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Cable Derating factors affecting Ampacity calculations during design

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1.0 Introduction

This article addresses key design considerations in the sizing of MV and LV cables. It begins with a definition of soil thermal resistivity and discusses methods such as Fluidized Thermal Backfill (FTB) for improving thermal performance. All relevant derating factors required for ampacity evaluation under actual site conditions are presented and illustrated through examples. Practical guidelines for selecting derating factors during the planning stage are provided. Next, the article examines uprating factor of cables that carry cyclic loads. The limitation in extrapolating standard formula for cyclic loading for solar plant application is brought out. Finally, the article concludes with field observations of unequal current distribution in Multiple Runs of parallel cables.

2.0 Soil Thermal Resistivity

Soil thermal resistivity (R_{TH}) is defined as “the difference in degrees centigrade between opposite faces of a one-meter cube of soil caused by the transference of one watt of heat and is expressed in °C- Meter / Watt. Refer Fig 1.

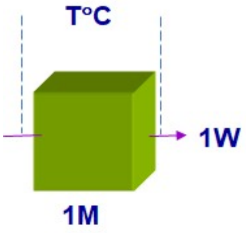

Figure 1

In Thermal Engineering, unit of temperature is Kelvin (K), which magnitude wise is same as °C.

Unit of R_{TH}: Kelvin- Meter / Watt - (K-m /W)

If R_{TH} = 2K-m/W, as in case of typical soil, to transfer 1 Watt of heat across 1 Meter Cube, differential temperature across the cube will be 2K or 2°C.

If R_{TH} = 40K-M / W, as in case of Air, to transfer 1 Watt of heat across 1 Meter Cube, differential temperature across the cube will be 40K or 40 °C. Air is very poor conductor of heat.

Current flowing in a conductor generates heat (I^2R losses). A resistance to heat flow between the cable and the surrounding medium causes the cable temperature to rise. Moderate increases in temperature are within the range for which the cable is designed, but temperatures above the design temperature shorten cable life (e.g. conductor temperature > 90°C).

Thermal resistivity of surrounding medium is influenced by following constituents:

- Quartz (R_{TH} = 0.1 K-m / W) – Excellent conductor of heat
- Other Minerals (R_{TH} = 0.4 K-m / W) – Good
- Water (R_{TH} =1.7 K-m / W) - Not good, but acceptable
- Air (R_{TH} =40 K-m / W) - Very poor conductor of heat

The following points need to be considered during back filling of soil after cable laying:

- Air pockets are to be minimized. The fill must be tightly packed to minimize air space, in order to achieve acceptably low thermal resistances. Air offers biggest obstacle to heat dissipation to surrounding medium. Replacing air with water helps in reducing thermal Resistivity. Refer Fig 2.

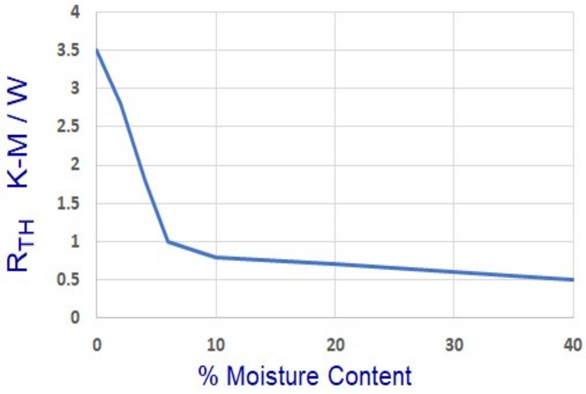

Figure 2

- Fill materials rich in quartz will have the lowest thermal resistivity
- FTB (Fluidized Thermal Backfill) can be poured around the cable for better heat dissipation. Typical R_{TH} of FTB is 0.75 K-m / W when dry to 0.5 K-m / W when wet.
- Bentonite as a back fill material is widely used. By mixing Bentonite clay with native soil, Soil thermal resistivity can be brought down from 2 K-m / W to 0.5 K-m / W. Derating Factor for Soil Thermal Resistivity (K2) used in cable sizing (Refer Sec 3.0) can be ignored., i.e., K2 = 1. It is to be emphasized that abundant water supply shall be ensured when soil is treated with Bentonite clay to achieve desired reduction in thermal resistivity. The other advantage of Bentonite over native soil is its consistency in performance as it retains the moisture for long. Similar effect of Bentonite clay for treating the soil to reduce *electrical resistivity* of soil (ρ) is

discussed in Cl 1.4 of Ref [4]. Resistivity of native soil is about 100Ω-M while that of Bentonite is less than 5Ω-M. This is beneficial for grounding applications.

3.0 Derating Factor Definition

As per actual site conditions, the ampacity of cable is reduced from nominal value by a factor, called 'Derating Factor' by practicing engineers. The same is referred to as Rating Factor in IS 3961-7 [1] and Correction Factor in IEC 60502-2 [2].

Cable Derating Factors as per actual site conditions are classified as follows:

- K1 – Derating factor for variation in ambient ground temperature with reference temperature of 30° C
- K2 – Derating factor for variation in thermal resistivity of soil with reference value of 1.5 K-m / W
- K3 – Group derating factor for multi-circuits in group
- K4 – Derating Factor for variation in depth of laying.

  Let 'd' be depth of burial of cable. If 'd' is within 1 meter, no derating is required. In case of LV and MV Cables below 22kV, derating due to depth of burial can be ignored (K4=1), as they are buried generally within a meter.

  In case of 22kV and 33kV cables, 'd' can be from 1 to 3 meters. In these cases, derating for d =1M can be considered 1 and for d = 3M can be considered 0.9. For values between 1 to 3 meters, derating factor can be linearly interpolated from 1 to 0.9.

- Effective Derating Factor KT = K1 x K2 x K3 x K4

3.1 Example

Cable: 1C x 300mm^2 Al, XLPE, 33kV, 12 Nos (4 Circuits)

Ground temperature = 40°C; Soil Thermal Resistivity = 2K-m / W

Case 1: Flat Formation (Directly buried in soil touching each other)

- Cable Ampacity in ground @ 30°C: 343A (Table - 6 of [1])
- Temperature Derating Factor for Ground temperature of 40°C, K1 = 0.91 (Table -14 of [1])
- Derating factor for Soil Thermal Resistivity of 2K-m / W, K2 = 0.88 (Table -20 of [1])
- Group Derating Factor (4 Circuits), K3 = 0.54 (Table - 26 of [1])
- Derating Factor for variation in depth of laying approximately 1 meter, K4= 1.0
- Effective Derating Factor KT= 0.91 x 0.88 x 0.54 x 1.0 = 0.8 x 0.54 = 0.432
- Effective Ampacity at site condition: 0.432 x 343 = 148A

- Effective Power per circuit (3 Cables): √3 x 33 x 0.148 = 8.5MW
- Effective Power for four circuits (12 Cables): 8.5 x 4 = 34MW

Case 2: Trefoil Formation (Passing through Hume pipes touching each other)

- Cable Ampacity in duct @ 30°C: 307A (Table - 6 of [1])
- Temperature Derating Factor for Ground temperature of 40°C, K1 = 0.91 (Table -15 of [1])
- Derating factor for Soil Thermal Resistivity of 2K-m / W, K2 = 0.90 (Table -21 of IS [1])
- Group Derating Factor (4 Circuits), K3 = 0.59 (Table - 27 of [1])
- Derating Factor for variation in depth of laying approximately 1 meter, K4= 1.0
- Effective Derating Factor KT: 0.91 x 0.90 x 0.59 x 1.0 = 0.82 x 0.59 = 0.483
- Effective Ampacity at sit condition: 0.483 x 307 = 148A
- Effective Power per circuit (3 Cables): √3 x 33 x 0.148 = 8.5MW
- Effective Power for four circuits (12 Cables): 8.5 x 4 = 34MW

It is interesting to observe that, in both cases - flat formation and trefoil, the ampacity at site conditions is same. The primary advantage of trefoil configuration lies in reducing magnetic flux coming out of cable system inducing currents in nearby ferrous metallic strictures leading to the heating of these structures. The advantage of trefoil configuration from thermal point of view is not that marked.

3.2 General guideline

Due to uncertainty in site data, following a simplified approach is recommended during design stage:

Ground Temperature Derating Factor K1 x Soil Thermal Resistivity Factor K2 ≈ 0.8

Group Derating Factor ≈ 0.7 (up to 3 circuits in a group with spacing).

Effective Derating Factor KT = 0.8 x 0.7 ≅ 0.6.

Attempting highly precise calculations using imprecise input data can be misleading. Considering uncertainties like unequal loading of parallel feeders (discussed in Sec 4.0), variation of actual load current from rated values, Design margin available in equipment rating, etc., adopting Effective Derating Factor of 0.6 is often more practical.

3.3 Applicability of Cyclic Rating Factor for cables in Solar Plants.

In the previous sections, we dealt with *derating factor* of cables. Here we will discuss *uprating factor* of cables that carry cyclic loads. The terminology used in standards for uprating factor is ‘Cyclic Rating Factor’. As Per Cl 3.0 of IEC 60853-1 [3], 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.

Typical application can be rolling mills, cranes, traction loads, etc., where the load current is not steady but varies cyclically. Typical curve is shown in Fig 3. To cater to this load, cable need not be rated for peak load current but can be less by a factor M. Let the Effective Derating Factor worked out, based on site condition, as per Sec 3.1 be 0.6. For the current shown in Fig 3, the Cyclic Rating Factor M = 1.16 (Refer Cl 7.1, Table III of [3], for detailed workout). Net Derating Factor = 0.6 x 1.16 = 0.7.

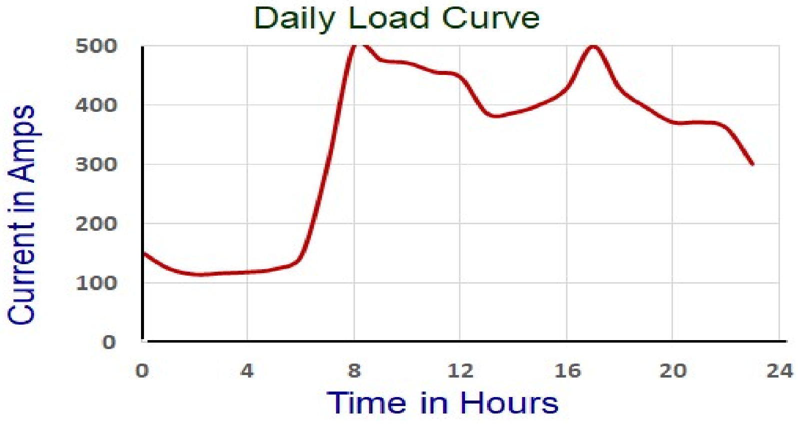

Figure 3

The typical daily load curve for a solar plant is shown in Fig 4. If we apply the same procedure given in IEC [3], we get M = 1.23, resulting in Net Derating Factor = 0.6 x 1.23 = 0.76. But this approach for solar plant application needs critical scrutiny.

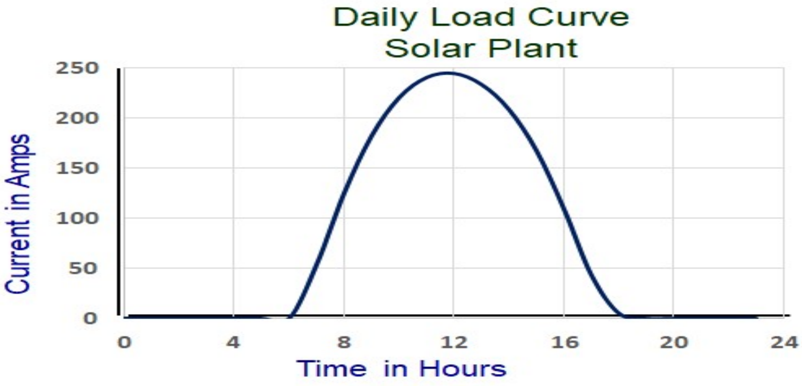

Figure 4

The spirit behind Fig 3, used in IEC example, is that during cyclic loading conditions, when the load current goes up and down periodically, the rated current considered in cable sizing can be less than maximum (peak) current without causing thermal damage. The load cycle has *both heating and partial cooling within a cycle*, such that the conductor temperature *does not reach steady-state* during the high-load period. The M factor (>1**)** arises because:

- The cable does *not reach the steady-state temperature corresponding to peak current*
- Hence, peak current can exceed continuous rating for short durations

But in case of Solar plant, the loading curve, shown in Fig 4, is not truly cyclic within a 24-hour window. It is just a single Bell curve. Fig 3 can be categorized as cyclic while Fig 4 is periodic. The load is high during day time (9 – 10 hours) and low or practically zero during night time ((14 – 15 hours). To interpret thermally:

- During day time, the heating time is long enough for cable temperature to reach steady state
- During night time, the cooling time is long enough for cable to cool nearly back to ambient

This is not cyclic loading in the IEC sense. It is closer to daily steady-state heating followed by near-complete cooling. There is no partial thermal accumulation across cycles. Each day behaves almost like a fresh steady-state heating case. Hence the concept M Factor (M>1) does not strictly apply to this case. For solar application, it is prudent to consider M =1. It is recommended that Cyclic Rating Factor shall not be used by designer for cable sixing in solar plant application.

4.0 Unbalance Current Distribution in Multiple Runs

When feeder current is large, multiple runs / phase are used. Current in each run, in actual site conditions, is not divided equally as per number of runs in parallel. If 4 Runs / Phase is laid, the current in each run is not 25%. It can be very skewed. Some runs may be heavily loaded and correspondingly other runs may be lightly loaded. In Fig 5, current measurements made at site, using clamp on CT, are shown. Since the readings are taken manually, one run of cable at a time, the readings are not exactly synchronous. As measurements are made in quick succession, the readings fairly represent quasi steady state values within reasonable accuracy. On the left, the feeder has 2 runs / phase. We expect the current to be divided equally between the two runs. But the current in each run is different. ΔI is the difference between currents in two runs which ideally should be zero. In R phase, it is as high as 65A. On the right, the feeder has 4 runs / phase. We expect the current to be divided equally (25%) among the four runs. But the current in each run is very different. ΔI (I_{MAX}-I_{MIN}) is highest in R phase and it is as high as 80A.

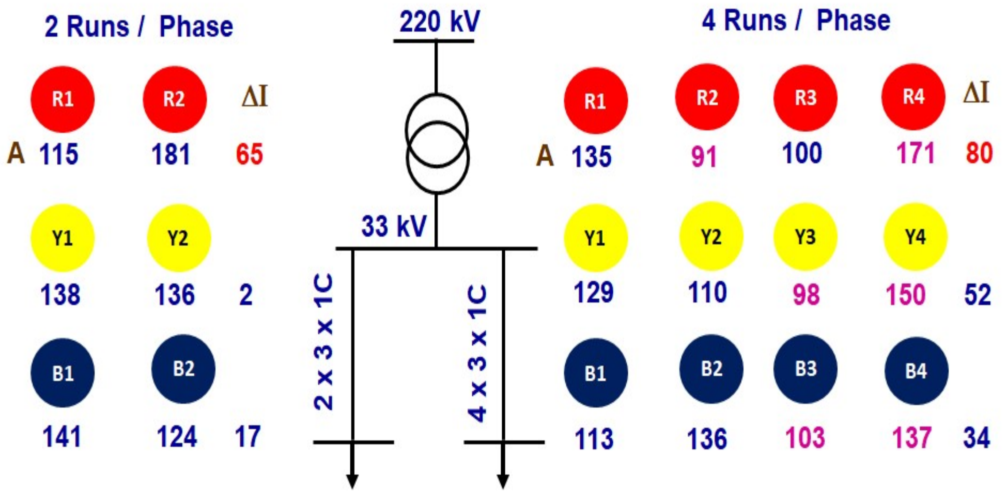

Figure 5

The situation is accentuated when the length is very short, say less than 10 Meters. Typical example is connection between DT (Distribution Transformer) and 415V PCC which are close to each other in substations. Current division happens as per KCL and when length of cable is short, even slight difference in cable impedance among the runs amplifies the skewness. Group Derating Factor given in catalogues and standards assume uniform loading which rarely happens in site conditions. Hence too much importance need not be given to 'accurately' estimate Group Derating Factor. At site, after taking full load, it is recommended to measure current through each run using Clamp on CT. This will give a rough indication of extent of unbalanced loading in parallel cables.

5.0 Conclusion

Soil thermal resistivity significantly influences cable ampacity and can be improved using engineered backfill materials such as Bentonite. Evaluation of Derating Factors K1 to K4 for cable ampacity evaluation based on site conditions is explained with examples. Derating factors must be applied judiciously, but excessive precision using uncertain data should be avoided. It is not recommended to apply Cyclic Rating Factor for Solar Plant application as the load curve is not truly cyclic from thermal point of view. When Multirun cables are used, the current distribution in each run need not be equal and can be highly skewed, especially if feeder length is very short.

6.0 References

[1] IS 3961 (Part 7) -2017: Recommended Current Ratings for XLPE Cables

[2] IEC 60502-2 -2005: Power cables with extruded insulation

[3] IEC 60853-1 -1985: Calculation of the cyclic and emergency current rating of cables

[4] Rajamani K, *Application Guide for Power Engineers – Part 1- Earthing and Grounding of Electrical Systems*, Notion Press, 2018.