to 200 meter then there will be increment in voltage drop will be 10 times. For the DC cable size of 4 mm2 , 6 mm2 and 10 mm2 an average voltage drop up to the size of 200 meter is, 1.33 %, 0.9 % and 0.51 % respectively at 200C and 1.61%, 1.1 % and 0.61 % respectively. We can say that by using 6 mm2 instead of 4 mm2 we can reduce 0.4 % to 0.5% loss similarly for 10 mm2 there is reduction of 0.8 % to 1.0 % loss compare to 4 mm2 DC cable and 0.4 % to 0.5% loss compare to 6 mm2 DC cable.

A. 4 mm2, 6 mm2 and 10 mm2 Average DC cable Voltage drop at 450C temperature for different length.

To validate the equation 2 as well as the practical onsite data, we have considered the data at the average cable temperature throughout the year which is 450C. According to this data, For the DC cable size of 4 mm2 voltage drop for 20 meter is

0.28 % and 2.1 % for 200 meter and an average voltage drop up to the size of 200 meter is 1.47 %. For the DC cable size of 6 mm2 voltage drop for 20 meter is 0.19 % and 1.88

% for 200 meter and an average voltage drop up to the size of 200 meter is 0.98 % which is 0.5% lower than 4 mm2. For the DC cable size of 10 mm2 voltage drop for 20 meter is

0.11 % and 1.09 % for 200 meter and an average voltage drop up to the size of 200 meter is 0.56 % which is 0.5% lower than 6 mm2 and 0.9 % lower than 10 mm2 DC cable.

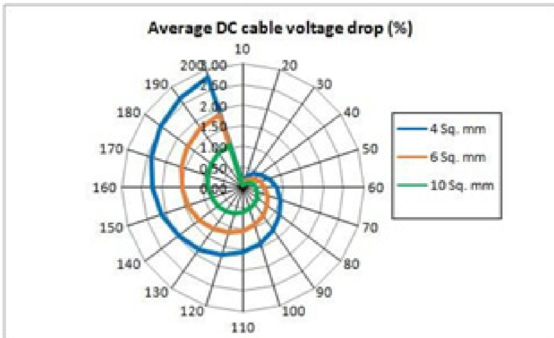

Figure 6. Average Voltage drop at 450C for different cable length

B. Example of Real Case Application/ Case study Application

An example of a 250 kW real case of utility scale Solar PV system is considered here to exemplify the effectiveness of the proposed model. In this section we have identified the cable loss and its economic effect for 4 mm2, 6 mm2 and 10 mm2 DC cable. Table 3 shows detail of Utility scale 250 kW solar PV plant which contain the 7 nos. of inverter. This plant has been set up for captive us and under net metering where FiT (Feed in Tarrif)/per unit rate is 7.5 INR/-. The analysis is carried out assuming solar cable lifespan of 25 years, consistent with the 25 years under net metering regulation of Gujarat state.

Table 3. : Solar Plant Details

Solar Plant location	Sanand GIDC, Ahmedabad, India		
Latitude & Longitude	23.0293504, 72.5778432		
Solar Project Capacity(kW)	250		
Inverter DC inputSolar capacity (kW)	35.7		
Inverter AC output capacity(kW)	33		
Solar Modulecapacity(Wp)	325		
Total Nos. ofSolar Module	769		
Nos. of. Solar module connectedin each Inverter	110		
Maximum voltageof solar panel (V)	38.8		
Maximum currentof solar panel (Amp)	8.40		
String connections(No. of module connected in series)			
1	(18+18) –Series +Parallel		
2	(18+18) –Series +Parallel		
3	(18) - Series		
4	(20) - Series		
Annual Generation(MWh)	400		
Cable length(DC)(meter)	140		
Total Cable length(meter)	3920		
Cross-sectionalarea (mm^2)	10	6	4
Cable cost permeter (INR)	65	35	25
Total cost (INR)	254800	137200	98000
Cable loss (%)	0.85	1.5	2.2
Generation loss(kWh)	3400	6000	8800
Revenue loss (cost of losses)(INR)	25500	45000	66000

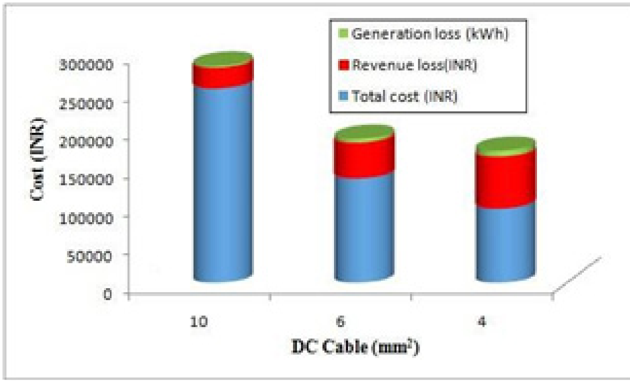

Figure 7. Overall cost of DC cable

Firstly, we have calculated the voltage drop for this condition with Equation no.(1) at STC

For string 1 and 2,

Vd= ((2*16*(1.95/1000) *140)/ (18*38.8)) *100

= 1.250859 %

For string 3

Vd = ((2*8*(1.95/1000) *140)/ (18*38.8)) *100

= 0.62543 %

For string 4

Vd = ((2*8*(1.95/1000) *140)/ (20*38.8)) *100

= 0.562887 %

Now, we have calculated voltage drop for this condition with Equation no. (2) At actual site condition

For String 1 and 2

Vd = ((2*16*(1.95*(1+(0.004041*(65-20)))/1000) *140)/ (18*38.8)) *100

= 1.48 %

For String 3

Vd = ((2*8*(1.95*(1+(0.004041*(65-20)))/1000) *140)/ (18*38.8)) *100

= 0.74 %

For String 4

Vd = ((2*8*(1.95*(1+(0.004041*(65-20)))/1000) *140)/ (20*38.8)) *100

= 0.66 %

Data obviously show that the voltage drop rises with temperature.

Table 4. Comparison of Voltage drop at STC and at Actual

String	Voltage drop at STC	Voltage drop at site condition
1	1.25	1.48
2	1.25	1.48
3	0.66	0.74
4	0.56	0.66

From table 3 it is seen that DC cable loss of 0.85%, 1.5% and 2.2% for 4 mm2, 6 mm2 & 10 mm2 diameter at 140 meter. From figure 7 it is seen that the generation loss is 3400 kWh, 6000 kWh, 8800 kWh for 4 mm2, 6 mm2 and10 mm2 DC cables, respectively. As shown in table 4. String 1 and 2 both are connected in parallel, where the string voltage and current are 700 V and 16.8 A, respectively for which a voltage drop of 1.48 % is noticed. For string 3 is with rating of 700 V and 8.4 A a voltage drop of 0.74 % and for string 4 with rating of 740 V and 8.4 A having a voltage drop of

0.66 % are observed. It shows that, Strings 1,2 and 4 have 18 % higher than actual voltage drop and 3 has 12% more voltage drop. By using 10 mm2 cable 2.4 times revenue can be saved over 4 mm2 and 1.8 times revenue can be saved over over 6 mm2 cables.

CONCLUSION

This paper presents an optimization approach to determine

the optimal sizing of DC cable in a solar PV system taking into account the total cost of cable and losses across the lifespan of the PV system. The aim is to determine the optimal size of the solar DC cable for solar PV system applications. The results of the proposed optimal model are validated against the real approach for current electricity price rates. This implies that the PV designer should consider to oversize the designed cable considerably in order to minimize the losses cost-effectively in the long run. The results suggest that cable designed from the proposed optimal model is able to satisfy both the voltage drop and thermal limits. Result shows that an average voltage drop varies 12% to 50% at different cable length. By choosing the proper cable size one can save 2400 kWh to 5400 kWh of energy generated annually which reduces annually 1200kg to 3000 Kg CO2 and subsequently 300Kg to 700 Kg coal, respectively could be prevented annually. With optimal design of DC cable one can reduce the cable loss below 1 % which is at par and it generates 1.8 to 2.4 times more revenue. As a result, when designing the solar cable, both losses and voltage drop limit will need to be considered simultaneously which leads to cost reduction of Balance of System and Levelized cost of Energy (LCOE).

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