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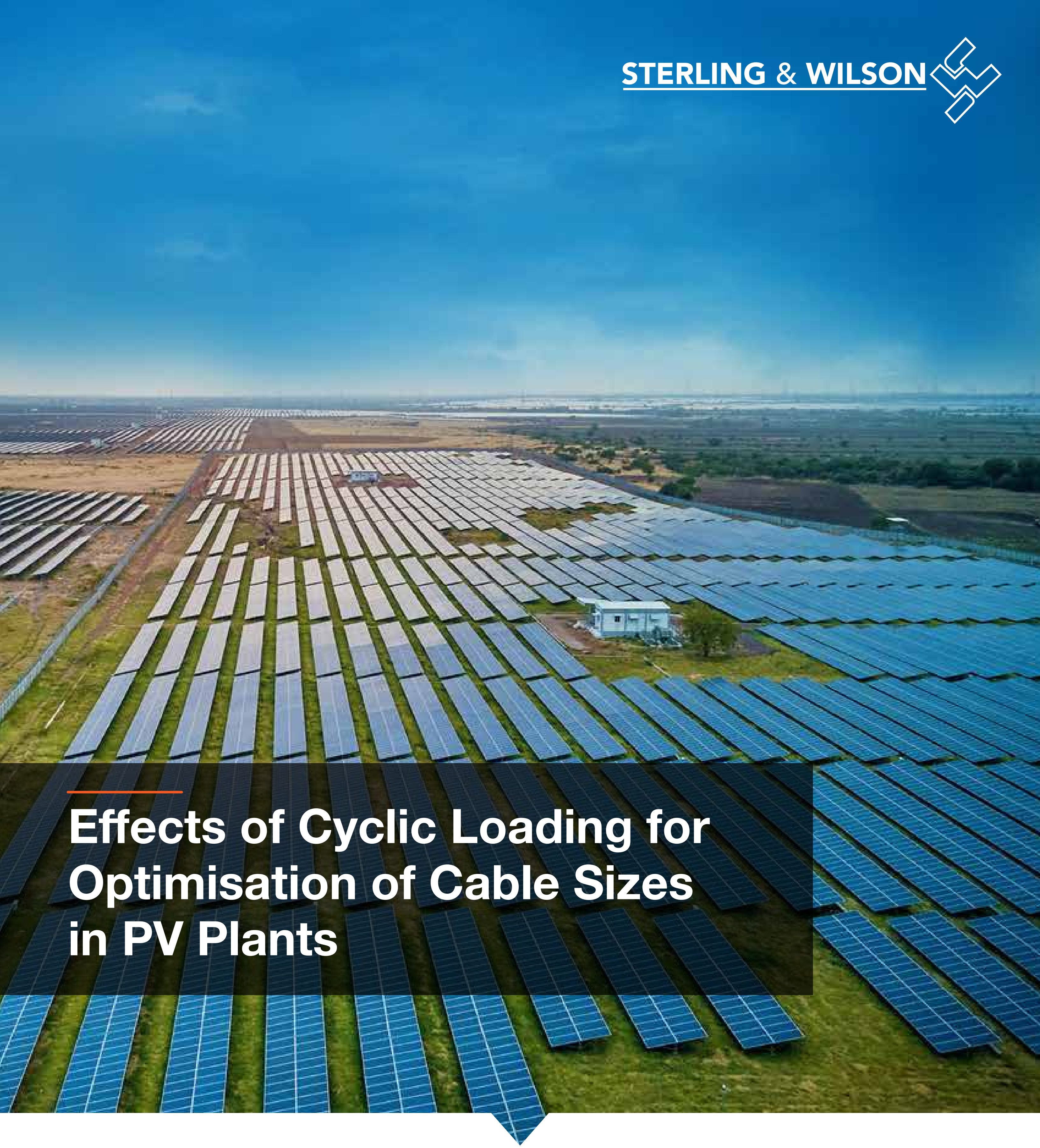

Effects of Cyclic Loading for Optimisation of Cable Sizes in PV Plants

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Abstract:

If the loading on a power cable is normally constant throughout the day, then the optimum cable size is determined based on the simple criteria that the de-rated current rating of the power cable in the service condition should be higher than the maximum load current. But how to determine the optimum cable size for a cyclic loading application? Shall the cable sizes remain same for a continuous loading condition & a cyclic loading condition having maximum load current magnitude equal to the magnitude of load current for constant loading or is it possible to further optimize the cable size for a cycling loading condition based on the load pattern?

In this paper the author intends to describe the methodology for optimization of power cable sizes for a cyclic loading condition which describes that how much the cables can be additionally loaded without the risk or causing economic damage, and to minimize the overrating capacity design for power cables in solar PV plants.

Introduction:

The generated power from a solar PV plant varies throughout the day with the variation in solar irradiation. The maximum power is usually generated around the noon time when the irradiation is maximum with the morning & afternoon time yielding lesser power due to lower irradiation. Therefore, the loading on power cables in solar PV plants are of different magnitude at different times of the day i.e. it is cyclic in nature which can be understood form the generation curve of solar plants i.e.- bell curve (refer figure-1). Normally one calculates the cable sizes in solar PV plants based on the maximum load current carried by the cable which basically corresponds to the maximum power generated by the PV plant at peak irradiance hours. But if the cyclic generating pattern of the PV plant is taken into consideration for the power cable sizing then the minimum required cable size can be further optimized, which may lead to substantial cost savings in a PV plant.

For a power cable which carries cyclic loads, the de-rated current of the cable in the service condition can be multiplied by the calculated cyclic loading factor, thereby achieving a higher value of the actual de-rated current carrying capacity of the cable. This cyclic loading factor mainly depends on the loading profile & the magnitude of the load current at different hours of the day and several other factors like the depth of laying & soil thermal resistivity etc. in case of buried cables. However, if the increased de-rated current rating of the power cable is found to be higher than the maximum load current magnitude of the cyclic loading profile then the actual final cable temperature shall never exceed the maximum permissible temperature of the cable.

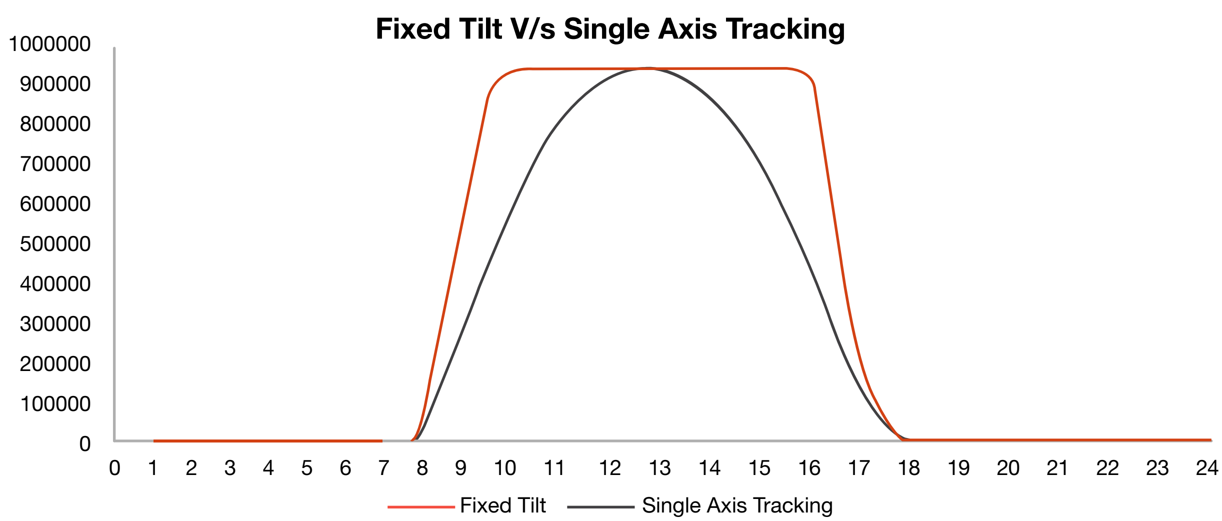


Figure – 1 (Typical generation profile of solar plants)

Bell curve generation profile can only be found in fixed solar panels or fixed type of structures used for mounting of solar panels, whereas Single-axis tracking solar panels follow the sun, so they produce a much "squarer" generation profile (refer figure-1). Overload capacity of cables is usually quantified by cyclic rating factor. Standard IEC60853-1 provides the method for calculating the cyclic rating factor for cables whose internal thermal capacitance can be neglected. Simplified method presented in this paper requires only knowledge about the shape of the load variation.

In solar power plants generation profile forecasting for PV plant can be done with the help of PV Syst. Software (Photovoltaic System Software). PV Syst. provides the hourly data of PV plant with respect to solar irradiance (GHI), site ambient temperature, Energy generation by solar array, Energy delivered to grid etc. (refer Table - 2).

PVSYST v6.47

Project	File	File date	Description
Geographical Site	ADWEA.PRI	00/00/0000h00	ADWEA
Meteo data	New.SIT	00/00/00 00h00	03/10/16 17h35
Simulation variant	Sweihan Project_SolarGIS_TMY.MET	00/00/00 00h00	Sweihan Project;United Arab Emirates:Asia
Simulation date	ADWEA.VDG	00/00/0000h00	Sweihan Project;SolarGISv2.1.2;TMY
		03/10/16 17h35	Fixed_Ingeteam_E-W_1.1776Wp

Simulation: Hourly values from 01/01/90 to 31/12/90

Date	GlobHor W/m²	T Amb	EArrMPP kW	EOutInv kW	E_Grid kW	Array A	UArray V
21-03-90 0:00	0	15	0	-40.2	-2372.5	0	0
21-03-901:00	0	14.5	0	-40.2	-2372.5	0	0
21-03-90 2:00	0	13.9	0	-40.2	-2372.5	0	0
21-03-90 3:00	0	13.4	0	-40.2	-2372.5	0	0
21-03-90 4:00	0	12.2	0	-40.2	-2372.5	0	0
21-03-90 5:00	0	10.4	0	-40.2	-2372.5	0	0
21-03-90 6:00	5.9943	10.4	0	-40.2	-2372.5	0	0
21-03-90 7:00	198	13.9	210684	208793	204777	26579p	791.73
21-03-90 8:00	441	19.1	490753	485934	477157	637336	770.44
21-03-90 9:00	662.99	21.5	721232	711997	697180	965394	747.48
21-03-9010:00	833	24.2	876945	863868	843905	1212732	723.29
21-03-9011:00	934.01	27.1	956067	942032	919574	1308515	721.31
21-03-90 12:00	965	29.4	972494	958487	935778	1308175	726.1
21-03-90 13:00	924.01	30.9	930483	915599	893706	1341052	693.69
21-03-9014:00	811.99	31.7	828432	815281	797060	1183026	700.46
21-03-9015:00	634.99	31.8	662304	652256	639224	926671	715.12
21-03-9016:00	408.01	30.6	431885	426152	418648	588600	734.12
21-03-9017:00	173.01	28.1	169954	167452	163918	228590	742.02
21-03-9018:00	25.996	24.5	22706	21279	18854	32184	702.57
21-03-9019:00	0	21.5	0	-40.2	-2372.5	0	0
21-03-90 20:00	0	20	0	-40.2	-2372.5	0	0
21-03-90 21:00	0	18.7	0	-40.2	-2372.5	0	0
21-03-90 22:00	0	17.8	0	-40.2	-2372.5	0	0
21-03-90 23:00	0	17.1	0	-40.2	-2372.5	0	0

Table– 1 (Hourly file of “Noor Abu Dhabi 1177MWp Solar PV Project at Sweihan, Abu Dhabi”)

* Table - 2 contains hourly data for 23rd march only as the maximum E-grid is forecasted on the same day in the complete year

Methodology for calculation of cyclic rating factor (M)

The cyclic rating factor is denoted by the letter M, and is that factor by which a daily cyclic current, whose maximum value is equal to the sustained (100% load factor) rated current permissible under steady-state conditions, may be multiplied for the conductor to attain, but not exceed, the standard maximum permissible temperature.

$$M = \frac{1}{\left(\sum_{i=0}^{5} Y_i \left[\frac{\theta_R\,(i+1)}{\theta_R\,(\infty)} - \frac{\theta_R\,(i)}{\theta_R\,(\infty)}\right] + \mu\left[1 - \frac{\theta_R(6)}{\theta_R(\infty)}\right]\right)^{1/2}}$$

Equation - 1.

Where,

M = Rating factor due to a cyclic variation of load current.

Yi = Coefficient proportional to the current-dependent losses in a cable between (i) and (i + 1) hours prior to the instant of highest conductor temperature.

θ_R **(i)** = Conductor temperature rise above ambient at time i hours.

θ_R **(∞)** = Conductor steady state temperature rise above ambient.

μ = Loss load factor for load current cycle under consideration.

Step -1 : Calculation of (Yi)

The daily load cycle is first expressed as 24-hourly values by scaling the whole cycle so that its maximum value is equal to unity (see Figures - 2a and 2b). The magnitude of each hourly value is then squared to give 24 values representing the cycle of cable joule losses (see Figure - 2c). The loss cycle is then decomposed into hourly rectangular pulses, each pulse magnitude being denoted by Y0, Y1 , Y2, ... Y23 (see Table 2), where Y_i is a measure of the squared current between i and (i + 1) hours prior to the expected time of the maximum conductor temperature. The magnitude of Y0 is therefore usually, but not necessarily, unity.

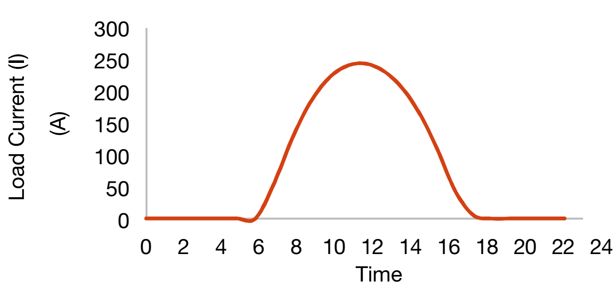


Figure – 2a (Load cycle as per hourly file)

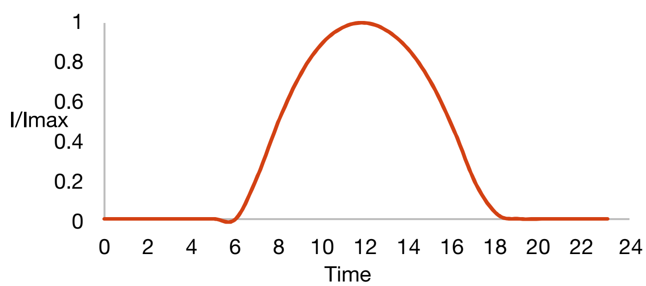


Figure – 2b (Cyclic Load divided by highest load)

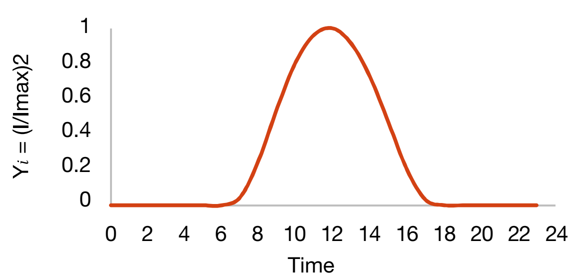


Figure – 2c Load-loss graph (Y_i)

Time (hours)	T Amb (°C)	Total PV plant Energy (21.03.2017) (kW)	Current (A)	Cyclic Load / highest load (I/Imax)	Yi = (I/Imax)2	Yi
1	14.5	0	0	0	0	Y11
2	13.9	0	0	0	0	Y10
3	13.4	0	0	0	0	Y9
4	12.2	0	0	0	0	Y8
5	10.4	0	0	0	0	Y7
6	10.4	0	0	0	0	Y6
7	13.9	204777	53.471	0.219	0.260	Y5
8	19.1	477157	124.595	0.510	0.260	Y4
9	21.5	697180	182.047	0.745	0.555	Y3
10	24.2	843905	220.360	0.902	0.813	Y2
11	27.1	919574	240.118	0.983	0.966	Y1
12	29.4	935778	244.349	1.000	1.000	Y0
13	30.9	893706	233.364	0.955	0.912	Y23
14	31.7	797060	208.127	0.852	0.725	Y22
15	31.8	639224	166.913	0.683	0.467	Y21
16	30.6	418648	109.317	0.447	0.200	Y20
17	28.1	163918	42.802	0.175	0.031	Y19
18	24.5	18854	4.923	0.020	0.000	Y18
19	21.5	0	0	0	0	Y17
20	20	0	0	0	0	Y16
21	18.7	0	0	0	0	Y15
22	17.8	0	0	0	0	Y14
23	17.1	0	0	0	0	Y13
24	15	0	0	0	0	Y12

Table – 2 Value of (Yi) and Denotation of (Y0, Y1, Y2…)

Step -2 : Calculation of (μ)

The loss load factor (μ) is given by –

$$\mu = \frac{1}{24}\sum_{i=0}^{23} Y_i$$

Equation - 2.

Step -3 : Calculation of θR(i)/ θR(∞)

$$\frac{\theta_R(i)}{\theta_R(\infty)} = 1 - k_1 + k_1\gamma(i)$$

Equation - 3.

Where,

$$k_1 = \frac{w(T_4 + \Delta T_4)}{\theta(\infty)}$$

Equation - 4.

$$T_4 = \frac{1}{2\pi}\rho_T[\ln(2u) + 2\ln(u)]$$

Equation - 5.

T4 = is the external thermal resistance of the cable. For isolated circuit of three touching cables laid in trefoil formation, equation 5 has been taken from Clause.No-2.2.4.3.1 of IEC 60287.

ΔT4 = increase in external thermal resistance of the cable under consideration due to the presence of other cables in the group

$$\Delta T_4 = \frac{\rho T \ln F}{2\pi}$$ Equation - 6.

θ(∞) = Conductor steady state temperature rise above ambient

ρT = Thermal resistivity of Soil ρT

$u = \frac{2L}{D_e}$, where L is the depth of cable laying and De is the external diameter of cable. Equation - 7.

W = Total losses of cable in w/m2 (to be defined by cable manufacturer)

Step -4 : Calculation of γ(i)

$$\Upsilon_{(i)} = \frac{-Ei\left(\frac{-D_e^2}{16t\delta}\right) + (N-1)\left\{-Ei\left(\frac{-df^2}{16t\delta}\right)\right\}}{2ln\left(\frac{4LF}{De}\right)}$$ Equation - 8.

Where,

N = Group of circuits

t = 3600 i

δ = Soil thermal diffusivity, if soil thermal resistivity is known, refer table – 3 for soil thermal diffusivity value.

Thermal resistivity (K.m/W)	Thermal diffusivity (m2/s)
0.5	0.8×10^{-6}
0.6	0.7×10^{-6}
0.7	0.6×10^{-6}
0.8	0.6×10^{-6}
0.9	0.5×10^{-6}
1.0	0.5×10^{-6}
1.2	0.4×10^{-6}
1.5	0.4×10^{-6}
2.0	0.3×10^{-6}
2.5	0.2×10^{-6}
3.0	0.2×10^{-6}

Table – 3 Value of soil thermal diffusivity

-Ei (-x) = is the exponential integral function. The exponential integral -Ei(-x) is defined in standard reference books e.g “Handbook of Mathematical Functions” by M. Abramowitz and I. Stegun.

As per IEC 60853-1, following equations to be used to define the value of exponential integral function –

For, 0 ≤ x ≤ 1

$$-\mathrm{E}i(-x) = -\ ln(x) + \sum_{i-0}^{5} \mathrm{a}_i x^i$$

Equation - 9.

Where:

a0 = -0.5772
a1 = 1.0000
a2 = -0.2499
a3 = 0.0552
a4 = -0.0098
a5 = 0.0011

For, 1 < x < ∞

$$-\mathrm{E}i(-x) = \frac{1}{xe^x}\left[\frac{x^2+a_1x+a_2}{x^2+b_1x+b_2}\right]$$

Equation - 10.

Where:

a1 = 2.3347
a2 = 0.2506
b1 = 3.3307
b2 = 1.6815

For, 1 < x < ∞

$$d_f = \frac{4L}{F^{1/(\mathrm{N}-1)}}$$

Equation - 11.

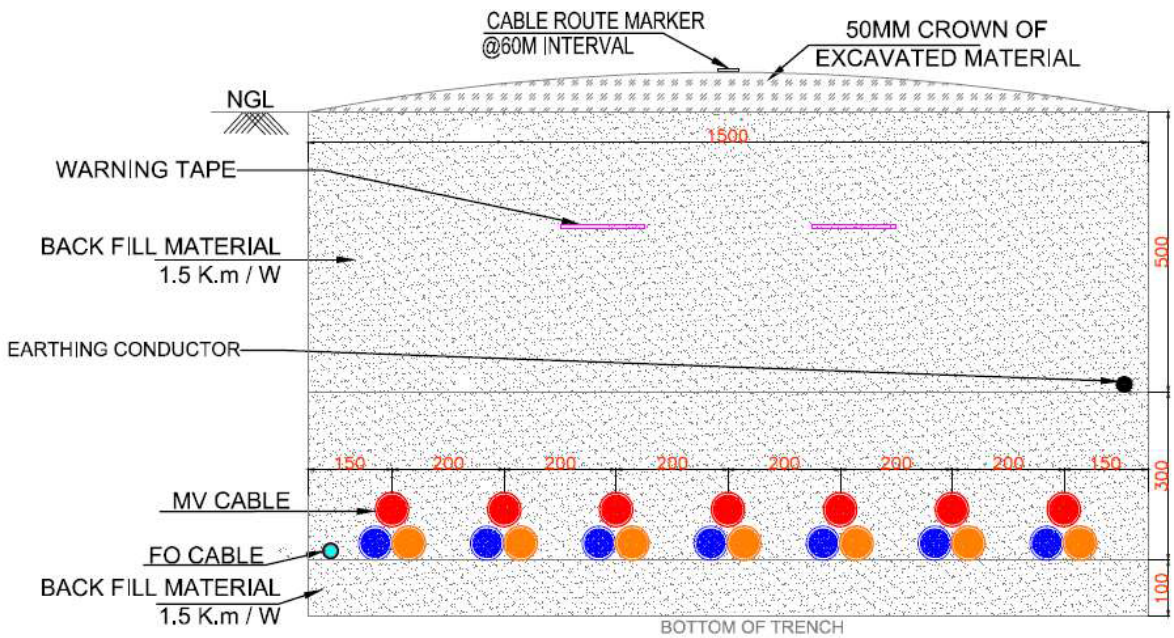
Coefficient used to express the steady state mutual heating caused by other cables in group F is given by -

$$F = \frac{\mathrm{d'}_{\mathrm{p1}} \cdot \mathrm{d'}_{\mathrm{p2}} \text{--------} \mathrm{d'}_{\mathrm{pk}} \text{--------} \mathrm{d'}_{\mathrm{p}(N-1)}}{\mathrm{d}_{\mathrm{p1}} \cdot \mathrm{d}_{\mathrm{p2}} \text{--------} \mathrm{d}_{\mathrm{pk}} \text{--------} \mathrm{d}_{\mathrm{p}(N-1)}}$$

Equation - 12.

Where,
d_{pk} = distance from the center of circuit k to center of circuit containing the hottest cable
$\mathrm{d'}_{\mathrm{pk}}$ = distance of image of center of circuit k to center of circuit containing the hottest cable.

Example: - Below mentioned example is picked up from as-built calculation for MV cable sizing (from RMU to main 33kV HT Panel) done by Sterling and Wilson for “Noor Abu Dhabi 1177MWp Solar PV Project at Sweihan, Abu Dhabi” which is the world largest single location solar power project. The calculation has been approved by owners engineer i.e.- “Fichtner, Germany”. As shown in figure –3, maximum 7 number of circuits considered in a single 1500mm wide trench (worst case), 33kV MV cable has been laid at a depth of 800mm with 200mm group spacing between the two adjacent circuits. The complete trench is filled with homogeneous soil of 1.5 K.m/W thermal resistivity value. 1Rx1Cx400Sqmm, Al, Ar. cable is considered to carry maximum load current of 244A from RMU to 33kV main HT panel. As confirmed by cable manufacturer the cable outer dia. is 55mm with total cable loss of 5.020 W/mtr. For load cycle please refer Figure -2a, 2b, 2c & Table-2.



Note: - For ease of calculation it has been assumed that the cable size selected is sufficient as per the short-circuit, voltage drop and power loss requirements.

Let us consider and analyze the following cases for cable sizing: -

Step -1: Normal calculation methodology for cable de-rated ampacity calculation as per IEC 60502-2

Normal calculation for cable sizing suggests that the cable de-rated cable ampacity (as per site conditions) shall be greater than the required load carrying capacity of the cable. Hence, K-factors need to be identified for cable deration which are defined below –

Cable de-ration factors as per actual site conditions as mentioned under IEC 60502-2 are: -
K_1 – 0.85 (Derating factor for variation in ambient ground temperature at 40deg C)
K_2 – 1 (Derating factor for variation in thermal resistivity of soil i.e.- TR value of 1.5 K.m/W)
K_3 – 1 (Derating Factor for variation in depth of laying @ 800mm)
K_4 – 0.58 (Maximum group derating factor for 7 circuits in group with 200mm group spacing)
$K_{Total} = K_1 \times K_2 \times K_3 \times K_4$

Hence, $\mathbf{K_{Total} = 0.493}$
1Cx400Sqmm, Al, Ar. cable current carrying ampacity = 470A (as confirmed by cable manufacturer)
Therefore, the de-rated cable ampacity shall be = 470 x K Total (derating factor) = 470 x 0.493 = **231.7A**

Hence, the de-rated ampacity of cable (231.7A) is lower than the required current carrying capacity of the cable (244A) As per the above case the cable size is not sufficient enough to carry the required current, because the cable needs to carry 244A maximum load current throughout the life which is the stringent condition not as per the actual load profile of the cable.

Step -2: Calculation of "M factor" as per IEC 60853-1

As per equation -2 and Table -2 the Load Loss Factor (μ) can be calculated as -

$$\mu = \frac{1}{24}\sum_{i=0}^{23} Y_i$$

$$\mu = \frac{Y0+Y1+Y2+Y3+Y4+Y5+Y6+Y7+Y8+Y9+Y10+Y11+Y12+Y13+Y14+Y15+Y16+Y17+Y18+Y19+Y20+Y21+Y22+Y23}{24}$$

$$\mu = \frac{1+0.966+0.813+0.555+0.260+0.048+0+0+0+0+0+0+0+0+0+0+0+0+0.031+0.20+0.467+0.725+0.912}{24}$$

μ = 0.249

As per equation -3,

$$\frac{\theta_R(i)}{\theta_R(\infty)} = 1 - k_1 + k_1\gamma(i)$$

As per equation -4,

$$k_1 = \frac{w(T_4 + \Delta T_4)}{\theta(\infty)}$$

Where,

W - 5.020 W/mtr.

ρ**T** - 1.5 K.m/W

$\theta_R(\infty)$ = 50°C (90 - 40, Maximum conductor temperature limit for XLPE cable is 90°C and ground temperature is 40°C)

As per equation -5,

$$T_4 = \frac{1}{2\pi}\rho_T[\ln(2u) + 2\ln(u)]$$

As per equation -7,

$$u = \frac{2L}{D_e}$$

Where,

L - 800mm or 0.8 meter

De - 55mm or 0.055 meter

Hence, u = (2x0.8)/0.055

u = 29.091

Therefore,

T_4 = {1x1.5x[ln(2x29.091) + 2 ln(29.091)]}/2*3.14

T_4 = 2.58 K.m/W

As per equation -6,

$$\Delta T_4 = \frac{\rho T \ln F}{2\pi}$$

As per equation -10,

$$F = \frac{d'_{p1} \cdot d'_{p2} \text{ -------- } d'_{pk} \text{ -------- } d'_{p(N-1)}}{d_{p1} \cdot d_{p2} \text{ -------- } d_{pk} \text{ -------- } d_{p(N-1)}}$$

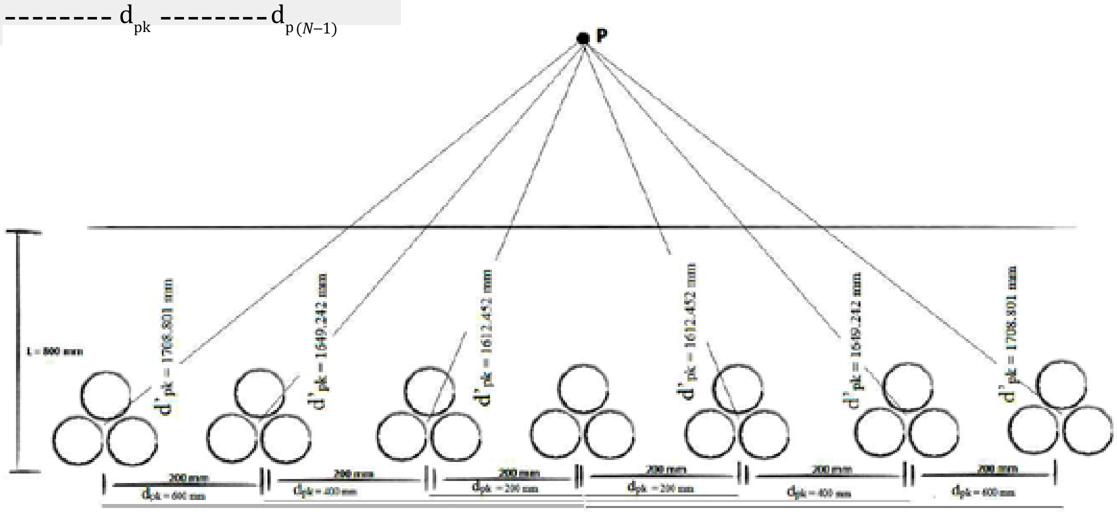


Figure – 4 (pictorial view for d_{pk} and d'_{pk} calculation)

With the help of Pythagoras Theorem values of d'_{pk} are found and shown in the above figure -4

$$F = \frac{1708.801 \times 1649.242 \times 1612.452 \times 1708.801 \times 1649.242 \times 1612.452}{200 \times 400 \times 600 \times 200 \times 400 \times 600}$$

F = 8962.780

Hence,

$\Delta T_4 = \frac{1.5 \times \ln (3 \times 8962.780)}{2 \times 3.14}$, F should be multiplied by 3 since the three single core shall be considered as a circuit

ΔT_4 = 2.44

Therefore,

$$K_1 = \frac{5.020 \times (2.58 + 2.44)}{50}$$

K1 = 0.504

As per equation -8,

$$\Upsilon_{(i)} = \frac{-Ei\left(\frac{-D_e^2}{\mathbf{16}t\delta}\right) + (N\text{-}1)\left\{-Ei\left(\frac{-df^2}{\mathbf{16}t\delta}\right)\right\}}{2\ln\left(\frac{4LF}{De}\right)}$$

Where,

t - 3600 x (i) …………… as per IEC 60853-1,
δ - 0.4 x 10^{-6} ……… for soil thermal resistivity of 1.5 K.m/W, as per table-3
De - 0.055 meter
N - 7 (number of circuits)
F - 8962.780
L - 0.8 meter

As per equation -11,

$$d_f = \frac{4L}{F^{1/(N-1)}}$$

Hence,

$$d_f = \frac{4 \text{ x } 0.8}{8962.78^{1/(7-1)}}$$

d_f = 0.702

For simplified calculation and computing the value of γi for 6 hours load period, tabular method can be used for calculation –

i (Load period in hours)	γi	$\left(\frac{-D_e^2}{16t\delta}\right)$	$\left(\frac{-d_f^2}{16t\delta}\right)$	$-Ei\left(\frac{-D_e^2}{16t\delta}\right)$	$-Ei\left(\frac{-d_f^2}{16t\delta}\right)$	$\frac{\theta_R(i)}{\theta_R(\infty)}$
0	0.00	0.000	0.000	0.0000	0.000	0.0000
1	0.06	0.131	21.389	1.5802	2.39E-11	0.5262
2	0.08	0.066	10.695	2.2109	2.08E-06	0.5383
3	0.10	0.044	7.130	2.5950	1.07E-04	0.5457
4	0.11	0.033	5.347	2.8720	8.26E-04	0.5512
5	0.12	0.026	4.278	3.0886	2.91E-03	0.5560
6	0.13	0.022	3.565	3.2666	6.85E-03	0.5606

Values of -Ei(x) to be calculated as per equation -9 & 10,
Values of γi to be calculated as per equation -8,
values of (θR(i) / θR(∞)) to be calculated as per equation -3.

Now, as per equation -1

$$M = \frac{1}{\left(\sum_{i=0}^{5} Y_i\left[\frac{\theta_R\,(i+1)}{\theta_R\,(\infty)} - \frac{\theta_R\,(i)}{\theta_R\,(\infty)}\right] + \mu\left[1 - \frac{\theta_R(6)}{\theta_R(\infty)}\right]\right)}$$

To simplify the calculation above equation can be divided into two parts –
Part -1

$$\sum_{i=0}^{5} Y_i\left[\frac{\theta_R\,(i+1)}{\theta_R\,(\infty)} - \frac{\theta_R\,(i)}{\theta_R\,(\infty)}\right]$$

For calculating the values for part -1 at each value of i (i.e. – from 0 to 5) tabular form can be used –

i (from 0 to 5)	γi		$\sum_{i=0}^{5} Y_i\left[\frac{\phi_R\,(i+1)}{\phi_R\,(\infty)} - \frac{\phi_R\,(i)}{\phi_R\,(\infty)}\right]$
0	Y0	1.000	0.5262
1	Y1	0.966	0.0117
2	Y2	0.813	0.0060
3	Y3	0.555	0.0031
4	Y4	0.26	0.0012
5	Y5	0.048	0.0002

Part -2

$$\mu\left[1-\frac{\theta_R(6)}{\theta_R(\infty)}\right])$$

Where,

μ - 0.249

θ_R**(6) /** θ_R**(∞)** - 0.5606

value of part -2 shall be - 0.249 x (1 - 0.5606) = 0.1094

Hence, substituting the values of part -1 and part -2 in equation -1

M = 1 / ((0.5262+0.00117+0.0060+0.0031+0.0002) + 0.1094))$^{1/2}$

M = 1 / (0.5484 + 0.1094)1/2

M = **1.23**

Step - 3: Actual de-rated ampacity of the cable after calculating "M factor"

From the above calculation we get the value of **M factor = 1.23**, which can be multiplied with the de-rated ampacity of 1Cx400Sqmm, Al, Ar. Cable which is 231.7A

Hence, the de-rated ampacity of cable shall be –

231.7A x 1.23 = **284.99 A**

After applying cyclic loading methodology, the cable de-rated ampacity is improved because of variation of cable load as per cyclic loading in PV plants.

Now the de-rated ampacity of cable (**284.99A**) is much higher than the required current carrying capacity of the cable (**244A**).

Conclusion: -

From the above example it can be concluded that if the cyclic loading factor being not considered the de-rated current rating of the cable is less than the maximum load current & hence the selected cable size may apparently seem to be insufficient for the application. Therefore, the normal tendency is to select a higher cable size which can be avoided by taking the cyclic loading factor into consideration to make the actual de-rated current rating of the cable higher than the maximum load current with the same cable size.

Since the power cables contribute to the overall cost of a solar PV plant by a substantial amount, therefore it is highly recommended to optimize the power cable sizes with the help of cyclic loading factor to minimize overall cost of the plant.

Reference: -

1 International Electrotechnical Commission, (1985). IEC 60853-1: Cyclic loading factor for cables up to and including 18/30 (36) kV

2 International Electrotechnical Commission, (2014). IEC 60502-2: Cables for rated voltages from 6 kV up to 30 kV (36 kV)

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