PHASE TO PHASE

Thermal loading capacity of cables and transformers

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CONTENTS

1 INTRODUCTION

The increase in Distributed Energy Resources (DERs) coupled with rise in energy demand on an exponential scale needs to be met with heavy infrastructure changes in the grid at a very rapid pace. This is obviously economically expensive and the time frame in which these need to be delivered makes it very difficult to achieve. The network operators are busy expanding the infrastructure but in the meantime, a question lingers if the existing network's hosting capacity is being utilized in a proper manner. This document aims to shed light on how the hosting capacity of components in the grid (cables and transformers) can be determined taking into consideration also their temperature properties proposing the so called **"Dynamic Approach"**.

Guide overview

The report consists of background and the methods used to determine the dynamic thermal loading capacities of transformers and cables in a Medium Voltage (MV) distribution network as well as thermal loading in Low Voltage (LV) networks. An explanation of how this feature is incorporated in Vision Network Analysis (Vision NA) is highlighted.

2 DYNAMIC APPROACH VS STATIC APPROACH

Traditionally, the loading of the components is determined based on the ratio of the actual current calculated by load flow to the nominal rated current of the component. In the present situation, most of the components are overloaded if this method is considered. This is referred to as **"Static Approach"** in this document.

An important aspect to determine if the component is indeed beyond its hosting capacity is to also look into its temperature state. The static approach pays no heed to this characteristic of the components. Hence, there comes into play the dynamic approach which takes into consideration the temperature properties of the components and determines the dynamic thermal loading also including the effect of the current loading on the component.

3 BRIEF OVERVIEW

The dynamic approach (called Cyclic calculation) is possible to be computed only when profile loadflow or data driven loadflow (DDLF) is performed in Vision Network Analysis since the norms are defined for an extended time series. The Data Driven load flow method is explained in detail in another document on the Phase to Phase website. The thermal loading calculation is based on the IEC norms 60287 [1] and 60853 [2] for cables and IEC norm 60076-7 [3] for the transformers. In the upcoming sections, context is provided on these norms and their implementation in Vision Network Analysis. The norms for cables have been already implemented in Vision Cable Analysis which have been updated as well as improved to also perform MV network analyses in Vision Network Analysis tool.

4 THERMAL LOADING CAPACITY OF A CABLE

The thermal loading of the cables is calculated on the basis of the two IEC norms 60287 and 60853 as previously mentioned. The soil and environment conditions as well as geometric properties of cables need to be taken into account for the calculation. The extensive documentation is available at [1] and [2] which are used to calculate the permissible current of the overloaded cables, cyclic rating factor and the conductor temperature as well as the maximum stationary current for every cable section in the network topology.

Conventionally, the loading of components is determined based on its nominal current. The current in a component varies with time and is typically regulated to be below its nominal value. Thermal time constants of components are large enough to allow short term overloading in terms of current but not above the rated temperature of the component. An in depth explanation of the entire working of this particular case and a few test results is available in [4].

5 THERMAL LOADING CAPACITY OF A TRANSFORMER

In a similar way, thermal loading as well as ageing of oil immersed power transformers can be computed using the norm IEC 60076-7 [3]. A lot of factors like the type of transformer, environmental conditions, thermal constants of the oil and the windings as well as the initial state of the transformer needs to be considered. In a similar way to the previous section, the conventional approach of limiting the hosting capacity only on the basis of nominal current is being challenged with this approach.

6 IMPLEMENTATION IN VISION NETWORK ANALYSIS (VISION NA)

The so called Cyclic calculation is an addition to the already existing loadflow and DDLF (state estimation) calculations in Vision Network Analysis. To use this feature, check the **Thermal** checkbox that is present when the profile load flow or DDLF option is selected. The location of the checkbox in the dialog boxes when clicked on them on the ribbon is as shown in Figure 1.

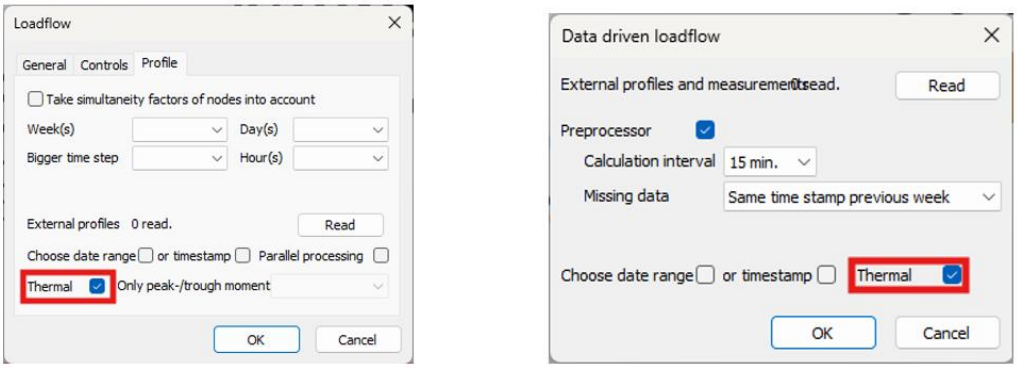


Figure 1 Cyclic checkbox in the dialog boxes (highlighted here)

Note: This functionality is only possible when the calculation is done for a profile of at least a day's duration and hence cannot be replicated for a single instance of load flow. If the cable types and their properties are not properly updated, warnings are shown as to which need to be updated in the Types.xlsx file.

A default minimum time interval of 1 hour is taken between two timestamps to calculate change in temperature in accordance with the cable norm. If the profile has duration of less than 1 hour, then the average of the current loading calculated from loadflow over an hour is taken as input for the calculation of the temperature properties. For the transformer norm, the profile is taken as is.

6.1 Customizing initialisation settings

In the general options tab, the environment variables of the cable and transformer can be adjusted along with temperature limits. A snapshot of the available options is shown in Figure 2. The drying type of soil, ground temperature, outer sheath temperature and heat diffusivity of soil can be setup for the cable. For the transformer, the maximum and minimum air temperature over an entire year as well as the hotspot and top oil temperature limits can be initialized.

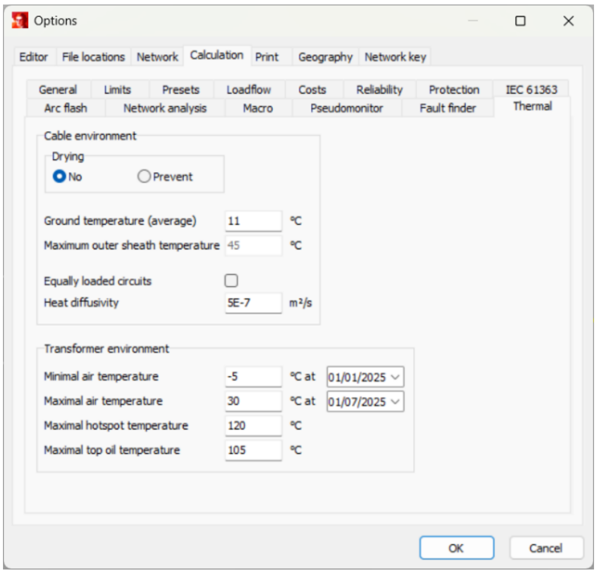


Figure 2 Thermal options

Table 1 shows additional temperature limits as defined by the norm which can be adjusted here. There obviously is an effect on the degradation of the components which needs to be taken into account depending on the loading. The default limits are considered on the basis of normal operation.

Temperature limits	Hot spot temperature	Top oil temperature
Normal	120	105
Long-term emergency	140	115
Short-term emergency	160	115

Table 1 Temperature limits based on loading

Sine-curve approach for ambient temperature:

Temperatures over the year exhibit a cyclical pattern, with warmer and colder periods repeating annually. This is due to the Earth's axial tilt and orbital motion around the Sun, which causes varying solar radiation intensity through the seasons. A sine function is ideal for modeling this behavior because:

- It is smooth and periodic (repeats every 12 months)
- It has a maximum and minimum, matching the hottest and coldest months
- It can be adjusted in amplitude, phase, and vertical shift to fit a specific climate

$$T(t) = A \cdot \sin\left(\frac{2\pi}{P} \cdot (t - \phi)\right) + C$$

where,

T(t) = temperature at time t (in months),
A = amplitude :half the range between max and min temperatures and seasonal variation,
P = period : 12 months
ϕ = phase shift : when the peak temperature occurs,
C = vertical shift : average temperature.

With the above approach, the output for the ambient profile can be constructed similarly as shown in Figure 3 which can further be used as input while computing top oil and hotspot temperatures in the transformer.

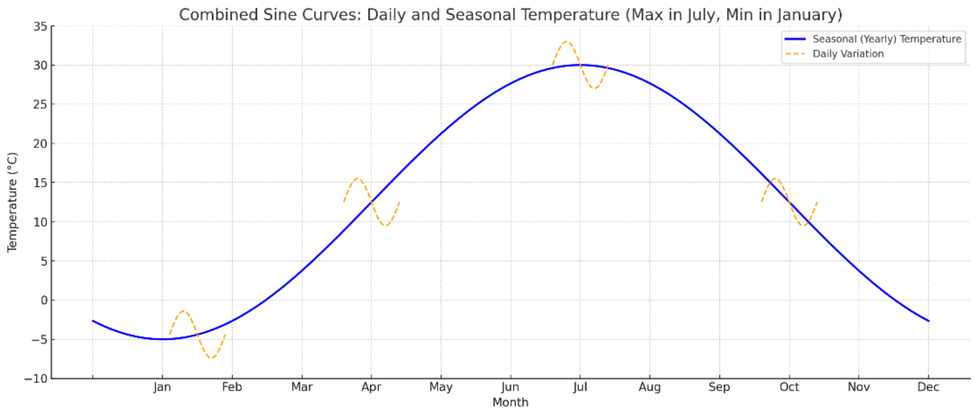


Figure 3 Illustration of ambient temperature variation with the sine curve approach

6.1.1 TRANSFORMER THERMAL SETTINGS

The transformer thermal settings can be further specified (in the Thermal tab) from the transformer window as shown in Figure 4. The default cooling type is taken as natural cooling for air and oil (ONAN). Hot spot factor is defined 1,3 as default which can be adjusted.

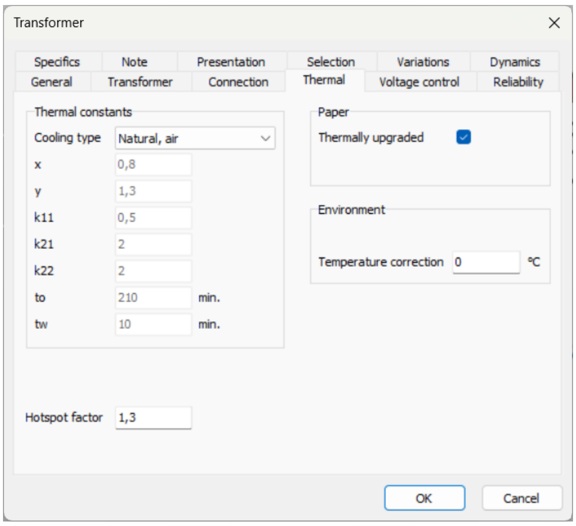


Figure 4 Snap shot of thermal constant settings for transformer

There are seven types of cooling modes defined from the norm [3] shown in Table 2 which are included as presets as well as an option to fill in specific values (the last option in the cooling type drop-down menu). When an ON- or OF- transformer is zigzag cooled, then the radial spacer thickness if less than 3 mm might cause restricted oil circulation which has an effect on the thermal constants.

Cooling type parameter	Definition
Natural,air,small	Oil Natural Air Natural small (sONAN)
Natural,air	Oil Natural Air Natural (ONAN)
Natural,air,restricted	Oil Natural Air Natural restricted (ONANr)
Forced,air	Oil Natural Air Forced (ONAF)
Forced,air,restricted	Oil Natural Air Forced restricted (ONAFr)
Forced,oil	Oil Forced (OF)
Forced,oil,restricted	Oil Forced restricted (OFr)
Direct,oil	Direct Oil (OD)

Table 2 Transformer cooling types

Further, the hotspot factor, the offset of temperature based on enclosure type as well as paper type can be selected. More on the enclosure types is mentioned in the norm in Table 5 [3].

6.1.2 DETERMINATION OF 'R' FOR A TRANSFORMER

R is the ratio of load losses at rated current to the no-load losses at rated voltage. This is needed for the calculation of the temperature of top oil as well as the windings defined as from the norm [3]. In Vision Network Analysis, this can be setup by filling in the values of Pk and Po as seen in Figure 5. Therefore here, R is the ratio of Pk and Po.

If these values are not entered or less than 0.1, then a default value of 20 is taken to proceed with the calculation.

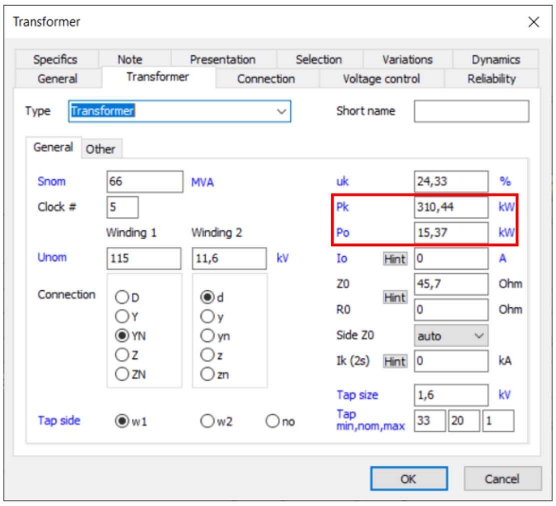


Figure 5 Transformer settings for determination of 'R' (highlighted here)

6.1.3 TRANSFORMER LOAD THERMAL SETTINGS

The transformer thermal calculation is further expanded to the transformer load objects in Vision Network Analysis. The selection range (see Figure 6) is more limited than the transformer to ensure easy use. Since transformer loads deal with MV/LV voltages, the thermal constants are taken as constant on the basis of the small ONAN (sONAN in Table 2) transformer from the norm.

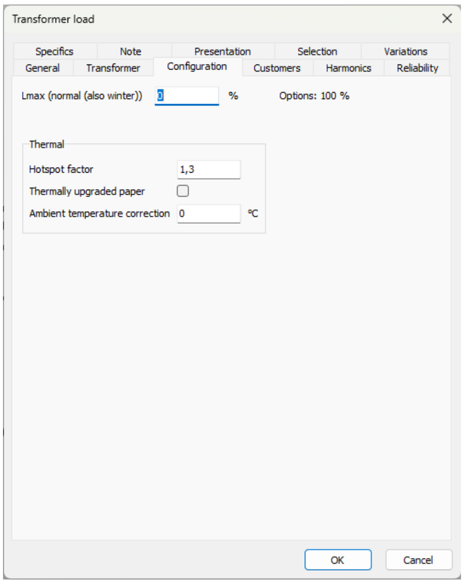


Figure 6 Snap shot of thermal settings for transformer load

The hotspot factor, ambient temperature correction and the paper type can be specified. If detailed modelling is a needed choice, it is possible to split (Select the object and then go to **Start|Topological|Split**) the transformer load object into transformer and a load which enables the usage of the full suite of parameters of the transformer as shown in Figure 4.

6.1.4 'G' FOR A CABLE SECTION

The thermal resistivity ***G*** (K·m/W) of a soil for each cable section can be configured taking into account the corresponding nominal current. This can be done by going to the cable properties and selecting the nominal current Inom for each cable section which corresponds to a specific thermal soil resistivity.

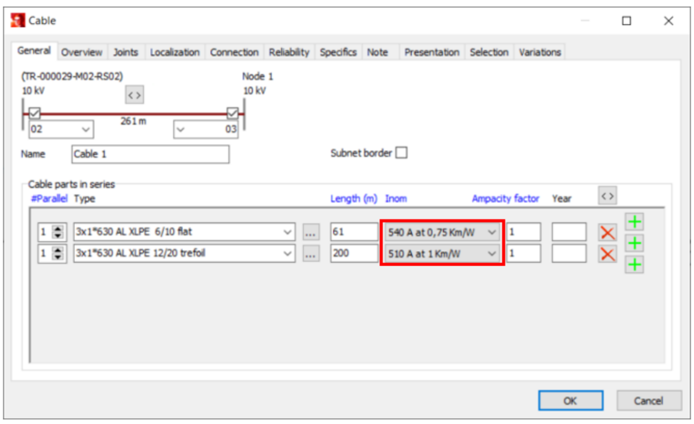


Figure 7 'G' value for cable sections (highlighted here)

This can be seen in Figure 7 and has a large impact on the determination of temperature for the cables which makes it important to accurately select the value.

6.2 Input format for Excel

The format for input Excel files is described for DDLF as well as profile load flow. The data can be provided as an input in the form of Excel sheets at this moment of time. Considering the bigger picture and practicality that might involve quite a large number of networks, other solutions will be considered for future implementations of these module.

6.2.1 INPUT FORMAT 1 (PROFILE LOAD FLOW)

An easy way to input profiles is to name the Excel file the same as the element name in the Vision Network Analysis file (.vnf). Then the Excel file format is as shown in Figure 8. The first column is the date and time with the second column being the active power values in **MW**. This format is specifically used to perform the profile load flow studies in Vision Network Analysis.

This format is a bit shorthanded when used for the DDLF module since it is encouraged to have at least two different types of values as inputs (for instance, active and reactive power) to decrease the uncertainty in the calculation.

	A	B	C	D	E
1	01/12/2022 00:00	0,068			
2	01/12/2022 01:00	0,0633			
3	01/12/2022 02:00	0,0601			
4	01/12/2022 03:00	0,0621			

Element Name

Figure 8 Active powers input with Excel

6.2.2 INPUT FORMAT 2 (DDLF)

The format of input profiles facilitated by Vision Network Analysis specifically for DDLF module is described here. The inputs that can be handled by the DDLF module are active/reactive power and current injections at the nodes; active/reactive power flows and currents in branches of the network. This format can also be used when loading profiles for profile load flow.

6.2.2.1 Assigning data to element (MV/LV transformer and industry users)

A particular format needs to be followed for the Excel sheet to recognize and differentiate between the inputs. To connect a profile/measurement with the element in Vision, the format of ***NodeName.ElementName*** needs to be used as shown in Figure 9. Depending on the type of input, the corresponding unit is also entered. For example ***W/kW/MW*** for active power, ***var/kvar/Mvar*** for reactive power, ***A/kA*** for currents and ***V/kV*** for voltages. Additionally, the standard deviations can also be specified through the input, for example ***W_std/kW_std/MW_std*** for active power and ***var_std/kvar_std/Mvar_std*** for reactive powers. This helps in assigning data to the corresponding element. It is advisable to input all parameters in the same class of units. The same process needs to be followed to assign data to industry users too.

Note: Active and reactive power injections at nodes are the most frequently used measurements.

	A	B	C	D	E
1	**datum & tijd**	**NodeName.ElementName**	**NodeName.ElementName**	**NodeName.ElementName**	**NodeName.ElementName**
2		*MW*	*Mvar*	*MW_std*	*Mvar_std*
3	07/02/2022	0,18493071	0,03836006	0,01383925	0,00281018

Figure 9: Data input format for elements

6.2.2.2 Assigning data to branch

In order to assign a profile to a branch, the name of the measuring field ***Name*** needs to be specified instead of the previous format used as shown in Figure 10. The rest of the procedure is similar as to the previous case of assigning to an element but here it is for the branch.

Note: Here, the measuring field represented by helps in identifying the branch and cross-referencing it. It is also side specific which means it indicates the side of the branch where the measurement is taken.

	A	B	C
1	**datum & tijd**	**Name**	**Name**
2		*kW*	*kvar*
3	01/01/2021	108	48

Figure 10: Input format for branch element

Note: The units of variables should be uniform in the Excel files throughout the measurement and profile files to avoid computational errors. Refer to the State Estimation document on this module for more details.

6.3 Matching the cable properties

To assess the thermal characteristics of the cables, it is important to also keep track of what its geometric and material properties are. For this, in the types file present in the root folder where Vision is installed there are now two additional sheets. One of them goes over the geometric properties of different kinds of cables (**CABLE GEOMETRY**) and the other one helps to match the names of the existing cables used in Vision Network Analysis in the CABLE sheet to the ones in the CABLE GEOMETRY sheet (**CABLE MAPPING**).

It is imperative that if new cable types which are not from the existing selection provided by Vision Network Analysis are used, then the CABLE GEOMETRY and CABLE MAPPING sheets need to be updated to obtain the results of the cyclic thermal) calculation.

7 EXAMPLE IN VISION NA

The cyclic calculation feature is explained here with the help of a simple network, and the obtained results are explained.

7.1 Network description

A network with three nodes, one transformer and two loads is taken for the purpose of demonstration as shown in Figure 11. The nominal voltage level of the network is 10 kV. The transformers are rated 50/10 kV.

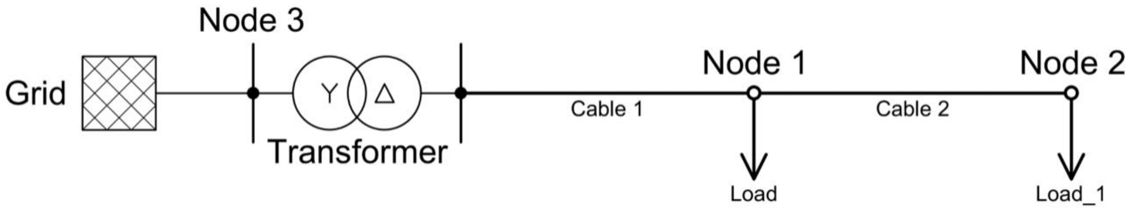


Figure 11: Example of a MV Network

7.2 Input

After selecting the required settings for either the profile load flow or DDLF calculation and also loading in the files in the required manner, it is possible to visualize the results of the thermal loading for the components (cables and transformers).

7.3 Viewing the cyclic results

After computation, the cyclic results can be viewed for cable or a transformer by right clicking it and using the Details button to display numerical results, the Graph button for making a plot and the Thermal button to visualise the temperature outcome. The temperature load rate is also available in the table of the Details button with the rest of the results from the load flow / DDLF calculation.

7.3.1 CABLE

On right clicking the cable, the details panel gives an overview of quite a few variables and there is also an option to view the temperature load rate (minimum and maximum) when the cyclic calculation is performed.

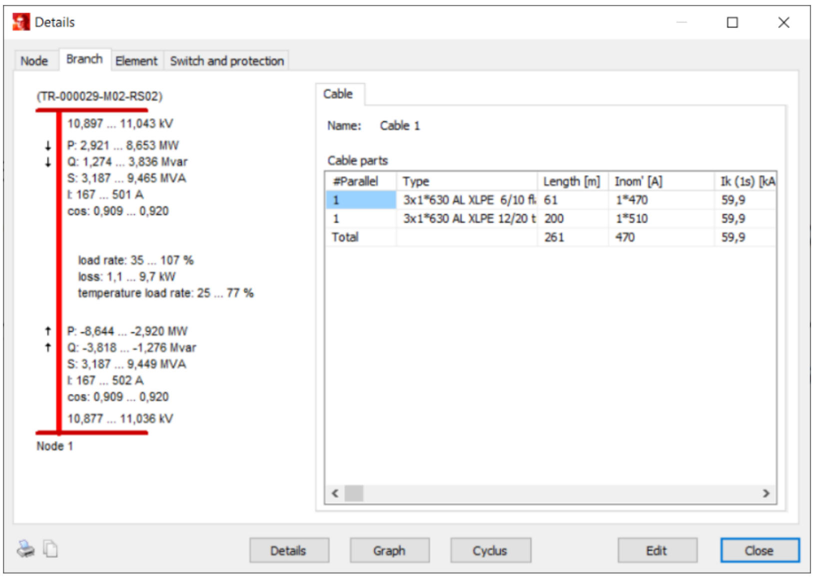


Figure 12: Results in detail form pop-up for a cable

When clicked on the Thermal option, a detailed visualization can be viewed which shows the conductor temperature with respect to the current profile that is obtained after performing load flow for every cable section as shown in Figure 13. The cable sections can be changed using the drop down menu in the form. The maximum allowed conductor temperature (dependent on the cable type) is plotted as a limit. From the IEC norms, the M- factor and the maximum factor for the current profile is determined as well as the maximum stationary current carrying capacity.

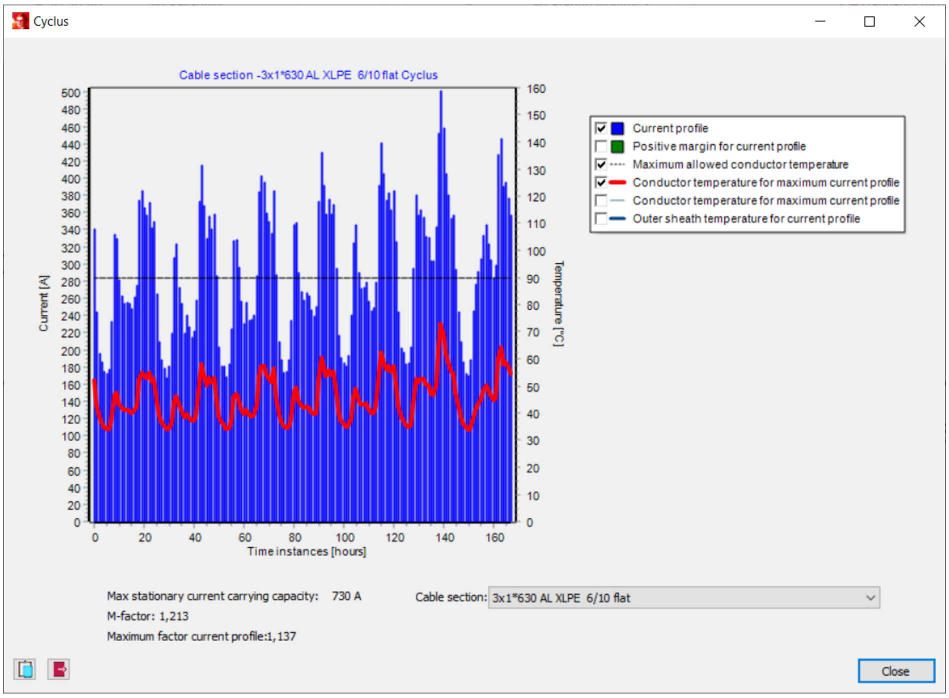


Figure 13 Thermal hosting capacity of cable

The outer sheath temperature can also be visualized by checking on the checkbox in the legend on the right hand side of the form. On the left hand side at the bottom of the form, there are options to export the conductor and outer sheath temperature results along with current profile to an Excel file for every cable section and also to copy the graph to clipboard.

7.3.2 TRANSFORMER

A similar output is also expected from a transformer. The overview is given in the details pane as seen in Figure 14 when right clicked on the transformer with it displaying also the temperature load rate and also the ageing of the transformer in days/day.

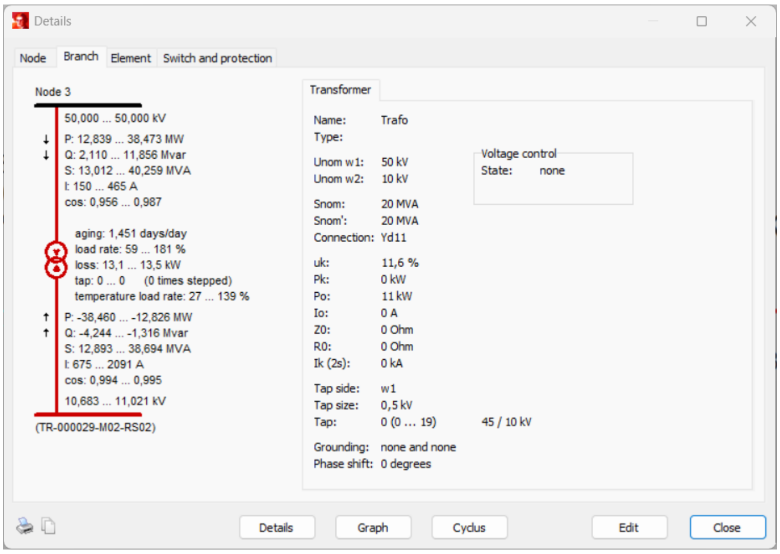


Figure 14 Results in detail form pop-up for a transformer

When clicked on the Thermal button, Figure 15 pops up which displays the hot spot temperature (in windings of the transformer), the top oil temperature and the ambient temperature (from the sine curve approach) against the current profile calculated from the load flow. By checking or unchecking the boxes on the legend, the specific curved can be hid.

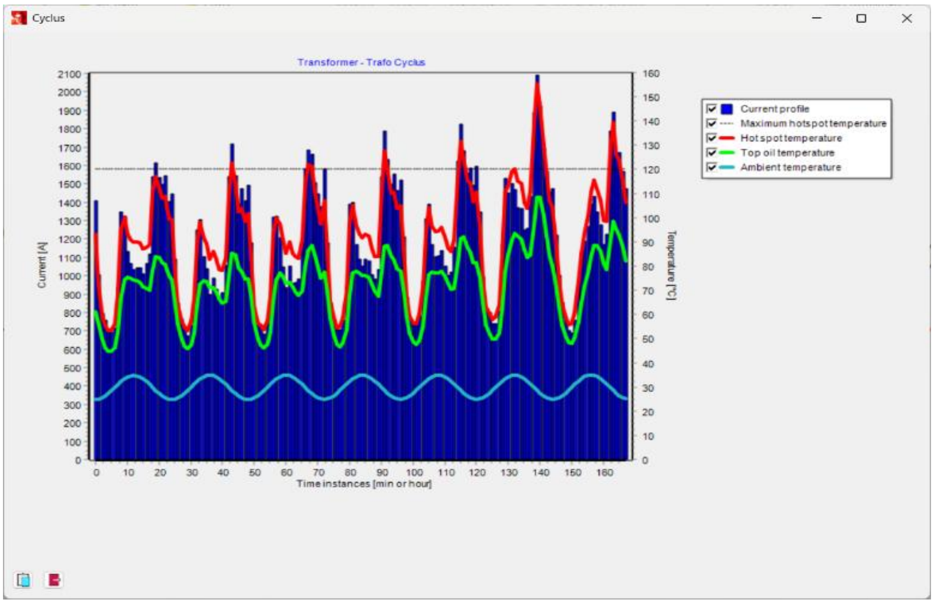
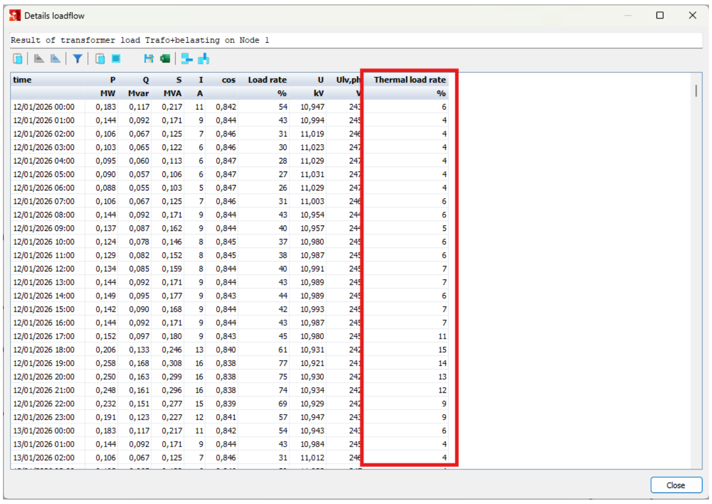


Figure 15 Thermal hosting capacity of transformer

Options to export the hot spot, top oil temperatures and ambient temperature against the current profile to Excel and to copy the graph to clipboard are available at the left hand side at the bottom of the form.

7.3.3 TRANSFORMER LOAD

If a transformer load is present in the network, the results of the thermal load rate can also be seen in the details as shown in Figure 16 (via de details button after right-clicking).



Details loadflow

Result of transformer load Trafo+belasting on Node 1

time	P	Q	S	I	cos	Load rate	U	Ulv,ph	Thermal load rate
	MW	Mvar	MVA	A		%	kV	V	%
12/01/2026 00:00	0,183	0,117	0,217	11	0,842	54	10,947	243	6
12/01/2026 01:00	0,144	0,092	0,171	9	0,844	43	10,994	245	4
12/01/2026 02:00	0,106	0,067	0,125	7	0,846	31	11,019	246	4
12/01/2026 03:00	0,103	0,065	0,122	6	0,846	30	11,023	247	4
12/01/2026 04:00	0,095	0,060	0,113	6	0,847	28	11,029	247	4
12/01/2026 05:00	0,090	0,057	0,106	6	0,847	27	11,031	247	4
12/01/2026 06:00	0,088	0,055	0,103	5	0,847	26	11,029	247	4
12/01/2026 07:00	0,106	0,067	0,125	7	0,846	31	11,003	246	6
12/01/2026 08:00	0,144	0,092	0,171	9	0,844	43	10,954	244	6
12/01/2026 09:00	0,137	0,087	0,162	9	0,844	40	10,957	244	5
12/01/2026 10:00	0,124	0,078	0,146	8	0,845	37	10,980	245	6
12/01/2026 11:00	0,129	0,082	0,152	8	0,845	38	10,987	245	6
12/01/2026 12:00	0,134	0,085	0,159	8	0,844	40	10,991	245	7
12/01/2026 13:00	0,144	0,092	0,171	9	0,844	43	10,989	245	7
12/01/2026 14:00	0,149	0,095	0,177	9	0,843	44	10,989	245	6
12/01/2026 15:00	0,142	0,090	0,168	9	0,844	42	10,993	245	7
12/01/2026 16:00	0,144	0,092	0,171	9	0,844	43	10,987	245	7
12/01/2026 17:00	0,152	0,097	0,180	9	0,843	45	10,980	245	11
12/01/2026 18:00	0,206	0,133	0,246	13	0,840	61	10,931	242	15
12/01/2026 19:00	0,258	0,168	0,308	16	0,838	77	10,921	241	14
12/01/2026 20:00	0,250	0,163	0,299	16	0,838	75	10,930	242	13
12/01/2026 21:00	0,248	0,161	0,296	16	0,838	74	10,934	242	12
12/01/2026 22:00	0,232	0,151	0,277	15	0,839	69	10,929	242	9
12/01/2026 23:00	0,191	0,123	0,227	12	0,841	57	10,947	243	9
13/01/2026 00:00	0,183	0,117	0,217	11	0,842	54	10,943	243	6
13/01/2026 01:00	0,144	0,092	0,171	9	0,844	43	10,984	245	4
13/01/2026 02:00	0,106	0,067	0,125	7	0,846	31	11,012	246	4

Close

Figure 16 Transformer load thermal loading results

8 SUMMARY POINTS

- The inclusion of this temperature dependent loading overview enhances the already existing output results of the network from the load flow/state estimation analysis in both MV and LV grids.
- The ageing of the transformers as defined from the norm works well for higher temperatures (>80°C) and for lower temperatures provides a bit underestimated results. This is a known problem with the Arrhenius (exponential) model and therefore a minimum ageing of 10% is introduced in case of lower loadings of transformer.
- The performance of the load flow/ state estimation calculation is not affected with the inclusion of the analytical methods to compute temperature loading in Vision NA.

9 REFERENCES

[1] International Electrotechnical Commission, "Electric cables - Calculation of the current rating," IEC 60287, 2014.

[2] International Electrotechnical Commission, "Calculation of the cyclic and emergency current rating of cables," IEC 60853, 2002.

[3] International Electrotechnical Commission, "Power transformers - Part 7: Loading guide for mineral-oil-immersed power transformers," IEC 60076-7, 2018.

[4] S. Nibhanupudi and A. Ishchenko, "Dynamic thermal Loading capacity of underground cables in Medium Voltage Distribution networks," CIRED, Vienna, 2024.