Transformer Thermal Impact Assessments for DC Withstand Capability

Examining the Impacts of Geomagnetically Induced Current (GIC) on Transformer Thermal Performance

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Technical Update, December 2019

EPRI Project Manager

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ABSTRACT

Severe geomagnetic disturbance (GMD) events pose a significant threat to reliability and resiliency of the interconnected bulk power system. The goal of this report is to identify transformer designs with the most thermal-limiting capacity to geomagnetically induced current (GIC). More than 40 transformer design types were evaluated accounting for primary variability in design parameters (for example, different core designs, winding geometry, voltage levels, and additional design considerations). This report presents the results of that analysis along with the individual transformer design details. In addition, the effects of harmonic currents on tertiary winding (TW) heating resulting from asymmetrical saturation were explored. This task was accomplished by examining seven electrical models of typical high-voltage autotransformers with TWs of varying design (i.e., different core designs, winding geometry, voltage levels, rated TW current densities, and additional design considerations).

The results of this study will be used for investigating worst-case hot spot heating conditions in transformer thermal impact assessments, further improving the technical basis of screening criteria used in GMD vulnerability assessments.

Keywords
Geomagnetic disturbance (GMD)
Geomagnetically induced current (GIC)
Transformer
Hot spot temperature
Thermal model

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PRIMARY AUDIENCE: Owners and system planners of power transformers (both on the bulk transmission network and generator step-up transformers)

KEY RESEARCH QUESTION

The goal of this research was to identify transformer designs most vulnerable to the effects of geomagnetically induced current (GIC) including the impacts of GIC-related harmonic currents on the tertiary winding (TW) heating.

RESEARCH OVERVIEW

More than 40 design types of transformers were examined accounting for variability in transformer design parameters. This transformer modeling was performed using a major manufacturer's validated modeling approach to predict transformer thermal response to GICs.

KEY FINDINGS

- Circulating currents with significant harmonics occur in delta-connected windings (TW windings), when DC is present in the transformer high-voltage system.
- Losses in the TW increase due to core saturation, with eddy losses in the winding increasing the most compared to the nominal condition without DC.
- No critical steady-state temperatures were reached in the seven investigated TW designs, even with 200 A DC per phase in the high-voltage windings.
- Tertiaries not using a continuously transposed conductor (CTC) in the TW in conjunction with a very low short-circuit, current-limiting inductance in the tertiary are most susceptible; however, the short-term emergency hot spot temperature for the TW in this research is also below a critical level even with high DC. Nevertheless, when a rectangular copper conductor is used, a thermal evaluation is recommended.
- The DC withstand capability study on tie bars shows that these structural parts can be significantly heated with DC in the high-voltage winding of the transformer, especially when DC effects are not considered in the design.
- The most thermal-limiting transformer was a single-phase, core-form with two-return legs autotransformer. The high number of turns in the 335/√3kV high-voltage system (N=1467, SW+CW), is one contributing factor to the very high temperature rise in the tie bars (same level of DC was applied in the series and common winding).

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EXECUTIVE SUMMARY

WHY THIS MATTERS
This research aims to identify and mitigate the potential risk that severe geomagnetic disturbance (GMD) events pose to reliability and resiliency of the interconnected bulk power system.

HOW TO APPLY RESULTS

This study will provide inputs to transformer thermal models for applying geoelectric field time series to represent worst-case hot spot heating conditions in transformer thermal impact assessments. The results of this study will further improve the technical basis of screening criteria used in GMD vulnerability assessments.

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1
DC WITHSTAND CAPABILITY STUDY ON DELTA WINDINGS

General

This chapter investigates the DC-capability of TW windings (delta-connected) for different transformers. In order to investigate the impact of DC, different types of transformers have been studied. This includes different core designs, winding geometry, voltage levels, rated TW current densities, etc. Table 1-1 shows the main technical data of the transformers under investigation. It can be seen, that in total seven transformers have been analyzed by this study. An individual report with the results of each unit is given in the electronic appendix of this document. The individual report is identified by its transformer no. E.g. *DeltaWinding_Heating_Study_Transformer_T1.pdf.*

Table 1-1
Investigated Transformers

Transformer		T1	T2	T3	T4	T5	T6	T7
Transformer Type		Auto	Auto	Auto	Auto	Auto	Auto	TRA[1)]
Core type (LEG)	-	5	3	3	5	1	1	5
TW position	-	Inner	Outer	Inner	Inner	Inner	Inner	Inner
TW nameplate rating	MVA	56	10	3	20	3.3	112	30
HV nameplate rating	MVA	560	420	600	670	333.3	373	300
HV voltage	kV	218.5	335	410	525	400/√3	525/√3	232
TV voltage	kV	13.2	13.1	21.0	23.0	22.0	13.8	10.0
TW rated current density	A/mm²	2.0	0.7	0.2	1.1	0.7	3.93	2.04

Core type description (see Appendix B):

1…Single-phase, core-form: one wound limb, two-flux return limbs (1LEG)

3…Three-phase, core-form: three-wound limbs (3LEG)

5…Three-phase, core-form: three-wound limbs, two-flux return limbs (5LEG)

[1)] TRA = Conventional transmission transformer (galvanically isolated windings)

Electrical Circuit for Investigation (Unloaded TW Condition)

Figure 1-1 shows an example of the used electrical circuit for the DC-investigation on the seven transformers. The AC voltage is applied on the high-voltage terminals together with a DC voltage to reach a DC current in each phase of the transformer. Six DC levels per phase are studied (10, 20, 40, 50, 100 and 200 A DC per phase). The currents of the series, common and tertiary windings are calculated for each investigated DC level. In order to identify only the effect of an additional DC current in the neutral of the high-voltage system when the transformer is energized with an AC voltage, an unloaded TW winding was simulated first. The used simulation models and their verification and background are briefly discussed in the Appendix A and in [1], [2], [3], [4], [5], [6] and [7].

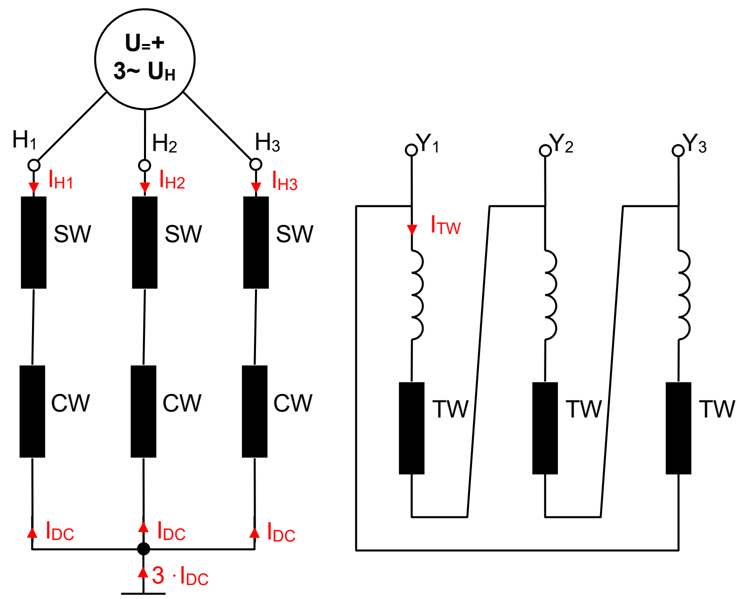


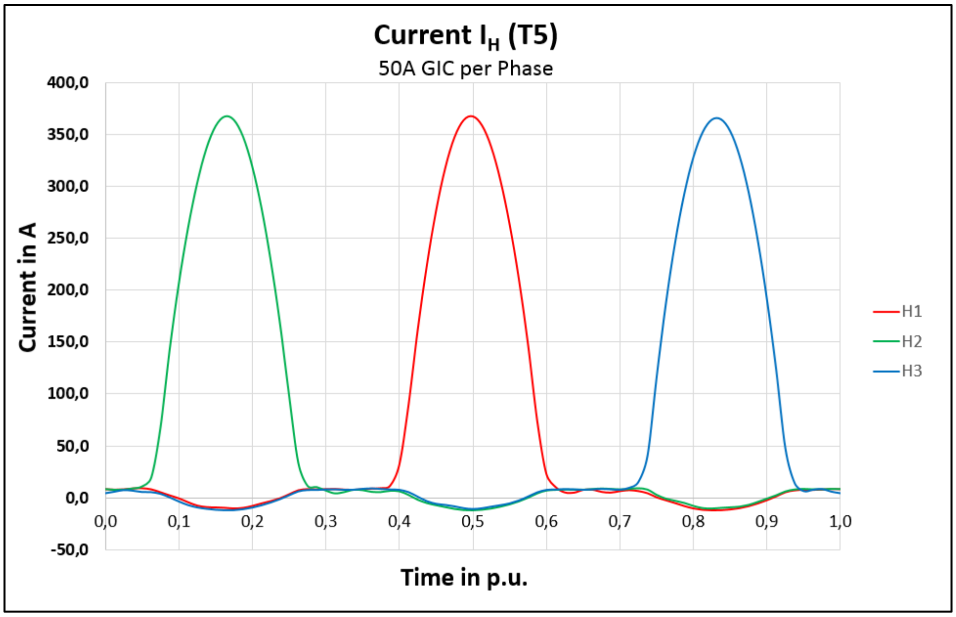
Figure 1-1
Electrical circuit for investigation (unloaded TW winding)

Current Behavior in SW- and in TW-Winding due to DC

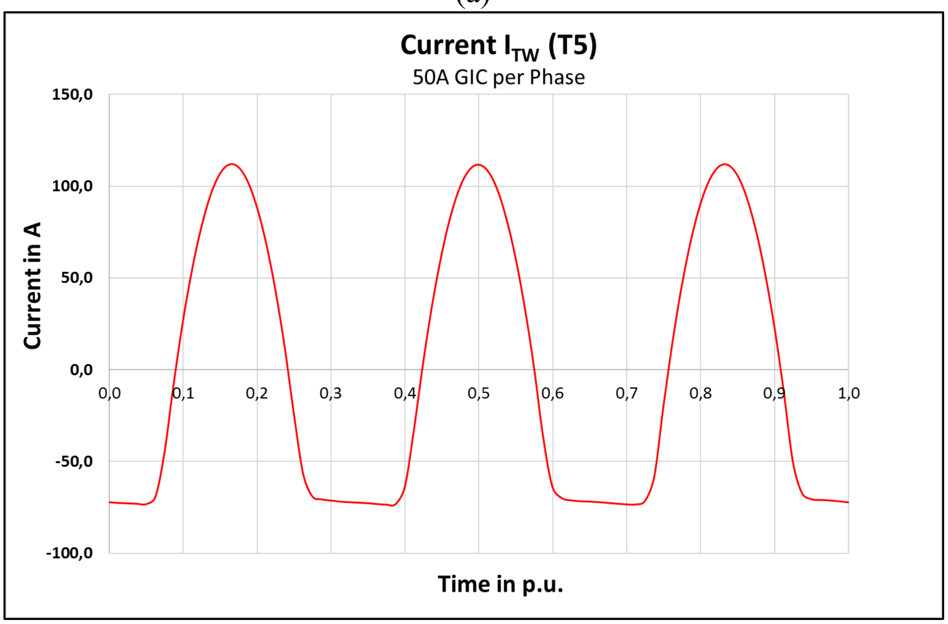
Wave Forms

Figure 1-2 gives an example for a current wave form in the high-voltage system (SW winding) and in the TW winding for transformer T5 when the electro-magnetic steady-state condition is reached. In this figure the DC current component in the SW and CW winding is 50 A DC per phase. The x-axis shows the normalized time of one period.

It can be seen, that a high current peak occurs in each phase of the SW current within one period. This is the increased exciting current peak due to the core saturation during a part of the cycle. However, not only the high-voltage winding is affected, because in the TW winding occurs a circulating current under DC, which is not the case when the transformer is operated only with an AC voltage. An example for the wave form of such a circulation current is Figure 1-2b. The calculated wave forms for each DC level and for each investigated transformer can be found in the individual reports of the transformers.



(a)



(b)

Figure 1-2
Current in (a) SW and (b) TW winding of transformer T5 with 50A DC per phase

Harmonics of Circulating Current

Figure 1-3 shows the frequency spectrum of the circulation current in the TW winding for transformer T5 with 50 A DC per phase. It can be seen, that the spectrum of this circulating current shows significant peaks at every third harmonic (e.g. 180Hz, 360Hz, 540Hz, etc.). The reason for the third harmonic components in the circulating current is caused by the core leg saturation which occurs periodically every 120 electrical degrees in each saturated phase. The circulating current is caused by an induced voltage due to a non-symmetrical flux component during core saturation of the three individual limbs. Consequently, a compensation current occurs in the delta connected tertiary winding.

The frequency spectrum for the other investigated DC currents and transformers are given in the individual reports for each transformer. It should be noted that the circulating current in transformers with a five-limb core shows also components at frequencies between. However, the third harmonic is also at five-limb transformers dominant.

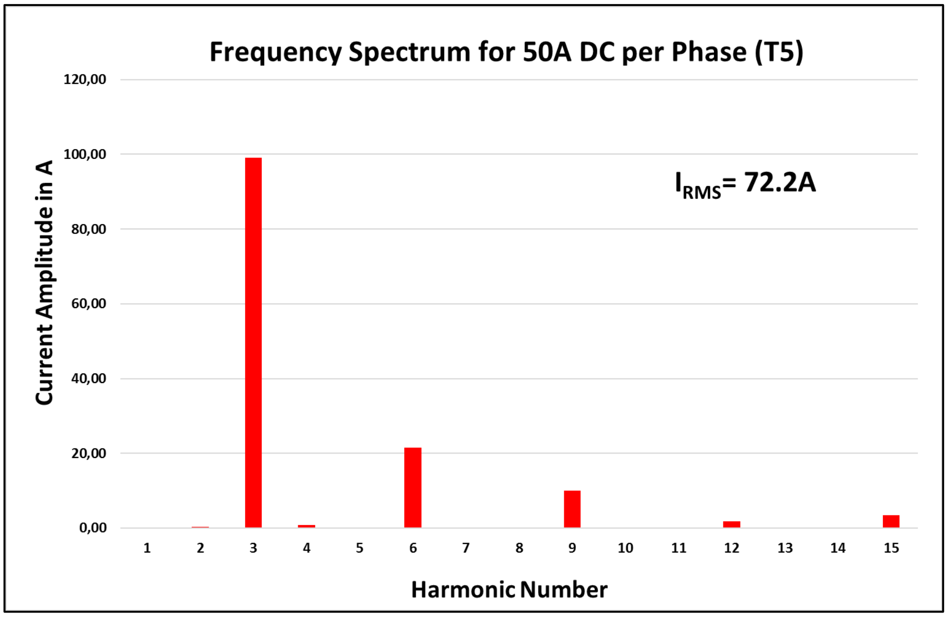


Figure 1-3
Spectrum of circulating current in TW winding with 50A DC per phase of transformer T5 (harmonic no. 1 = fundamental component)

RMS Value of Circulating Current

In order to show the order of magnitude of such TW circulating currents under DC, Figure 1-4 illustrates the increase of the RMS value of circulating current with the DC level for all investigated transformers.

Figure 1-4 illustrates an essential effect due to DC, namely the different response to a DC current due to different core types. Single-phase transformers and units with a five-limb core show an increase of the current beginning with zero. However, the RMS value of the circulating currents in the units T2 and T3 show at the beginning almost no increase. The reason is the core type of these transformers, because they have a three-limb core. In such transformers a certain amount of DC must be applied in the high-voltage winding in order to reach the core saturation. This contrasts with other core types, where the saturation starts already at very low DC levels.

In Figure 1-4 there can also be seen a difference in the magnitude of the TW current. For example, T1 has a higher magnitude compared to T4. The reason is the lower voltage class of T1. The lower the number of turns in the tertiary winding the lower is the inductance and the higher the circulating current.

Transformer T6 shows the highest increase of the RMS values. However, this is no indication that the TW winding of T6 is significantly stressed because also the nominal current of T6 is high. In Figure 1-5 is the DC-current in per unit of the nominal RMS value shown. There you can see, that the per unit value of the TW-current of T6 is very low.

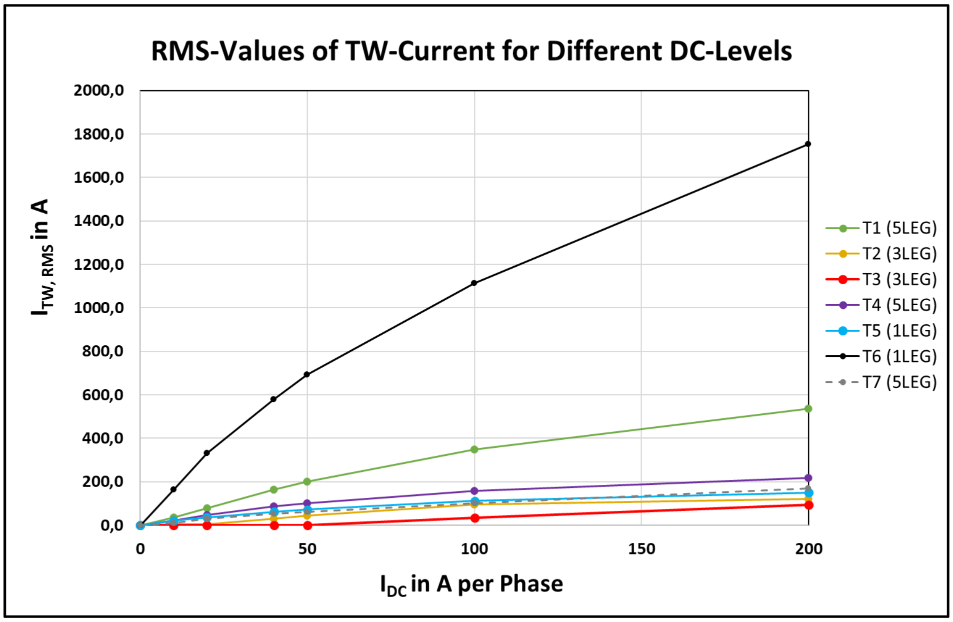


Figure 1-4
RMS-Values of TW-Current for different DC-Levels

Figure 1-5 below illustrates the RMS value of the occurring circulating currents in the TW winding in per unit of the nominal RMS value of the TW current for the respective transformer. It can be seen, that for lower DC levels the RMS value of the circulating current does not reach the nominal specified value at the name plate (the per unit value is lower than one). However, with 200 A DC per phase, the RMS value of the circulating current in transformer T5 reaches the RMS value of the nominal current. For example, the nominal TW current at the nameplate (AC condition) of transformer T5 is 151.5 A and the RMS value of the circulating current in the unloaded TW winding with 200 A DC is 150.5 A.

However, also these per unit values do not have a significant meaningfulness to evaluate whether a critical hot spot temperature is reached with DC, because the nominal nameplate rating gives no answer about the real thermal capability of the winding. To identify the thermal loading of a TW winding, a detailed loss and heating calculation is required as shown in the following chapter.

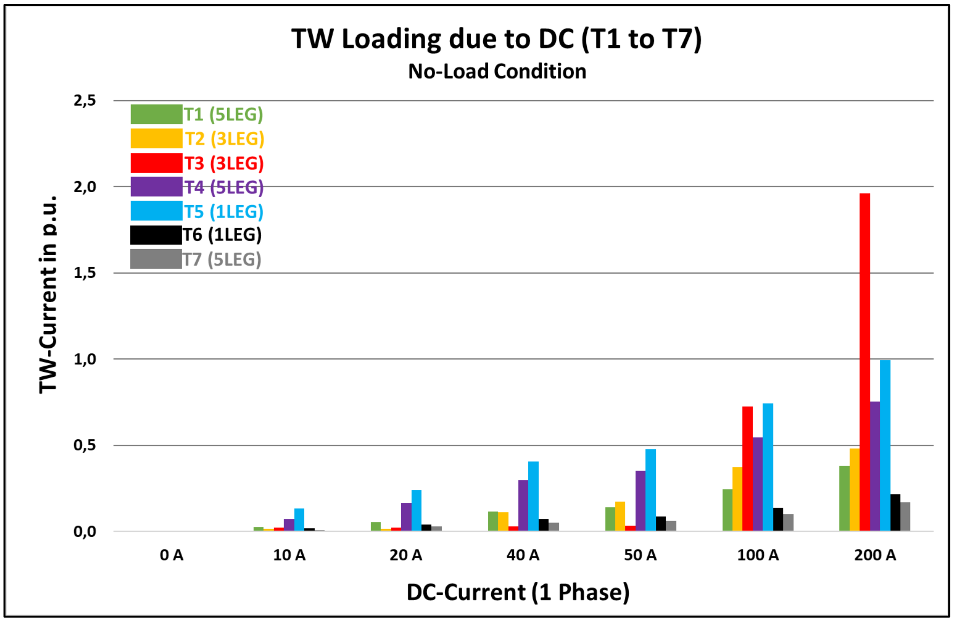


Figure 1-5
Increase of TW circulating current due to DC (T1 to T7, RMS value in per unit of nominal value)

Behavior of I^2R- and Eddy Losses (Unloaded TW winding)

Examples of I^2R- and Eddy Losses

Figure 1-6, Figure 1-7, Figure 1-8 and Figure 1-9 show the behavior of the I^2R and eddy losses with DC. To demonstrate this behavior, the transformers T1 and T5 are chosen, because one transformer has a high nominal TW rating (T1, 18.6 MVA/phase) and the other one has a very low nominal rating (T5, 3.3 MVA/phase). Furthermore, the results of transformer T3 and T7 are shown in the figure, because these transformers are the only one which has a rectangular copper conductor in the tertiary winding. The green line in the figures represents the total losses in the TW winding in their nominal condition. This means the losses in the TW winding with their nominal power (name plate) without DC.

It can be seen, that in transformer T1 the losses at different DC levels do not reach the losses of the nominal condition. This contrasts with transformer T5. Here the losses for the nominal condition are already reached with 40 A DC per phase. This is interesting, because Figure 1-5 shows, that the RMS value of the circulating current is in this transformer at 40 A DC only about 0.45 per unit of the nominal value. However, the losses of nominal condition are already reached at 40 A DC per phase. The reason is the eddy loss behavior under DC. Figure 1-6 to Figure 1-9 show, that for all transformers the eddy losses are increasing strongly with the DC current and that they are significant bigger than the eddy losses at the nominal AC condition. Therefore, the nominal loss condition can be exceeded easily in TW windings, especially when the nominal rating is low as shown with transformer T5. However, this has no significance on the real thermal capability of the winding as discussed in the following.

The major outcome of Figure 1-6, Figure 1-7, Figure 1-8 and Figure 1-9 is given when the TW winding losses under DC are compared with the solid red line in the diagram, because the red line represents the loss condition in the winding which is required to reach a steady-state hotspot temperature (HS) of 100 K above ambient. This represents the IEEE long time emergency limit with an ambient temperature of 40 °C. It must be noted, that the steady-state temperature represents the worst-case condition when the DC current is applied a long time (about 1 hour). However, a GIC event has a very transient nature. Therefore, these steady-state temperatures will not be reached in case of GIC, because tertiary windings have thermal time constant in the range of several minutes.

Nevertheless, it can be seen, that especially the losses in transformer T5 are far below this limit, already in the nominal condition without DC. The reason is that the TW winding of transformer T5 has a very low nominal rating (3.3 MVA per phase) as mentioned above. This result also in a very low current density (0.7 A/mm²). However, due to the mechanical stability and short circuit limits, there must be always a certain amount of copper in the winding which lead to this small nominal current density. As a consequence, the losses which represent the real thermal capability of the winding are significantly higher than the losses in the winding in the nominal condition.

This means these figures already indicate that also the hotspot temperatures in these windings will not reach critical values under DC.

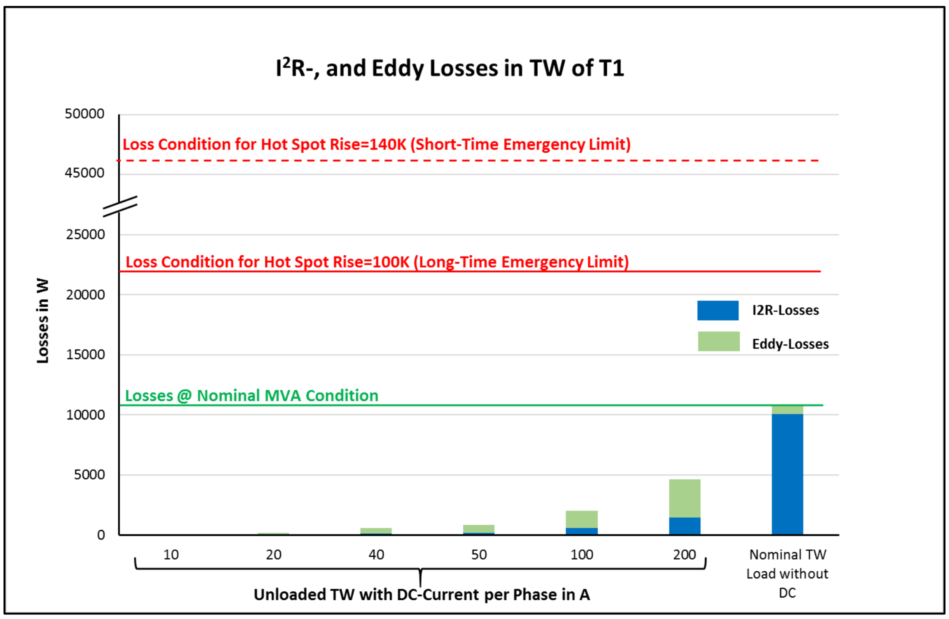


Figure 1-6
I2R- and Eddy Losses with DC (unloaded TW condition, Transformer T1)

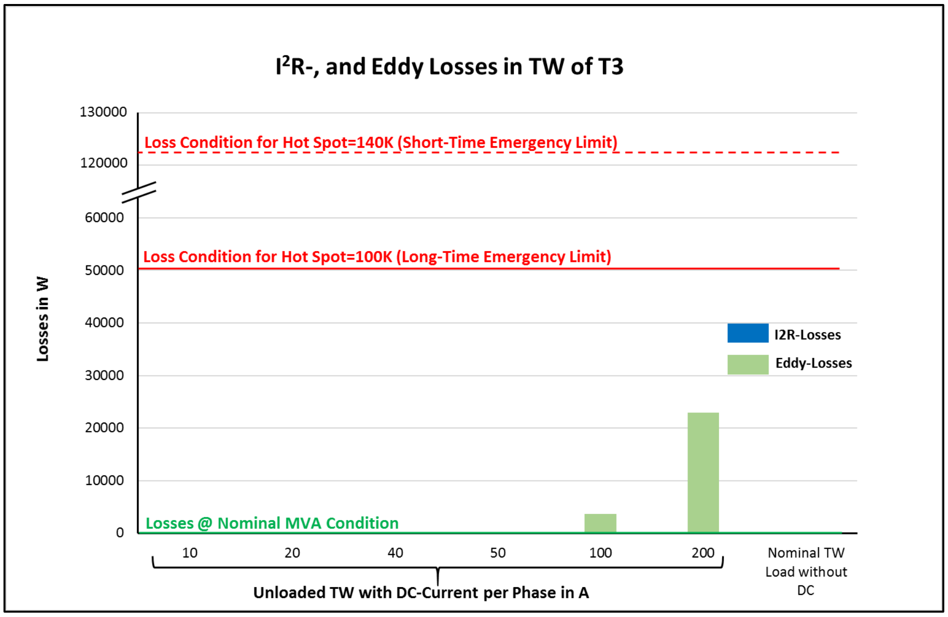


Figure 1-7
I2R- and Eddy Losses with DC (unloaded TW condition, Transformer T3)

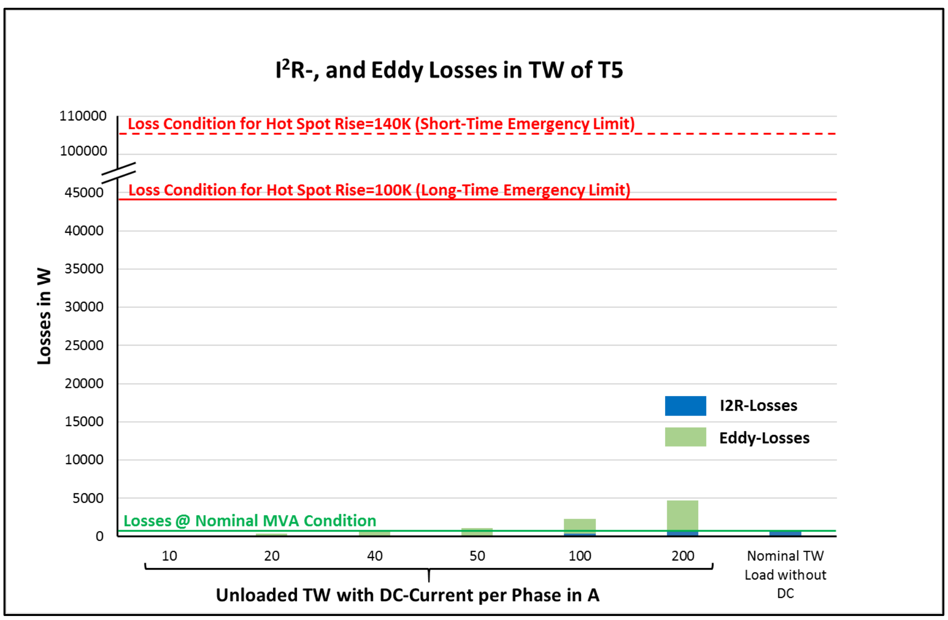


Figure 1-8
I2R- and Eddy Losses with DC (unloaded TW condition, Transformer T5)

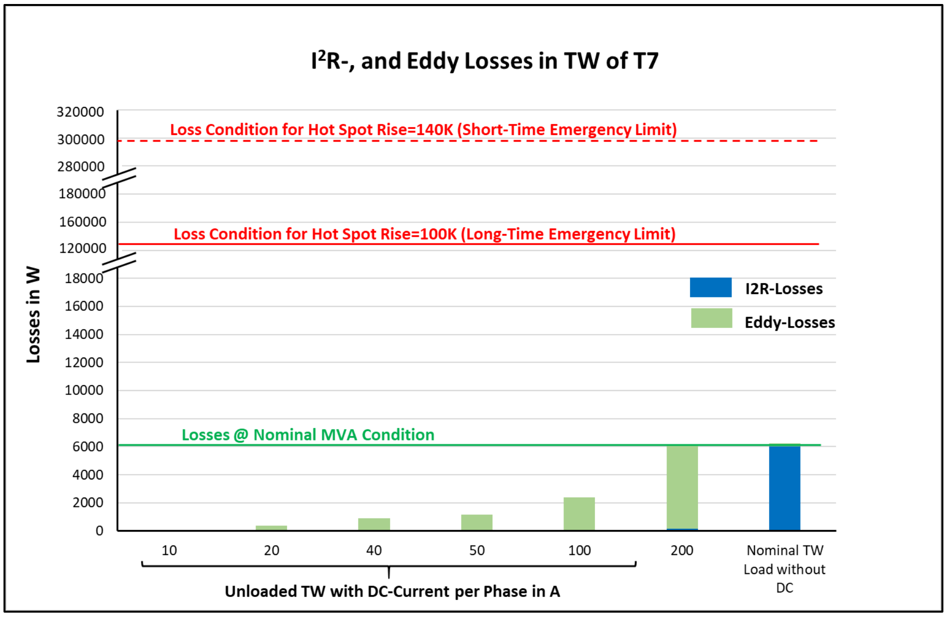


Figure 1-9
I2R- and Eddy Losses with DC (unloaded TW condition, Transformer T7)

Behavior of Hotspot Temperatures

In Figure 1-10 the steady-state hotspot temperatures in the TW winding are shown. All studied transformers have different nominal top-oil temperatures based on their cooling system therefore as a consequence the hotspot rises in Figure 1-10 starts at different levels. However, as already discussed above, all transformers reach no critical temperatures levels under DC. It must be noted, that Figure 1-10 shows the hotspots under DC with an unloaded TW winding. However, it is possible, that a TW winding is also loaded when the DC occurs in the high-voltage winding. Therefore, the following chapter of this document investigates also loaded conditions.

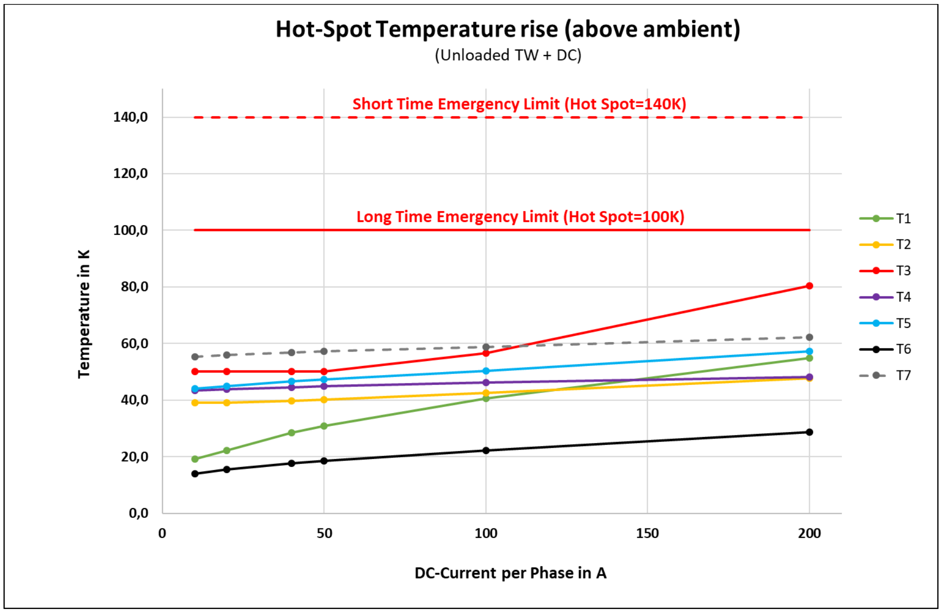


Figure 1-10
Hotspot temperature rise with DC (above ambient, unloaded TW condition, all transformers)

Influence of Nominal AC Loading in the TW Winding

Electrical Circuit for Investigation (Loaded TW Condition)

Figure 1-11 shows the used electrical circuit for the DC-investigations with a loaded TW winding. Here the TV system is grounded with ohmic resistances in order to produce a nominal tertiary load condition.

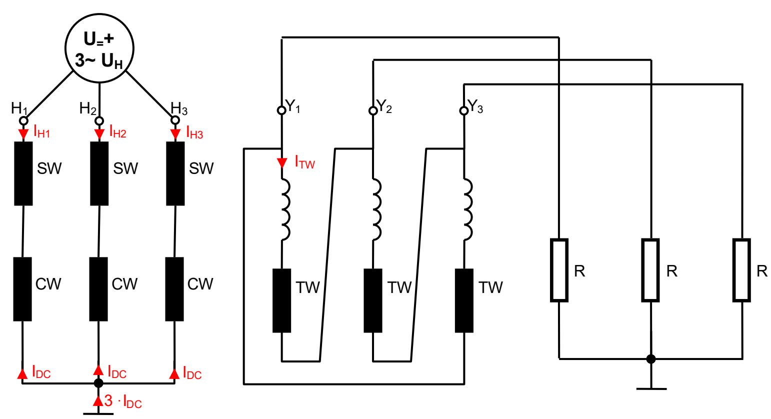


Figure 1-11
Electrical circuit for investigation (loaded TW condition)

Frequency Spectrum for 50A DC per Phase of T5

Based on the electrical circuit of Figure 1-11 , the wave form of the currents is calculated with a DC current of 200 A DC per phase plus a loaded TW winding. In that way the unloaded and loaded condition can be compared. Figure 1-12 compares the harmonics of the circulating current for the TW winding of transformer T5, for an unloaded as well for a loaded condition. It can be seen, that the third harmonic, and the multiple of it, are more or less the same for unloaded and loaded condition. However, in the loaded condition also the harmonic at the fundamental component is present in the frequency spectrum. This lead in the loaded condition to a higher RMS value of the current than in the unloaded condition.

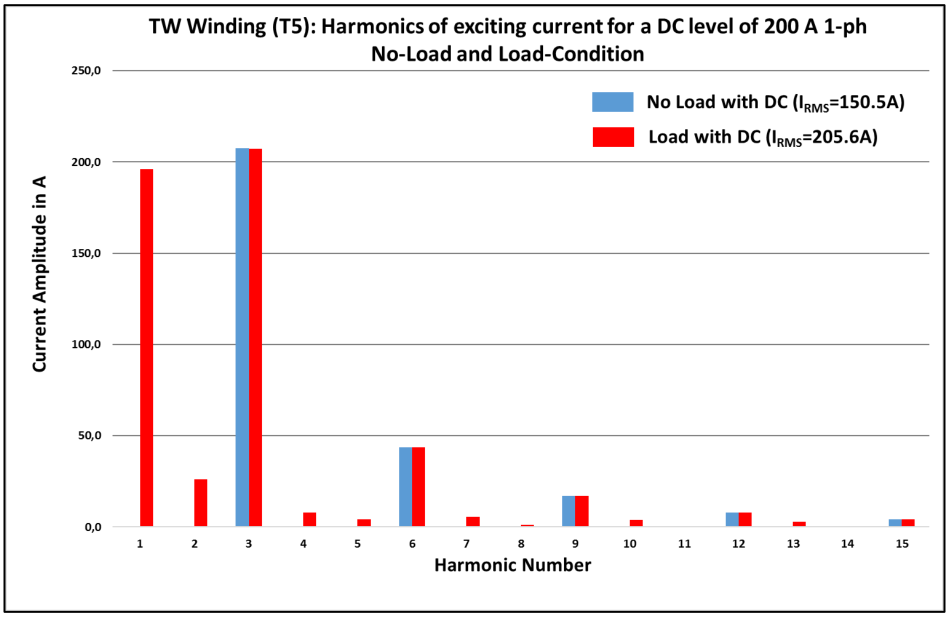


Figure 1-12
Spectrum of tertiary circulating current with 200 A DC per phase of transformer T5 (loaded vs. unloaded TW winding, harmonic no. 1 = fundamental component)

Behavior of I^2R- and Eddy Losses (Loaded TW Condition)

I^2R- and Eddy Losses in TW of T1, T3, T5 and T7

Figure 1-13, Figure 1-14, Figure 1-15 and Figure 1-16 show for the highest DC level (200 A DC per phase) the loss difference between the loaded and unloaded TW condition for transformer T1, T3, T5 and T7. In addition, also the losses are shown, when the TW windings have their nominal AC load without DC. The reasons why these transformers are chosen are explained above with Figure 1-6, Figure 1-7, Figure 1-8 and Figure 1-9.

Of course, the losses in the TW winding increases with DC compared with the nominal AC condition without DC. The first reason is, that the I^2R losses increase due to the higher RMS value of the TW current in case of DC due to the circulating current. However, based on the nominal load of the winding, the I^2R losses can be very small when they are compared to the eddy losses (see transformer T3). The second reason is the significant increase of the eddy losses compared to the nominal condition. Here must be noted, that the eddy losses under DC are almost the same between the loaded and unloaded condition. This indicates, that the dominating additional loss component due to the DC (the eddy losses) is the same between loaded and unloaded condition.

However, it can also be seen from the figure, that when the TW winding is loaded, no critical temperatures will be reached with an additional DC level up to 200 A DC per phase in the high-voltage winding. The loss conditions in the windings are far below a critical level.

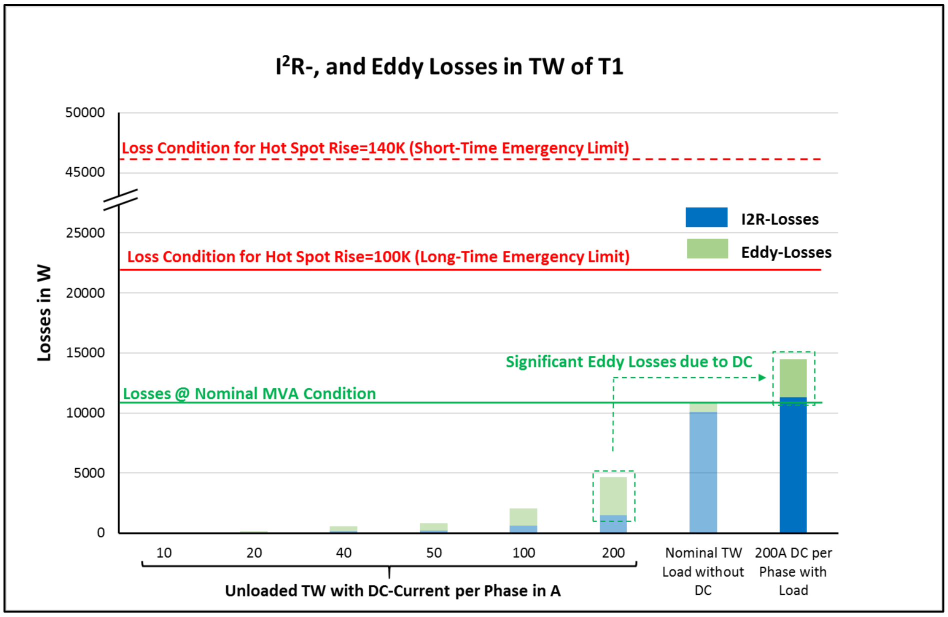


Figure 1-13
I2R- and Eddy Losses of T1 with DC (loaded vs. unloaded TW condition)

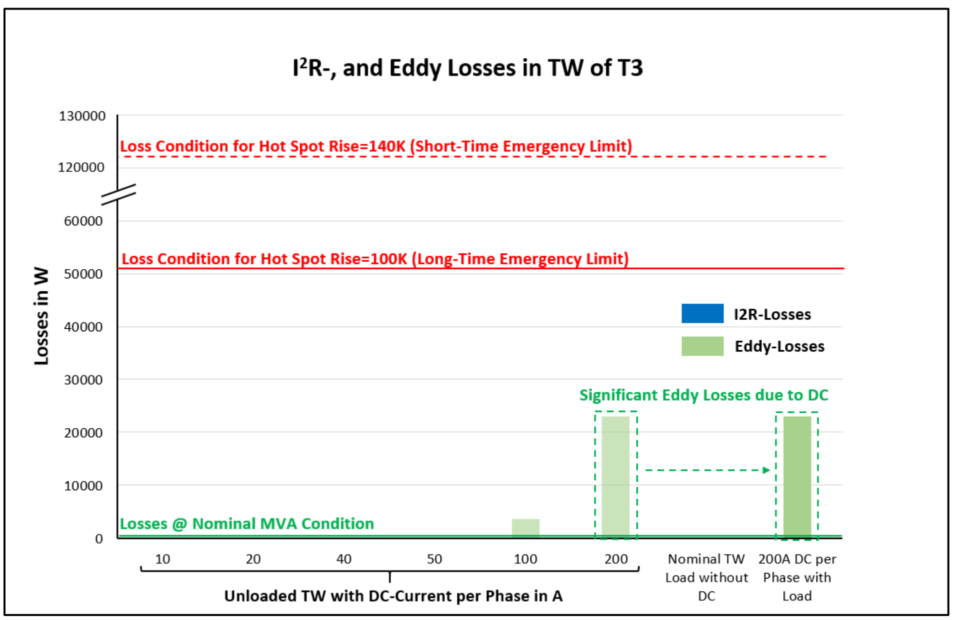


Figure 1-14
I2R- and Eddy Losses of T3 with DC (loaded vs. unloaded TW condition

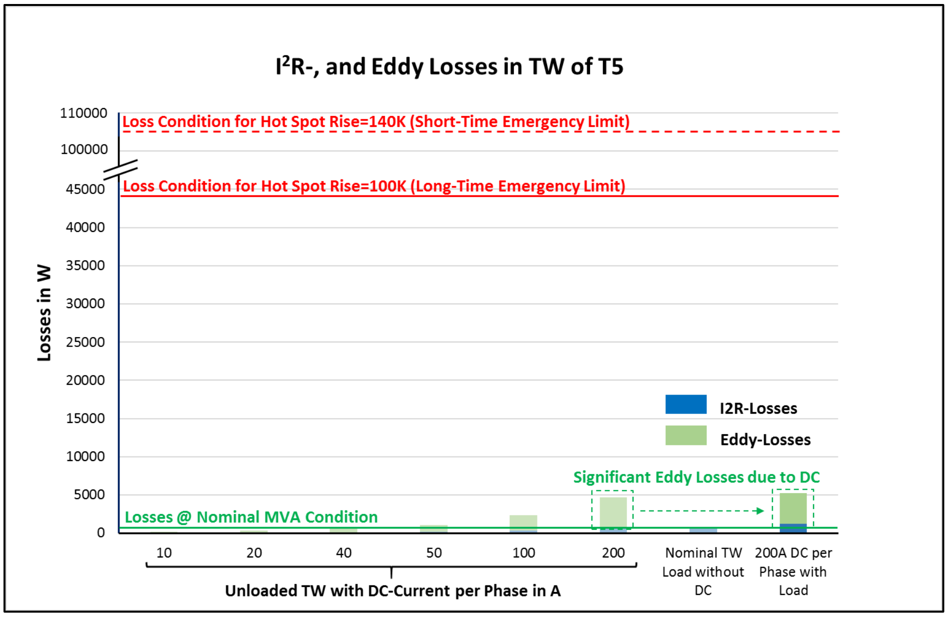


Figure 1-15
I2R- and Eddy Losses of T5 with DC (loaded vs. unloaded TW condition)

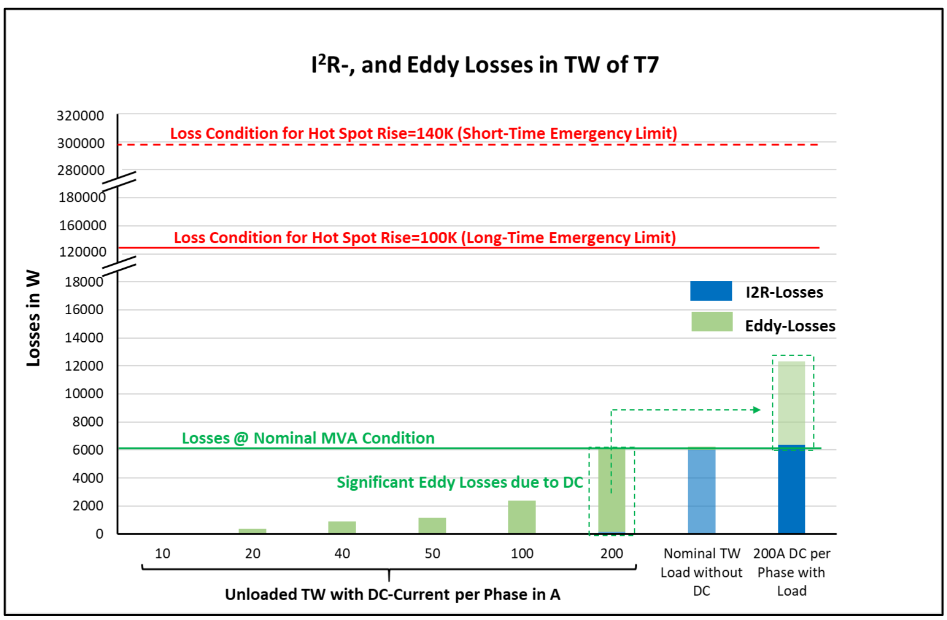


Figure 1-16
I2R- and Eddy Losses of T7 with DC (loaded vs. unloaded TW condition)

Influence Type in TW Winding of Conductor on DC Capability

When the eddy loss increase of Figure 1-13 to Figure 1-16 is studied, then it can be seen that especially transformer T3 has a relatively high eddy loss increase with DC. Furthermore, Figure 1-10 shows, that the steady-state hotspot temperatures in the TW winding of transformer T3 are the highest once.

A reason for this behavior was the flat conductor (rectangular copper conductor) in the TW winding. In order to verify this reason, another transformer with a flat conductor in the TW winding was investigated. This transformer is T7. T7 has similar technical data like T1 (both 5 LEG, similar number of turns, etc.). Although, the transformer T7 has a flat conductor in the TW-winding and the additional hotspot temperature rises in the TW winding, due to the DC-currents, are very low. At first, this was an unexpected result. To verify this behavior, also the transformer T1 was simulated with a realistic flat conductor in the TW-winding. The results of this assumption are shown in Figure 1-17. It can be seen, compared to Figure 1-13, that the eddy losses increase dramatically. Here the sum of losses with 200 A DC (no-load and load condition) exceed the limit for long-time emergency limit.

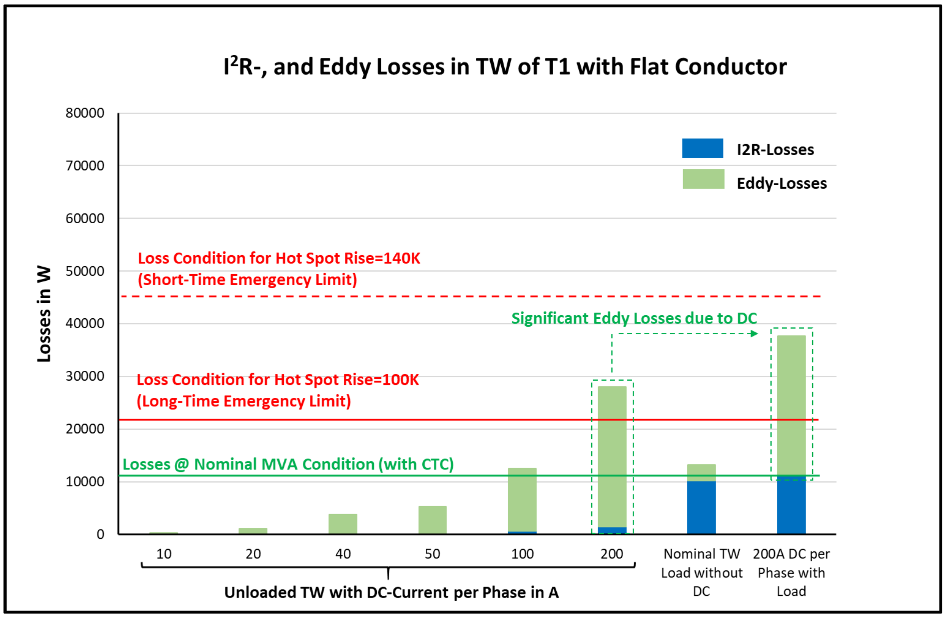


Figure 1-17
I2R- and Eddy Losses of T1 with DC and assumed flat conductor in the TW-winding (loaded vs. unloaded TW condition)

This raises the question why the increase of losses in transformer T1 with flat conductor is significant but not for T7. The answer is given with the induced voltage in tertiary winding due the unsymmetrical core saturation and the resulting circulating current.

In Figure 1-18 the induced voltage and in Figure 1-19 the circulating current in the TW winding of T1 and T7 is shown. It can be seen, that the induced voltage in the TW-winding of T1 and T7 are nearly the same, but the resulting circulating currents are very different. The reason for this behavior is that not only the inductance of the tertiary winding itself determines the circulating current for a certain induced voltage. It is very common that autotransformers have installed a current limiting reactor in the delta-connected TW winding. This current-limiting reactor is an additional reactor (inductance) in the transformer tank to limit the tertiary fault currents in case of an external short circuit in the power grid. This short-circuit current limiting reactor in transformer T1 has an inductance of 0.84mH, whereas the current limiting inductance of T7 is 2.54mH. So, the inductance of this current limiting reactor of T7 is approximately three times higher than the inductance of T1. Therefore, the current in the TW-winding of T7 is much lower, than the current in the TW-winding of T1 and as a result also the additional eddy losses under DC are much lower.

As conclusion it can be stated: The use of a flat conductor in the TW-winding does not necessarily have to lead to high hotspot temperatures. Only when the transformer has no or a very low short-circuit current limiting inductance, then the temperatures in the TW winding can exceed the long-time emergency limit when an additional DC current is flowing in the high-voltage winding.

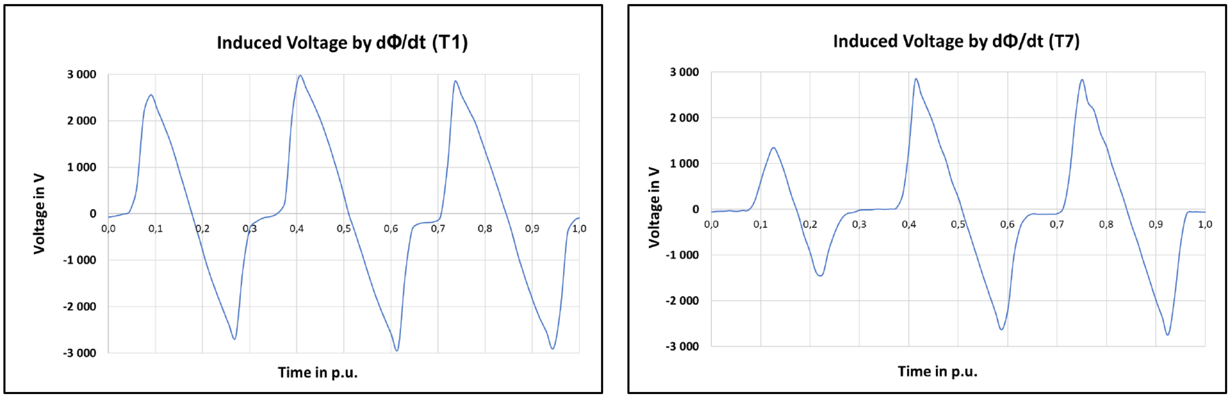


Figure 1-18
Induced voltage of T1 and T7 in the TW-winding with 200 A DC

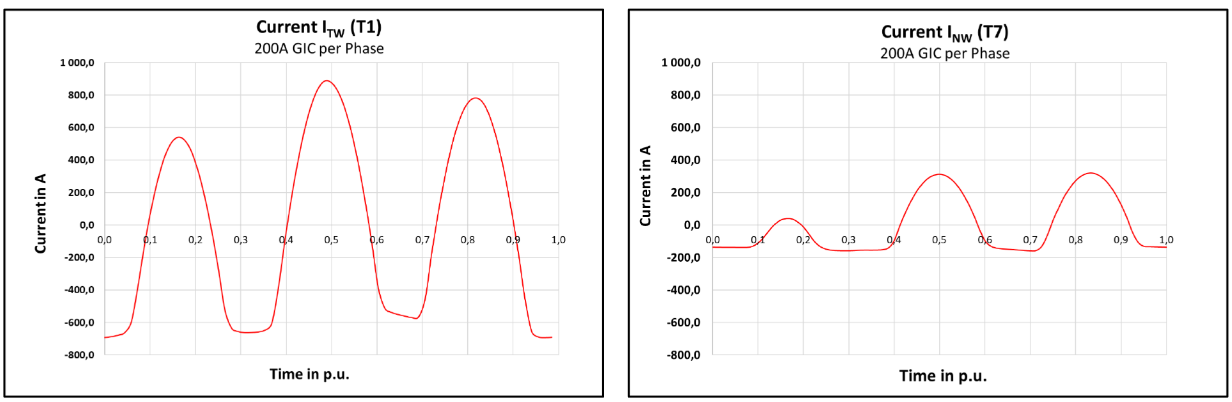


Figure 1-19
Current wave form of T1 and T7 in the TW-winding with 200 A DC

Conclusion

This study shows, that circulating currents with significant harmonics occur in delta-connected windings (TW windings), when a DC current is present in the high-voltage system of a transformer. For single-phase and five limb core transformers the increase of this circulating current starts already at very low DC levels near zero. This contrasts with three-limb cores where a certain amount of a DC must be present in the high-voltage winding before a circulating current occurs. The reason is given by the core saturation as shown in Figure 1-4.

It is also shown, that the losses in the TW winding increases due to the core saturation, especially the eddy losses rise significantly compared to the nominal condition without DC. Nevertheless, the study shows, that no critical steady-state temperatures are reached, even with 200 A DC per phase in the high-voltage winding. The hotspot rises of all seven investigated transformers are below 140 K (IEEE short-time emergency limit at 40 °C ambient). The study shows, that the nominal condition of losses (nominal rating) can be easily exceeded due to DC, but the nominal condition is not meaningful for the real thermal capability of the TW windings of the investigated transformers. The reason is, that the windings which have a very low nominal rating have also a very low nominal current density. Therefore, the real thermal capability of winding is significant higher, and the noticeable eddy loss increase under DC was still not an issue for these seven investigated transformers. That means for the investigated transformers are even DC levels up to 200 A DC not problematic. However, it must be noted that the TW winding in transformer T3 shows a much higher eddy loss increase as the other ones. One reason is that this winding uses not a Continuously Transposed Conductor (CTC) in the TW winding. This type of winding design might occur in older transformers with low TW winding rating compared to the main winding rating. In present transformer designs it is very common to use CTCs for the tertiary winding in order to get lower load losses. However, the hotspot temperature is even with DC for this investigated winding of T3 below a critical level, because the nominal rating of the winding is low and it is a three-phase, 3-leg transformer which has a higher DC capability due to the core type.

Nevertheless, this observation shows, when rectangular copper conductors are used in TW windings, significant heating under DC may be possible. However, it could be shown in this study, that the usage of a flat conductor in the TW-winding does not necessarily lead to critical high hotspot temperatures. It is only when the TW winding is made with a flat conductor and the transformer has a very low short-circuit current limiting inductance, then the temperatures in the TW winding can exceed higher temperature levels when an additional DC current is flowing in the high-voltage winding. Albeit, in the configurations studied under this research even the case where the two most susceptible configurations were combined – no TW winding exceeded the short-term emergency heating limits.

2
DC WITHSTAND CAPABILTY STUDY ON TIE BARS

General

This chapter investigates the DC withstand capability of tie bars nearby the core in power transformers. In order to investigate the impact of DC, different types of transformers have been studied. This includes different core designs, winding geometry, voltage levels, etc. Table 2-1 shows the main technical data of the transformers under investigation. It can be seen, that in total 42 transformers have been analyzed by this study. The used simulation models and their verification and background are briefly discussed in the Appendix A and in [1], [2], [3], [4], [5], [6] and [7]. An individual report with the results of each individual unit is given in the electronic appendix of this document. The individual report can be identified by its Transformer No. (e.g. *TieBar_Heating_Study_Transformer_T1.pdf)*.

Table 2-1
Overview of transformer designs under investigation

Transformer No.	Core Type	HV rating	HV voltage	Type
-	-	MVA	kV	-
T1	1	92	526	GSU
T2	1	374	525	Auto
T3	2	500	525	Auto
T4	3	300	525	Auto
T5	3	560	525	Auto
T6	4	292	500	Auto
T7	4	672	500	Auto
T8	4	460	525	Auto
T9	5	840	500	Auto
T10	5	300	525	GSU
T11	2	100	735	GSU
T12	4	373.33	765	Auto
T13	4	750	746	Auto
T14	1	167	400	Auto
T15	1	360	420	Auto
T16	2	121,33	433	GSU
T17	2	94	410	GSU
T18	3	750	420	Auto
T19	3	160	400	GSU
T20	4	570	405	GSU
T21	5	450	405	TRA
T22	5	310	400	GSU
T23	5	910	420	GSU
T24	1	100	335	Auto
T25	1	133.33	345	Auto
T26	3	120	275	TRA

Transformer No.	Core Type	HV Rating	HV Voltage	Type
-	-	MVA	kV	-
T27	3	500	275	Auto
T28	3	200	330	Auto
T29	4	500	345	GSU
T30	5	500	345	Auto
T31	5	800	345	Auto
T32	5	315	345	GSU
T33	1	133.33	230	Auto
T34	1	66,6	231	Auto
T35	2	100	230	GSU
T36	3	160	230	Auto
T37	3	290	230	GSU
T38	3	420	230	Auto
T39	4	300	242	GSU
T40	4	466	240	GSU
T41	5	240	225	GSU
T42	5	560	230	Auto

Core type description:

1…Single-phase, core-form: one wound limb, two-flux return limbs (1LEG)
2…Single-phase, core-form, two wound limbs (2LEG)
3…Three-phase, core-form: three-wound limbs (3LEG)
4…Single-phase, core-form, two-wound limbs, two-flux return limbs (4LEG)
5…Three-phase, core-form: three-wound limbs, two-flux return limbs (5LEG)

However, to include in this study also potential differences in the tie bar design, and not only variations in basic transformer data as shown in Table 2-1, also the thermal impact of two different tie bar geometries has been investigated. Figure 2-1 shows an example for such geometry assumptions. Design 1 represents a solution where flat bars are used, cooled on both sides, whereas Design 2 assumes nearly square bars, cooled only at one side. This assumption was done to study a potential range of achievable temperatures with various realistic designs. These two design cases can be seen as two extremes in order to cover the worst- and best-case condition. However, these designs were chosen in order to investigate these design differences and the transformers listed in Table 2-1 are not necessarily designed with one of the assumed extreme conditions. The real design is somewhere between these two extremes.

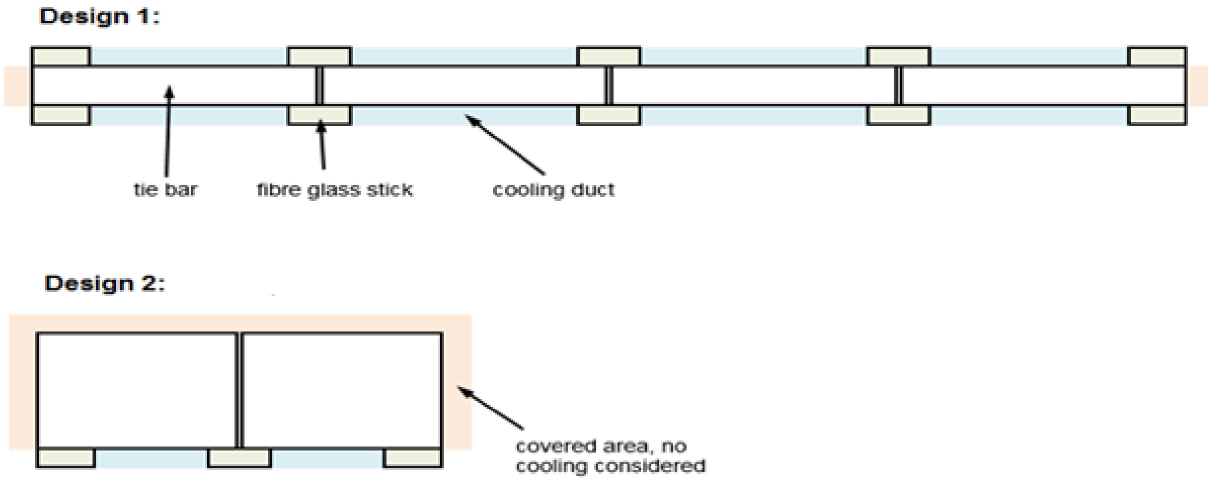


Figure 2-1
Example of used tie bar geometries

Summary of Results

Figure 2-2 compares the results of each investigated transformer in this study. It can be seen, that Design 1 (blue points) represents an optimized solution in order to reach a high DC withstand capability, whereas Design 2 (red points) shows very high temperature rises, especially at higher DC levels. Furthermore, it can be seen, that especially for Design 2 the transformer design-specific data (core design, winding geometry, number of turns, etc.) have a big influence on the heating of the tie bar with a DC in the high-voltage winding. At the same DC level, the temperature rise between the 42 transformers varies significantly. This shows, that the design-specific parameters must be known in order to identify correctly the heating of the tie bar under the presence of a DC current in the high-voltage winding.

It should be mentioned, that Transformer T24 was identified as most critical unit within the investigated units. However, a deeper look in the technical data of this transformer shows, that this transformer has a very high number of turns in the high-voltage winding (N=1467), which is one reason for the extremely high temperature rise. E.g. 25 A DC in a transformer with 1000 turns causes approximately the same DC excitation as 50 A DC in a transformer with 500 turns. This means not the DC level is relevant, it is always the DC current multiplied with the DC carrying turns.

Furthermore, it should be noted, that Figure 2-2 shows steady-state temperature rises due to DC. However, DC pulses in respect to GIC have normally only durations of several seconds up to maximal few minutes. That means, to calculate the heating for such short durations, the transient thermal behavior of the tie bar must be considered. This can be done with a thermal time constant, which depends also on the tie bar design. Reasonable values for the thermal time constants are four minutes for Design 1 and eight minutes for Design 2. In that way, the heating of the tie bar can be also calculated for a certain DC profile as shown in the individual report of each investigated transformer.

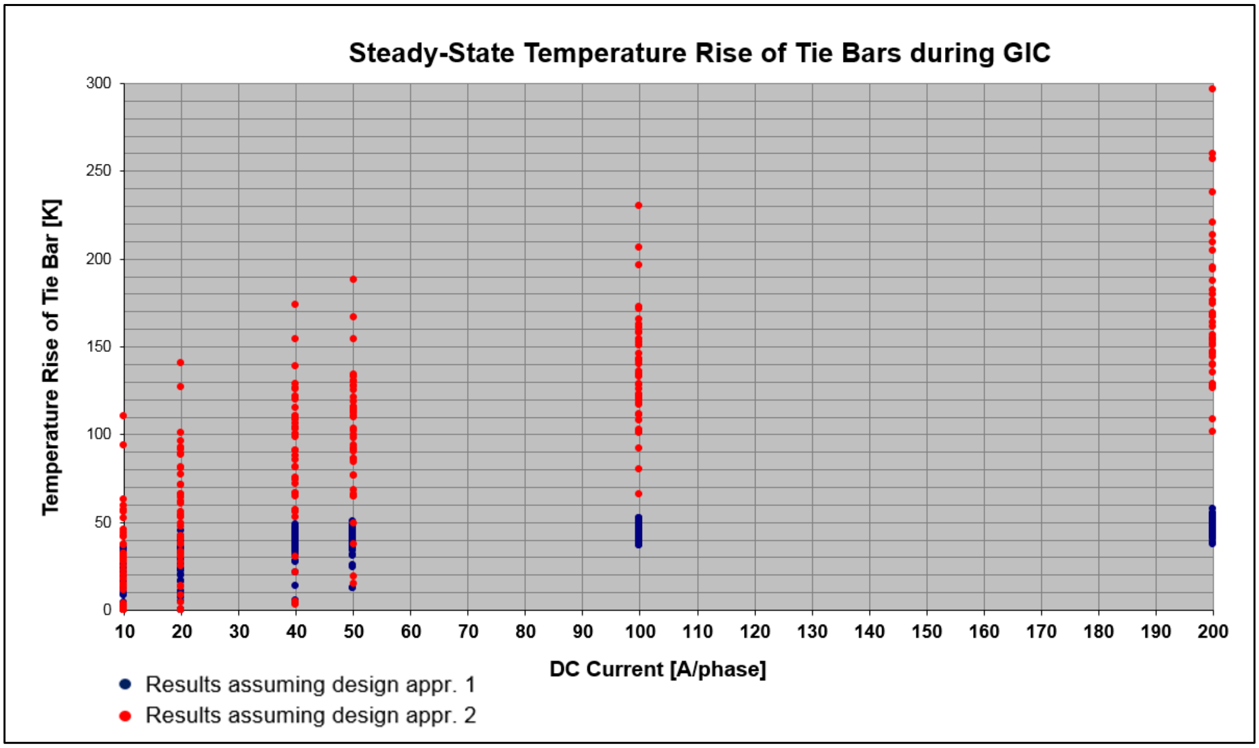


Figure 2-2
Steady state temperature rises (above top oil) of investigated designs

Conclusion

This DC withstand capability study on tier bars shows, that structural parts can be significantly heated with an additional DC current in the high-voltage winding of the transformer. Especially when DC effects are not considered in the design, then very high steady-state hotspot temperatures are possible which exceed the long-time as well as the short time emergency limit of IEEE for structural parts (e.g. maximal 160 °C (long-time) and 200 °C (short-time) for structural parts in contact with glass fiber material). However, DC magnitudes which are caused by GIC have normally very short durations. In that case the transient thermal behavior of the tie bar (time constant) must be considered, in order to determine the transient thermal response to a certain DC profile.

This study also shows, that the required design-parameters of a transformer must be known in order to identify correctly the DC-caused steady-state tie bar heating, because it is influenced significantly by different design parameters. The major parameters, in addition to the core-type, are the number of DC carrying turns, the geometry and the cooling condition of the tie bars and the height and diameters of the excited winding. Consequently, the knowledge of the required design-parameters is fundamental to evaluate the heating with an additional DC current in the high-voltage winding.

3
REFERENCES AND ABBREVIATIONS

References

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2. J. Raith and U. Schichler, “Risk Assessment of Electrical Equipment under the Influence of GIC.” Paper presented at CMD conference, Xi’An, China (2016).
3. J. Raith and S. Außerhofer, “GIC strength verification of power transformers in a high-voltage laboratory.” Paper presented at University of Cape Town – GIC workshop, South Africa (2014).
4. J. Raith, B. Wagner, and S. Außerhofer, “Risk evaluation for power transformers during solar storms.” Paper presented at CIGRE SC A2 Joint Colloquium, Zürich, Switzerland (2013). Report PS1-IE037.
5. W. Seitlinger, “Transformer model, based on the magnetic circuit.” Paper presented at CIGRE, Paris, France (2006). Report A2-205.
6. O. Bíró, G. Koczka, G. Leber, K. Preis, and B. Wagner, “Finite Element Analysis of Three-Phase Three-Limb Power Transformers Under DC Bias,” *IEEE Transactions on Magnetics*. Vol. 50, No. 2, pp. 565–568 (2014).
7. O. Bíró, G. Koczka, and K. Preis, “Finite element solution of nonlinear eddy current problems with periodic excitation and its industrial applications,” *Applied Numerical Mathematics*. Vol. 79, pp. 3–17 (2014).
8. J. Raith, *Risk Assessment of Power Transformers under the Influence of GIC*. Doctoral thesis at Graz University of Technology, Styria, Austria, 2019.

Abbreviations

AC	Alternating Current
AUT	Auto Transformer
CTC	Continuously Transposed Conductor
CW	Common Winding
DC	Direct Current
GIC	Geomagnetically Induced Current
GMD	Geomagnetic Disturbance
GSU	Generator Step-up Transformer
H1...H3	High Voltage terminals
HS	Hot spot temperature rise
HV	High Voltage
Hz	Hertz
IEEE	Institute of Electric and Electronic Engineers
NERC	North American Electric Reliability Corporation
R	Resistor

RMS	Root Mean Square
SW	Series Winding
T1…Txx	Transformer tags
TRA	Conventional transmission transformer (galvanic isolated windings)
TV	Tertiary Voltage
TW	Tertiary Winding
Tx (yLEG)	Transformer x indicating the core type yLEG
Y1...Y3	Low Voltage terminals

A
MODEL BACKGROUND

The simulation models which were used to investigate the behavior of the TW windings and the tie bars in this study are developed by Siemens. This means the basis of this study are suitable electro-magnetic models and thermal models, which take the specific designs of the transformers into consideration. It must be noted that these models are also verified with high-sophisticated FEM-3D techniques ([6], [7]) and unique GIC measurements ([1], [2], [3], [4]). This means, several DC experiments with different types of transformers has been performed in a Siemens high-voltage laboratory in order to ensure correct modeling approaches. It total were five transformers where tested regarding their electro-magnetic and thermal response to different DC levels. This includes, three-limb and four-limb, single-phase transformers as well as three-limb and five-limb, three-phase transformers. However, not only the thermal response of the critical components was measured, also the quantity which causes the eddy loss heating in case of DC was verified by a measurement. This means, the validation process included also the measured magnetic flux in the tie bars in case of core saturation due to DC. As a result, a design-specific and measured validated temperature model for DC could be developed ([1], [2]). An example for measured and calculated temperatures during such a DC experiment is shown in Figure 3-1. It can be seen, that the calculation model simulates the measurement in an accurate manner.

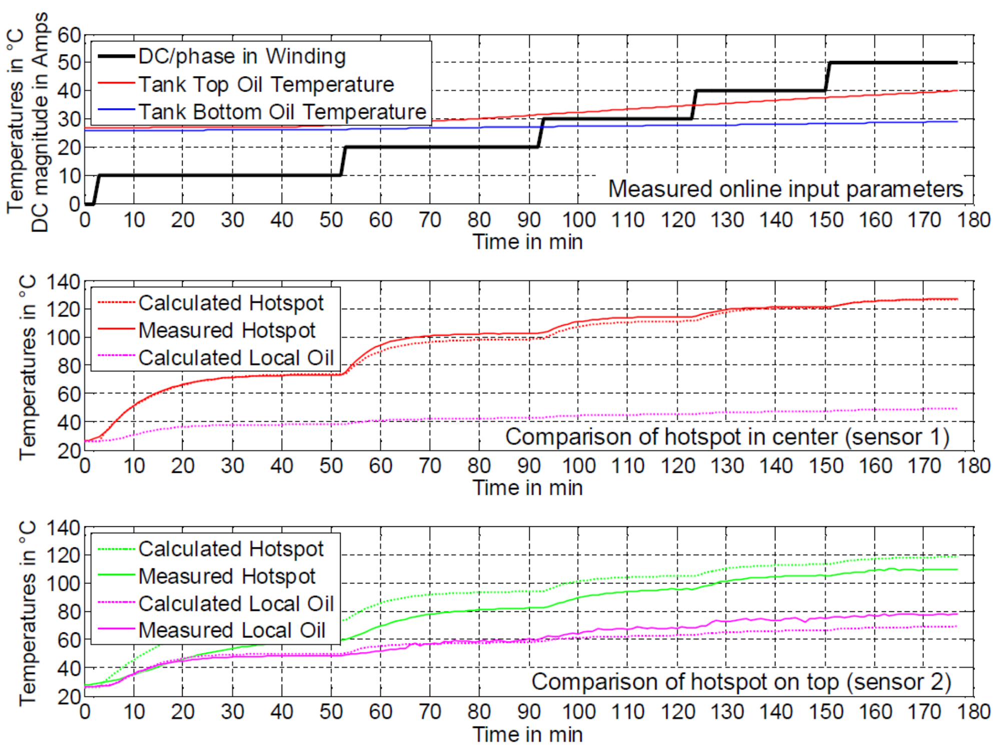


Figure A-1
Measured vs. simulated temperatures during a DC test [2]

Used modeling approaches in this document and verification methods are discussed in [8]. However, different literature which show already parts of this thesis is already available which can be found in [1], [2], [3] and [4]. Details of the used models are given in [5], [6] and [7].

B
CORE TYPES

1…Single-phase, core-form: one wound limb, two-flux return limbs (1LEG)

2…Single-phase, core-form, two wound limbs (2LEG)

3…Three-phase, core-form: three-wound limbs (3LEG)

4…Single-phase, core-form, two-wound limbs, two-flux return limbs (4LEG)

5…Three-phase, core-form: three-wound limbs, two-flux return limbs (5LEG)

Core Type 1:

Single-phase, core-form: one wound limb, two-flux return limbs (1LEG)

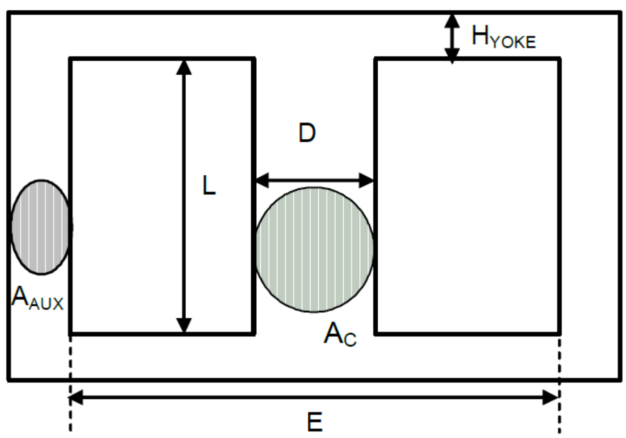


Figure B-1
Sketch of geometry of core type 1

Core Type 2:

Single-phase, core-form, two wound limbs (2LEG)

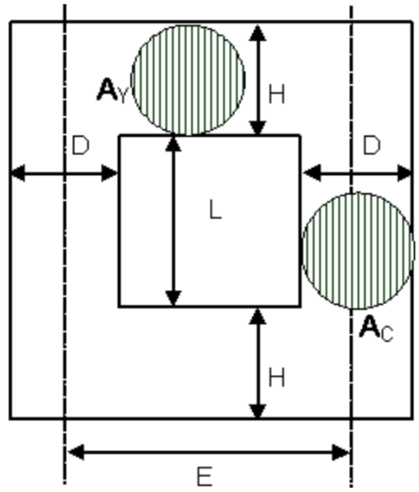


Figure B-2
Sketch of geometry of core type 2

Core Type 3:

Three-phase, core-form: three-wound limbs (3LEG)

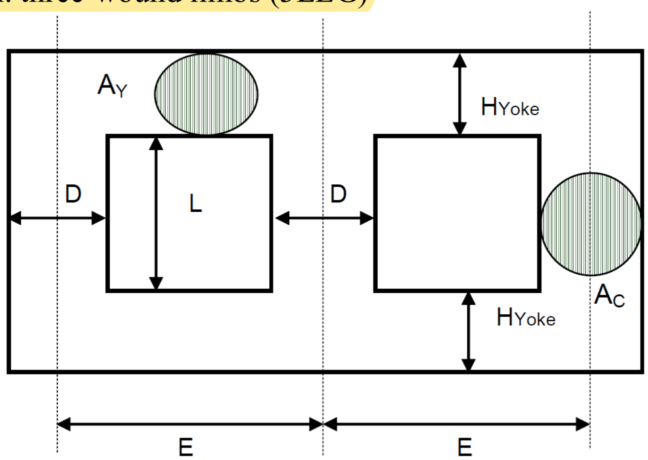


Figure B-3
Sketch of geometry of core type 3

Core Type 4:

Single-phase, core-form, two-wound limbs, two-flux return limbs (4LEG)

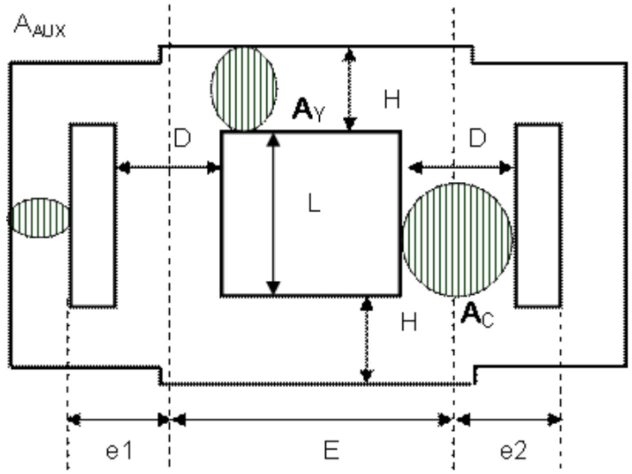


Figure B-4
Sketch of geometry of core type 4

Core Type 5:

Three-phase, core-form: three-wound limbs, two-flux return limbs (5LEG)

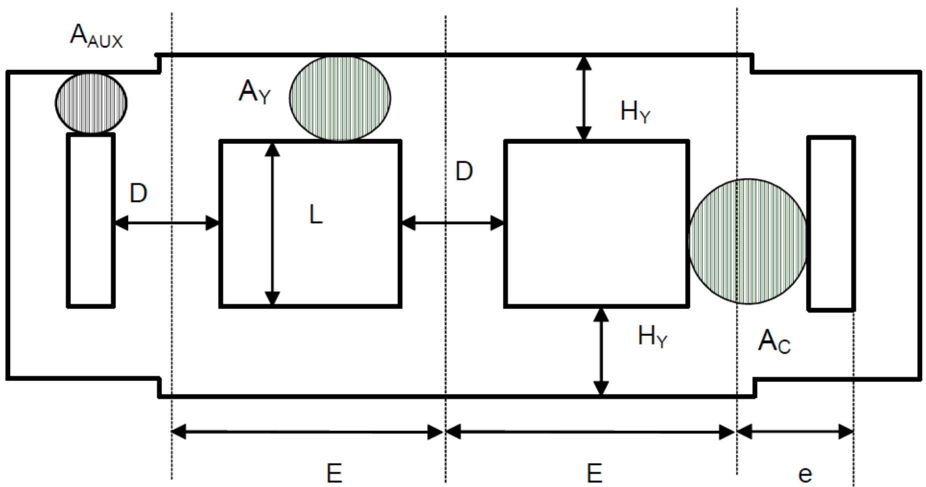


Figure B-5
Sketch of geometry of core type 5

C
LIST OF INDIVIDUAL REPORTS

EPRI – GIC Study

Task I: Study of Thermal Impact of GIC on Delta/Tertiary Windings

Transformer T1

Content

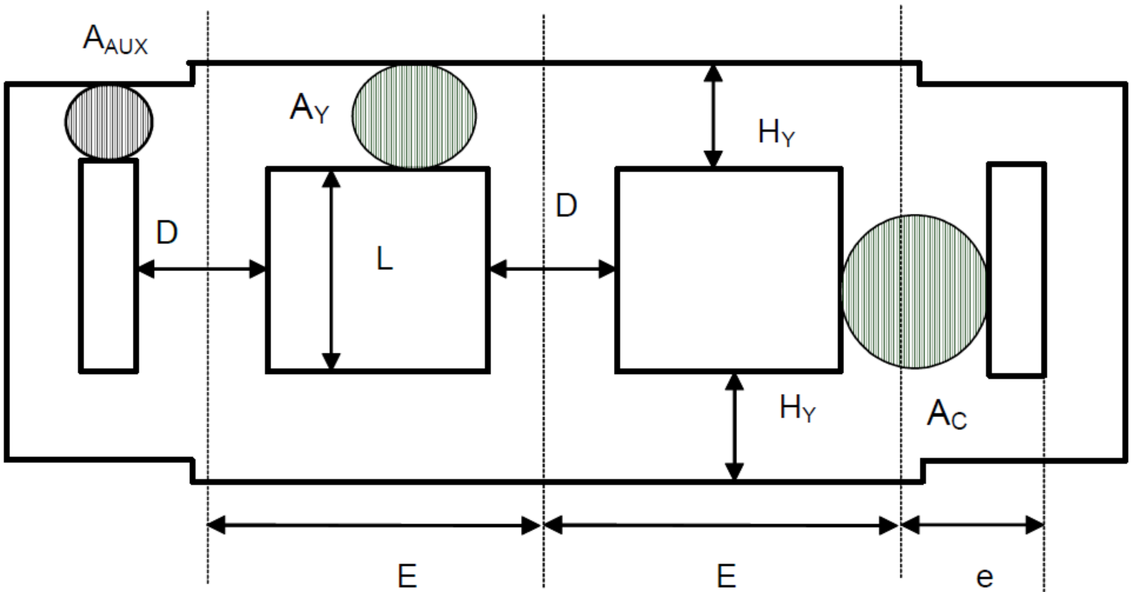
General Data

Transformer Data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T1
Transformer type	Auto
HV nameplate rating	560MVA
TW nameplate rating	56MVA
Number of phases	3
Voltage levels	218.5kV // 138kV // 13.2kV
Winding affected by DC	HV
Core type	5



L [mm]	2840
D [mm]	952
H_Y [mm]	540
E [mm]	2060
e [mm]	1050
A_C [m2]	0.6164
A_Y [m2]	0.3504
A_{Aux} [m2]	0.3091

Figure 1: Sketch of core geometry

DC Levels Overview

The report contains steady-state results for the electrical and thermal response of the tertiary winding for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Compensating Current Under DC

The current in the high-voltage and tertiary winding are calculated for each DC level. In order to identify only the effect of an additional DC current in the neutral of the high-voltage system an unloaded TV-system was simulated. Figure 2 shows the used electrical circuit. Figure 3 to Figure 8 show the calculated wave forms of the currents in both systems.

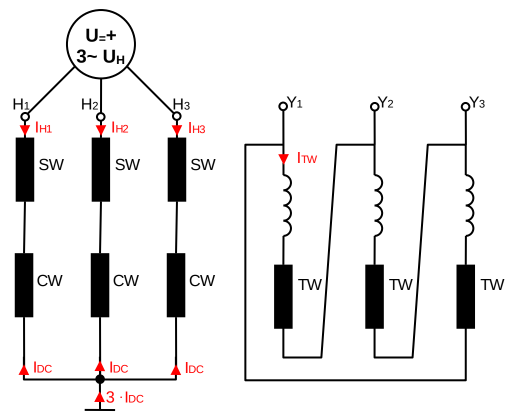


Figure 2: Electrical circuit (unloaded TV-system)

Current Wave Forms with 10A DC per Phase

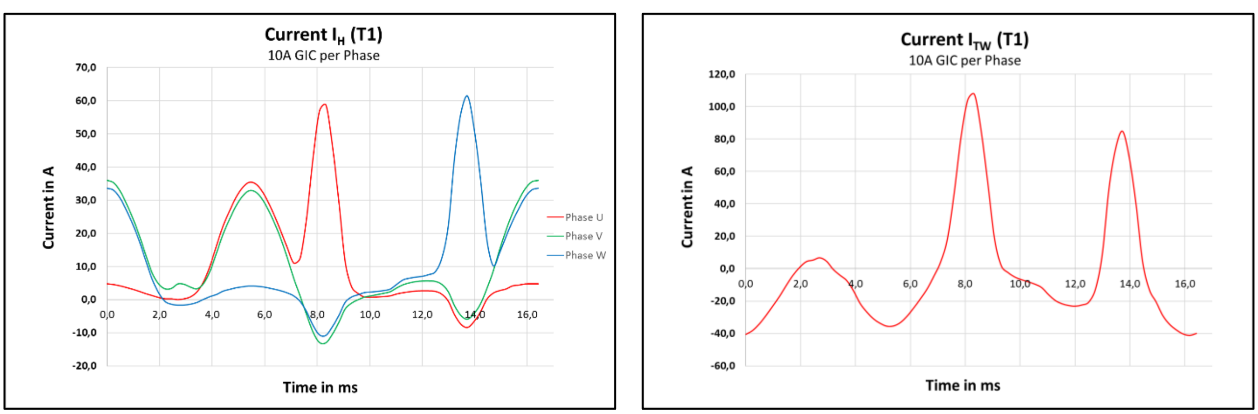


Figure 3: Current wave form with 10A DC per phase

Current Wave Forms with 20A DC per Phase

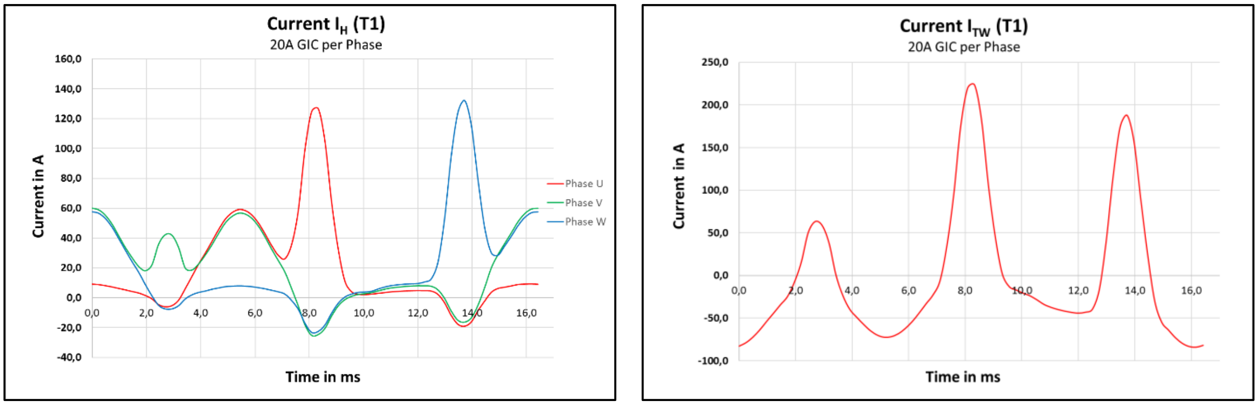


Figure 4: Current wave form with 20A DC per phase

Current Wave Forms with 40A DC per Phase

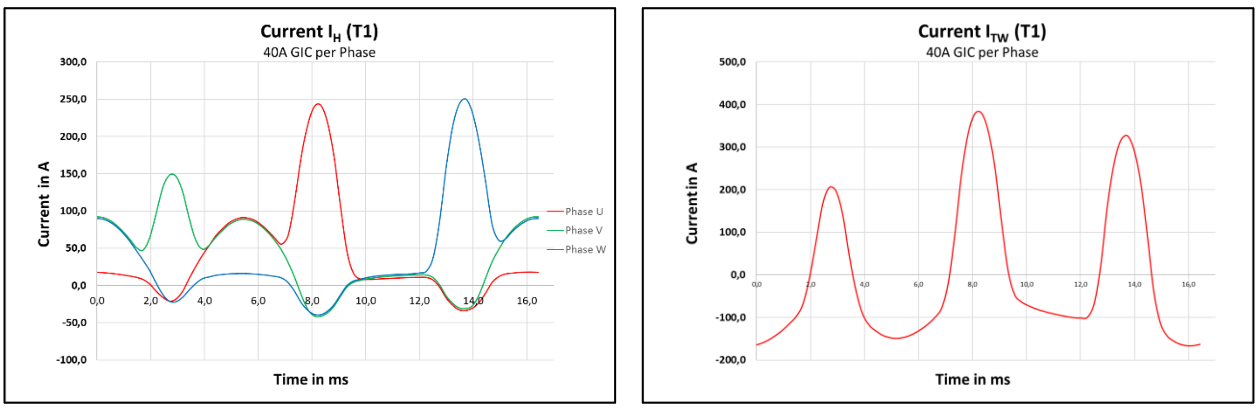


Figure 5: Current wave form with 40A DC per phase

Current Wave Forms with 50A DC per Phase

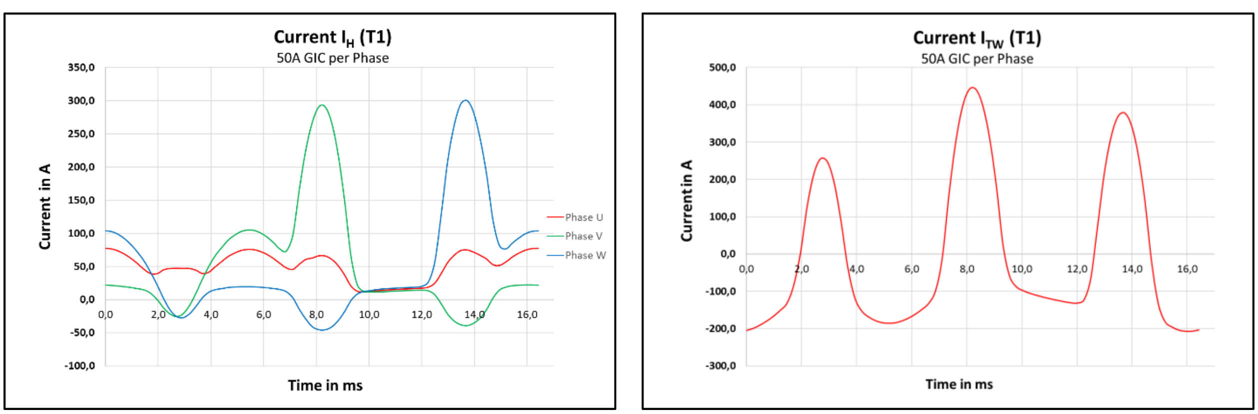


Figure 6: Current wave form with 50A DC per phase

Current Wave Forms with 100A DC per Phase

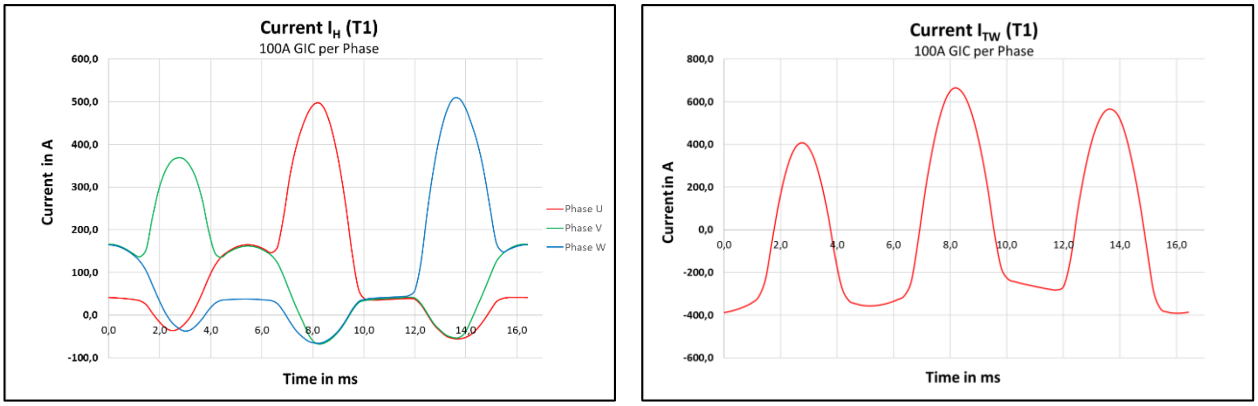


Figure 7: Current wave form with 100A DC per phase

Current Wave Forms with 200A DC per Phase

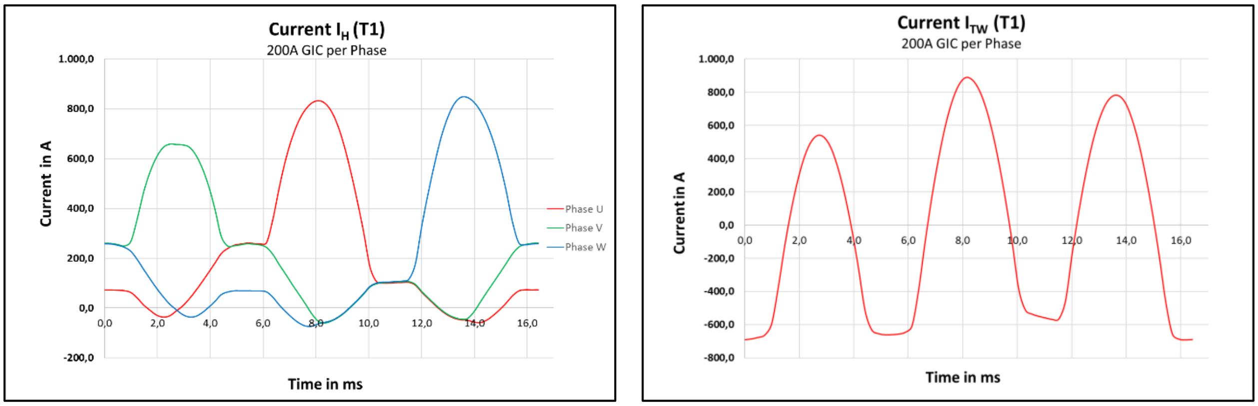
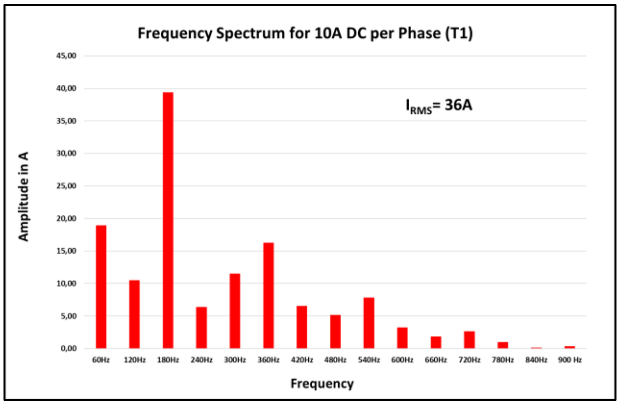


Figure 8: Current wave form with 200A DC per phase

Harmonics of Compensating Current

With the waveforms of Figure 3-8, an FFT analysis was done in order to demonstrate the different frequency components. Figure 9 to 11 show the harmonics of the compensating current in the TW winding with the different DC-currents in the high-voltage system. In addition, the RMS value of the current is shown in each figure.

Harmonics for 10A and 20A DC per Phase



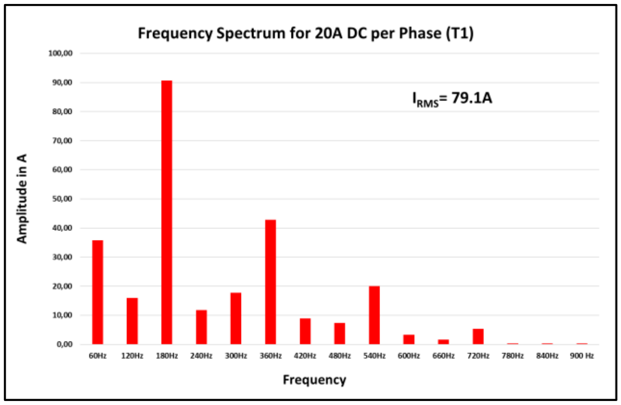
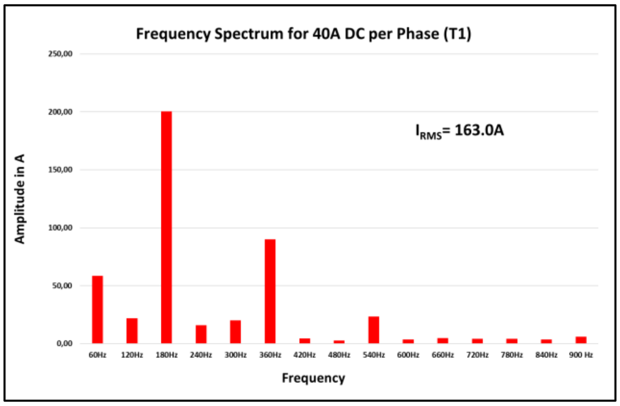


Figure 9: Harmonics for 10A and 20A DC per phase

Harmonics for 40A and 50A DC per Phase



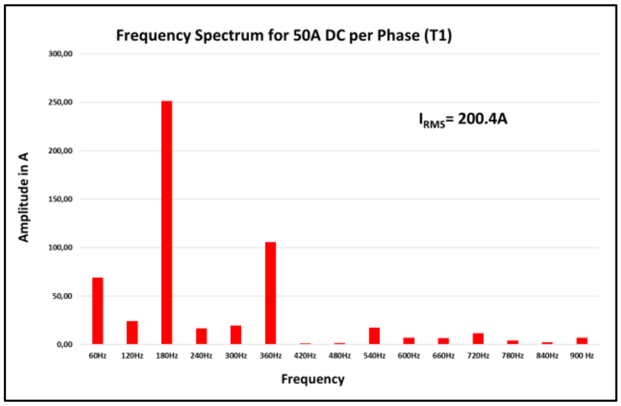


Figure 10: Harmonics for 40A and 50A DC per phase

Harmonics for 100A and 200A DC per Phase

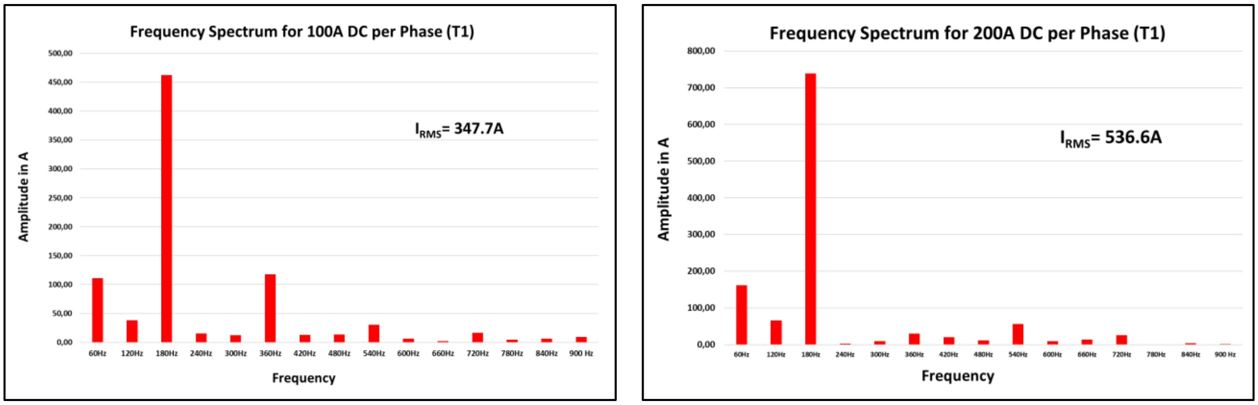


Figure 11: Harmonics for 100A and 200A DC per phase

TW "Loading" due to DC (RMS value of circulating current)

Figure 12 shows the "loading" of the TW winding due to DC. This means the RMS value of the circulating current under DC is shown in per unit of the rated AC current in the TW winding. The rated AC current of the TW winding is 1413.9A. It can be seen, that even with 200 A DC per phase the RMS value of the rated condition is not reached.

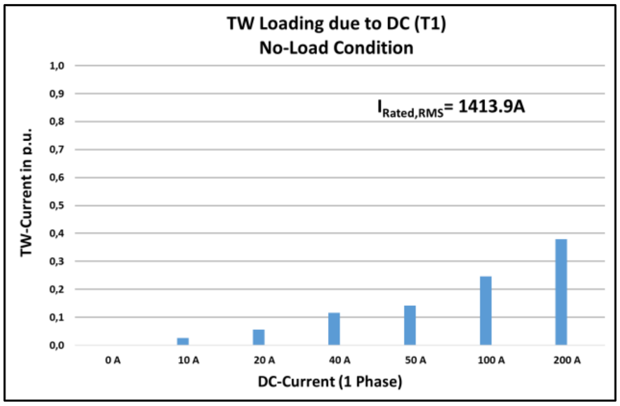


Figure 12: TW loading due to DC (No-Load Condition)

Thermal behavior under DC

The temperature rises of the tertiary winding, which are caused by the compensating currents of the previous clause are calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [K]	16
Top oil temperature [K]	54

Losses in Tertiary winding due to DC

The following table demonstrates the total losses in tertiary winding with different DC levels per phase in the high-voltage winding.

Table 3: Total losses of tertiary winding with DC

DC level per phase [A]	I^2R losses [kW]	Eddy losses [kW]
10	0.007	0.039
20	0.032	0.140
40	0.135	0.451
50	0.205	0.625
100	0.619	1.429
200	1.485	3.169

Steady-state hotspot temperature rise of tertiary winding above Topoil due to DC

The following table demonstrates the steady-state hotspot temperature rises (above ambient) in the tertiary winding for different DC levels.

Table 4: Hotspot temperature rise (above ambient) of TW winding with DC

DC level per phase [A]	Hotspot rise [K]
10	19.1
20	22.3
40	28.4
50	30.8
100	40.6
200	54.9

Graphical result for steady state temperature rises for different DC levels

Figure 13 shows the calculated steady-state hotspot rise of the tertiary winding for different DC levels. It can be seen, that the hotspot temperatures are far below critical levels (max. 100K, according to IEEE long time emergency condition at 40°C ambient).

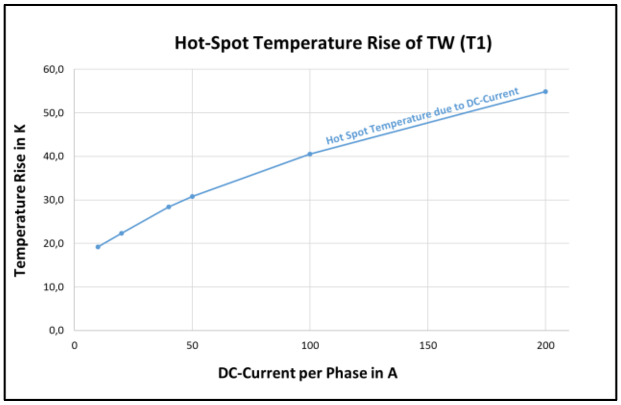


Figure 13: Hotspot temperature rise (above ambient) with DC

EPRI – GIC Study

Task I: Study of Thermal Impact of GIC on Delta/Tertiary Windings

Transformer T2

Content

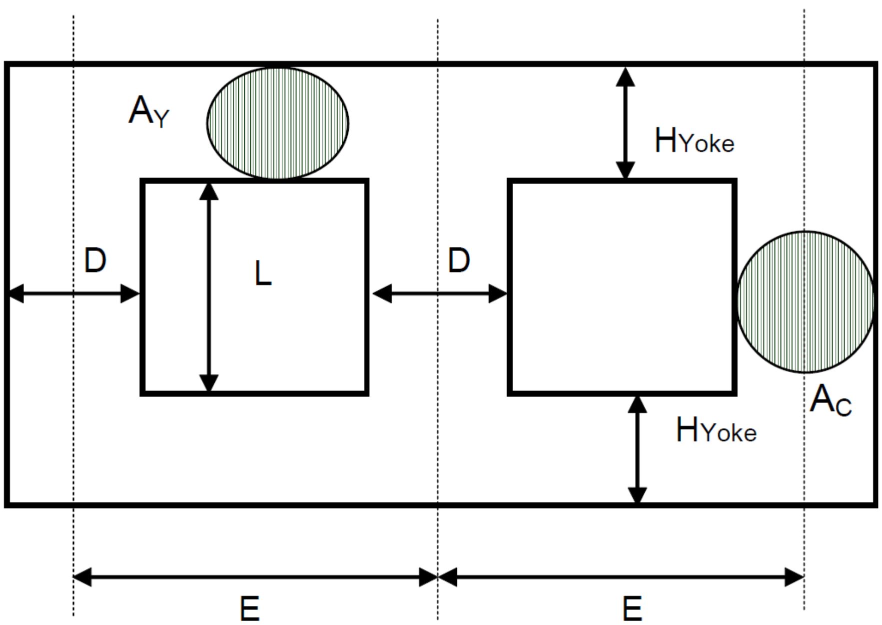
General Data

Transformer Data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T2
Transformer type	Auto
HV nameplate rating	420MVA
TW nameplate rating	10MVA
Number of phases	3
Voltage levels	335kV // 136kV // 13.2kV
Winding affected by DC	HV
Core type	3



L [mm]	1950
D [mm]	882
H_Y [mm]	850
E [mm]	2360
A_C [m2]	0.5461
A_Y [m2]	0.547

Figure 1: Sketch of core geometry

DC Levels Overview

The report contains steady-state results for the electrical and thermal response of the tertiary winding for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Compensating Current Under DC

The current in the high-voltage and tertiary winding are calculated for each DC level. In order to identify only the effect of an additional DC current in the neutral of the high-voltage system an unloaded TV-system was simulated. Figure 2 shows the used electrical circuit. Figure 3 to Figure 8 show the calculated wave forms of the currents in both systems.

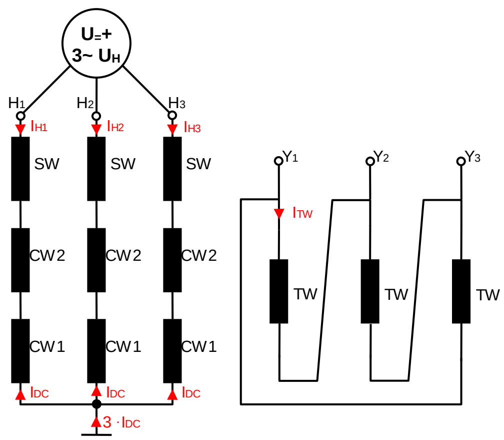


Figure 2: Electrical circuit (unloaded TV-system)

Current Wave Forms with 10A DC per Phase

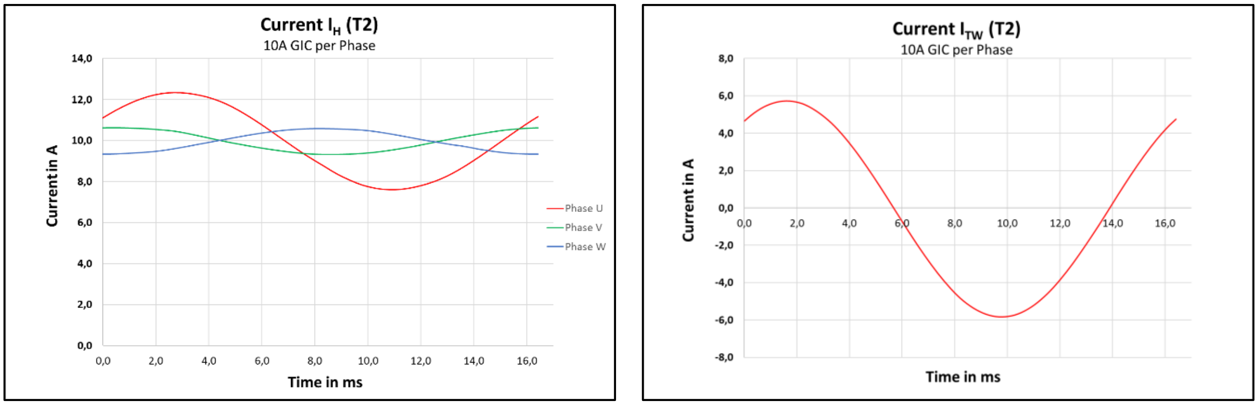


Figure 3: Current wave form with 10A DC per phase

Current Wave Forms with 20A DC per Phase

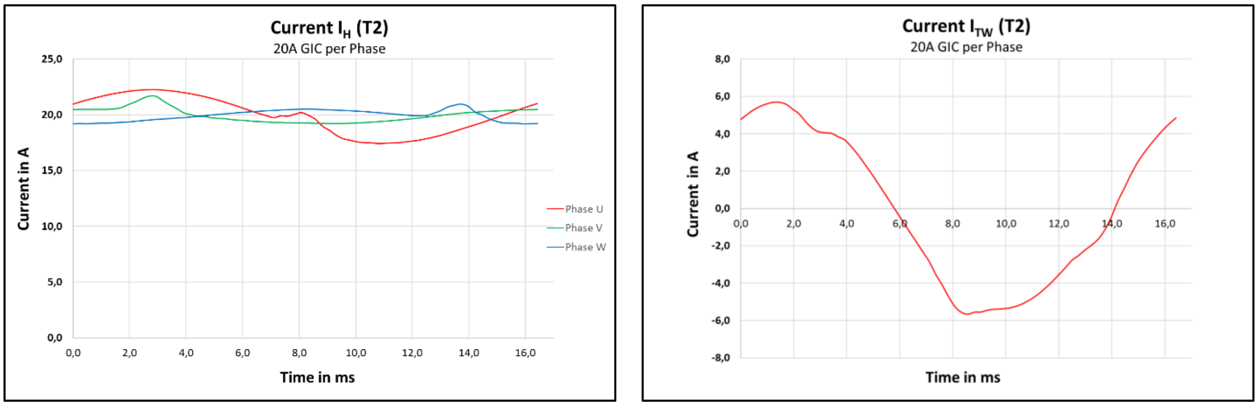


Figure 4: Current wave form with 20A DC per phase

Current Wave Forms with 40A DC per Phase

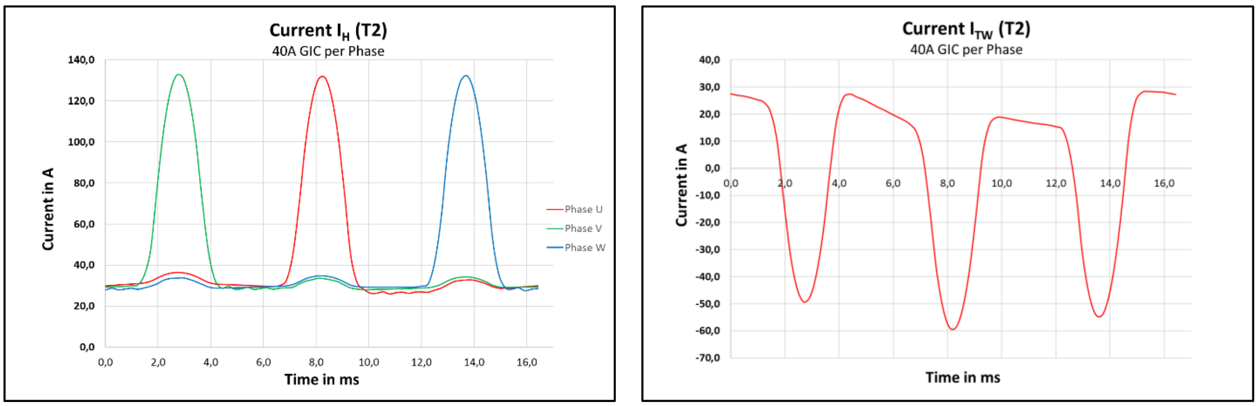


Figure 5: Current wave form with 40A DC per phase

Current Wave Forms with 50A DC per Phase

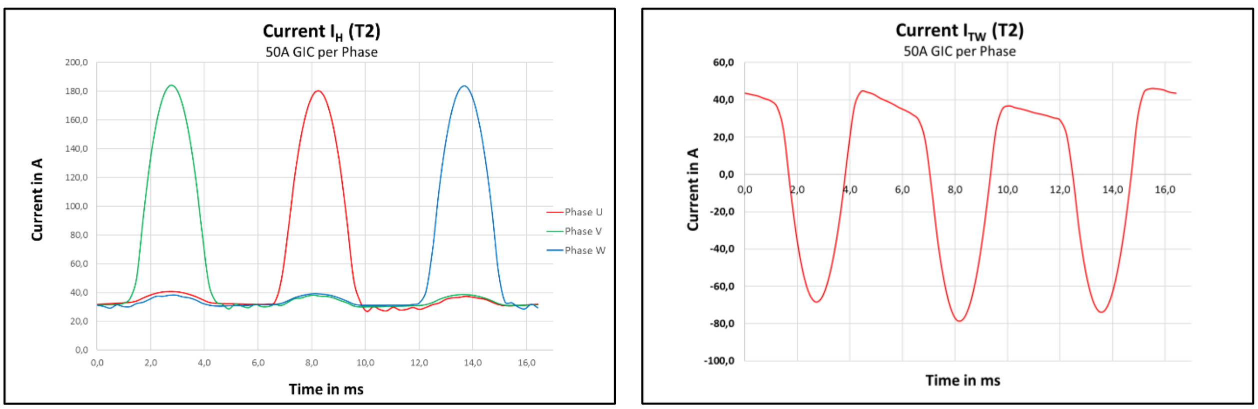


Figure 6: Current wave form with 50A DC per phase

Current Wave Forms with 100A DC per Phase

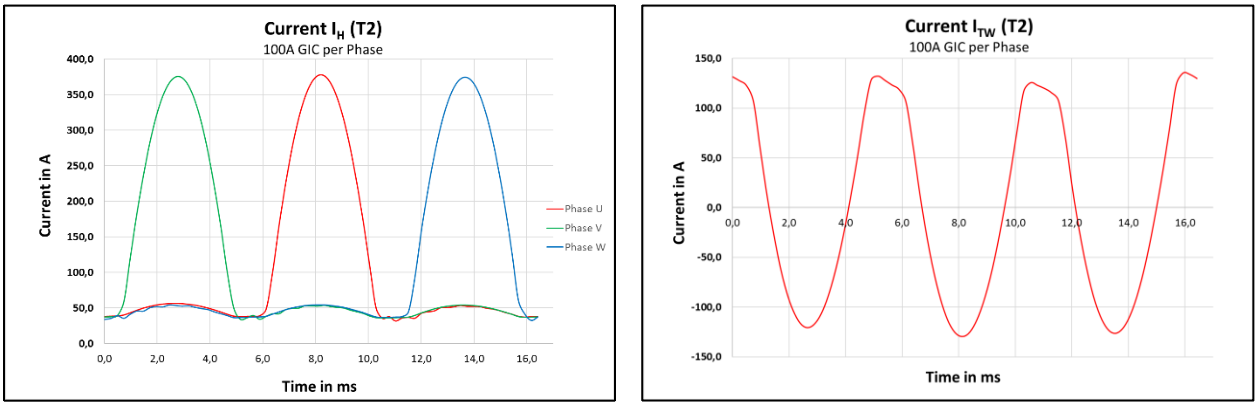


Figure 7: Current wave form with 100A DC per phase

Current Wave Forms with 200A DC per Phase

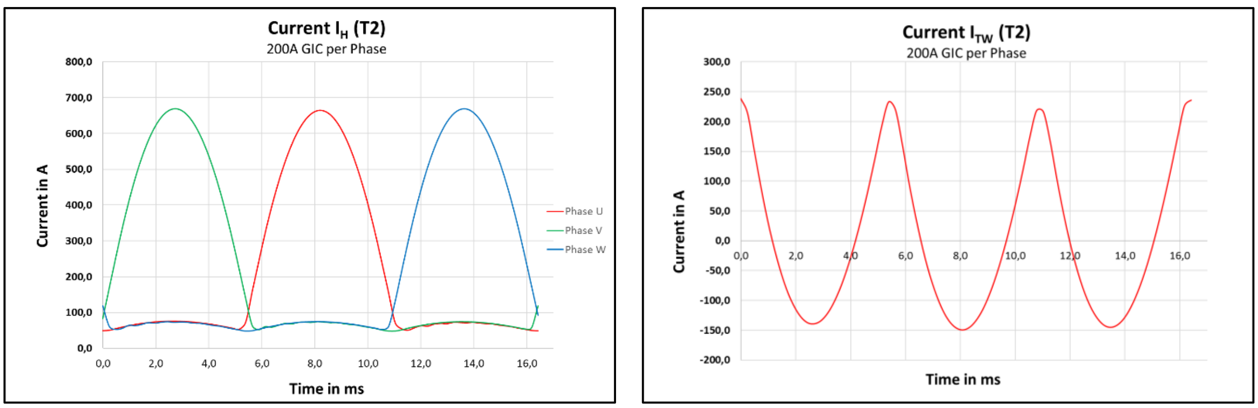


Figure 8: Current wave form with 200A DC per phase

Harmonics of Compensating Current

With the waveforms of Figure 3-8, an FFT analysis was done in order to demonstrate the different frequency components. Figure 9 to 11 show the harmonics of the compensating current in the TW winding with the different DC-currents in the high-voltage system. In addition, the RMS value of the current is shown in each figure.

Harmonics for 10A and 20A DC per Phase

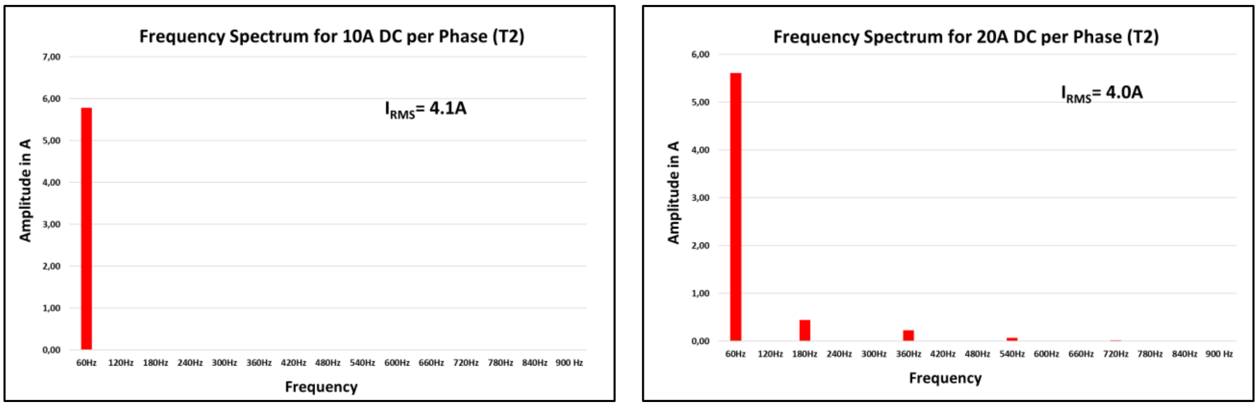


Figure 9: Harmonics for 10A and 20A DC per phase

Harmonics for 40A and 50A DC per Phase

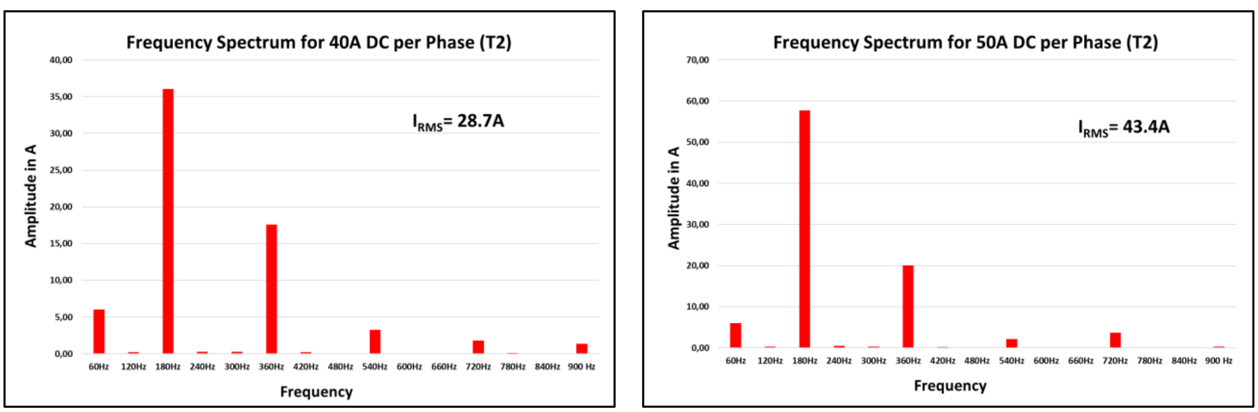


Figure 10: Harmonics for 40A and 50A DC per phase

Harmonics for 100A and 200A DC per Phase

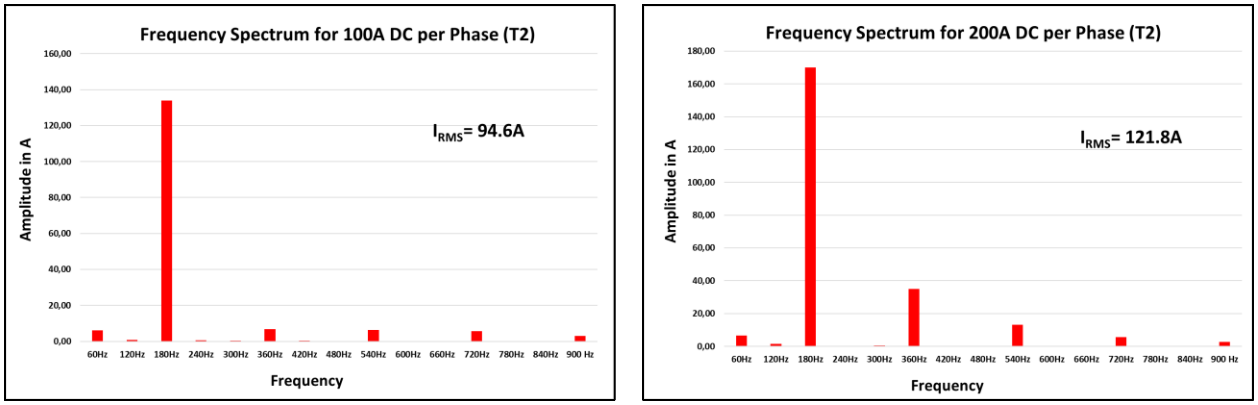


Figure 11: Harmonics for 100A and 200A DC per phase

TW "Loading" due to DC (RMS value of circulating current)

Figure 12 shows the "loading" of the TW winding due to DC. This means the RMS value of the circulating current under DC is shown in per unit of the rated AC current in the TW winding. The rated AC current of the TW winding is 252.3 A. It can be seen, that even with 200 A DC per phase the RMS value of the rated condition is not reached.

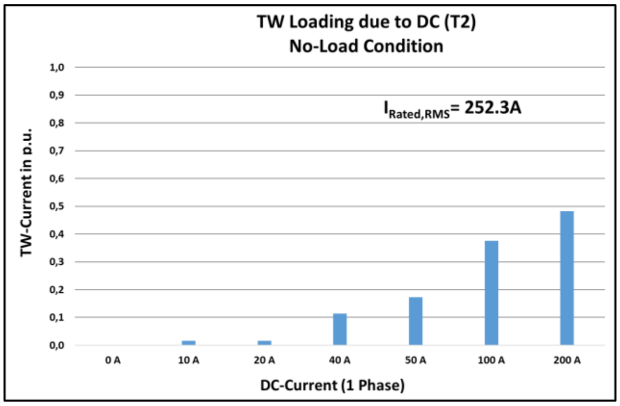


Figure 12: TW loading due to DC (No-Load Condition)

Thermal behavior under DC

The temperature rises of the tertiary winding, which are caused by the compensating currents of the previous clause are calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [K]	34
Top oil temperature [K]	39

Losses in Tertiary winding due to DC

The following table demonstrates the total losses in tertiary winding with different DC levels per phase in the high-voltage winding.

Table 3: Total losses of tertiary winding with DC

DC level per phase [A]	I^2R losses [kW]	Eddy losses [kW]
10	0.0005	0.0009
20	0.0005	0.0009
40	0.023	0.137
50	0.052	0.280
100	0.252	1.218
200	0.438	3.555

Steady-state hotspot temperature rise of tertiary winding above Topoil due to DC

The following table demonstrates the steady-state hotspot temperature rises (above ambient) in the tertiary winding for different DC levels.

Table 4: Hotspot temperature rise (above ambient) of TW winding with DC

DC level per phase [A]	Hotspot rise [K]
10	39.0
20	39.0
40	39.7
50	40.2
100	42.6
200	47.7

Graphical result for steady state temperature rises for different DC levels

Figure 13 shows the calculated steady-state hotspot rise of the tertiary winding for different DC levels. It can be seen, that the hotspot temperatures are far below critical levels (max. 100K, according to IEEE long time emergency condition at 40°C ambient).

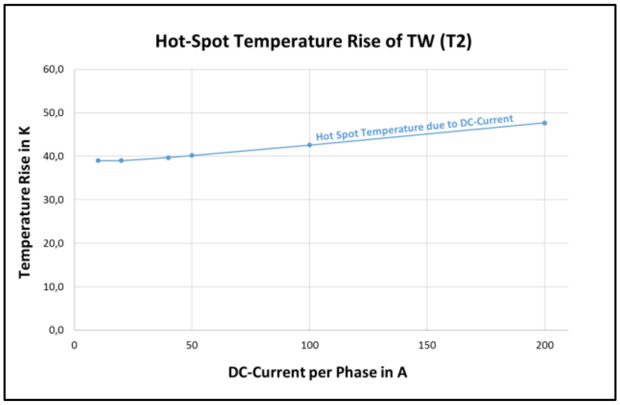


Figure 13: Hotspot temperature rise (above ambient) with DC

EPRI – GIC Study

Task I: Study of Thermal Impact of GIC on Delta/Tertiary Windings

Transformer T3

Content

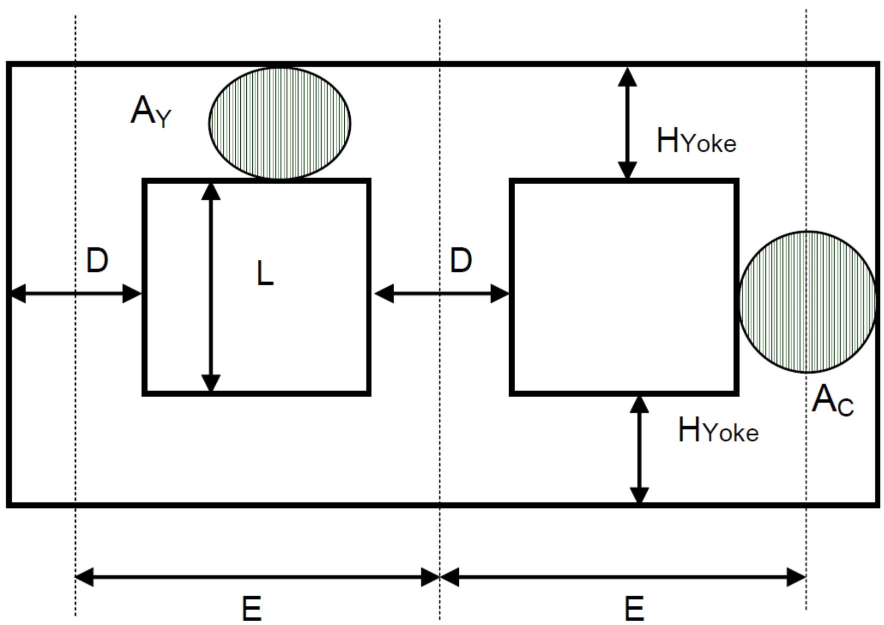
General Data

Transformer Data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T3
Transformer type	Auto
HV nameplate rating	600MVA
TW nameplate rating	3MVA
Number of phases	3
Voltage levels	410kV // 145kV // 21kV
Winding affected by DC	HV
Core type	3



L [mm]	2030
D [mm]	1230
H_Y [mm]	1160
E [mm]	2304
A_C [m2]	1.07446
A_Y [m2]	1.07446

Figure 1: Sketch of core geometry

DC Levels Overview

The report contains steady-state results for the electrical and thermal response of the tertiary winding for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Compensating Current Under DC

The current in the high-voltage and tertiary winding are calculated for each DC level. In order to identify only the effect of an additional DC current in the neutral of the high-voltage system an unloaded TV-system was simulated. Figure 2 shows the used electrical circuit. Figure 3 to Figure 8 show the calculated wave forms of the currents in both systems.

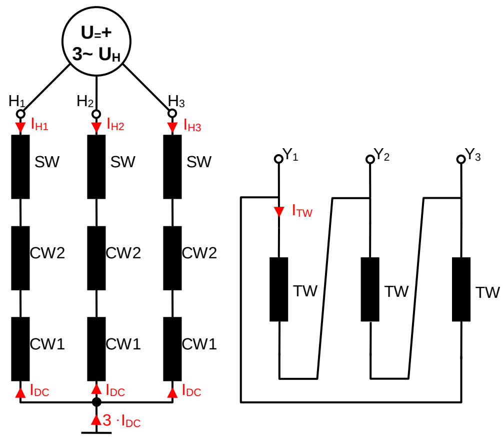
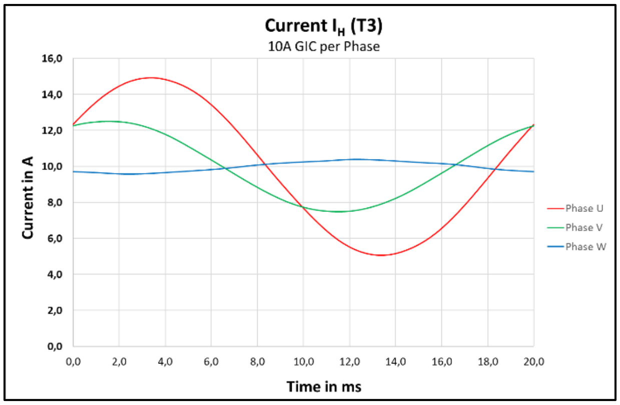


Figure 2: Electrical circuit (unloaded TV-system)

Current Wave Forms with 10A DC per Phase



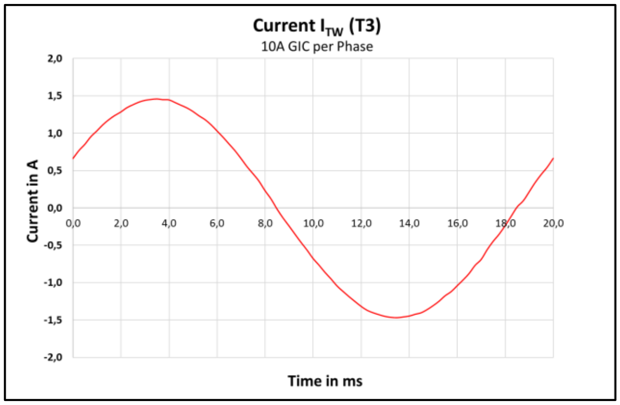


Figure 3: Current wave form with 10A DC per phase

Current Wave Forms with 20A DC per Phase

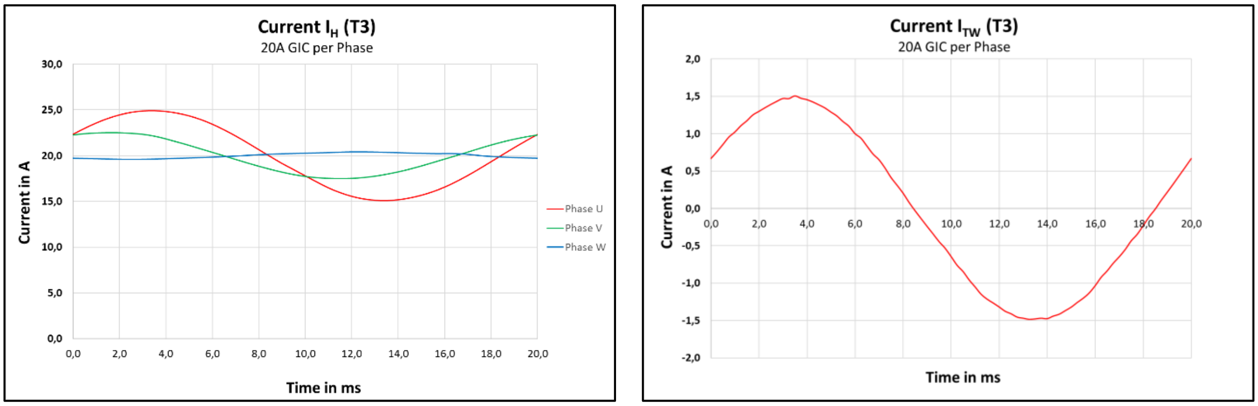


Figure 4: Current wave form with 20A DC per phase

Current Wave Forms with 40A DC per Phase

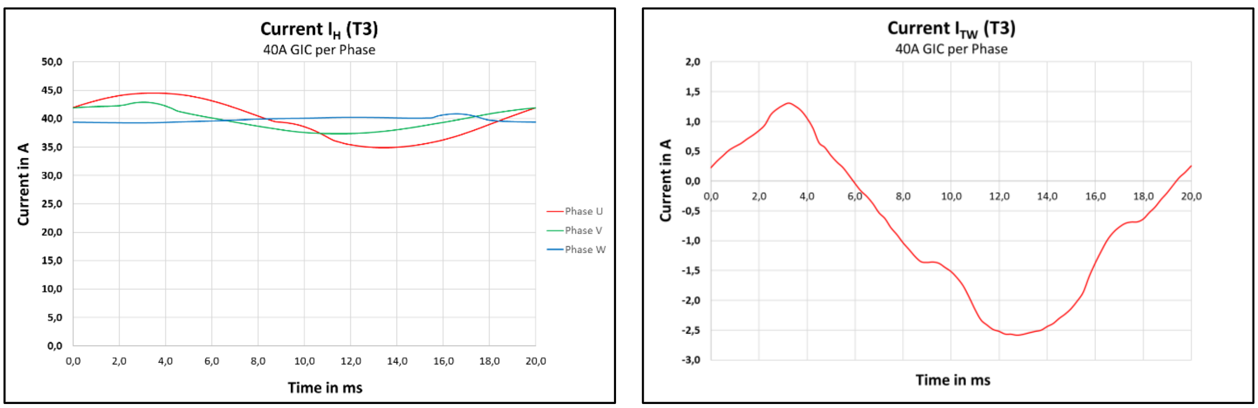


Figure 5: Current wave form with 40A DC per phase

Current Wave Forms with 50A DC per Phase

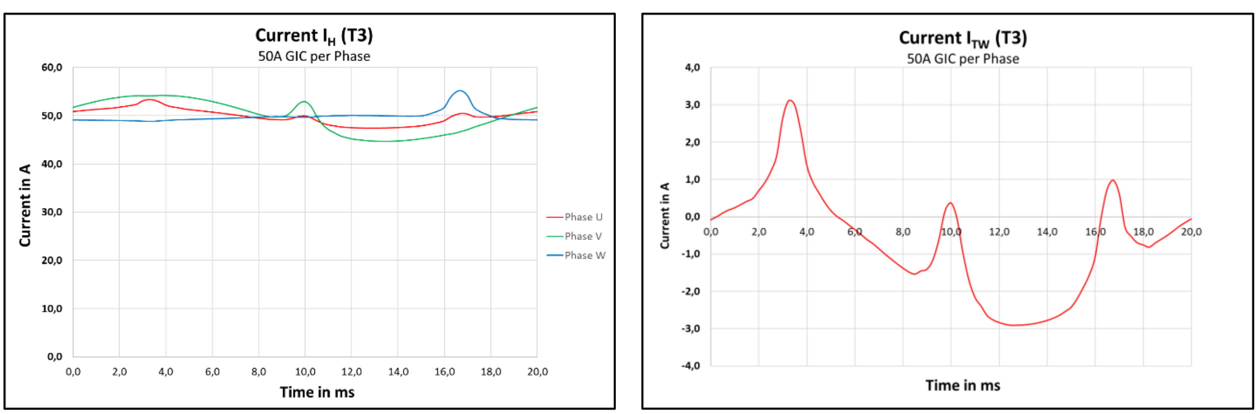


Figure 6: Current wave form with 50A DC per phase

Current Wave Forms with 100A DC per Phase

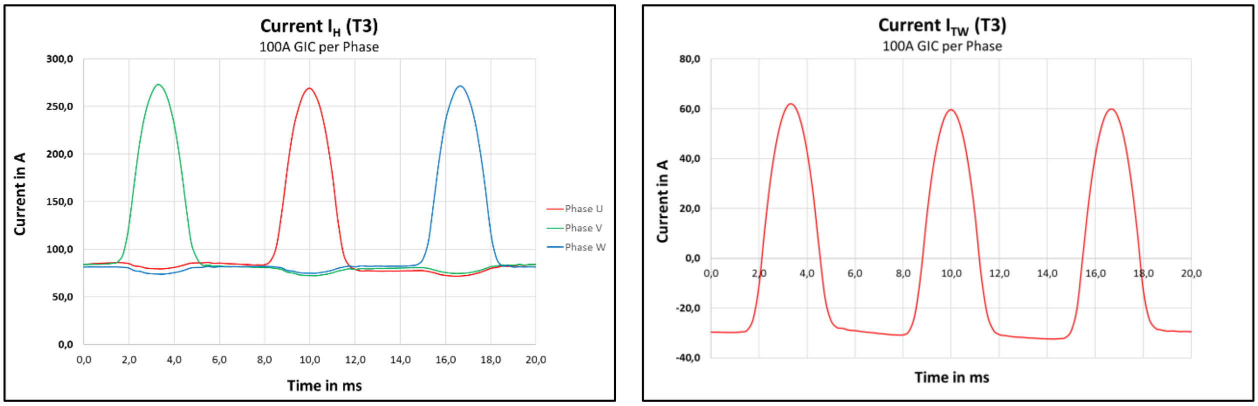


Figure 7: Current wave form with 100A DC per phase

Current Wave Forms with 200A DC per Phase

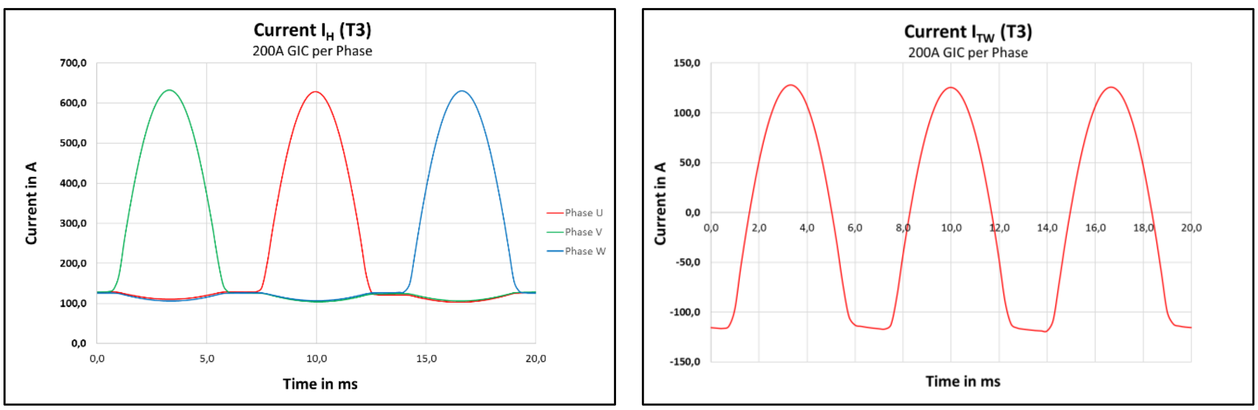


Figure 8: Current wave form with 200A DC per phase

Harmonics of Compensating Current

With the waveforms of Figure 3-8, an FFT analysis was done in order to demonstrate the different frequency components. Figure 9 to 11 show the harmonics of the compensating current in the TW winding with the different DC-currents in the high-voltage system. In addition, the RMS value of the current is shown in each figure.

Harmonics for 10A and 20A DC per Phase

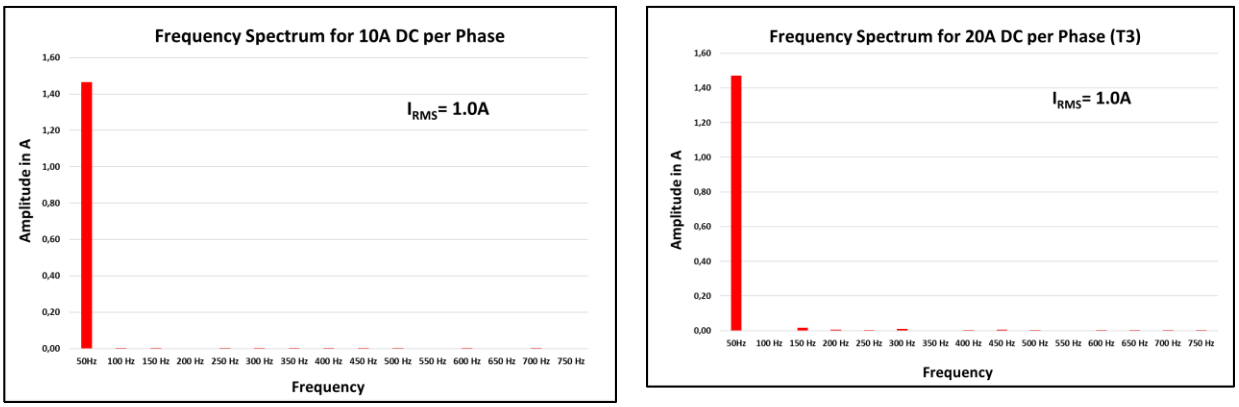


Figure 9: Harmonics for 10A and 20A DC per phase

Harmonics for 40A and 50A DC per Phase

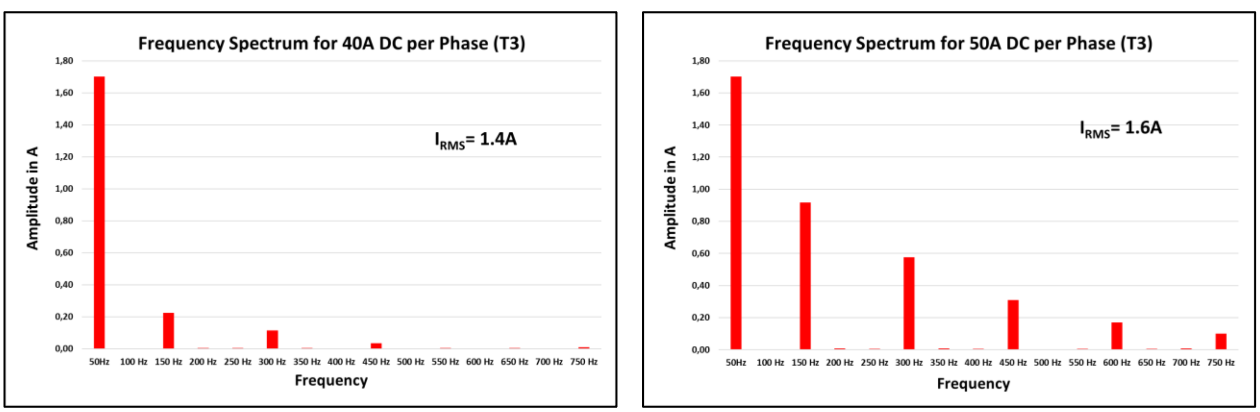


Figure 10: Harmonics for 40A and 50A DC per phase

Harmonics for 100A and 200A DC per Phase

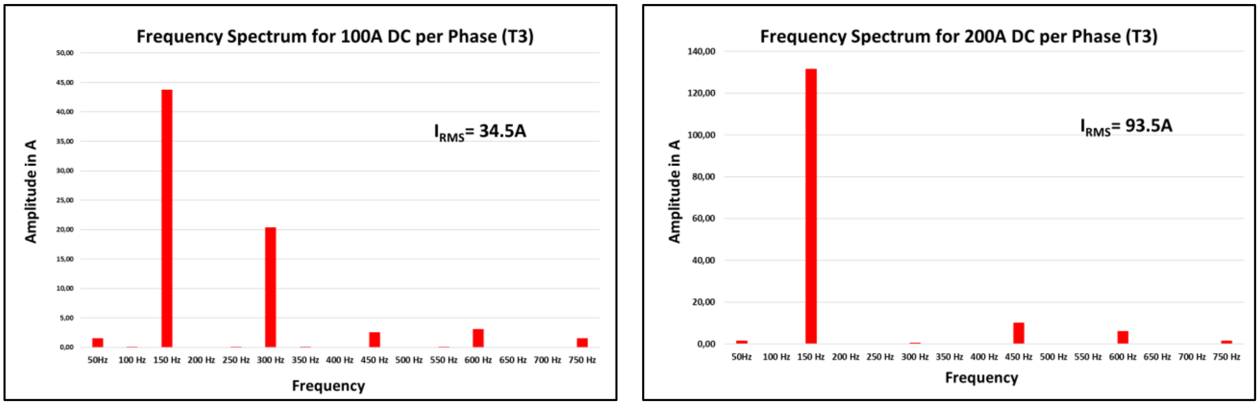


Figure 11: Harmonics for 100A and 200A DC per phase

TW "Loading" due to DC (RMS value of circulating current)

Figure 12 shows the "loading" of the TW winding due to DC. This means the RMS value of the circulating current under DC is shown in per unit of the rated AC current in the TW winding. The rated AC current of the TW winding is 47.6 A. It can be seen, that even with 200 A DC per phase the RMS value of the rated condition is not reached.

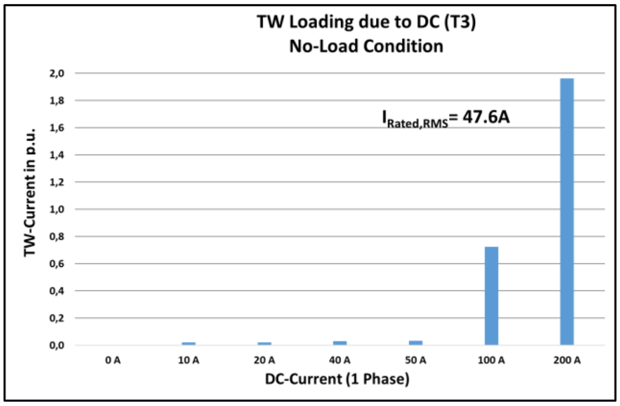


Figure 12: TW loading due to DC (No-Load Condition)

Thermal behavior under DC

The temperature rises of the tertiary winding, which are caused by the compensating currents of the previous clause are calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [K]	42
Top oil temperature [K]	50

Losses in Tertiary winding due to DC

The following table demonstrates the total losses in tertiary winding with different DC levels per phase in the high-voltage winding.

Table 3: Total losses of tertiary winding with DC

DC level per phase [A]	I^2R losses [kW]	Eddy losses [kW]
10	0.0	0.003
20	0.0	0.003
40	0.0	0.003
50	0.0	0.005
100	0.026	3.57
200	0.187	22.8

Steady-state hotspot temperature rise of tertiary winding above Topoil due to DC

The following table demonstrates the steady-state hotspot temperature rises (above ambient) in the tertiary winding for different DC levels.

Table 4: Hotspot temperature rise (above ambient) of TW winding with DC

DC level per phase [A]	Hotspot rise [K]
10	50.1
20	50.1
40	50.1
50	50.1
100	64.8
200	80.4

Graphical result for steady state temperature rises for different DC levels

Figure 13 shows the calculated steady-state hotspot rise of the tertiary winding for different DC levels. It can be seen, that the hotspot temperatures are far below critical levels (max. 100K, according to IEEE long time emergency condition at 40°C ambient).

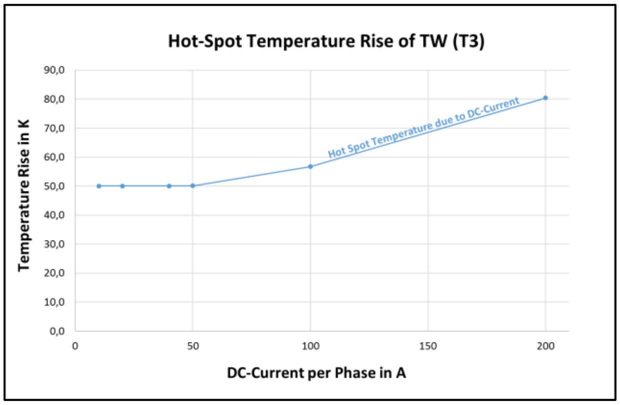


Figure 13: Hotspot temperature rise (above ambient) with DC

EPRI – GIC Study

Task I: Study of Thermal Impact of GIC on Delta/Tertiary Windings

Transformer T4

Content

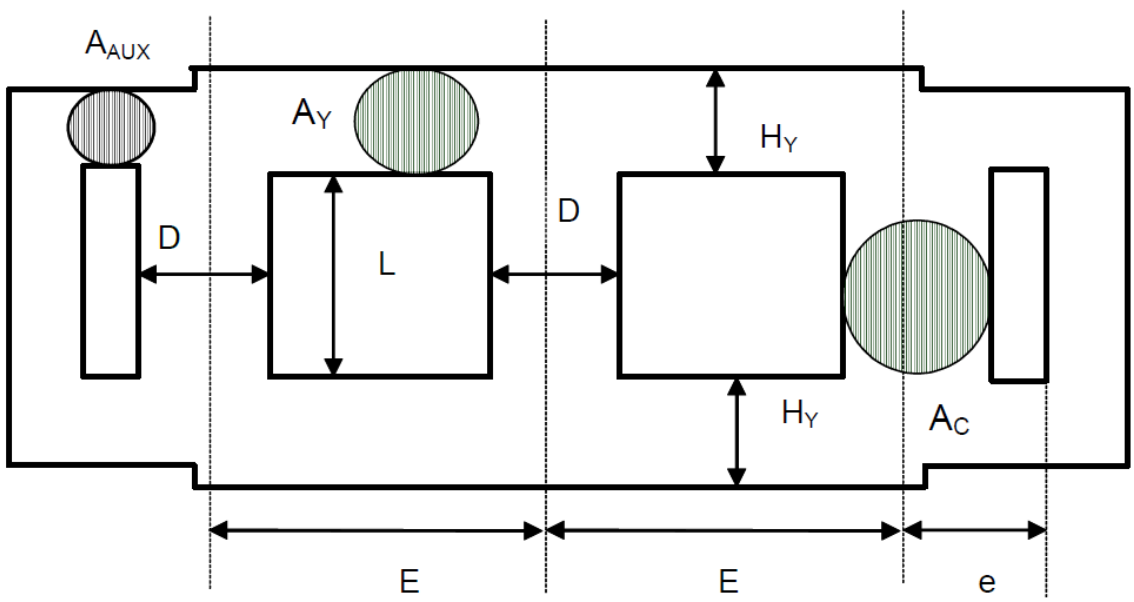
General Data

Transformer Data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T4
Transformer type	Auto
HV nameplate rating	670MVA
TW nameplate rating	20MVA
Number of phases	3
Voltage levels	525kV // 230kV // 23kV
Winding affected by DC	HV
Core type	5



L [mm]	3080
D [mm]	972
H_Y [mm]	550
E [mm]	1970
e [mm]	1014
A_C [m2]	0.6741
A_Y [m2]	0.3846
A_{Aux} [m2]	0.3379

Figure 1: Sketch of core geometry

DC Levels Overview

The report contains steady-state results for the electrical and thermal response of the tertiary winding for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Compensating Current Under DC

The current in the high-voltage and tertiary winding are calculated for each DC level. In order to identify only the effect of an additional DC current in the neutral of the high-voltage system an unloaded TV-system was simulated. Figure 2 shows the used electrical circuit. Figure 3 to Figure 8 show the calculated wave forms of the currents in both systems.

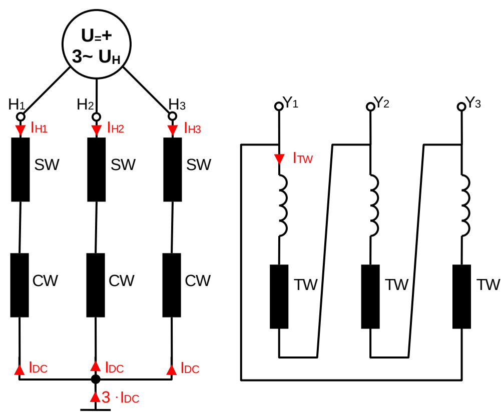


Figure 2: Electrical circuit (unloaded TV-system)

Current Wave Forms with 10A DC per Phase

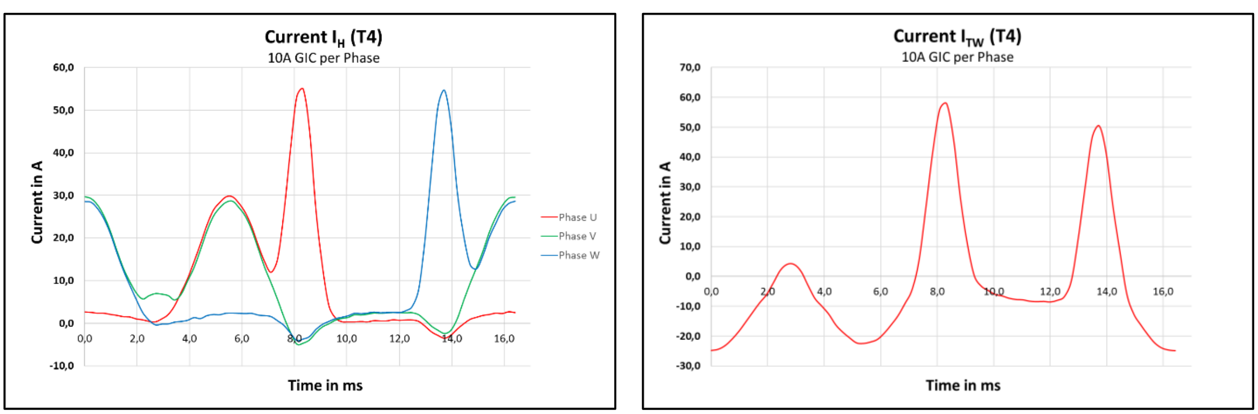


Figure 3: Current wave form with 10A DC per phase

Current Wave Forms with 20A DC per Phase

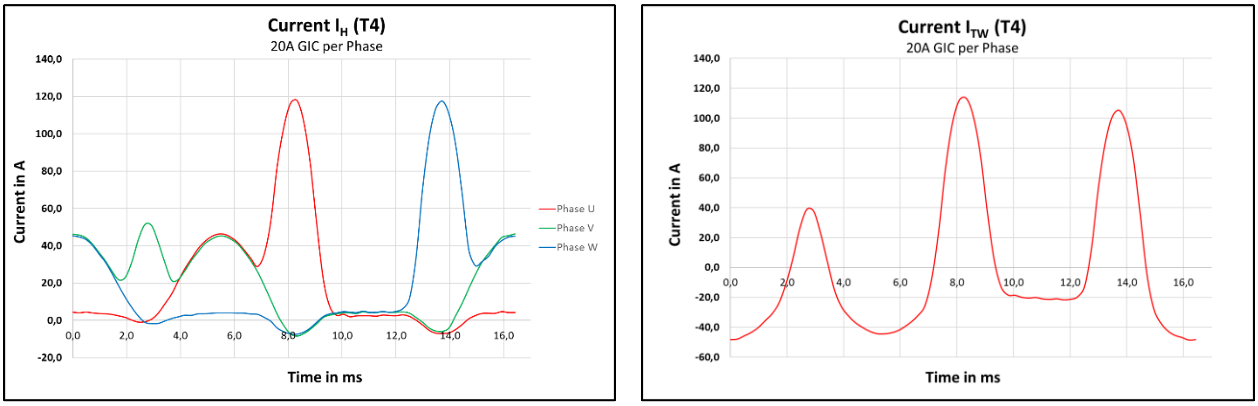


Figure 4: Current wave form with 20A DC per phase

Current Wave Forms with 40A DC per Phase

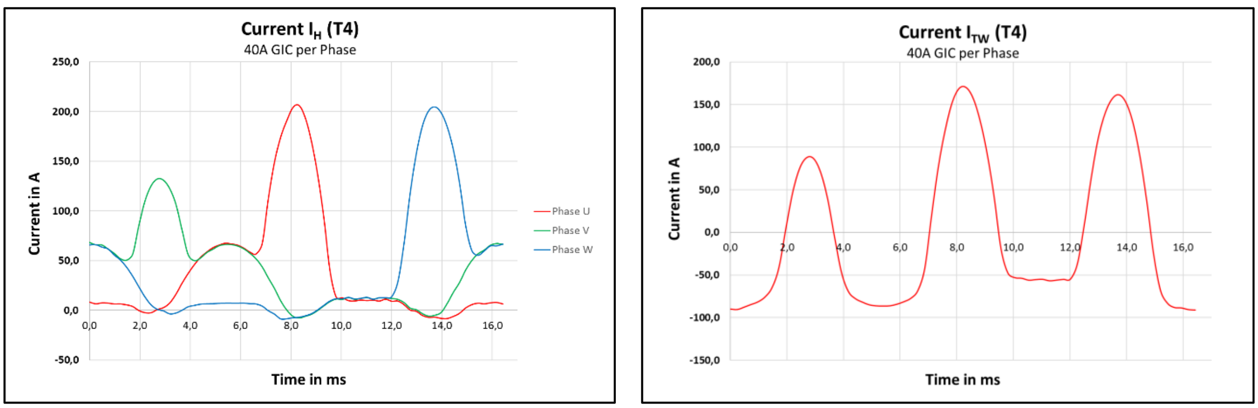


Figure 5: Current wave form with 40A DC per phase

Current Wave Forms with 50A DC per Phase

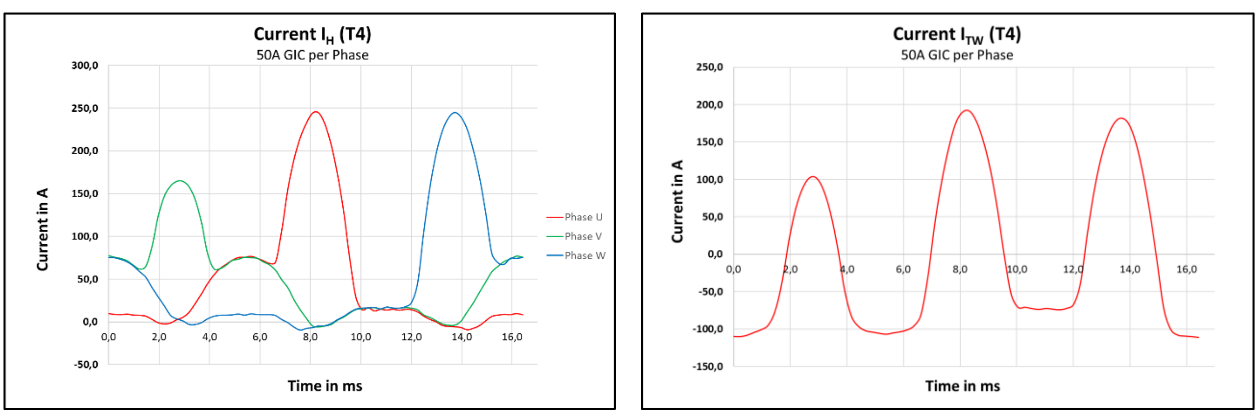


Figure 6: Current wave form with 50A DC per phase

Current Wave Forms with 100A DC per Phase

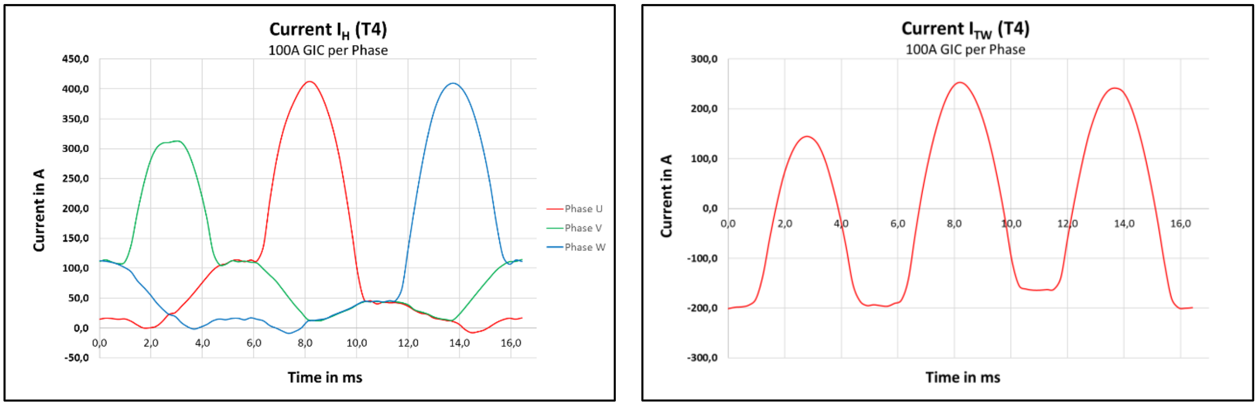


Figure 7: Current wave form with 100A DC per phase

Current Wave Forms with 200A DC per Phase

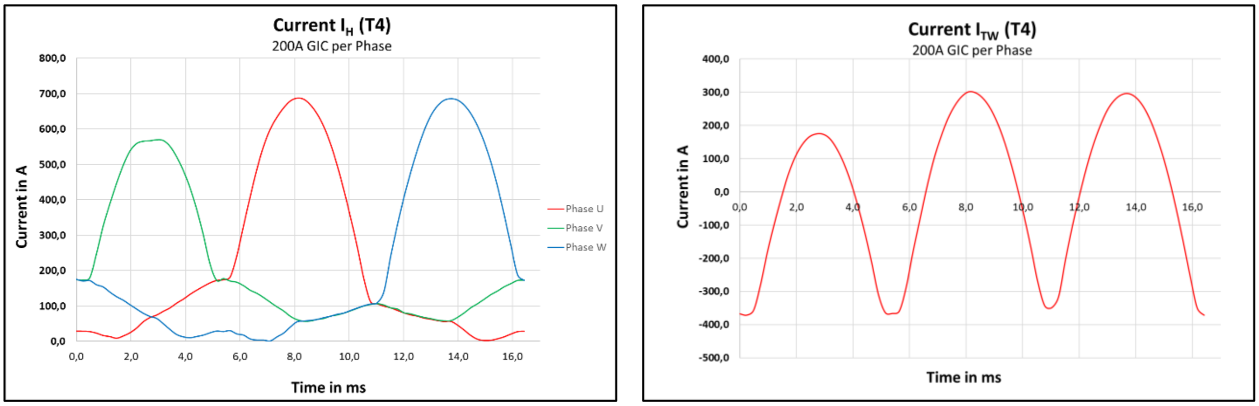
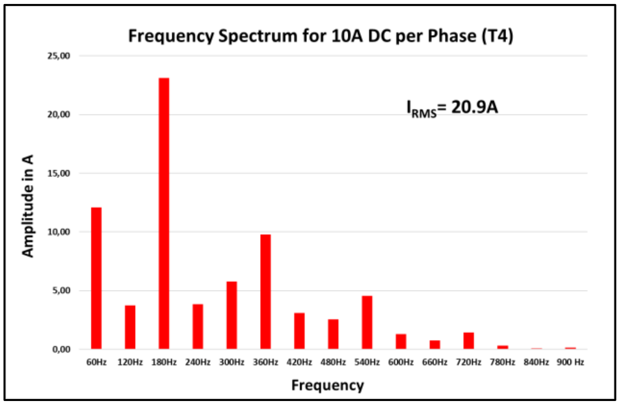


Figure 8: Current wave form with 200A DC per phase

Harmonics of Compensating Current

With the waveforms of Figure 3-8, an FFT analysis was done in order to demonstrate the different frequency components. Figure 9 to 11 show the harmonics of the compensating current in the TW winding with the different DC-currents in the high-voltage system. In addition, the RMS value of the current is shown in each figure.

Harmonics for 10A and 20A DC per Phase



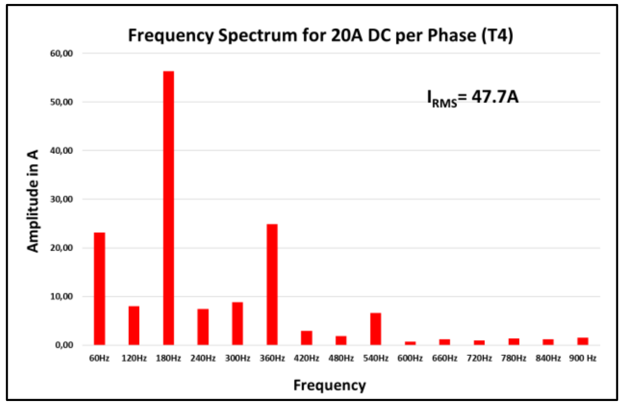
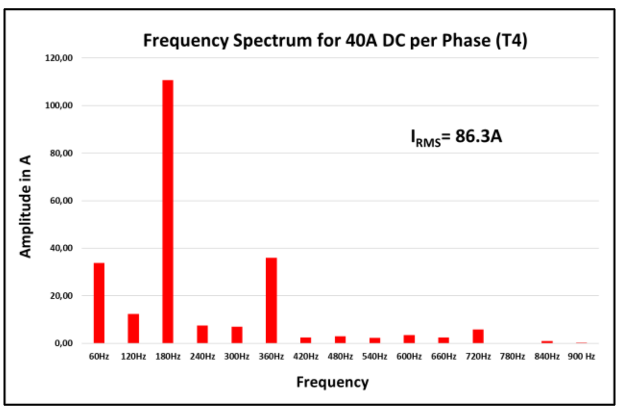


Figure 9: Harmonics for 10A and 20A DC per phase

Harmonics for 40A and 50A DC per Phase



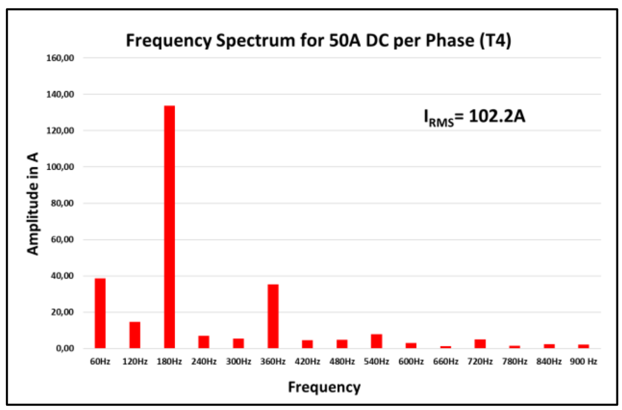


Figure 10: Harmonics for 40A and 50A DC per phase

Harmonics for 100A and 200A DC per Phase

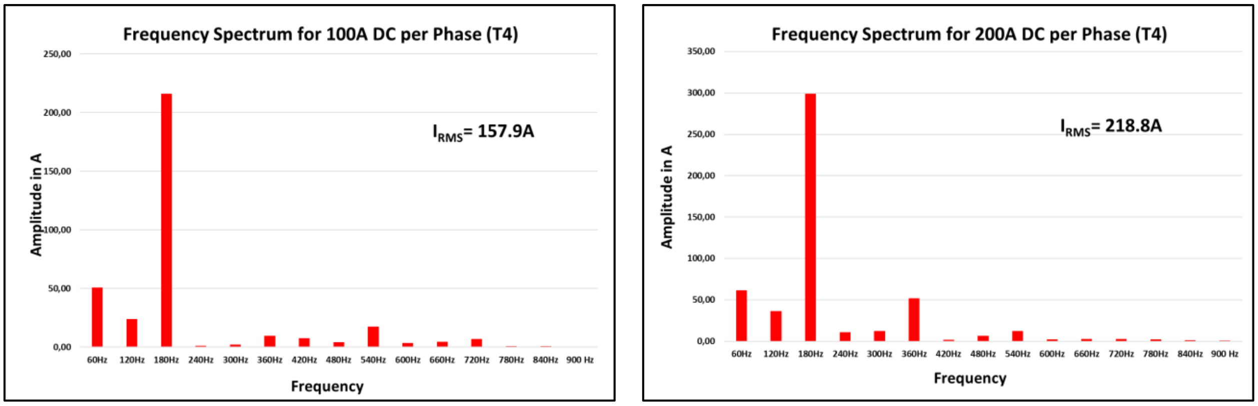


Figure 11: Harmonics for 100A and 200A DC per phase

TW "Loading" due to DC (RMS value of circulating current)

Figure 12 shows the "loading" of the TW winding due to DC. This means the RMS value of the circulating current under DC is shown in per unit of the rated AC current in the TW winding. The rated AC current of the TW winding is 289.8A. It can be seen, that even with 200 A DC per phase the RMS value of the rated condition is not reached.

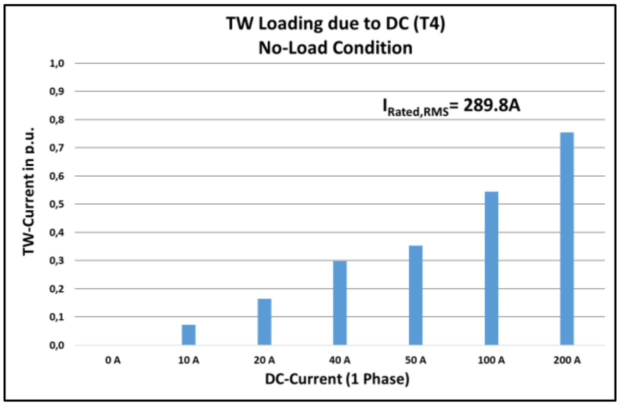


Figure 12: TW loading due to DC (No-Load Condition)

Thermal behavior under DC

The temperature rises of the tertiary winding, which are caused by the compensating currents of the previous clause are calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [K]	35
Top oil temperature [K]	43

Losses in Tertiary winding due to DC

The following table demonstrates the total losses in tertiary winding with different DC levels per phase in the high-voltage winding.

Table 3: Total losses of tertiary winding with DC

DC level per phase [A]	I^2R losses [kW]	Eddy losses [kW]
10	0.01	0.042
20	0.054	0.155
40	0.175	0.373
50	0.246	0.485
100	0.593	1.079
200	1.172	2.289

Steady-state hotspot temperature rise of tertiary winding above Topoil due to DC

The following table demonstrates the steady-state hotspot temperature rises (above ambient) in the tertiary winding for different DC levels.

Table 4: Hotspot temperature rise (above ambient) of TW winding with DC

DC level per phase [A]	Hotspot rise [K]
10	43.3
20	43.8
40	44.5
50	44.8
100	46.2
200	48.1

Graphical result for steady state temperature rises for different DC levels

Figure 13 shows the calculated steady-state hotspot rise of the tertiary winding for different DC levels. It can be seen, that the hotspot temperatures are far below critical levels (max. 100K, according to IEEE long time emergency condition at 40°C ambient).

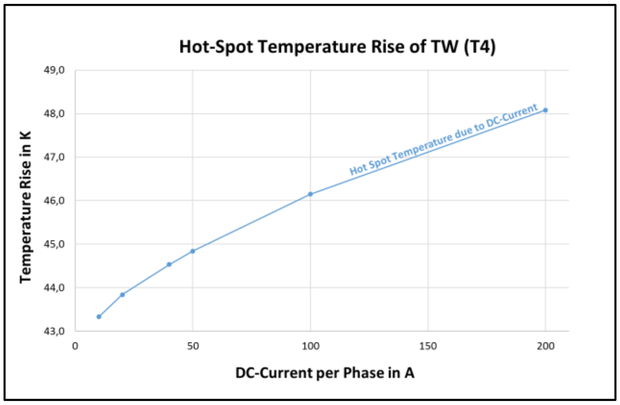


Figure 13: Hotspot temperature rise (above ambient) with DC

EPRI – GIC Study

Task I: Study of Thermal Impact of GIC on Delta/Tertiary Windings

Transformer T5

Content

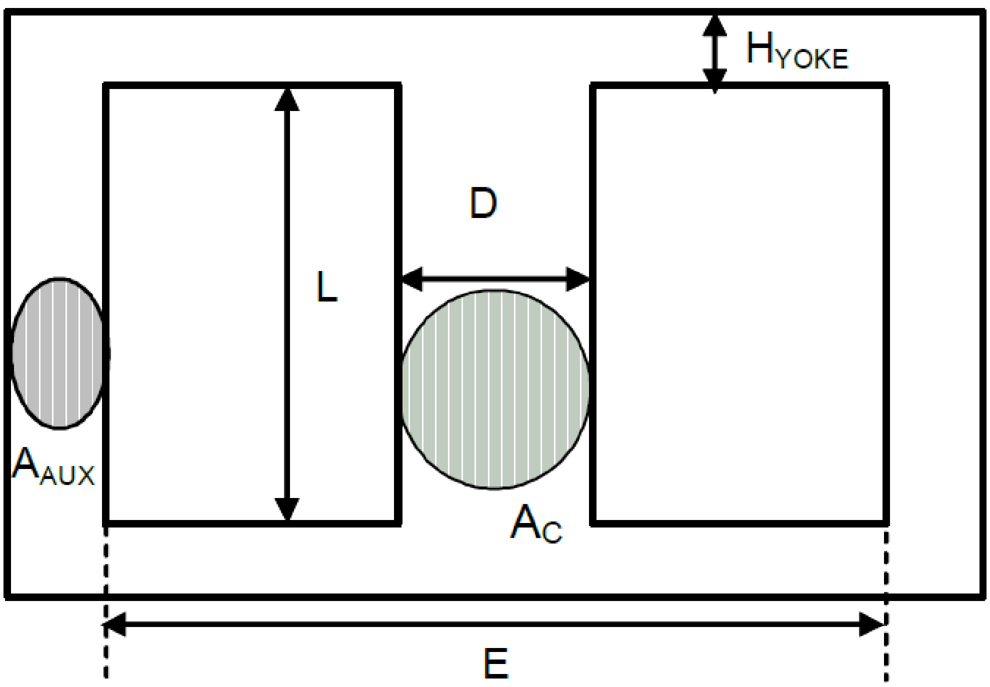
General Data

Transformer Data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T5
Transformer type	Auto
HV nameplate rating	333.33MVA
TW nameplate rating	3.333MVA
Number of phases	1
Voltage levels	400/√3kV // 275/√3kV // 23kV
Winding affected by DC	HV
Core type	1



L [mm]	3455
D [mm]	872
H_Y [mm]	430
E [mm]	2356
A_C [m2]	0.5343
A_{Aux} [m2]	0.2691

Figure 1: Sketch of core geometry

DC Levels Overview

The report contains steady-state results for the electrical and thermal response of the tertiary winding for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Compensating Current Under DC

With the waveforms of Figure 3-8, an FFT analysis was done in order to demonstrate the different frequency components. Figure 9 to 11 show the harmonics of the compensating current in the TW winding with the different DC-currents in the high-voltage system. In addition, the RMS value of the current is shown in each figure.

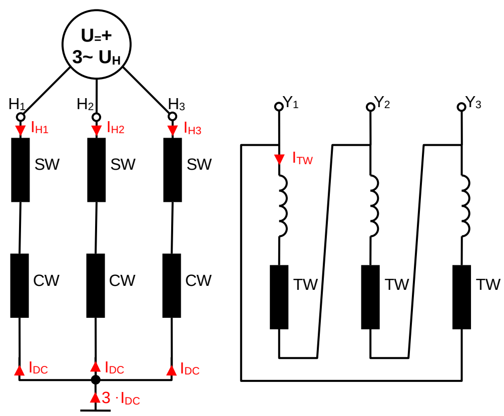


Figure 2: Electrical circuit (unloaded TV-system)

Current Wave Forms with 10A DC per Phase

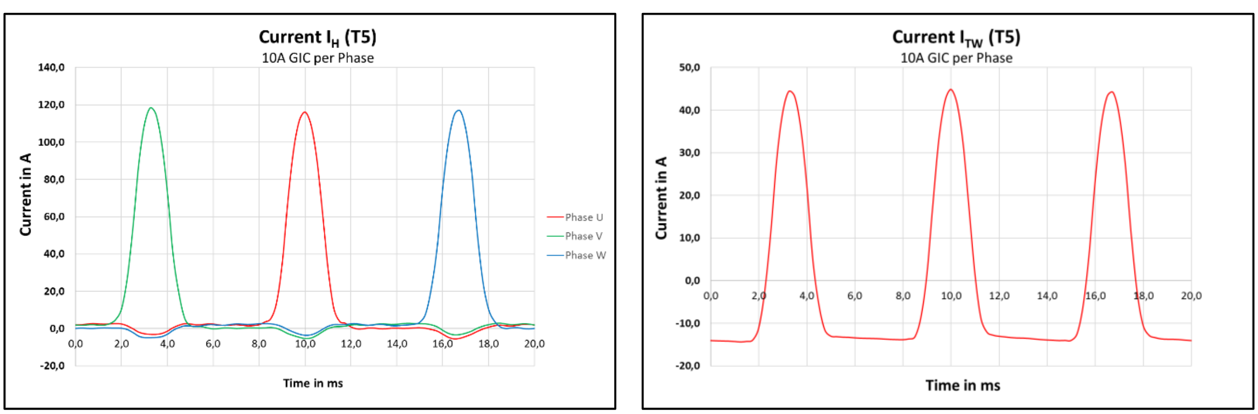
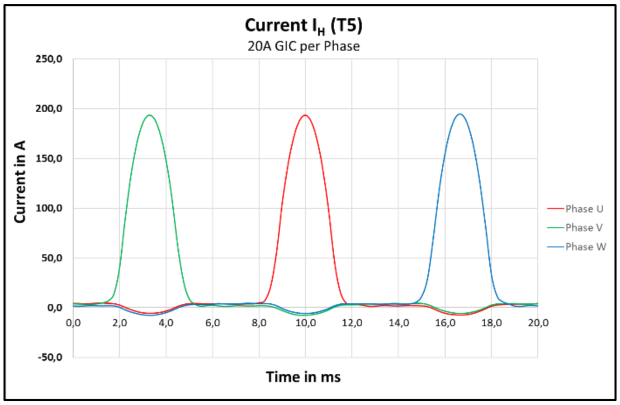


Figure 3: Current wave form with 10A DC per phase

Current Wave Forms with 20A DC per Phase



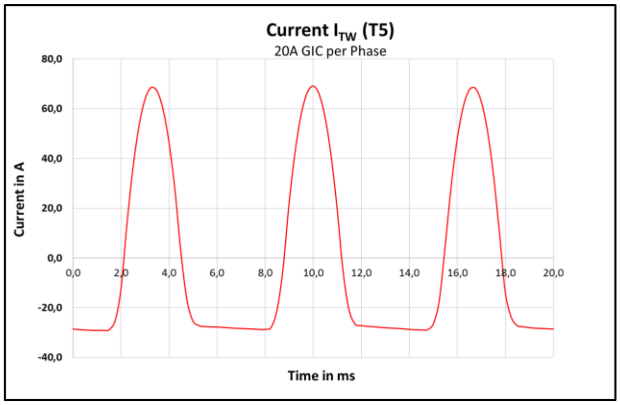
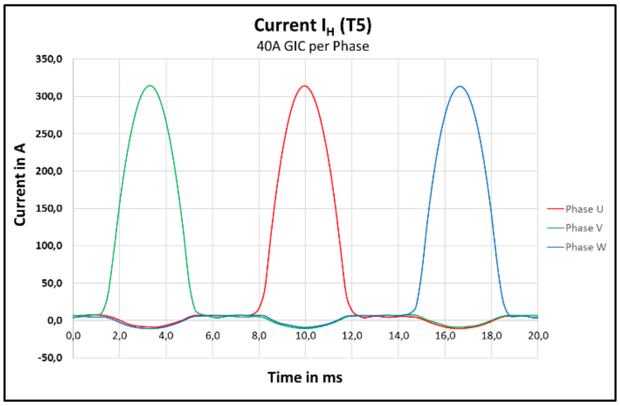


Figure 4: Current wave form with 20A DC per phase

Current Wave Forms with 40A DC per Phase



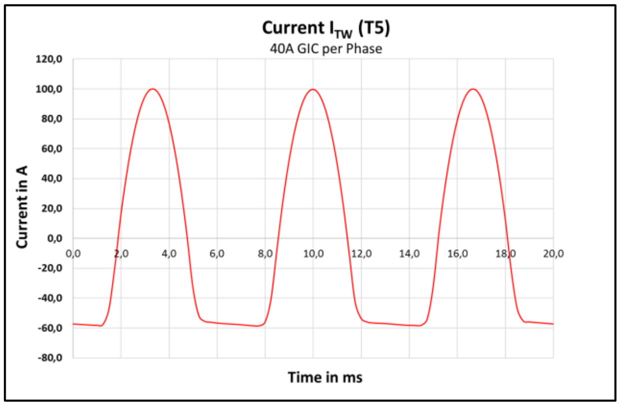
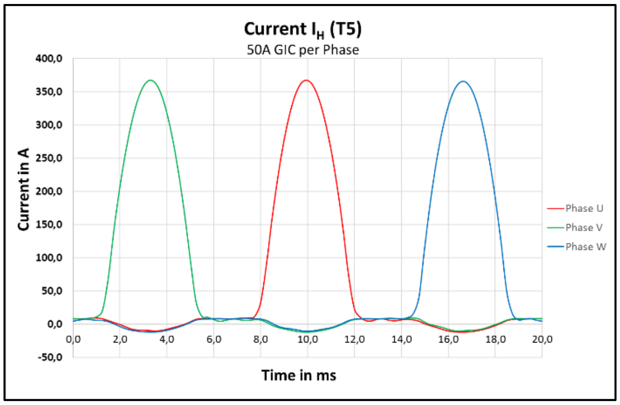


Figure 5: Current wave form with 40A DC per phase

Current Wave Forms with 50A DC per Phase



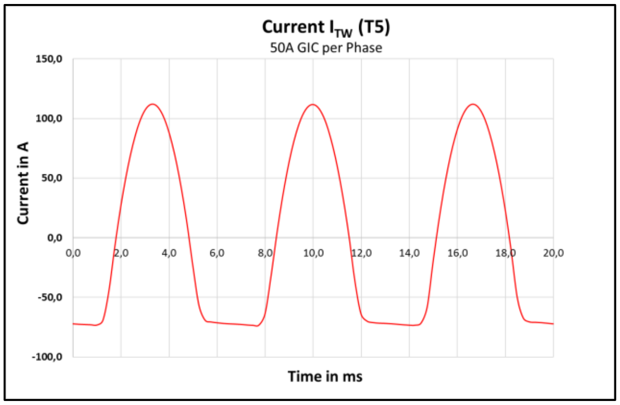


Figure 6: Current wave form with 50A DC per phase

Current Wave Forms with 100A DC per Phase

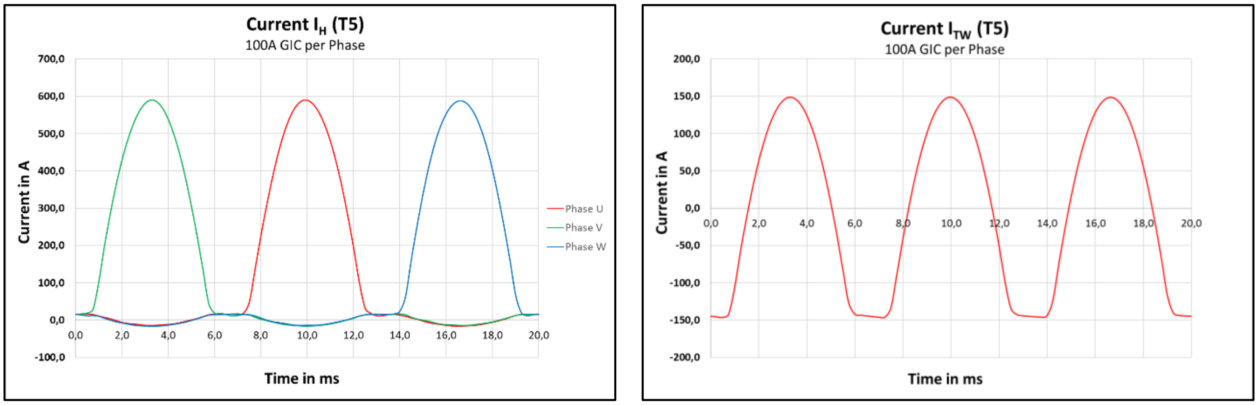


Figure 7: Current wave form with 100A DC per phase

Current Wave Forms with 200A DC per Phase

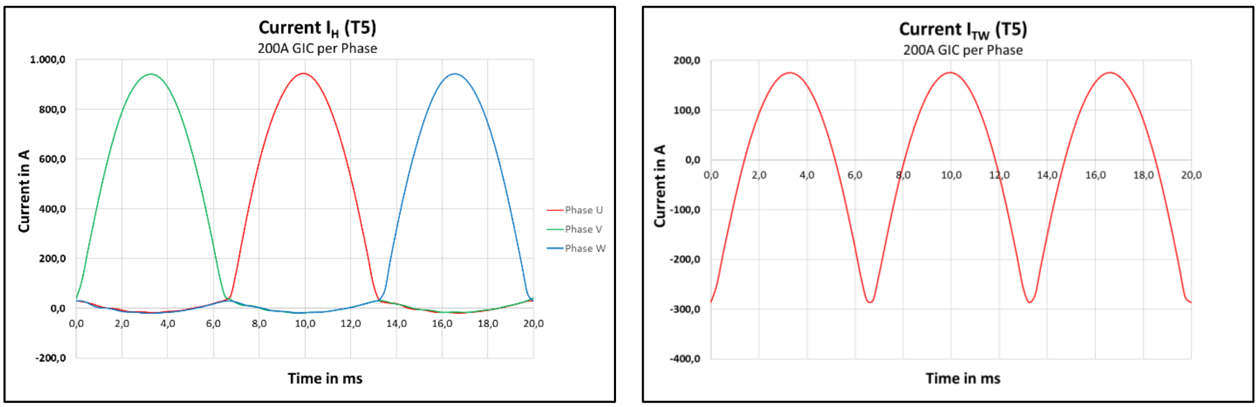
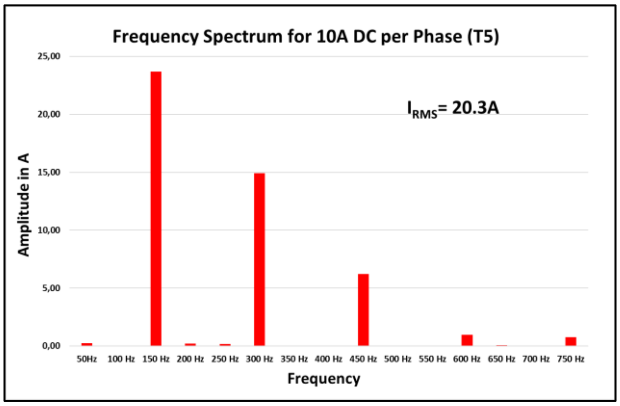


Figure 8: Current wave form with 200A DC per phase

Harmonics of Compensating Current

Figure 9 to 11 show the harmonics of the compensating current in the TW winding with the different DC-currents in the high-voltage system.

Harmonics for 10A and 20A DC per Phase



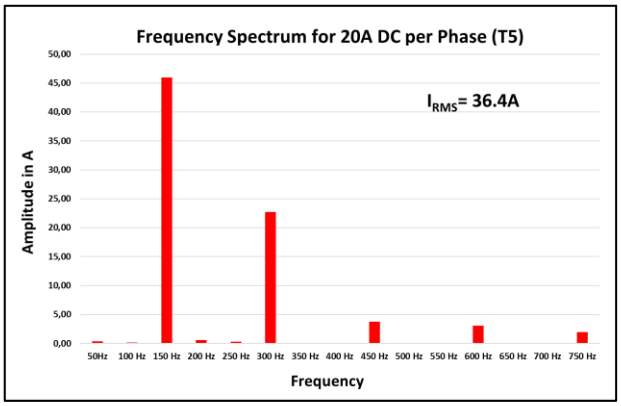
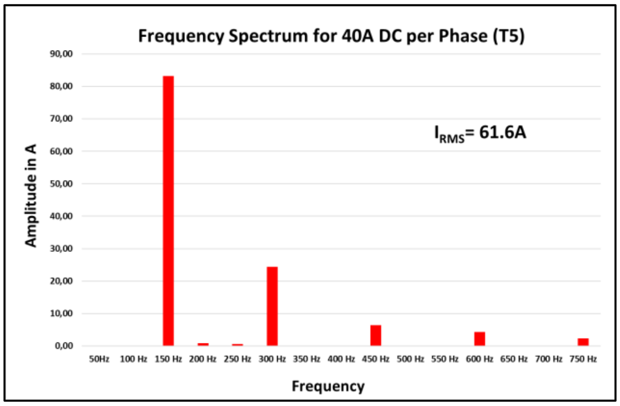


Figure 9: Harmonics for 10A and 20A DC per phase

Harmonics for 40A and 50A DC per Phase



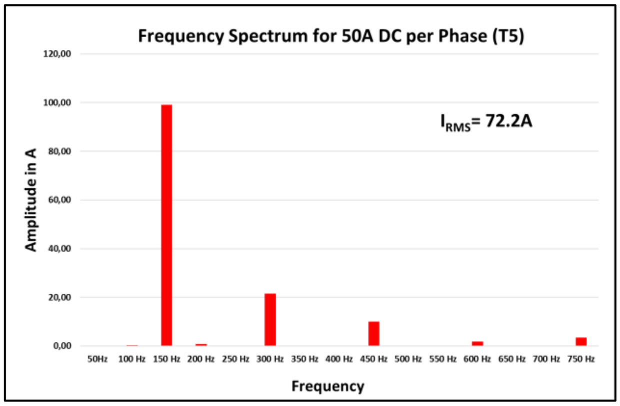


Figure 10: Harmonics for 40A and 50A DC per phase

Harmonics for 100A and 200A DC per Phase

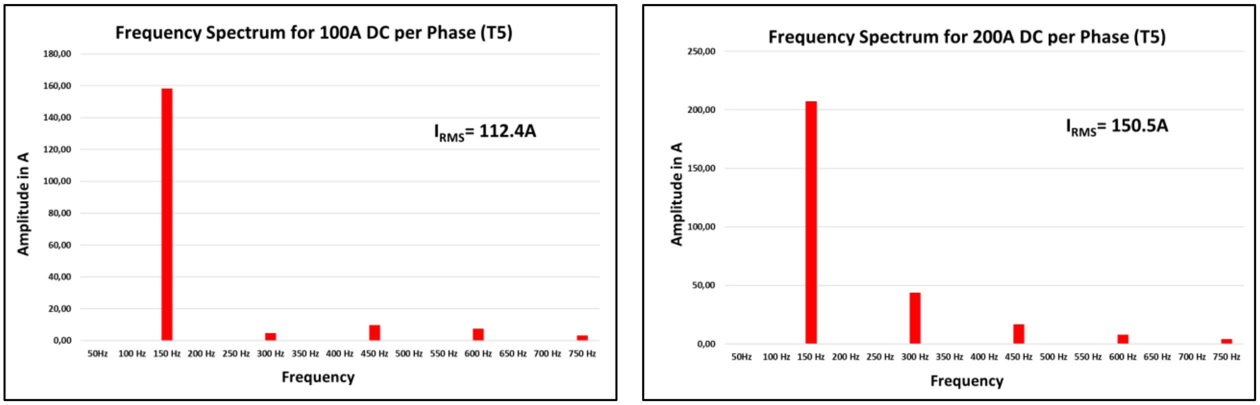


Figure 11: Harmonics for 100A and 200A DC per phase

TW "Loading" due to DC (RMS value of circulating current)

Figure 12 shows the "loading" of the TW winding due to DC. This means the RMS value of the circulating current under DC is shown in per unit of the rated AC current in the TW winding. The rated AC current of the TW winding is 151.5A. It can be seen, that even with 200 A DC per phase the RMS value of the rated condition is not reached.

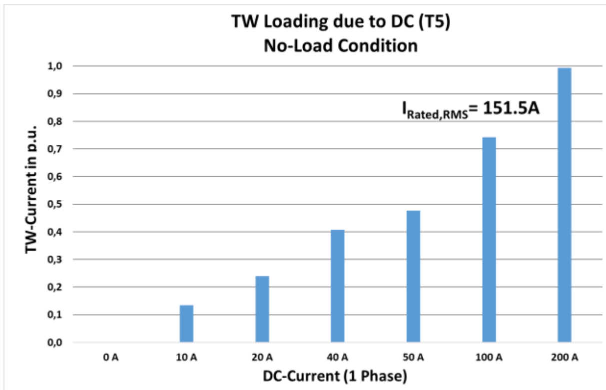


Figure 12: TW loading due to DC (No-Load Condition)

Thermal behavior under DC

The temperature rises of the tertiary winding, which are caused by the compensating currents of the previous clause are calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [K]	37
Top oil temperature [K]	43

Losses in Tertiary winding due to DC

The following table demonstrates the total losses in tertiary winding with different DC levels per phase in the high-voltage winding.

Table 3: Total losses of tertiary winding with DC

DC level per phase [A]	I^2R losses [kW]	Eddy losses [kW]
10	0.012	0.129
20	0.038	0.328
40	0.109	0.713
50	0.150	0.917
100	0.363	1.938
200	0.653	4.021

Steady-state hotspot temperature rise of tertiary winding above Topoil due to DC

The following table demonstrates the steady-state hotspot temperature rises (above ambient) in the tertiary winding for different DC levels.

Table 4: Hotspot temperature rise (above ambient) of TW winding with DC

DC level per phase [A]	Hotspot rise [K]
10	44.1
20	45.0
40	46.6
50	47.3
100	50.3
200	57.3

Graphical result for steady state temperature rises for different DC levels

Figure 13 shows the calculated steady-state hotspot rise of the tertiary winding for different DC levels. It can be seen, that the hotspot temperatures are far below critical levels (max. 100K, according to IEEE long time emergency condition at 40°C ambient).

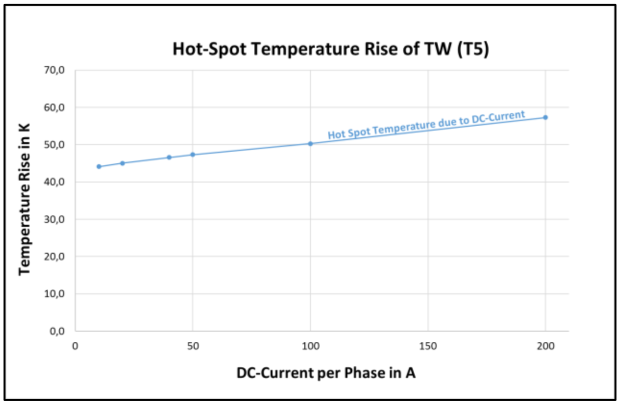


Figure 13: Hotspot temperature rise (above ambient) with DC

EPRI – GIC Study

Study of Thermal Impact of GIC on Delta/Tertiary Windings

Transformer T6

Content

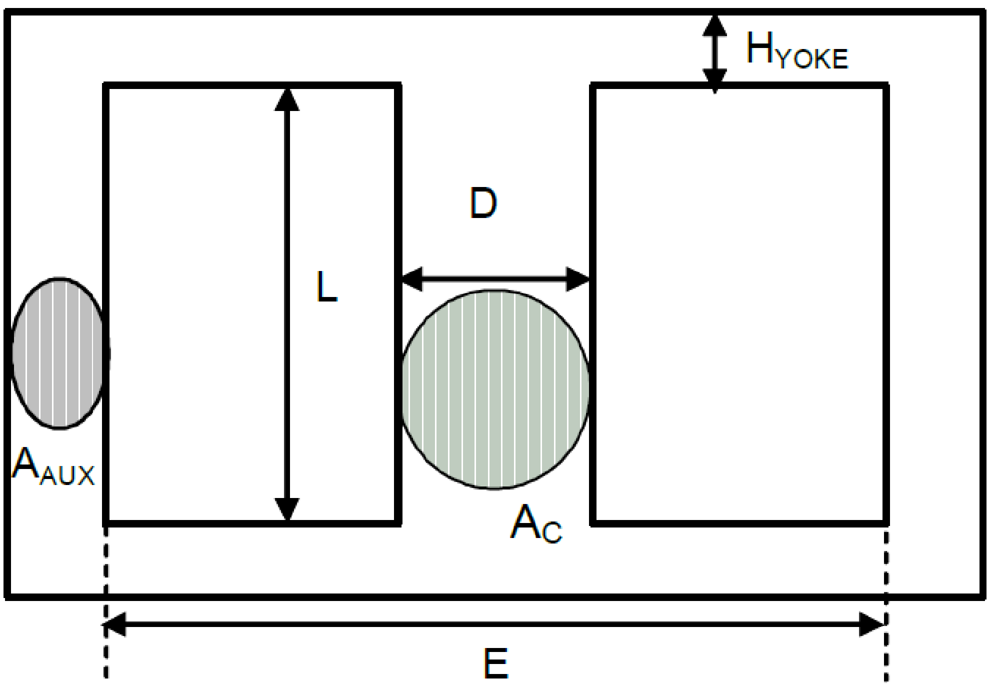
General Data

Transformer Data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T6
Transformer type	Auto
HV nameplate rating	373MVA
TW nameplate rating	112MVA
Number of phases	1
Voltage levels	525/√3kV // 230/√3kV // 13,8kV
Winding affected by DC	HV
Core type	1



L [mm]	2940
D [mm]	1198
H_Y [mm]	590
E [mm]	2544
A_C [m2]	1.0325
A_{Aux} [m2]	0.5176

Figure 1: Sketch of core geometry

DC Levels Overview

The report contains steady-state results for the electrical and thermal response of the tertiary winding for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Compensating Current Under DC

With the waveforms of Figure 3-8, an FFT analysis was done in order to demonstrate the different frequency components. Figure 9 to 11 show the harmonics of the compensating current in the TW winding with the different DC-currents in the high-voltage system. In addition, the RMS value of the current is shown in each figure.

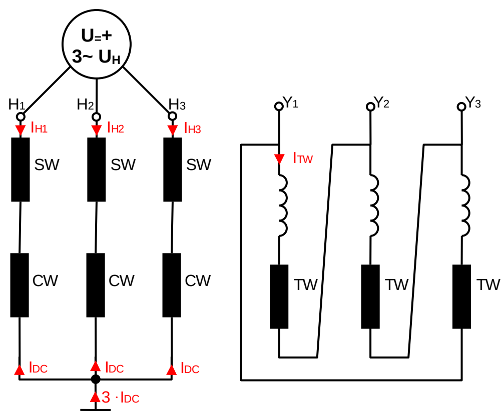


Figure 2: Electrical circuit (unloaded TV-system)

Current Wave Forms with 10A DC per Phase

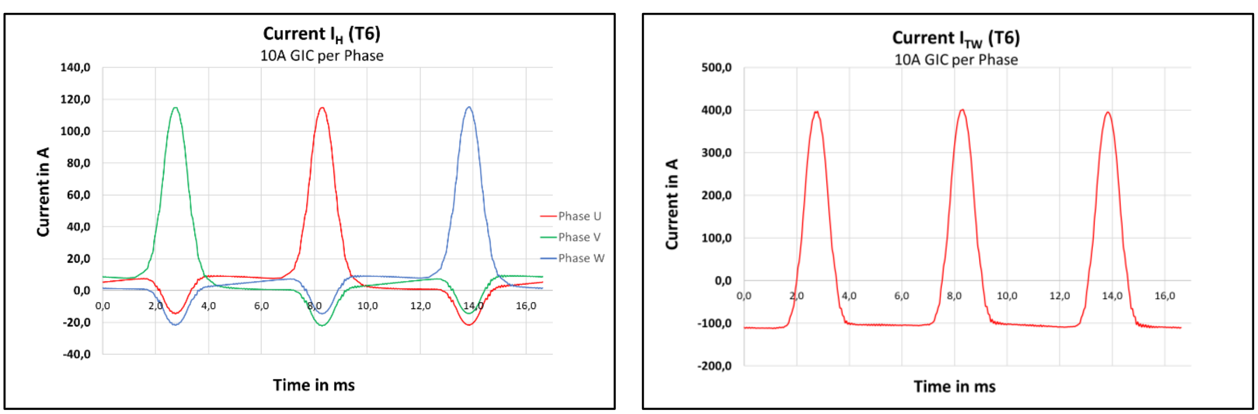


Figure 3: Current wave form with 10A DC per phase

Current Wave Forms with 20A DC per Phase

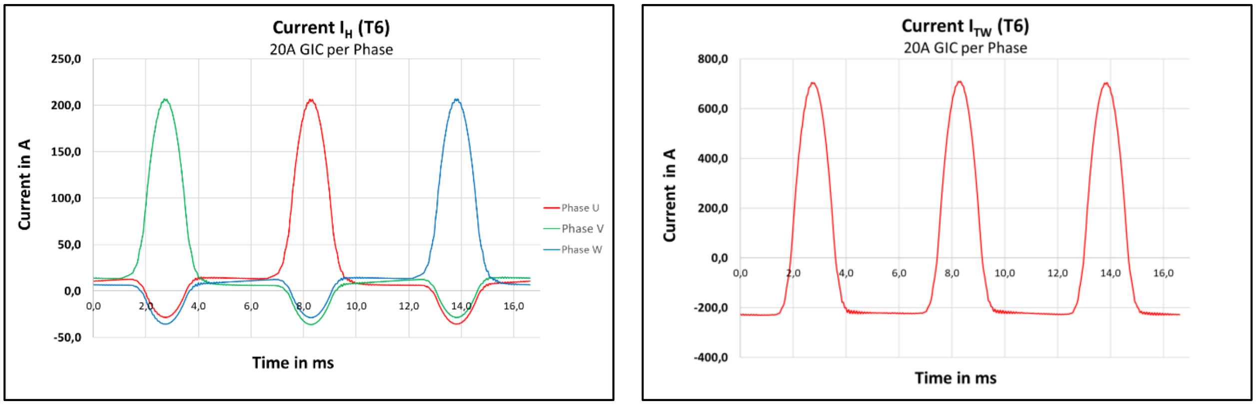


Figure 4: Current wave form with 20A DC per phase

Current Wave Forms with 40A DC per Phase

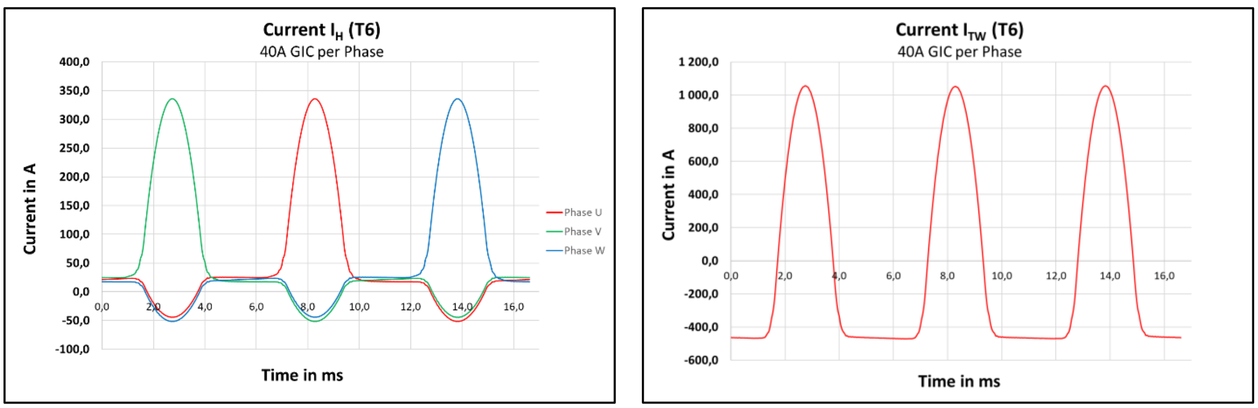


Figure 5: Current wave form with 40A DC per phase

Current Wave Forms with 50A DC per Phase

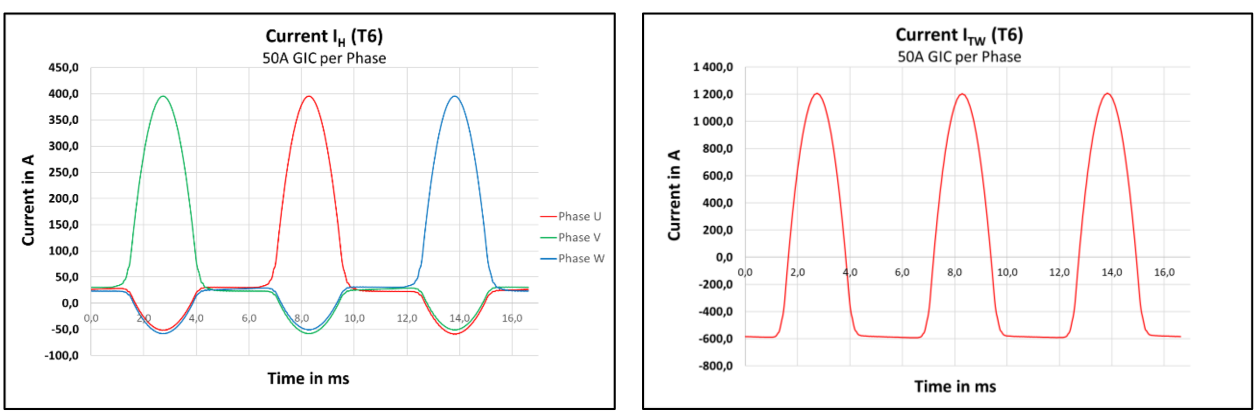
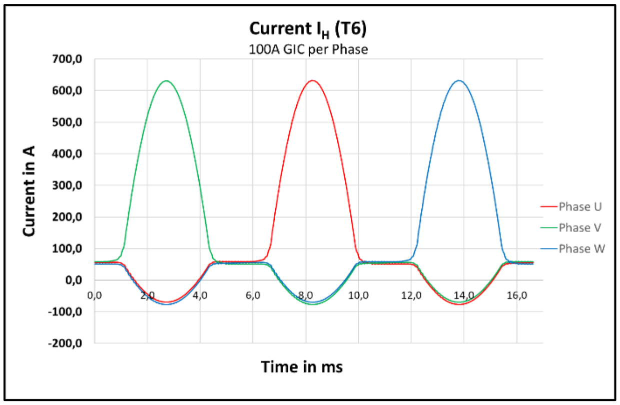


Figure 6: Current wave form with 50A DC per phase

Current Wave Forms with 100A DC per Phase



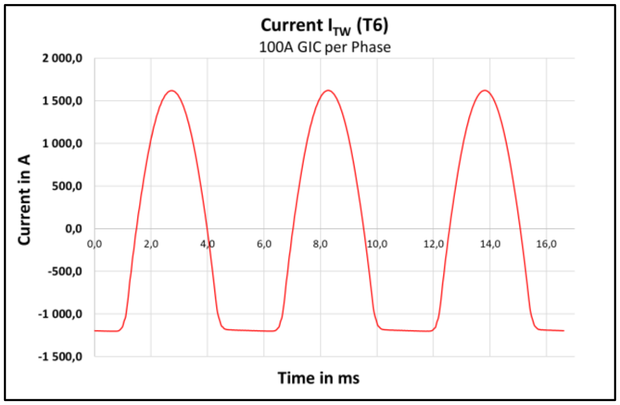
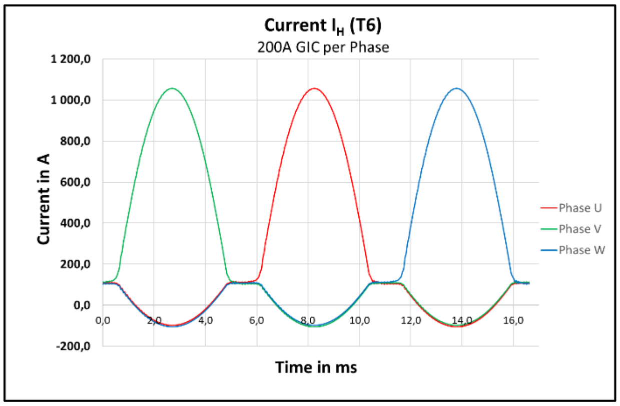


Figure 7: Current wave form with 100A DC per phase

Current Wave Forms with 200A DC per Phase



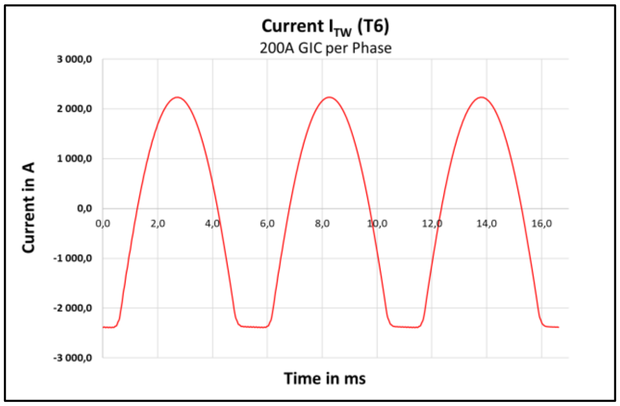


Figure 8: Current wave form with 200A DC per phase

Harmonics of Compensating Current

Figure 9 to 11 show the harmonics of the compensating current in the TW winding with the different DC-currents in the high-voltage system.

Harmonics for 10A and 20A DC per Phase

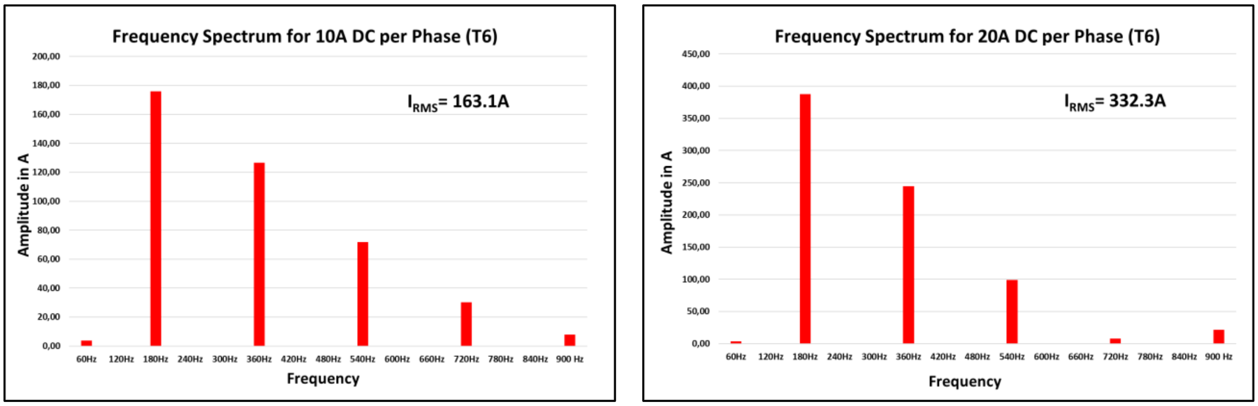


Figure 9: Harmonics for 10A and 20A DC per phase

Harmonics for 40A and 50A DC per Phase

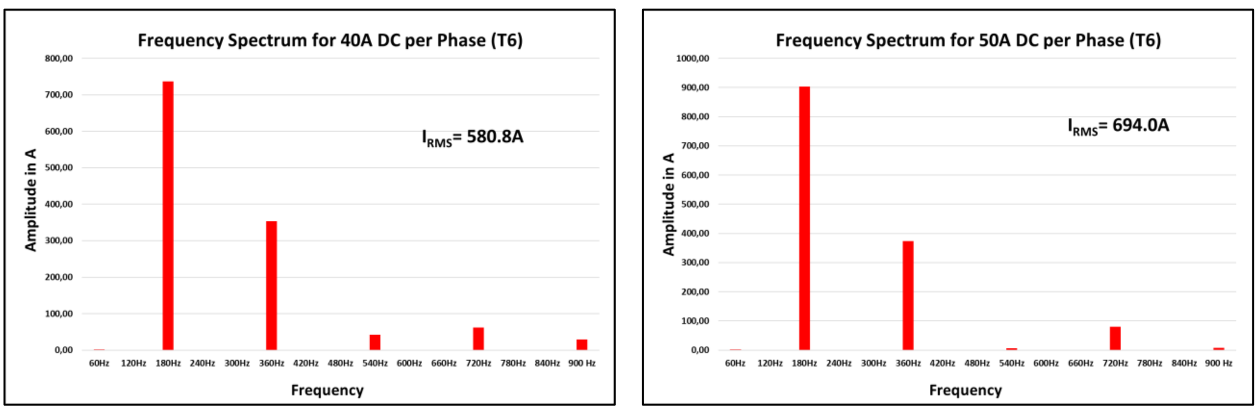
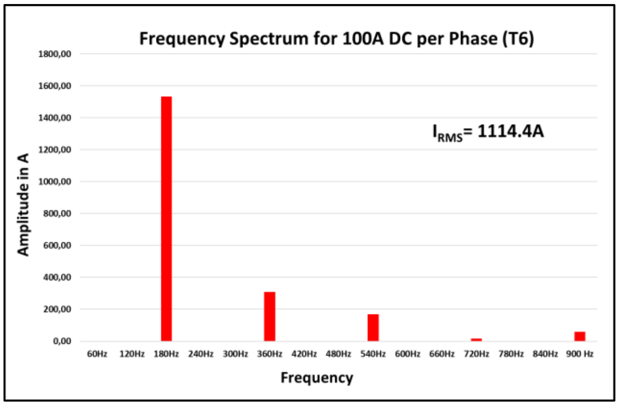


Figure 10: Harmonics for 40A and 50A DC per phase

Harmonics for 100A and 200A DC per Phase



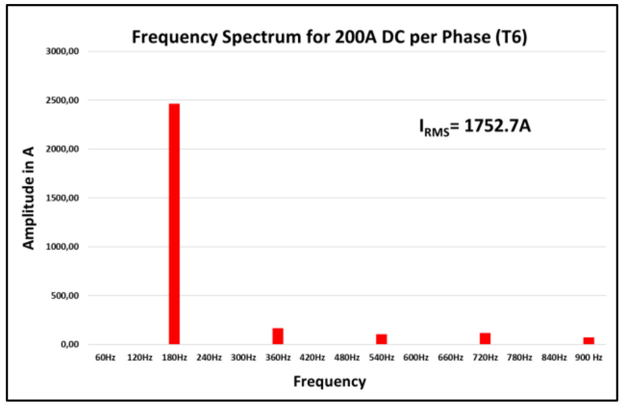


Figure 11: Harmonics for 100A and 200A DC per phase

TW “Loading” due to DC (RMS value of circulating current)

Figure 12 shows the “loading” of the TW winding due to DC. This means the RMS value of the circulating current under DC is shown in per unit of the rated AC current in the TW winding. The rated AC current of the TW winding is 8115.8A. It can be seen, that even with 200 A DC per phase the RMS value of the rated condition is not reached.

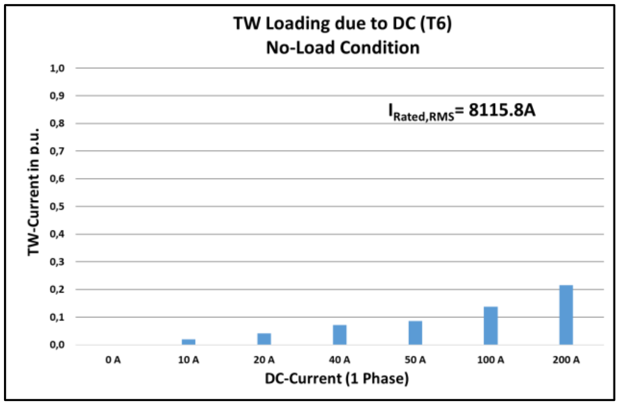


Figure 12: TW loading due to DC (No-Load Condition)

Thermal behavior under DC

The temperature rises of the tertiary winding, which are caused by the compensating currents of the previous clause are calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [K]	12
Top oil temperature [K]	44

Losses in Tertiary winding due to DC

The following table demonstrates the total losses in tertiary winding with different DC levels per phase in the high-voltage winding.

Table 3: Total losses of tertiary winding with DC

DC level per phase [A]	I^2R losses [kW]	Eddy losses [kW]
10	0.032	0.236
20	0.131	0.717
40	0.399	1.666
50	0.569	2.101
100	1.479	4.343
200	3.651	9.498

Steady-state hotspot temperature rise of tertiary winding above Topoil due to DC

The following table demonstrates the steady-state hotspot temperature rises (above ambient) in the tertiary winding for different DC levels.

Table 4: Hotspot temperature rise (above ambient) of TW winding with DC

DC level per phase [A]	Hotspot rise [K]
10	13.9
20	15.6
40	17.7
50	18.6
100	22.3
200	28.7

Graphical result for steady state temperature rises for different DC levels

Figure 13 shows the calculated steady-state hotspot rise of the tertiary winding for different DC levels. It can be seen, that the hotspot temperatures are far below critical levels (max. 100K, according to IEEE long time emergency condition at 40°C ambient).

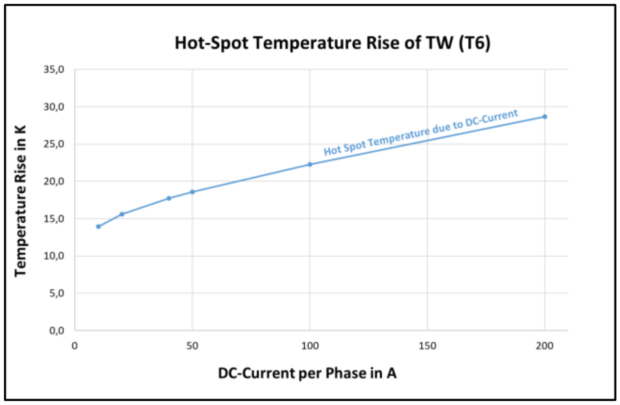


Figure 13: Hotspot temperature rise (above ambient) with DC

EPRI – GIC Study

Study of Thermal Impact of GIC on Delta/Tertiary Windings

Transformer T7

Content

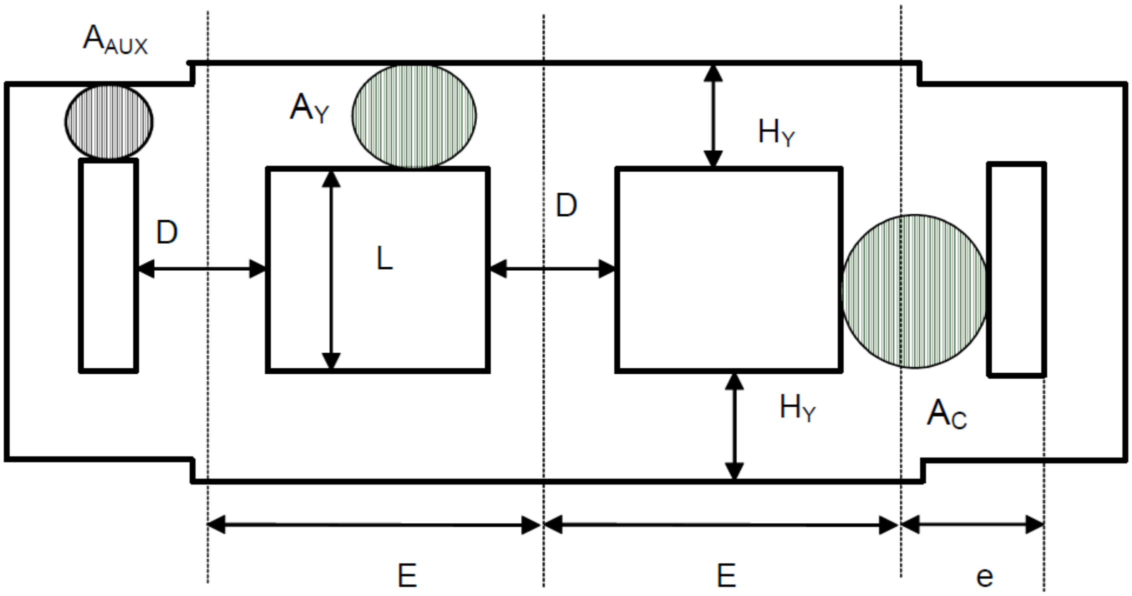
General Data

Transformer Data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T7
Transformer type	Transmission Transformer
HV nameplate rating	300MVA
TW nameplate rating	30MVA
Number of phases	3
Voltage levels	232kV // 116kV // 10kV
Winding affected by DC	HV
Core type	5



L [mm]	2640
D [mm]	1150
H_Y [mm]	827.6
E [mm]	2070
e [mm]	1070
A_C [m2]	0.9432
A_Y [m2]	0.538
A_{Aux} [m2]	0.475

Figure 1: Sketch of core geometry

DC Levels Overview

The report contains steady-state results for the electrical and thermal response of the tertiary winding for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Compensating Current Under DC

The current in the high-voltage and tertiary winding are calculated for each DC level. In order to identify only the effect of an additional DC current in the neutral of the high-voltage system an unloaded TV-system was simulated. Figure 2 shows the used electrical circuit. Figure 3 to Figure 8 show the calculated wave forms of the currents in both systems.

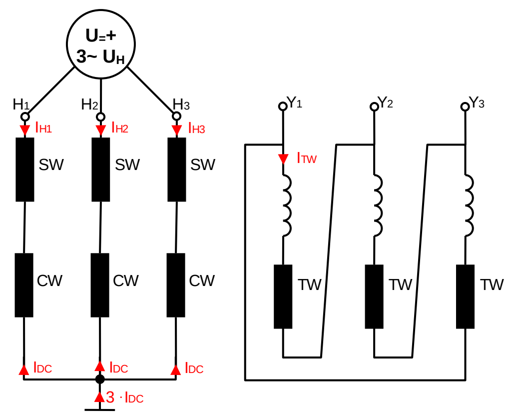


Figure 2: Electrical circuit (unloaded TV-system)

Current Wave Forms with 10A DC per Phase

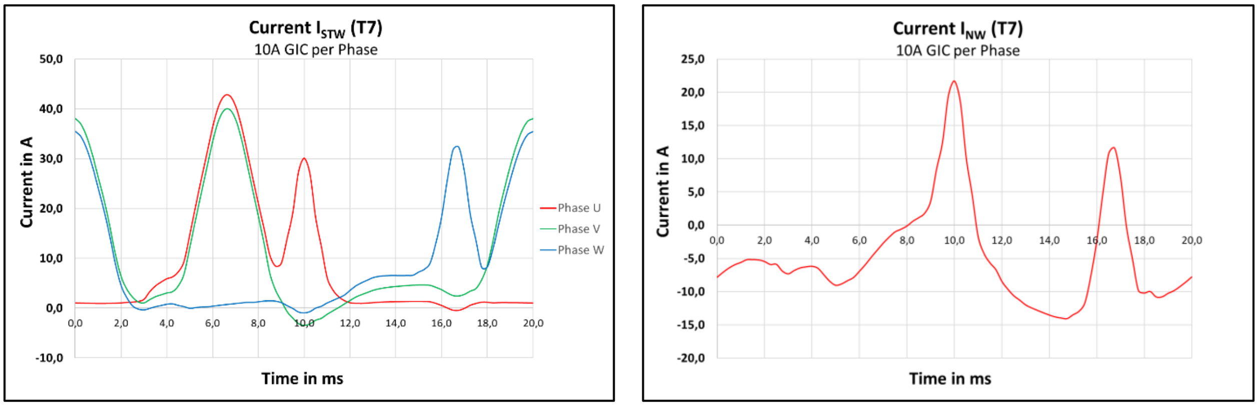


Figure 3: Current wave form with 10A DC per phase

Current Wave Forms with 20A DC per Phase

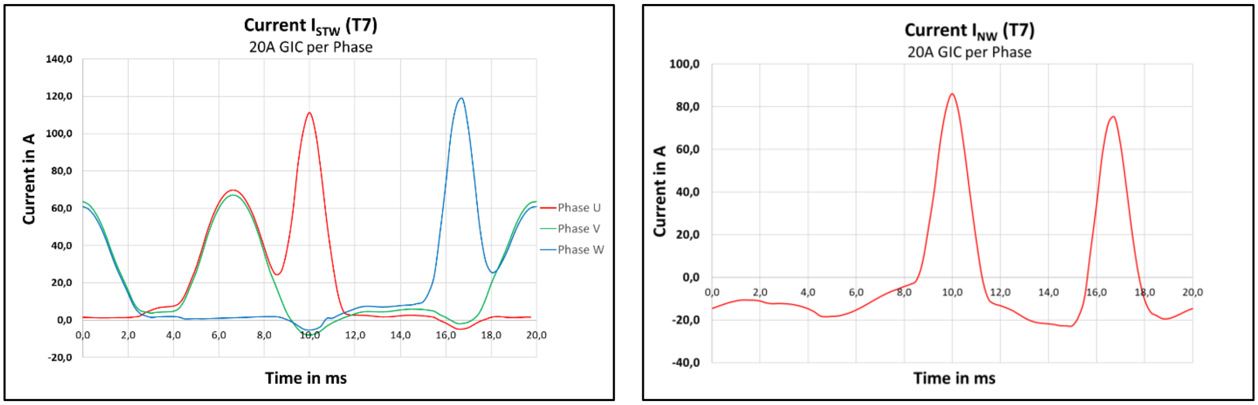


Figure 4: Current wave form with 20A DC per phase

Current Wave Forms with 40A DC per Phase

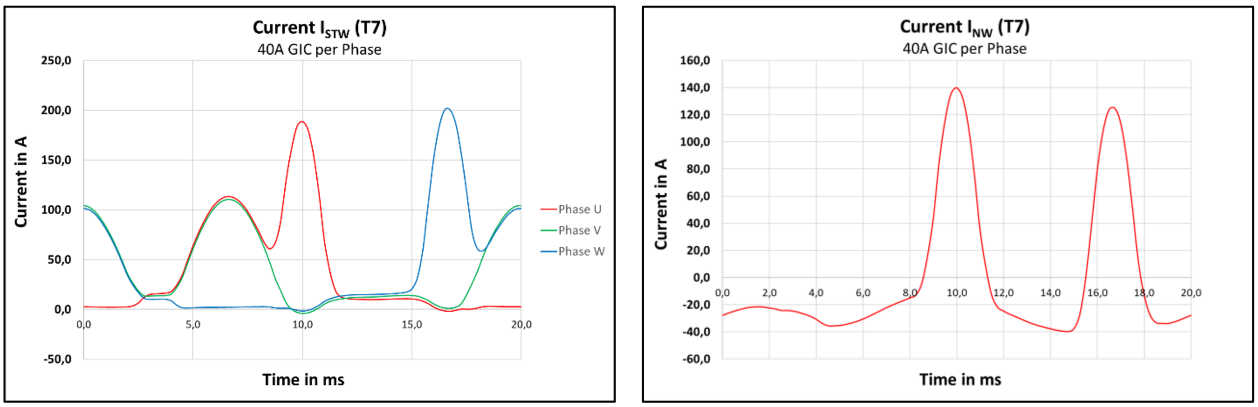


Figure 5: Current wave form with 40A DC per phase

Current Wave Forms with 50A DC per Phase

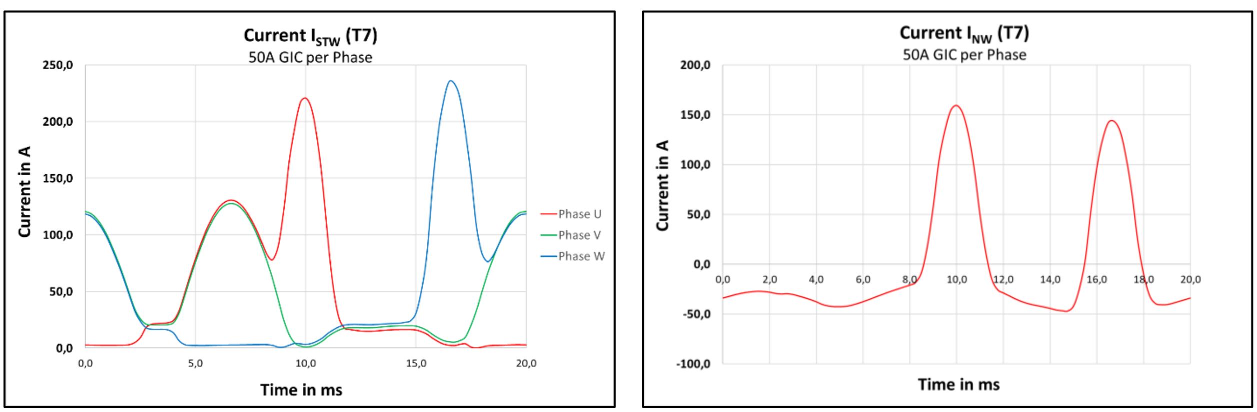


Figure 6: Current wave form with 50A DC per phase

Current Wave Forms with 100A DC per Phase

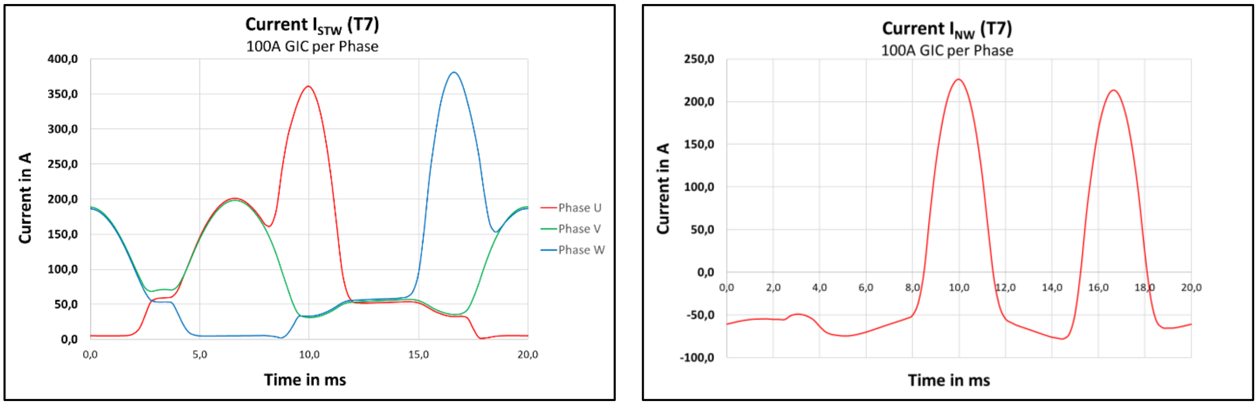


Figure 7: Current wave form with 100A DC per phase

Current Wave Forms with 200A DC per Phase

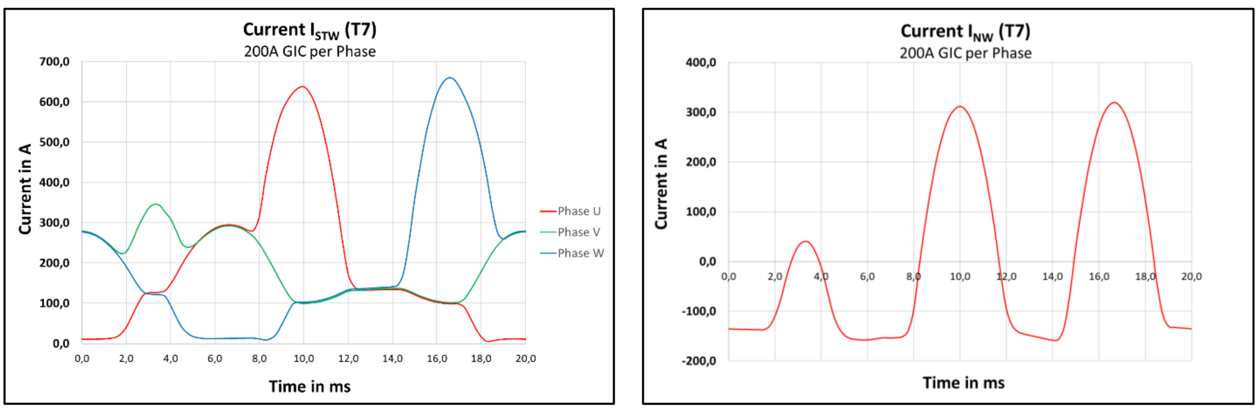


Figure 8: Current wave form with 200A DC per phase

Harmonics of Compensating Current

With the waveforms of Figure 3-8, an FFT analysis was done in order to demonstrate the different frequency components. Figure 9 to 11 show the harmonics of the compensating current in the TW winding with the different DC-currents in the high-voltage system. In addition, the RMS value of the current is shown in each figure.

Harmonics for 10A and 20A DC per Phase

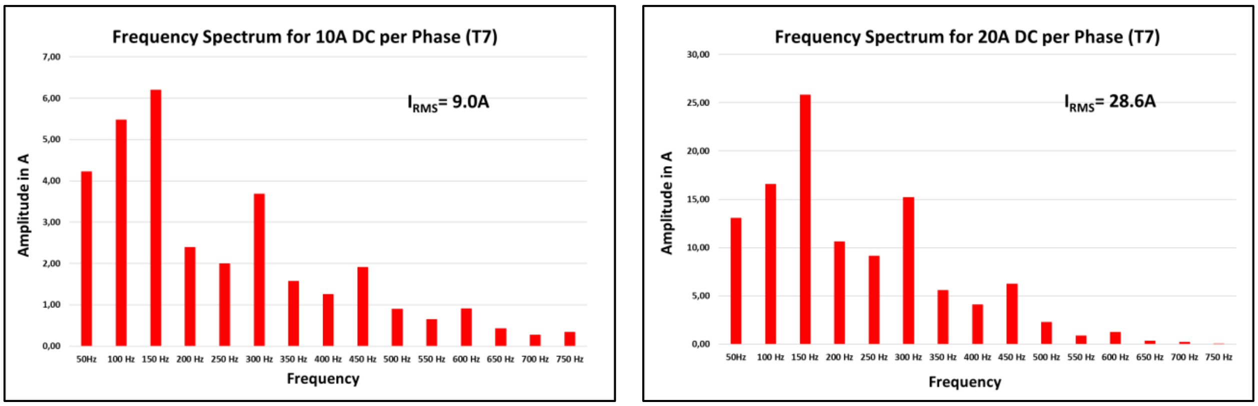


Figure 9: Harmonics for 10A and 20A DC per phase

Harmonics for 40A and 50A DC per Phase

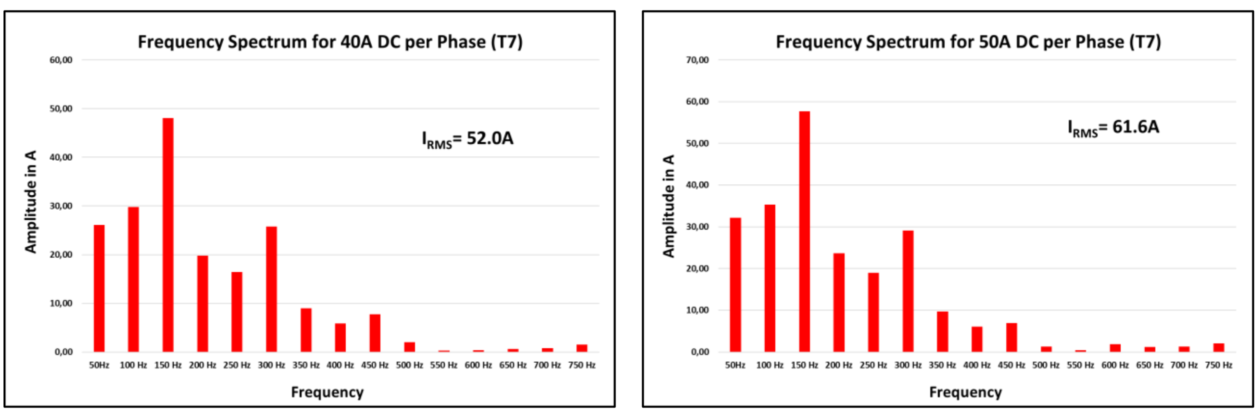


Figure 10: Harmonics for 40A and 50A DC per phase

Harmonics for 100A and 200A DC per Phase

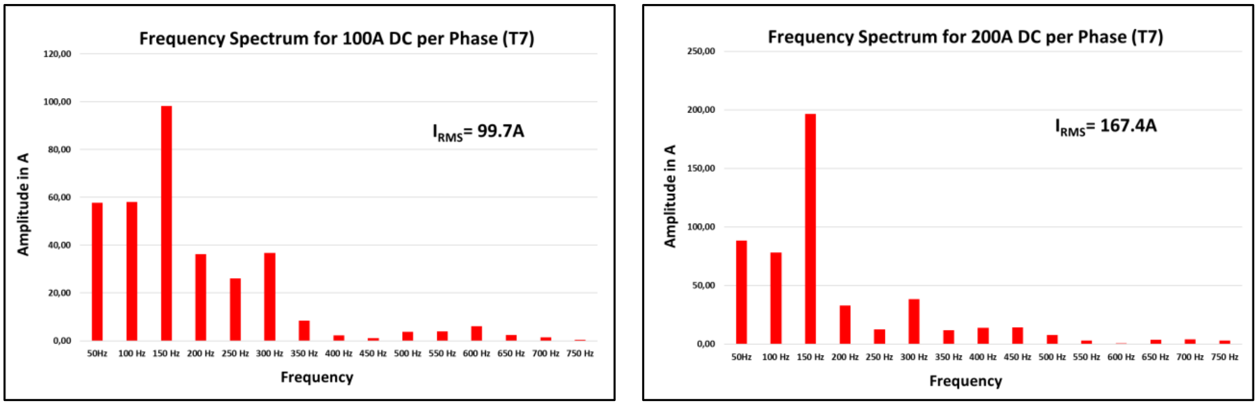


Figure 11: Harmonics for 100A and 200A DC per phase

TW “Loading” due to DC (RMS value of circulating current)

Figure 12 shows the “loading” of the TW winding due to DC. This means the RMS value of the circulating current under DC is shown in per unit of the rated AC current in the TW winding. The rated AC current of the TW winding is 1000.0A. It can be seen, that even with 200 A DC per phase the RMS value of the rated condition is not reached.

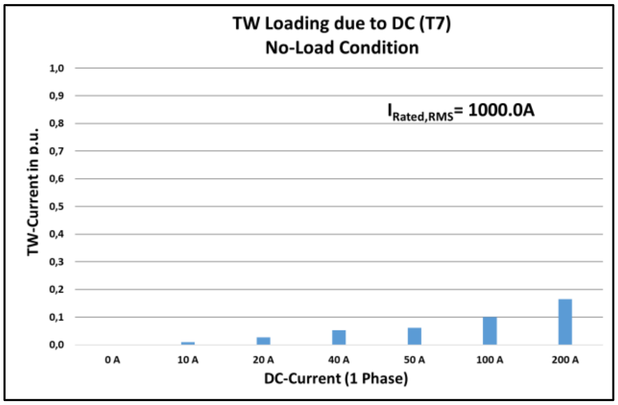


Figure 12: TW loading due to DC (No-Load Condition)

Thermal behavior under DC

The temperature rises of the tertiary winding, which are caused by the compensating currents of the previous clause are calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [K]	47
Top oil temperature [K]	55

Losses in Tertiary winding due to DC

The following table demonstrates the total losses in tertiary winding with different DC levels per phase in the high-voltage winding.

Table 3: Total losses of tertiary winding with DC

DC level per phase [A]	I^2R losses [kW]	Eddy losses [kW]
10	0.001	0.048
20	0.005	0.353
40	0.017	0.892
50	0.023	1.147
100	0.060	2.339
200	0.170	5.896

Steady-state hotspot temperature rise of tertiary winding above Topoil due to DC

The following table demonstrates the steady-state hotspot temperature rises (above ambient) in the tertiary winding for different DC levels.

Table 4: Hotspot temperature rise (above ambient) of TW winding with DC

DC level per phase [A]	Hotspot rise [K]
10	55.3
20	56.0
40	56.9
50	57.2
100	58.7
200	62.2

Graphical result for steady state temperature rises for different DC levels

Figure 13 shows the calculated steady-state hotspot rise of the tertiary winding for different DC levels. It can be seen, that the hotspot temperatures are far below critical levels (max. 100K, according to IEEE long time emergency condition at 40°C ambient).

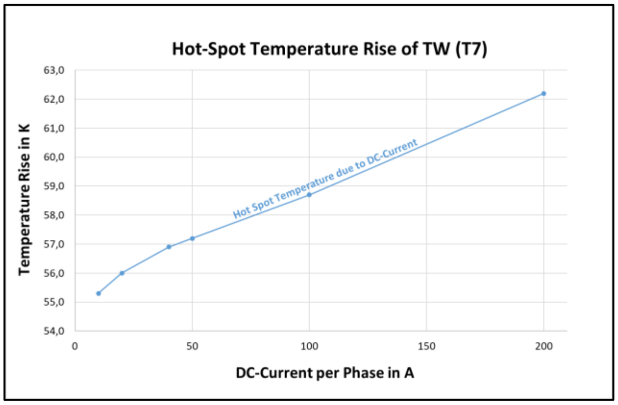


Figure 13: Hotspot temperature rise (above ambient) with DC

DC Capability study – Tie bars

Transformer T1

Content

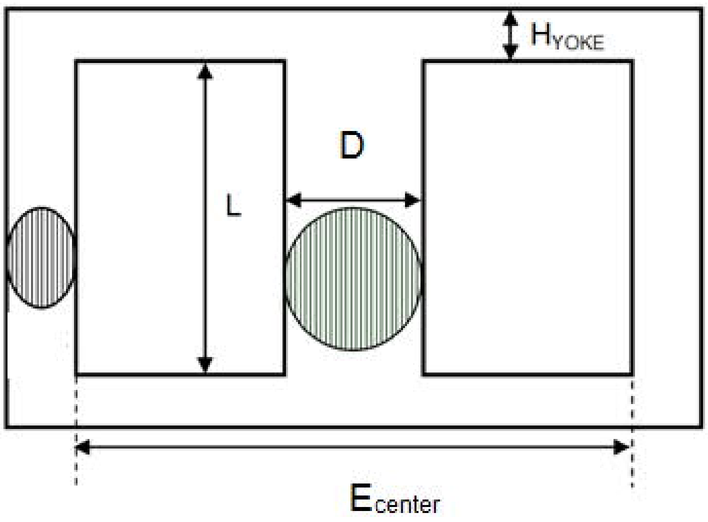
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T1
Transformer type	GSU
Rated power	92 MVA
Number of phases	1
Voltage levels	526/√3 kV // 34.5/√3 kV // 13.8 kV
Winding affected by DC	HV
Core type	1



L [mm]	2966
D [mm]	948
H yoke [mm]	470
E center [mm]	1986
A limb [m2]	0.64353
A yoke [m2]	0.324124

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.7653 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	35.1	62.6
20	44.8	101.0
40	48.9	128.7
50	50.7	134.5
100	52.2	150.4
200	55.3	167.2

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

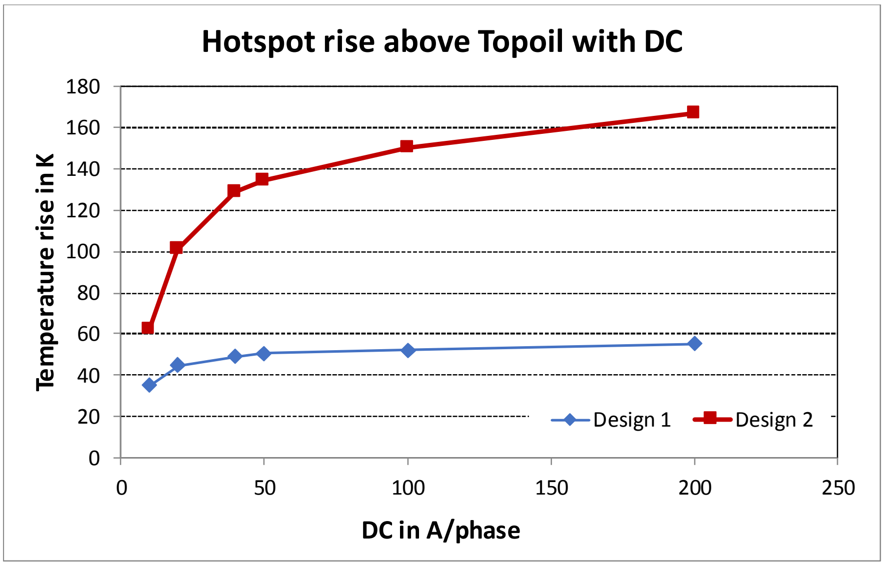


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

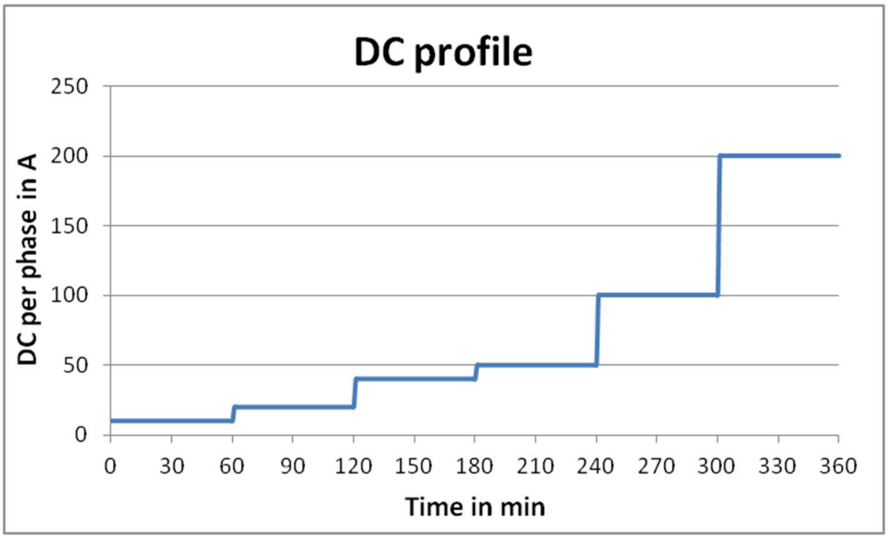


Figure 3: DC profile

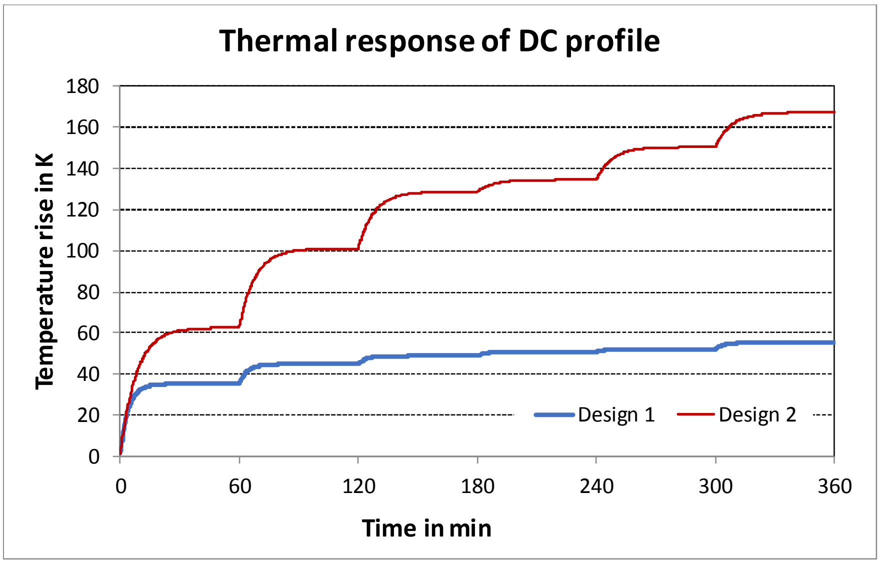


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T2

Content

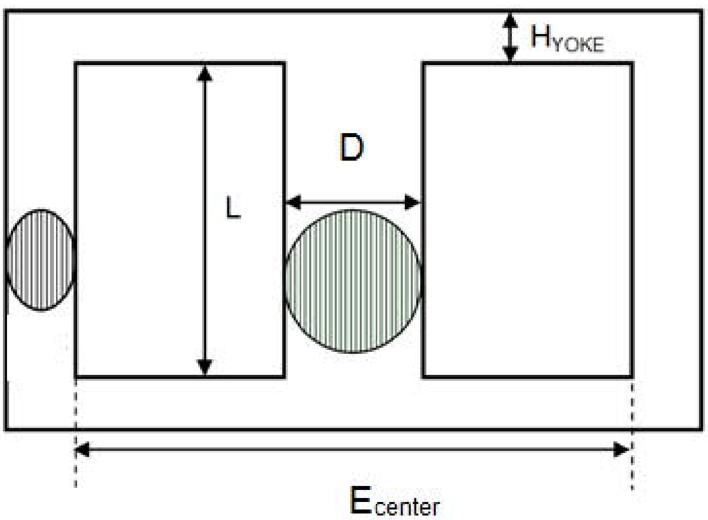
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T2
Transformer type	Auto
Rated power	374 MVA
Number of phases	1
Voltage levels	525/√3 kV // 230/√3 kV // 13.8 kV
Winding affected by DC	HV
Core type	1



L [mm]	3020
D [mm]	1160
H yoke [mm]	570
E center [mm]	2400
A limb [m2]	0.96496
A yoke [m2]	0.48433

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.3751 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	25.6	37.3
20	39.5	71.1
40	46.6	110.3
50	48.2	121.0
100	52.2	152.4
200	54.8	187.3

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

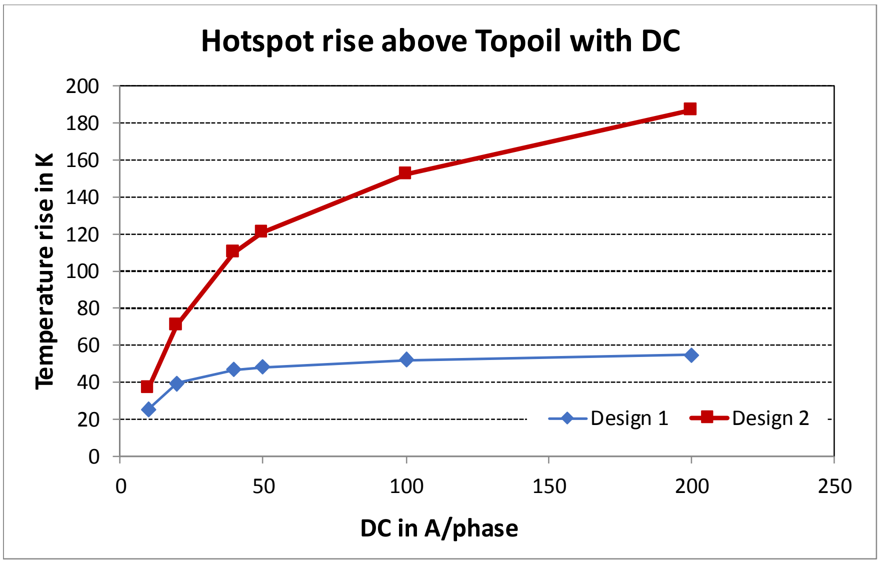


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

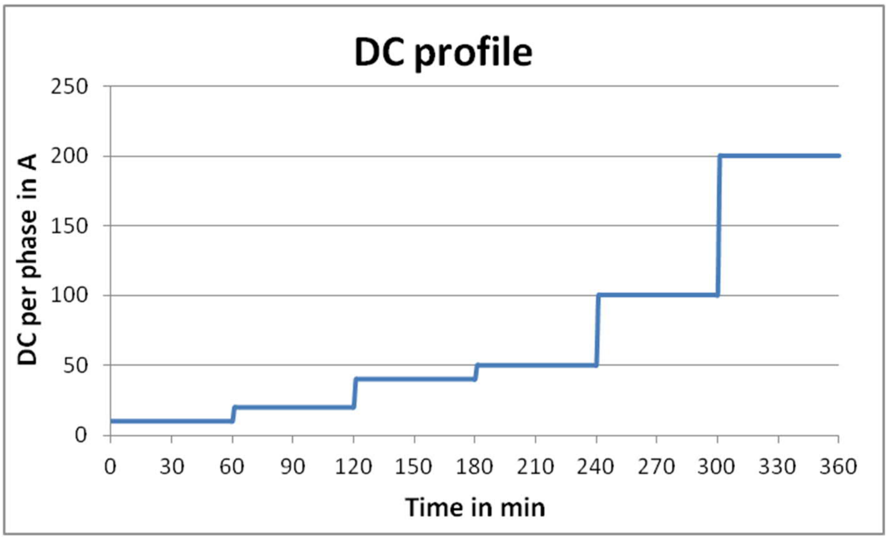


Figure 3: DC profile

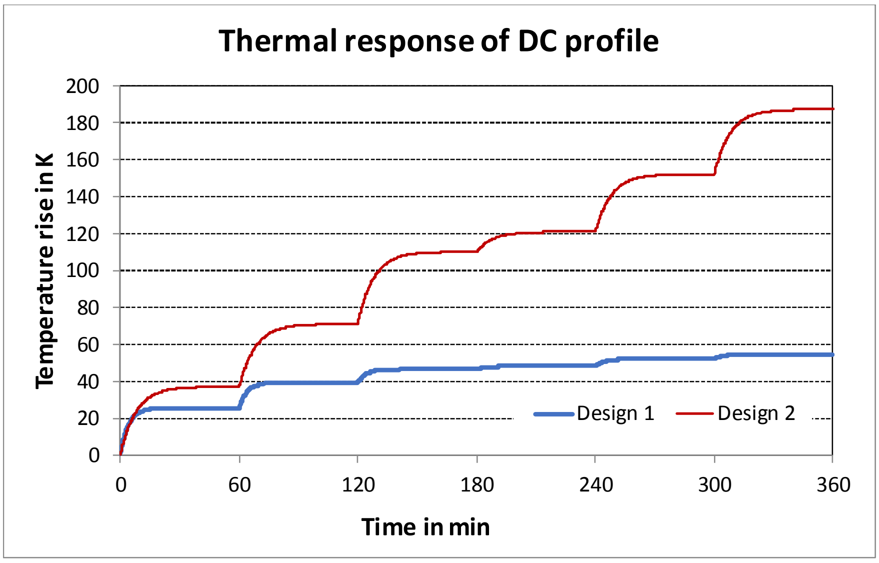


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T3

Content

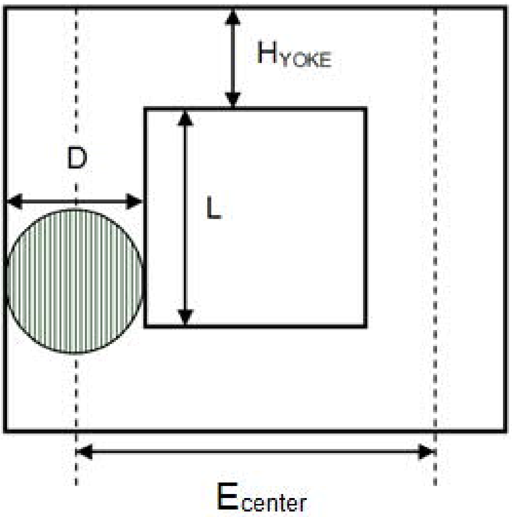
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T3
Transformer type	Auto
Rated power	500 MVA
Number of phases	1
Voltage levels	525/√3 kV // 230/√3 kV // 34.5 kV
Winding affected by DC	HV
Core type	2



L [mm]	2250
D [mm]	1064
H yoke [mm]	1050
E center [mm]	2270
A limb [m2]	0.79722
A yoke [m2]	0.79722

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.6014 H (per leg)

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	17.1	28.5
20	28.2	60.2
40	37.9	98.5
50	39.8	110.6
100	43.3	140.1
200	47.6	175.8

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

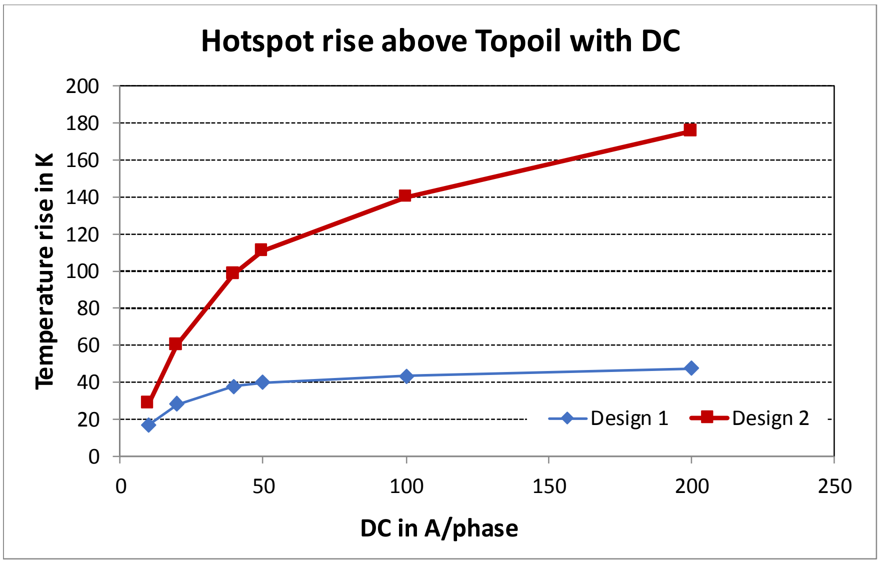


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

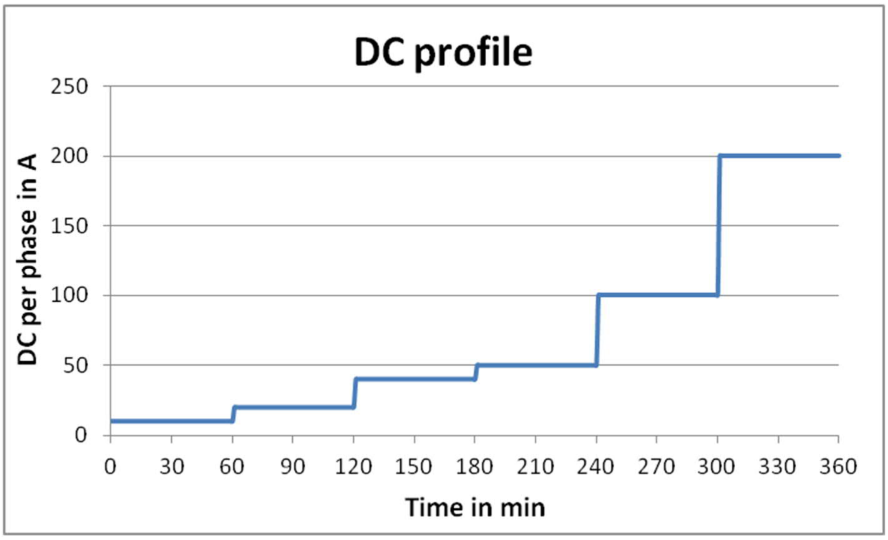


Figure 3: DC profile

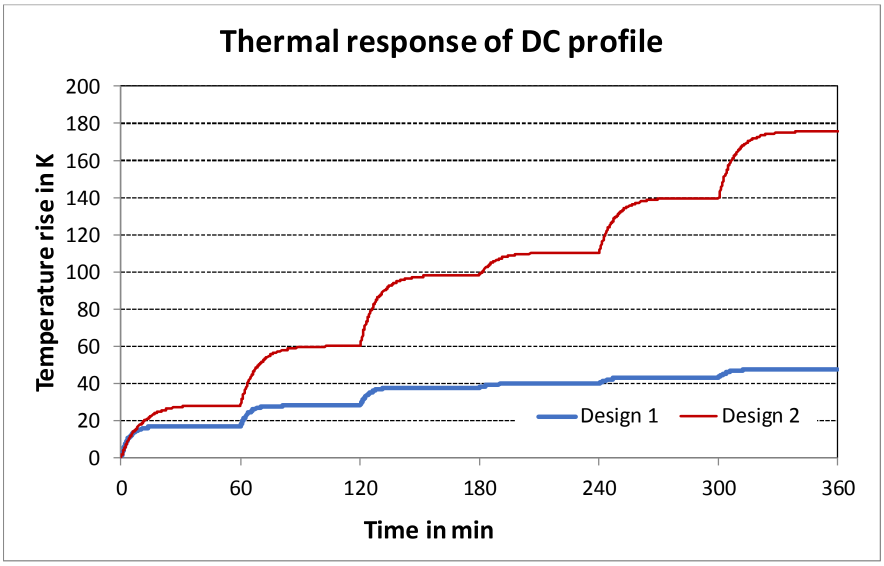


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T4

Content

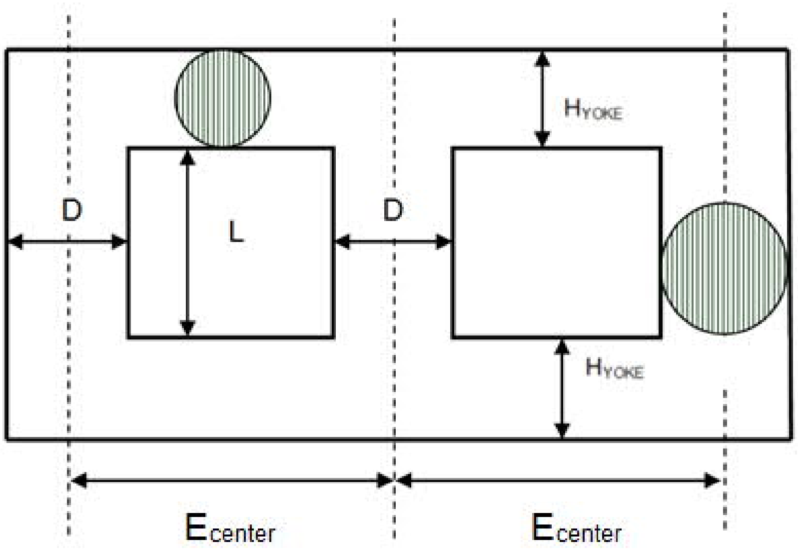
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T4
Transformer type	Auto
Rated power	300 MVA
Number of phases	3
Voltage levels	525 kV // 115 kV // 13.8 kV
Winding affected by DC	HV
Core type	3



L [mm]	2460
D [mm]	910
H yoke [mm]	900
E center [mm]	1866
A limb [m2]	0.584011
A yoke [m2]	0.584011

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.7147 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] “Design 1”	Tie bar hot spot rise [K] “Design 2”
10	1.0	0.5
20	19.8	30.7
40	43.0	110.0
50	45.6	127.9
100	49.9	171.6
200	53.6	220.5

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

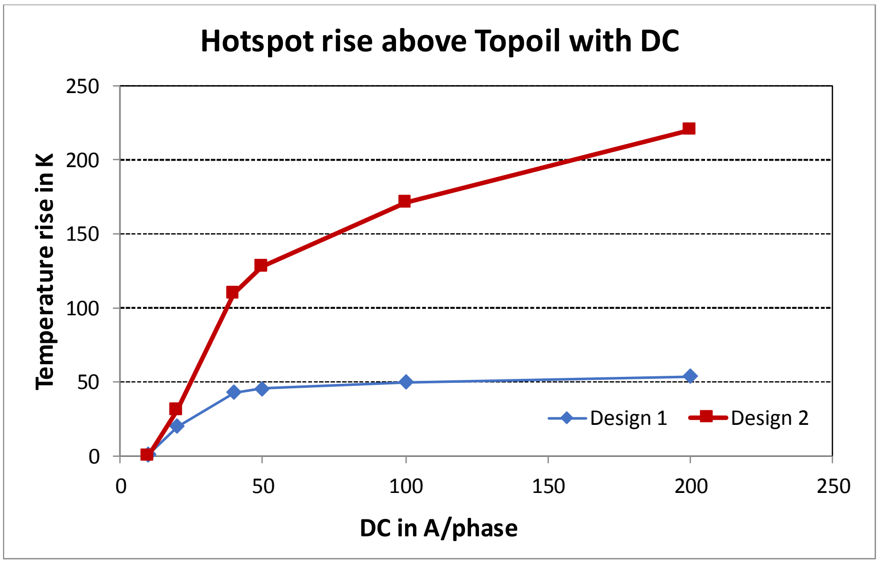


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

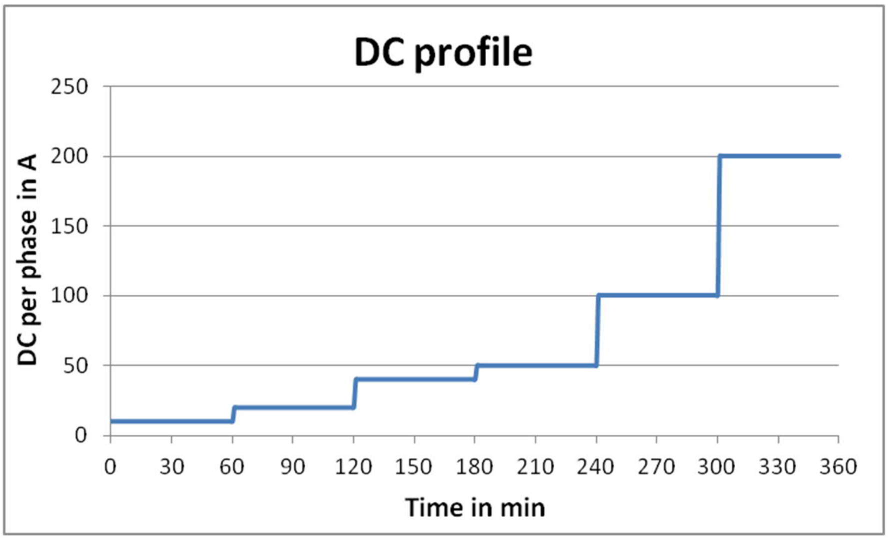


Figure 3: DC profile

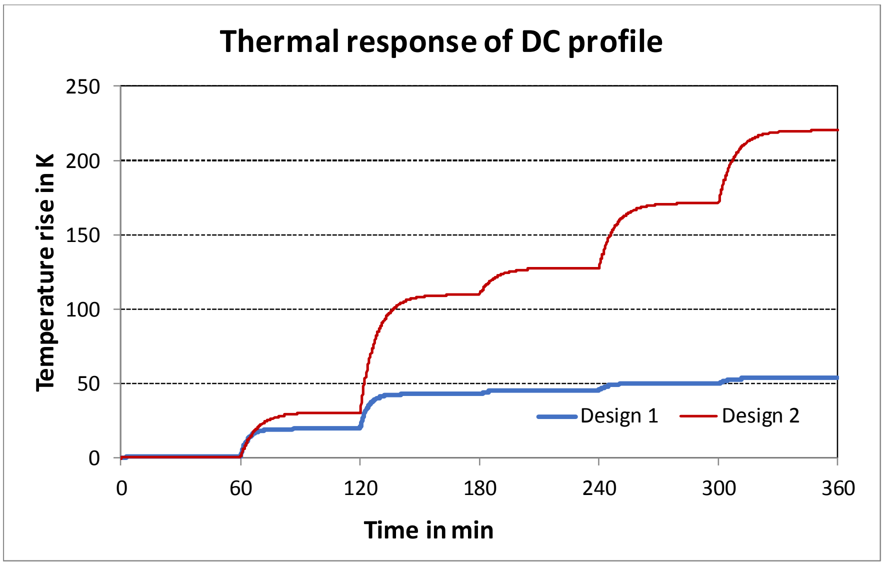


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T5

Content

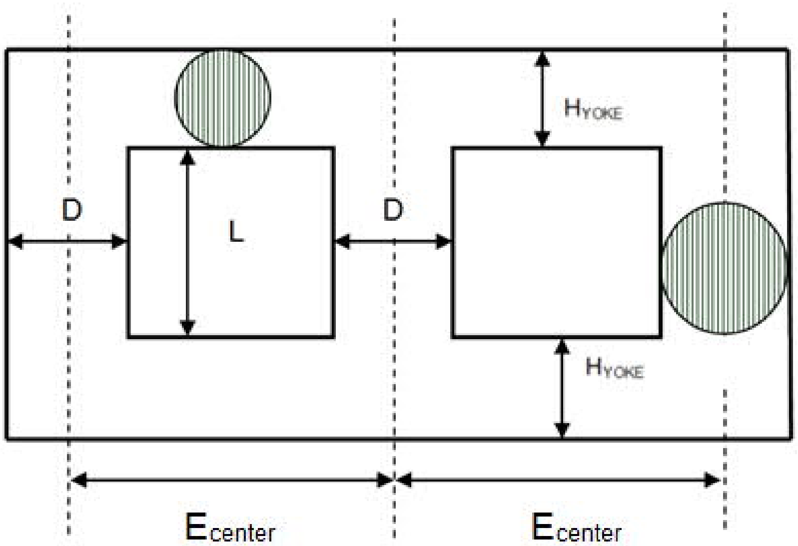
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T5
Transformer type	Auto
Rated power	560 MVA
Number of phases	3
Voltage levels	525 kV // 230 kV
Winding affected by DC	HV
Core type	3



L [mm]	2360
D [mm]	916
H yoke [mm]	900
E center [mm]	2144
A limb [m2]	0.589283
A yoke [m2]	0.589491

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.8076 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	1.6	0.8
20	23.1	37.1
40	40.4	109.9
50	42.5	127.8
100	46.5	172.3
200	52.2	238.0

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

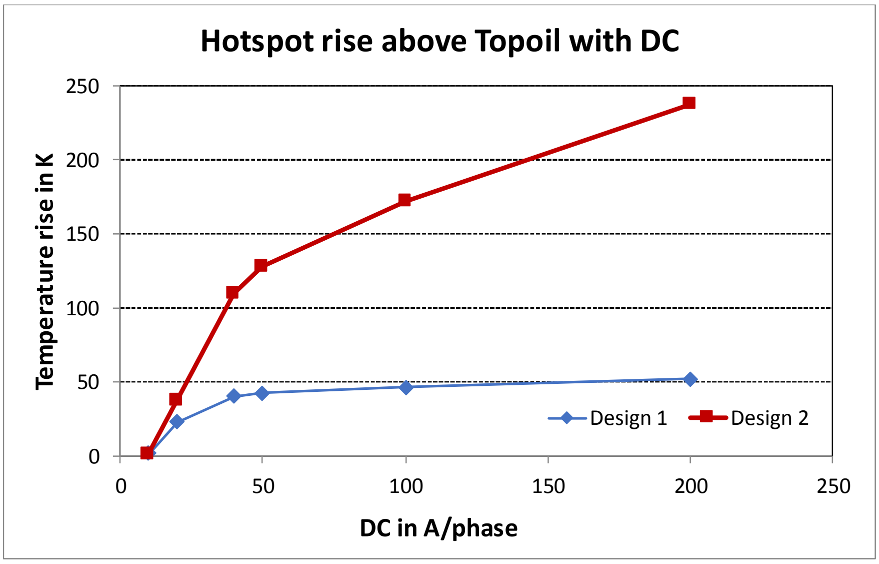


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

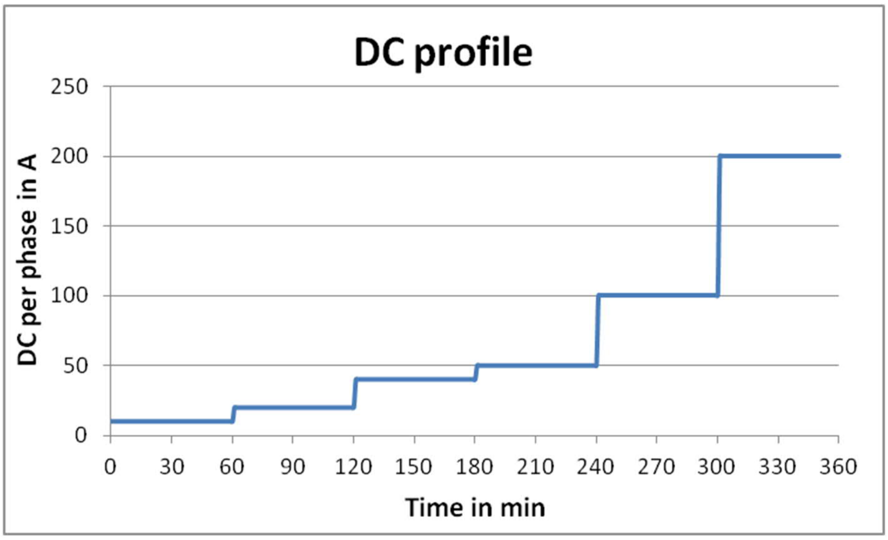


Figure 3: DC profile

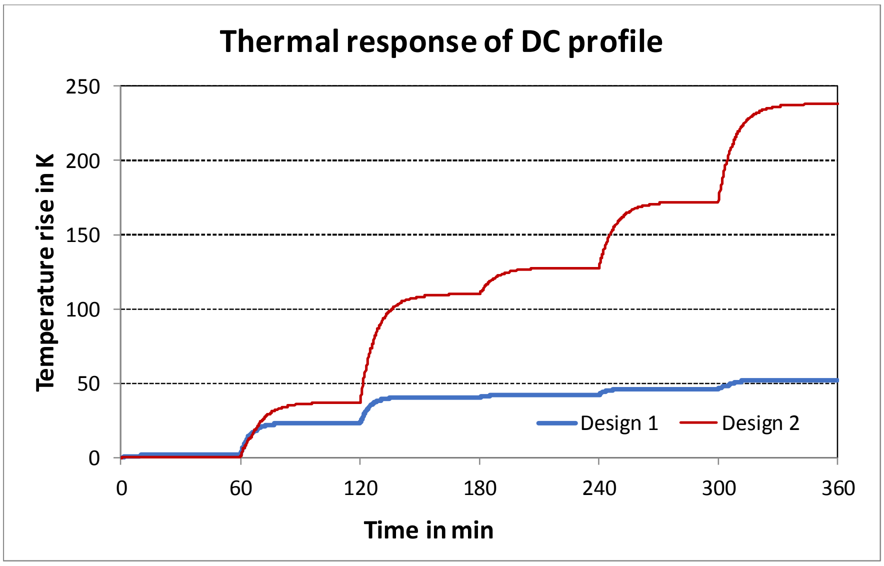


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T6

Content

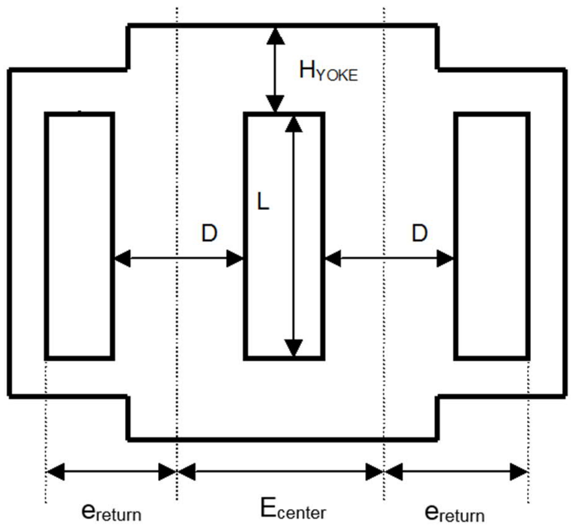
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T6
Transformer type	Auto
Rated power	292 MVA
Number of phases	1
Voltage levels	500/√3 kV // 230/√3 kV // 13.8 kV
Winding affected by DC	HV
Core type	4



L [mm]	2810
D [mm]	962
H yoke [mm]	530
E center [mm]	2036
A limb [m2]	0.653232
A yoke [m2]	0.430379
A return [m2]	0.223478
e return [mm]	1123

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.7872 H (per leg)

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	20.0	32.1
20	32.2	65.7
40	40.9	103.7
50	42.1	114.0
100	46.3	141.5
200	47.8	168.2

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

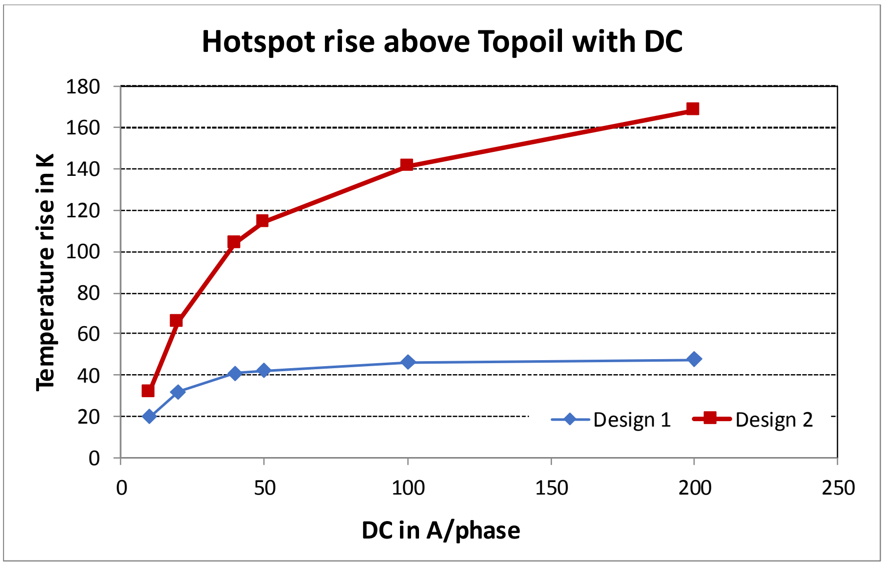


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

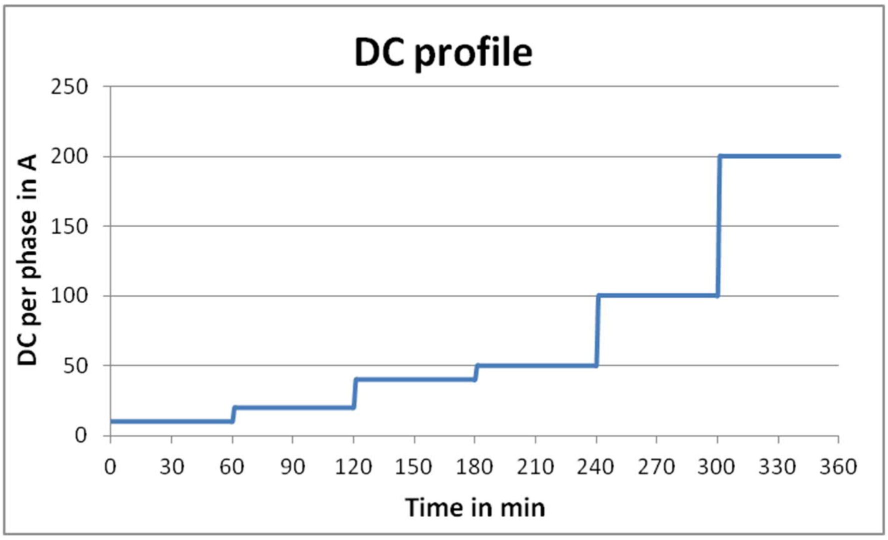


Figure 3: DC profile

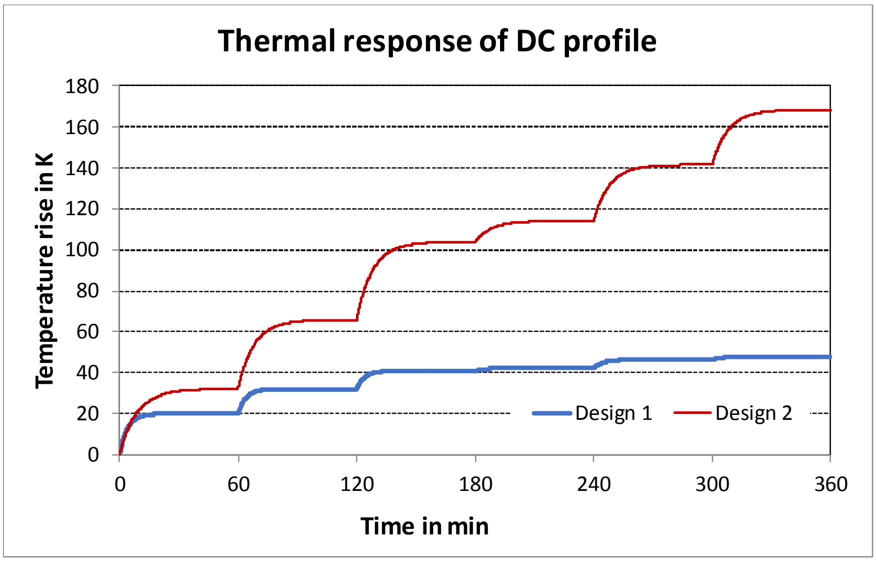


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T7

Content

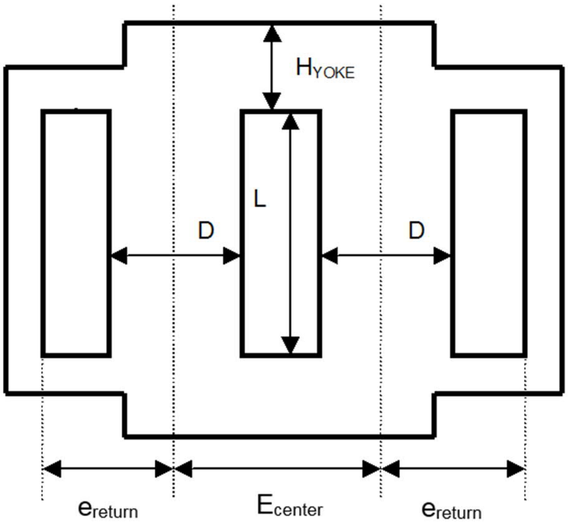
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T7
Transformer type	Auto
Rated power	672 MVA
Number of phases	1
Voltage levels	500/√3 kV // 230/√3 kV // 13.8 kV
Winding affected by DC	HV
Core type	4



L [mm]	2510
D [mm]	1204
H yoke [mm]	790
E center [mm]	2350
A limb [m2]	1.019907
A yoke [m2]	0.770064
A return [m2]	0.249843
e return [mm]	1274

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.3441 H (per leg)

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	12.6	17.8
20	22.8	37.6
40	35.5	72.0
50	38.9	84.7
100	44.0	120.9
200	48.6	153.7

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

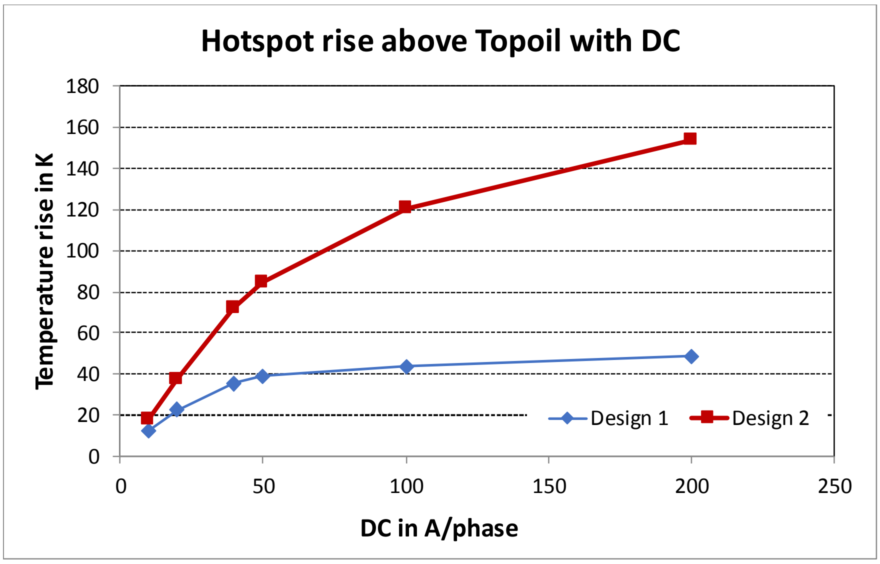


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

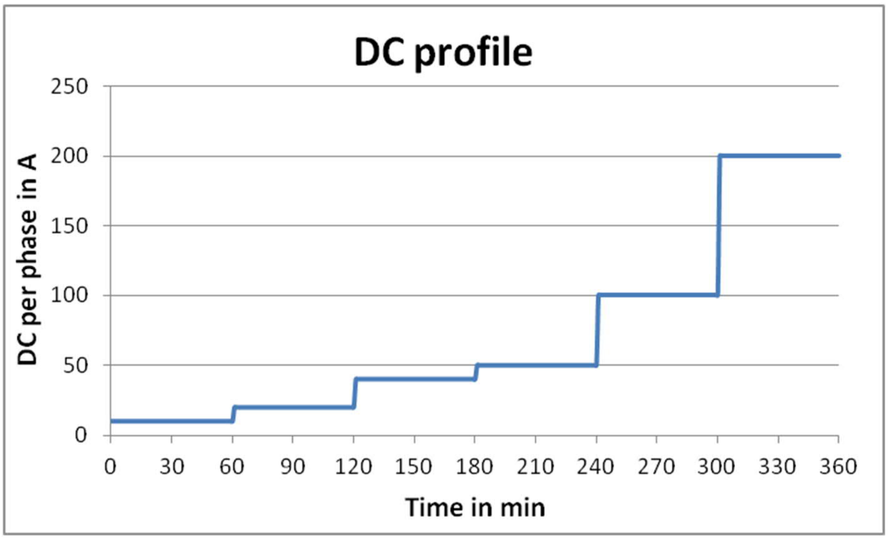


Figure 3: DC profile

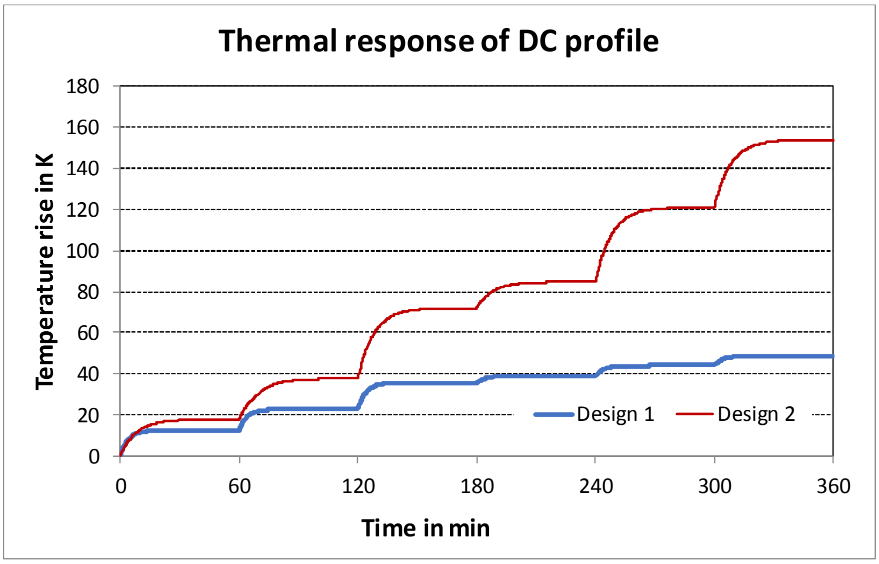


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T8

Content

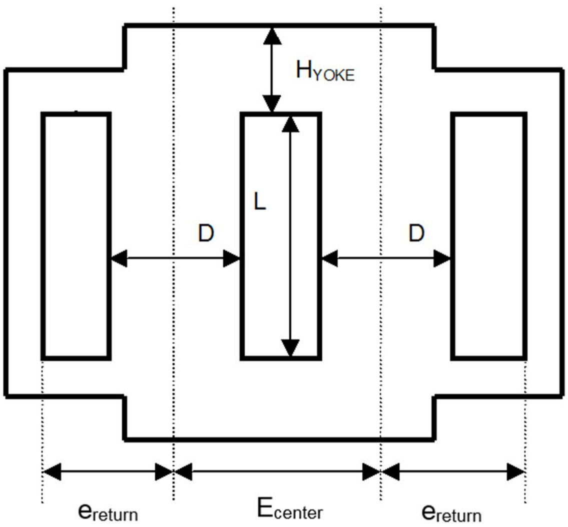
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T8
Transformer type	Auto
Rated power	460 MVA
Number of phases	1
Voltage levels	525/√3 kV // 230/√3 kV // 34.5 kV
Winding affected by DC	HV
Core type	4



L [mm]	3040
D [mm]	980
H yoke [mm]	600
E center [mm]	1940
A limb [m2]	0.679832
A yoke [m2]	0.492387
A return [m2]	0.188139
e return [mm]	1060

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.6635 H (per leg)

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] “Design 1”	Tie bar hot spot rise [K] “Design 2”
10	19.7	27.8
20	32.2	54.1
40	42.1	90.9
50	44.2	103.7
100	48.1	133.2
200	52.2	167.1

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

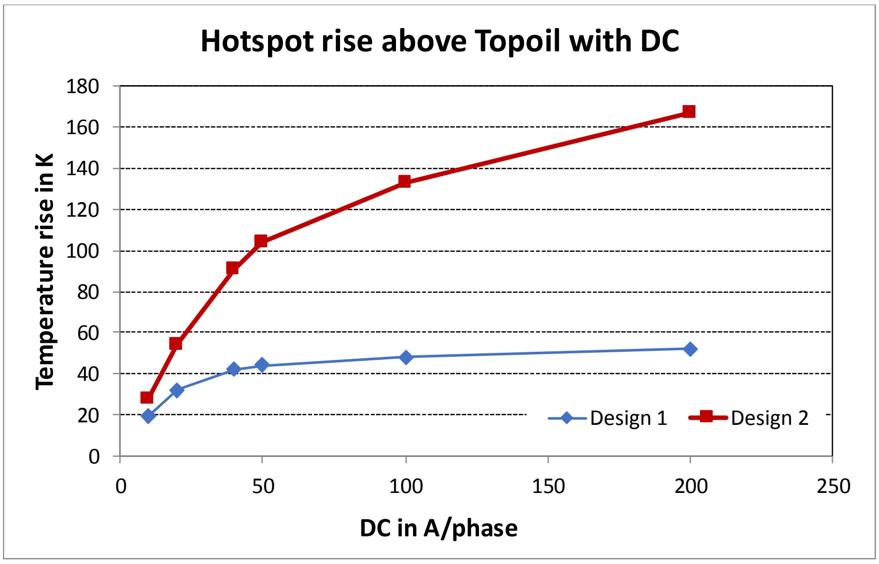


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

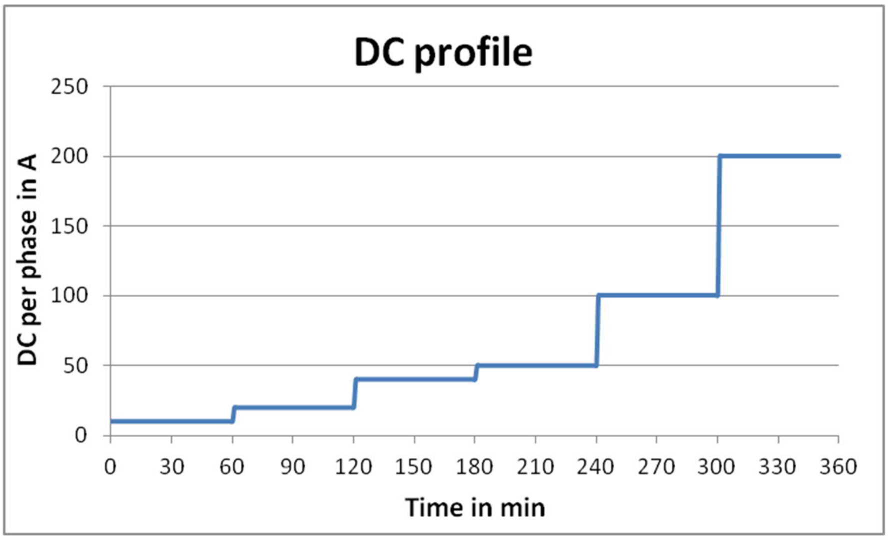


Figure 3: DC profile

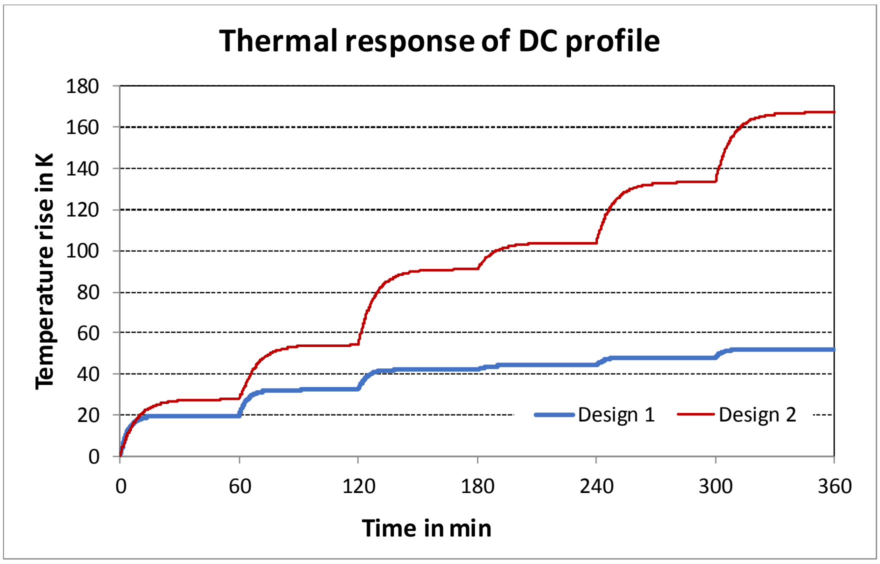


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T9

Content

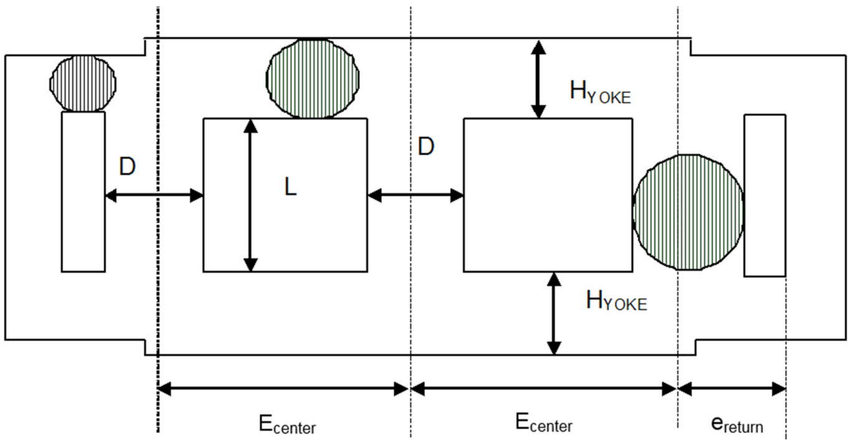
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T9
Transformer type	Auto
Rated power	840 MVA
Number of phases	3
Voltage levels	500 kV // 345 kV
Winding affected by DC	HV
Core type	5



L [mm]	3160
D [mm]	910
H yoke [mm]	510
E center [mm]	2150
A limb [m2]	0.586786
A yoke [m2]	0.333691
A return [m2]	0.294017
e return [mm]	1110

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.4586 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	23.9	41.6
20	36.2	77.1
40	42.6	115.3
50	44.0	125.2
100	47.4	157.8
200	49.0	193.7

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

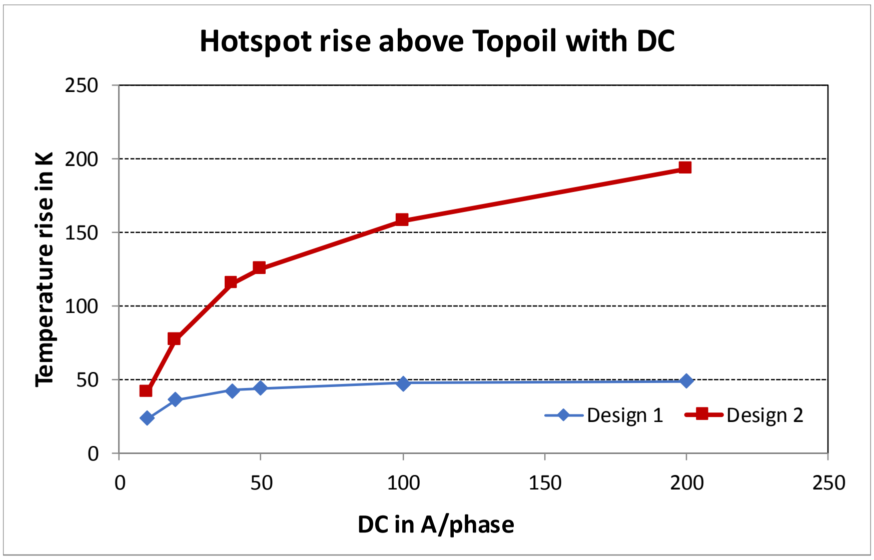


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

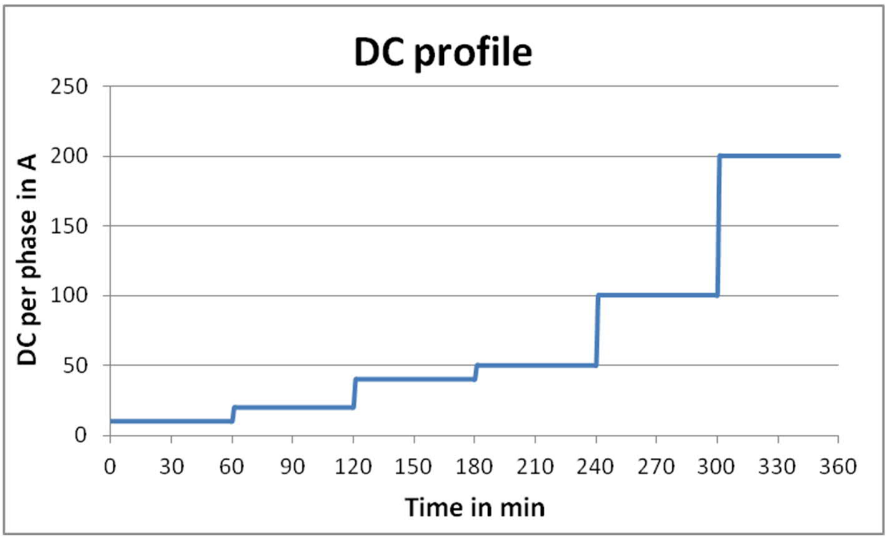


Figure 3: DC profile

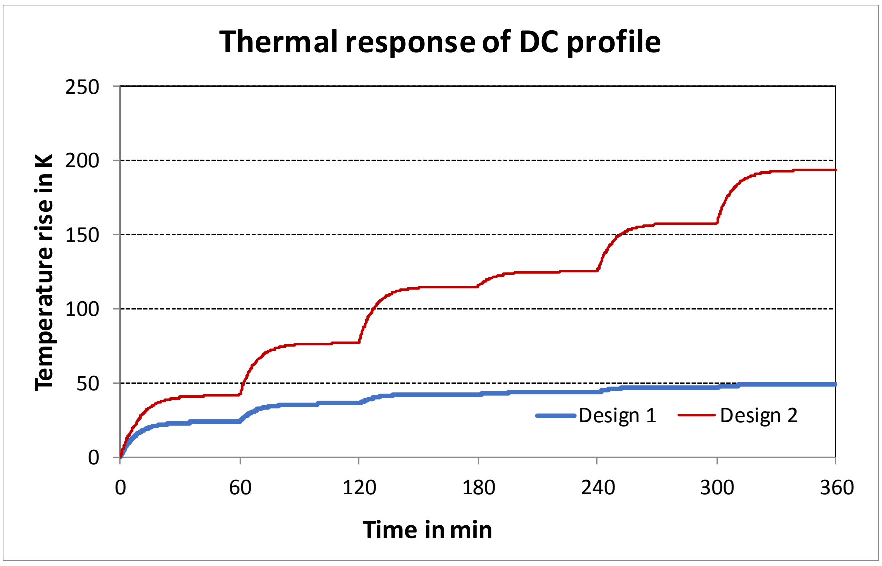


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T10

Content

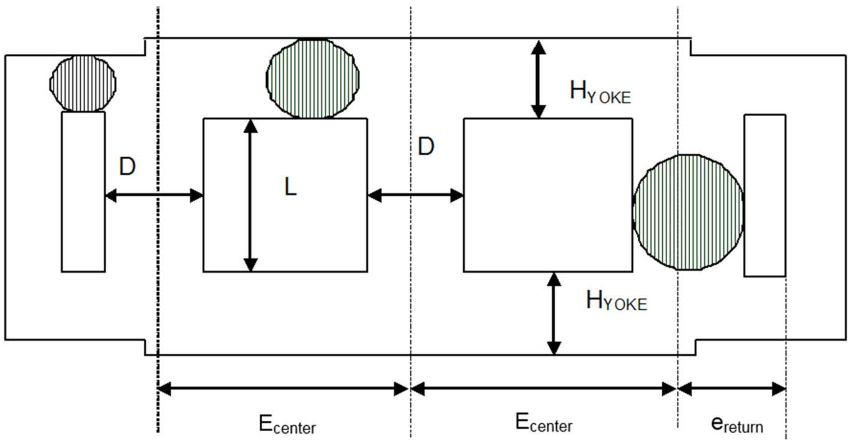
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T10
Transformer type	GSU
Rated power	300 MVA
Number of phases	3
Voltage levels	525 kV // 18 kV
Winding affected by DC	HV
Core type	5



L [mm]	2800
D [mm]	1006
H yoke [mm]	560
E center [mm]	1870
A limb [m2]	0.72013
A yoke [m2]	0.409848
A return [m2]	0.361782
e return [mm]	964

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.4986 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	22.1	36.8
20	36.3	65.9
40	43.2	103.5
50	45.1	115.9
100	48.0	142.2
200	50.1	161.4

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

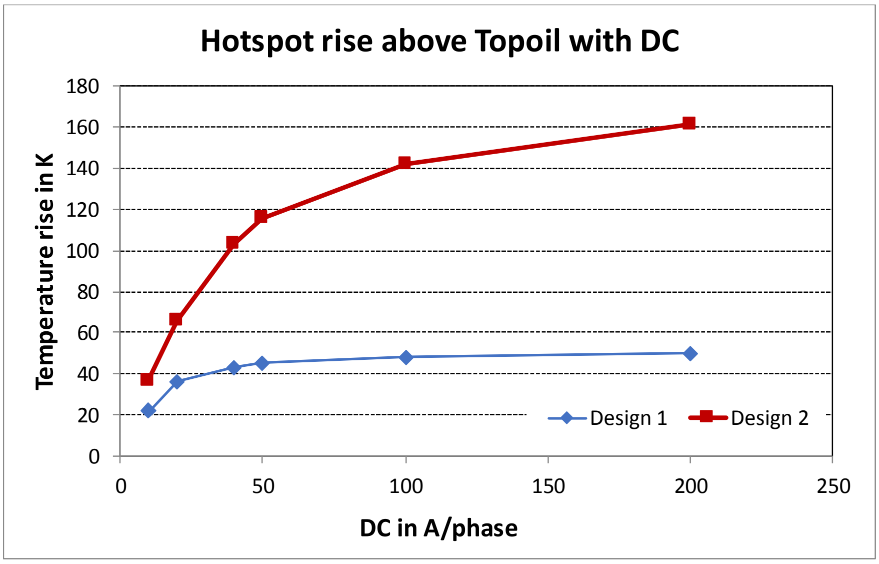


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

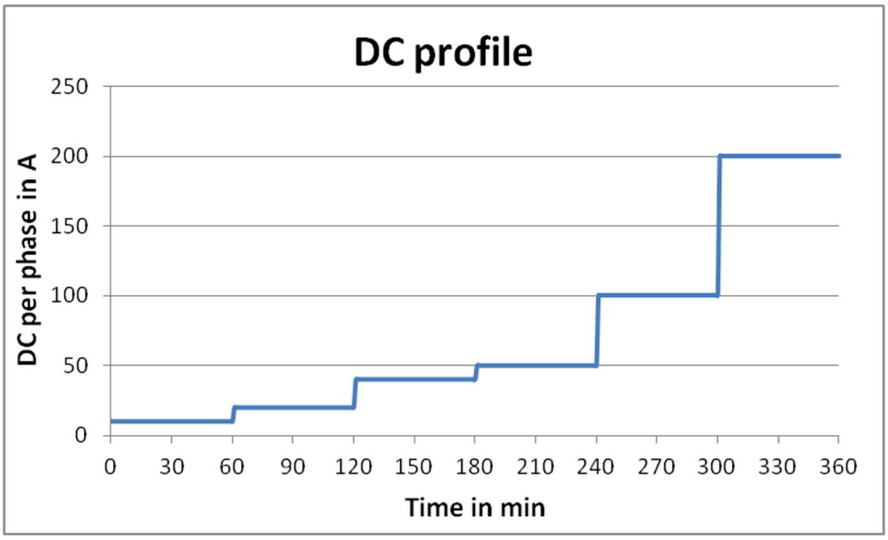


Figure 3: DC profile

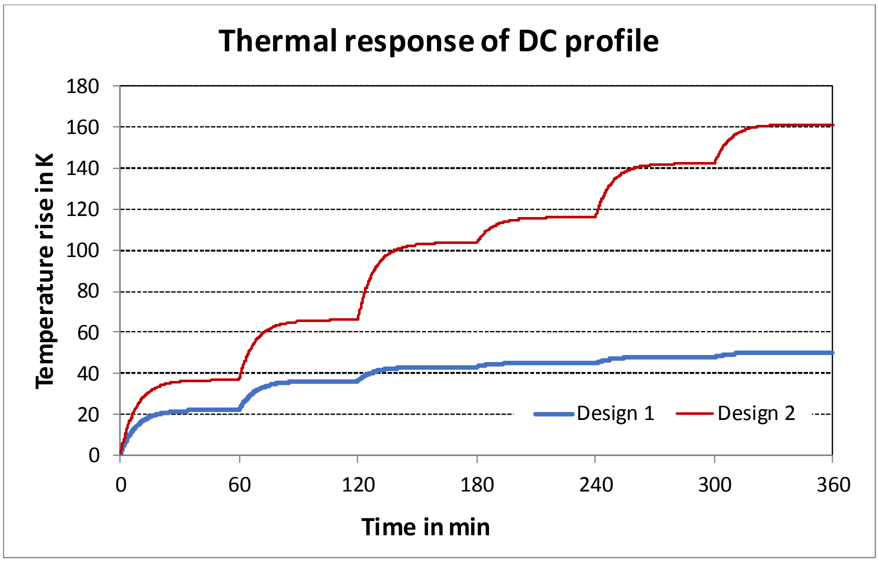


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T11

Content

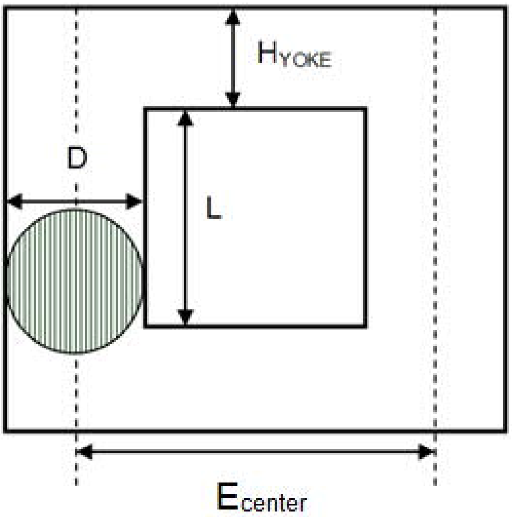
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T11
Transformer type	GSU
Rated power	100 MVA
Number of phases	1
Voltage levels	735/√3 kV // 26 kV
Winding affected by DC	HV
Core type	2



L [mm]	2392
D [mm]	956
H yoke [mm]	940
E center [mm]	1664
A limb [m2]	0.64758
A yoke [m2]	0.648135

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 2.2361 H (per leg)

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	33.3	56.8
20	41.9	92.6
40	46.0	126.5
50	47.2	133.7
100	49.2	153.9
200	51.3	174.6

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

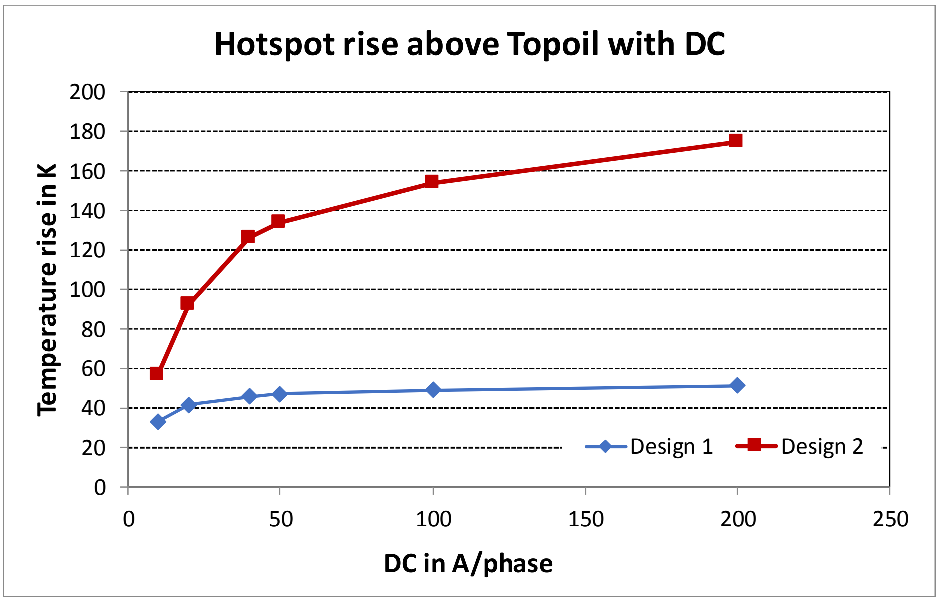


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

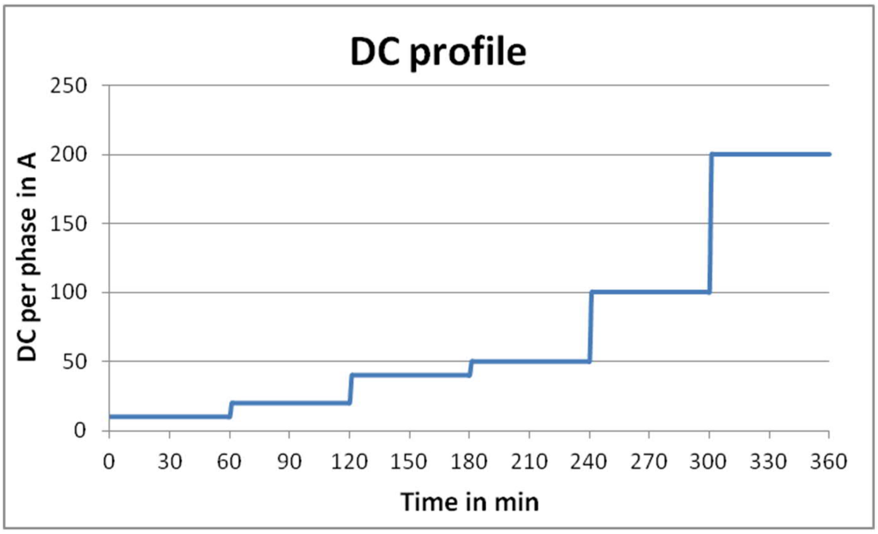


Figure 3: DC profile

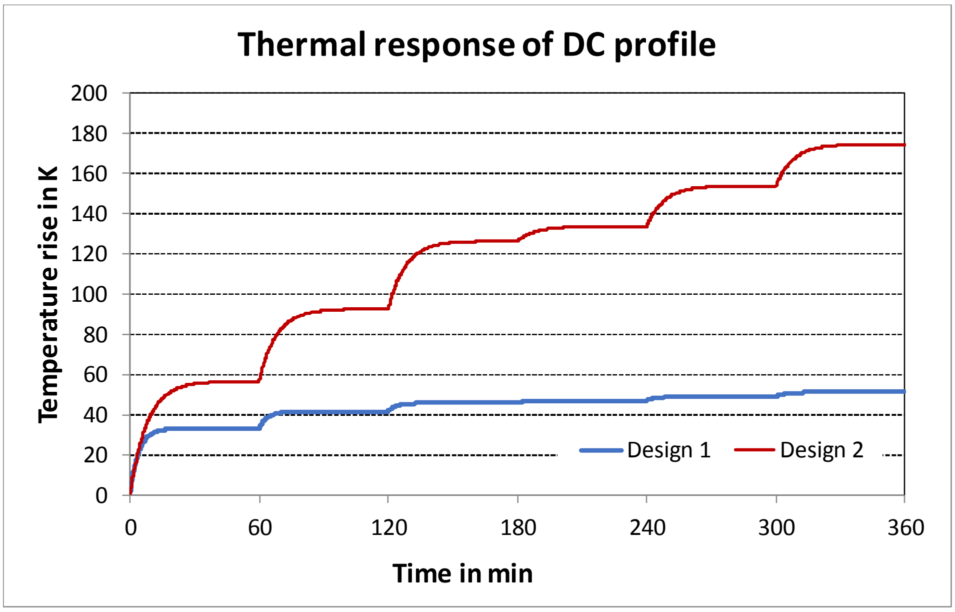


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T12

Content

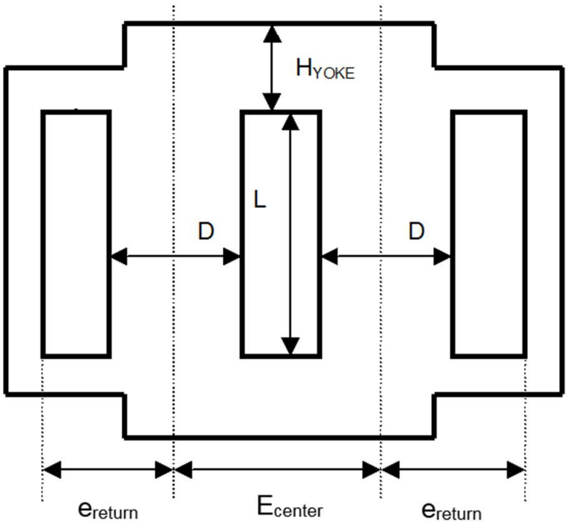
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T12
Transformer type	Auto
Rated power	373.33 MVA
Number of phases	1
Voltage levels	765/√3 kV // 345/√3 kV // 33 kV
Winding affected by DC	HV
Core type	4



L [mm]	2890
D [mm]	854
H yoke [mm]	580
E center [mm]	1942
A limb [m2]	0.508319
A yoke [m2]	0.382112
A return [m2]	0.126207
e return [mm]	1095

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 1.995 H (per leg)

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	31.4	52.3
20	41.7	89.0
40	46.6	120.0
50	48.0	130.3
100	50.5	160.5
200	53.1	194.8

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

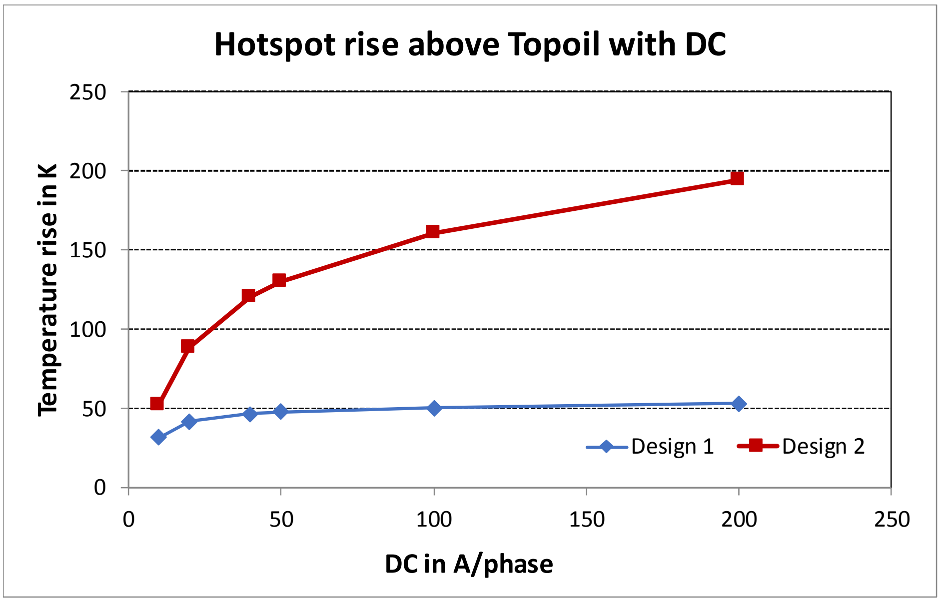


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

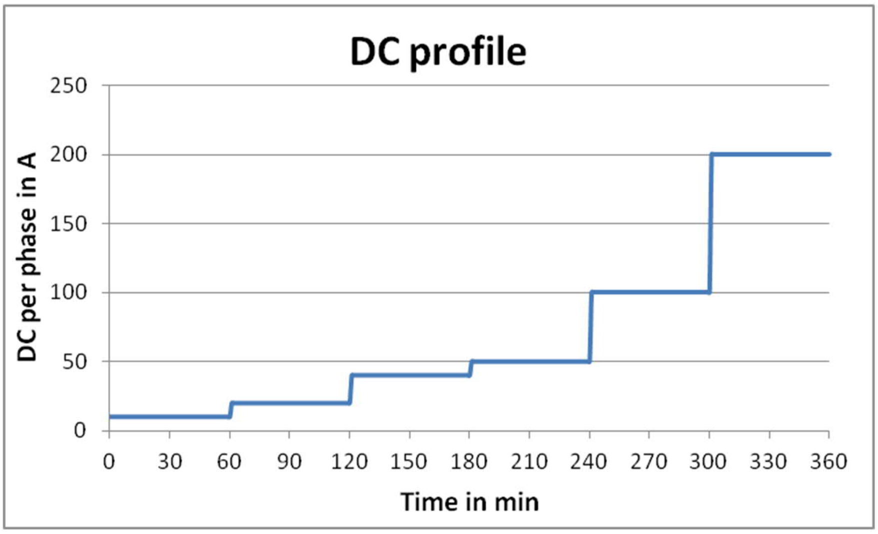


Figure 3: DC profile

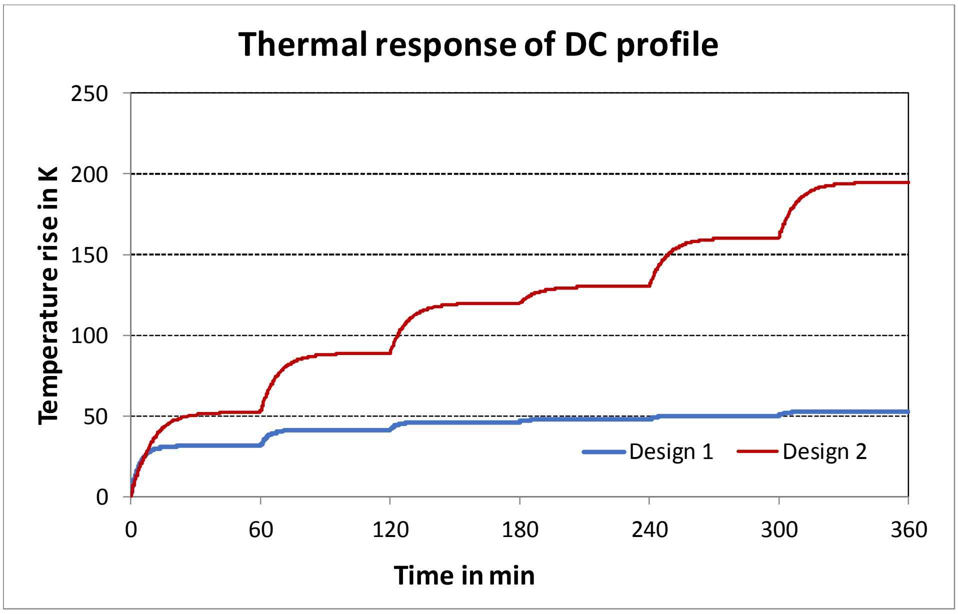


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T13

Content

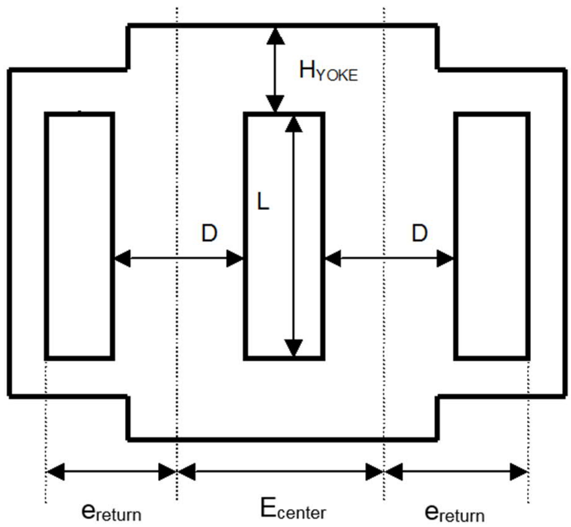
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T13
Transformer type	Auto
Rated power	750 MVA
Number of phases	1
Voltage levels	746/√3 kV // 345/√3 kV // 34.5 kV
Winding affected by DC	HV
Core type	4



L [mm]	2900
D [mm]	1070
H yoke [mm]	670
E center [mm]	2168
A limb [m2]	0.807748
A yoke [m2]	0.574483
A return [m2]	0.232916
e return [mm]	1222

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.9279 H (per leg)

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	22.7	30.6
20	35.8	61.6
40	44.6	100.1
50	46.3	112.2
100	51.0	142.9
200	53.4	179.6

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

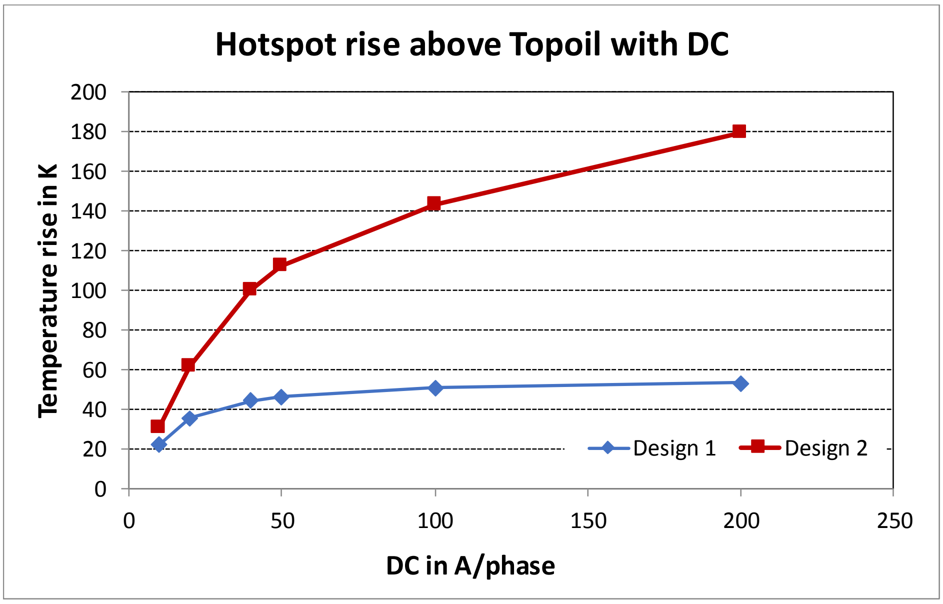


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

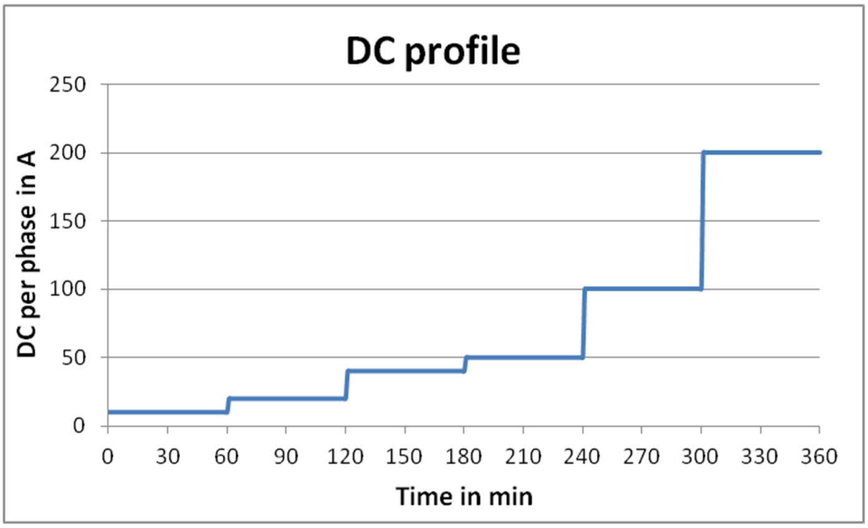


Figure 3: DC profile

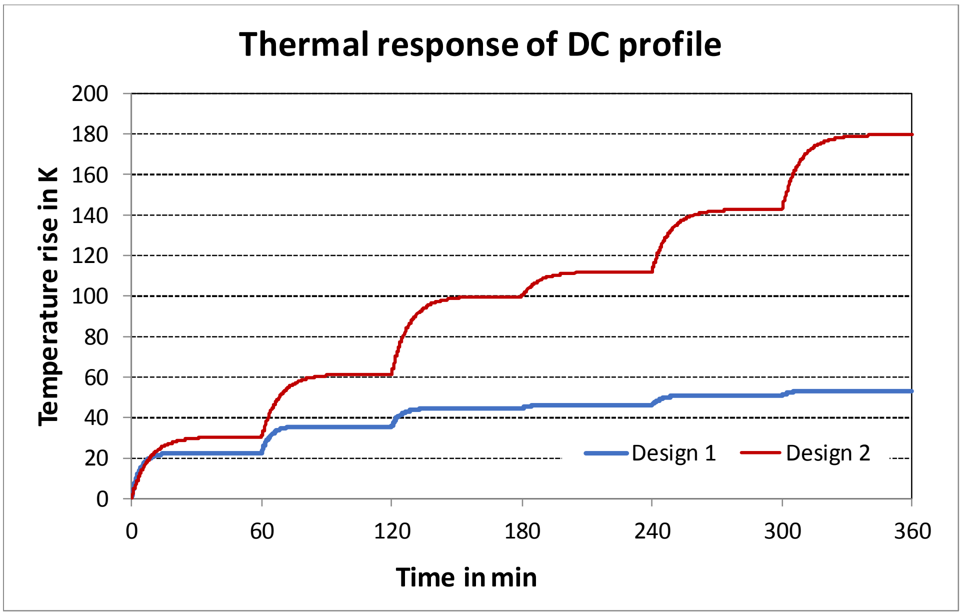


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T14

Content

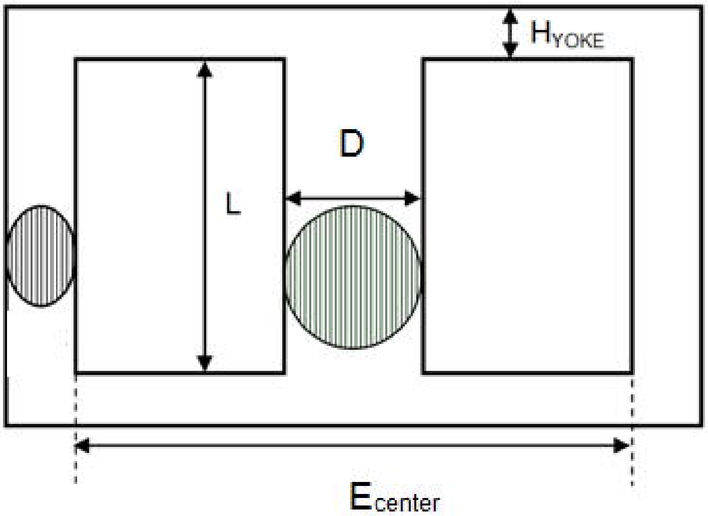
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T14
Transformer type	Auto
Rated power	167 MVA
Number of phases	1
Voltage levels	400/√3 kV // 231/√3 kV // 34 kV
Winding affected by DC	HV
Core type	1



L [mm]	2750
D [mm]	912
H yoke [mm]	450
E center [mm]	2186
A limb [m2]	0.603811
A yoke [m2]	0.302713

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.6738 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	30.6	59.1
20	38.5	88.5
40	42.2	106.4
50	44.2	112.9
100	45.2	134.2
200	47.1	154.9

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

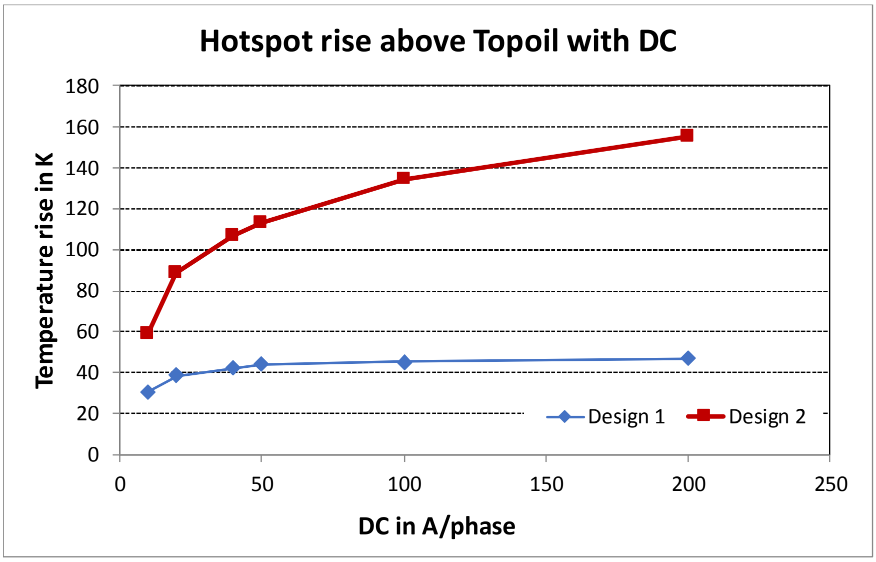


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

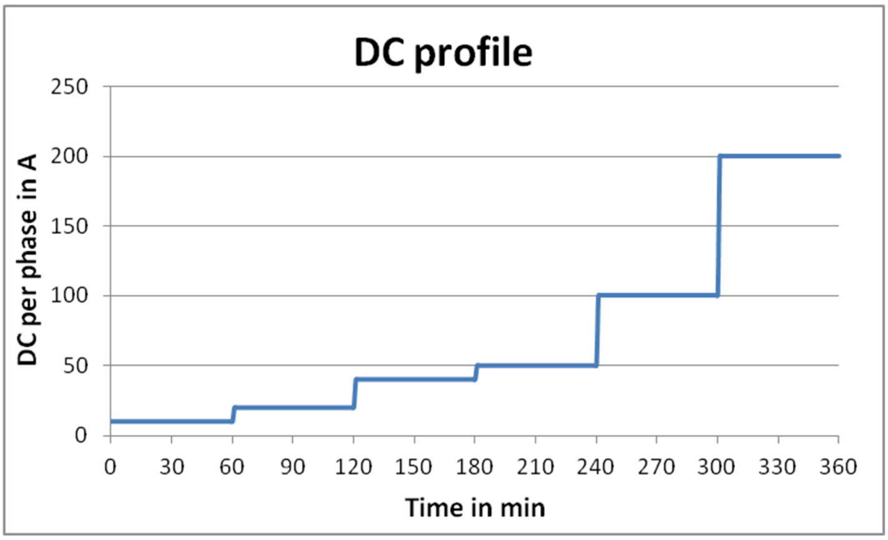


Figure 3: DC profile

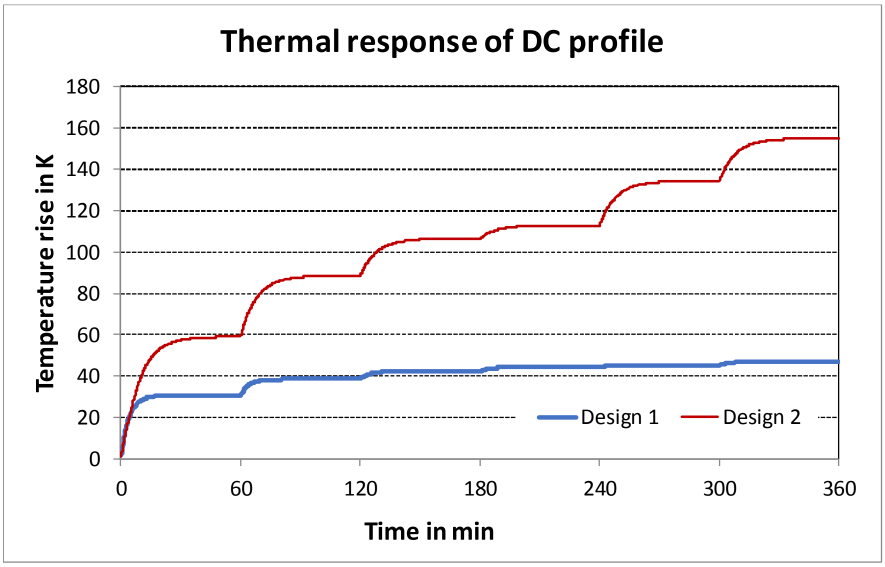


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T15

Content

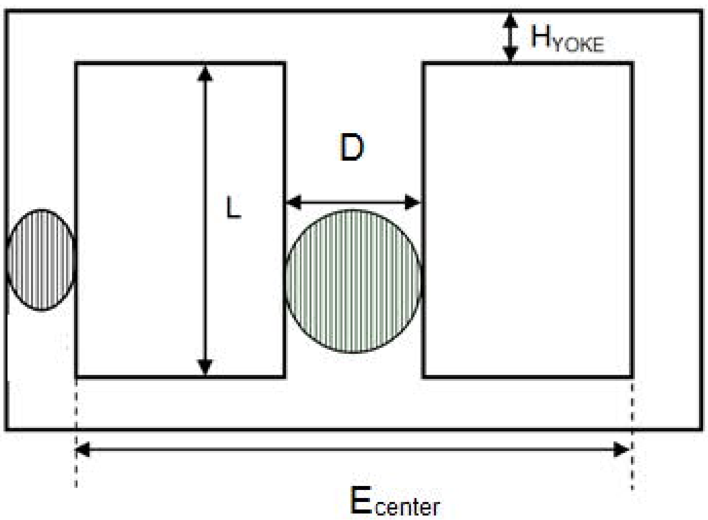
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T15
Transformer type	Auto
Rated power	360 MVA
Number of phases	1
Voltage levels	420/√3 kV // 235/√3 kV // 13 kV
Winding affected by DC	HV
Core type	1



L [mm]	3200
D [mm]	998
H yoke [mm]	490
E center [mm]	2312
A limb [m2]	0.707715
A yoke [m2]	0.3541

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.4978 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	24.5	45.6
20	35.1	81.1
40	39.6	108.6
50	40.6	113.7
100	43.1	135.5
200	45.8	163.4

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

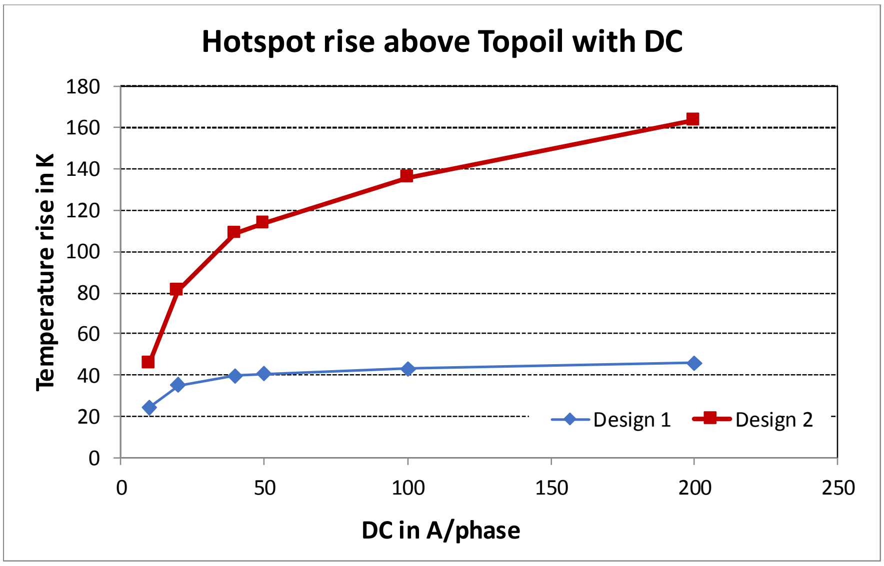


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

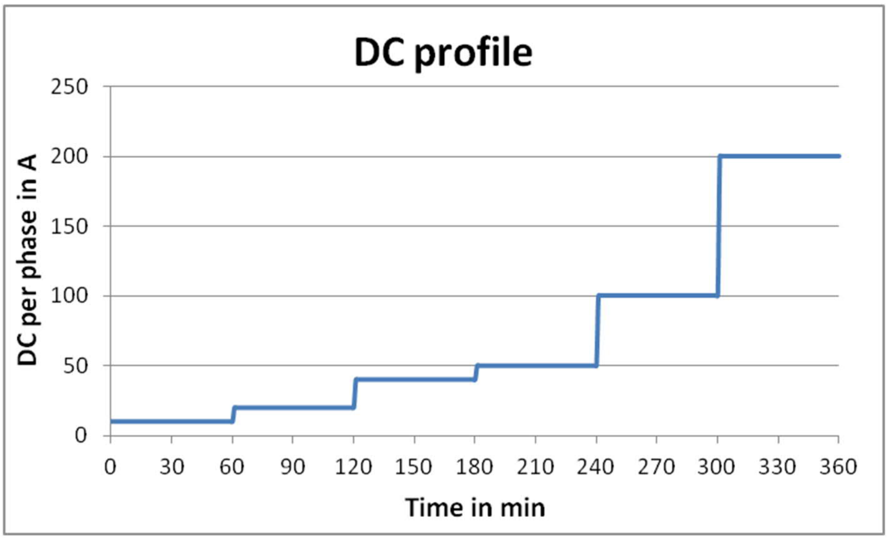


Figure 3: DC profile

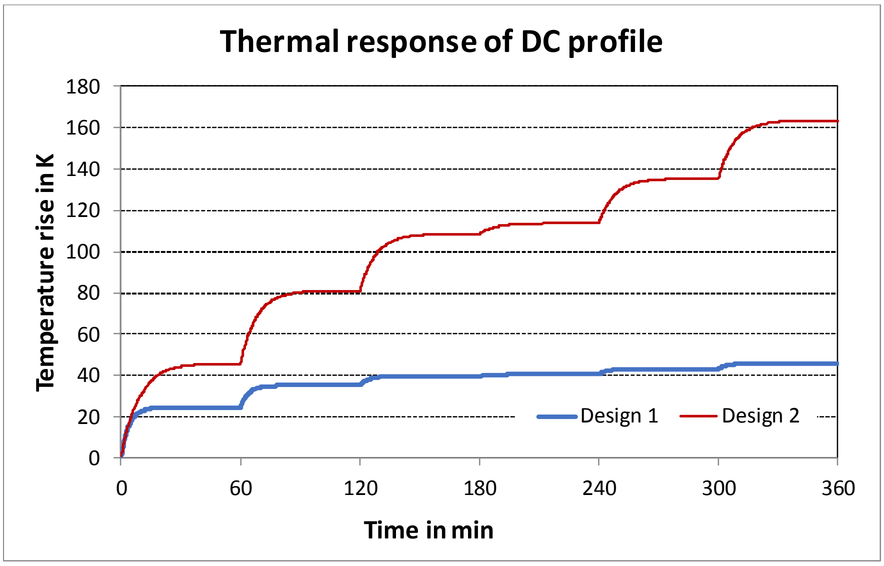


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T16

Content

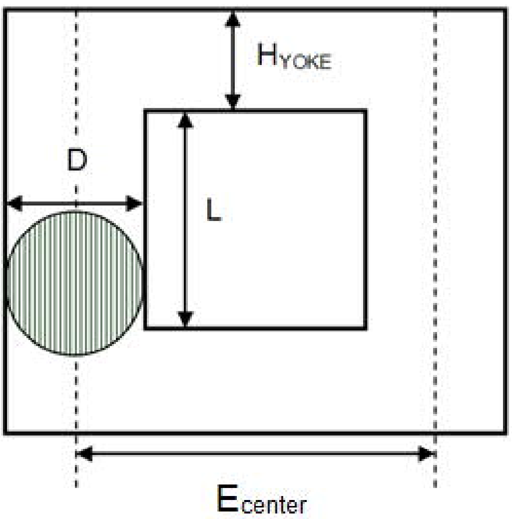
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T16
Transformer type	GSU
Rated power	121.33 MVA
Number of phases	1
Voltage levels	433/√3 kV // 16.8 kV // 16.8 kV
Winding affected by DC	HV
Core type	2



L [mm]	1990
D [mm]	1066
H yoke [mm]	1050
E center [mm]	1732
A limb [m2]	0.8099
A yoke [m2]	0.8099

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.6925 H (per leg)

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	21.7	29.9
20	33.5	55.7
40	38.9	90.5
50	40.3	102.0
100	42.9	127.8
200	46.5	150.4

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

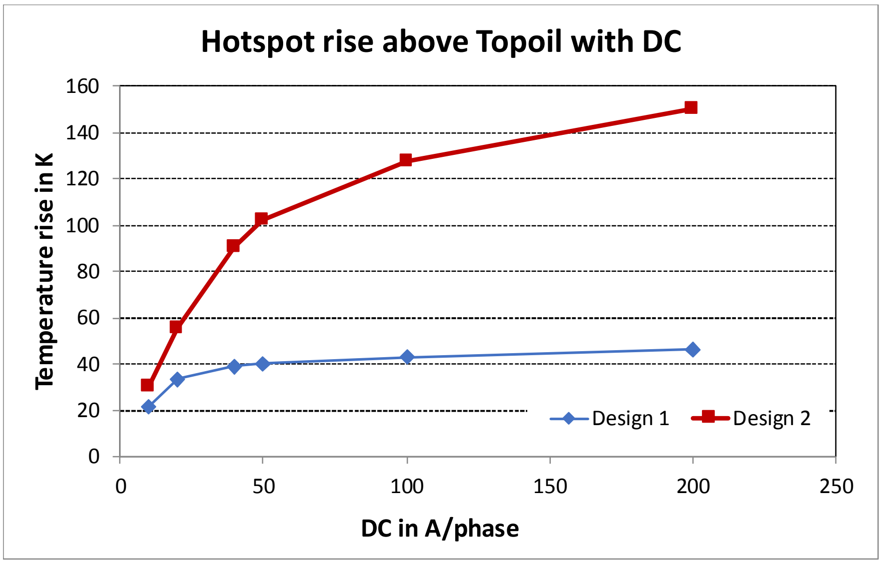


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

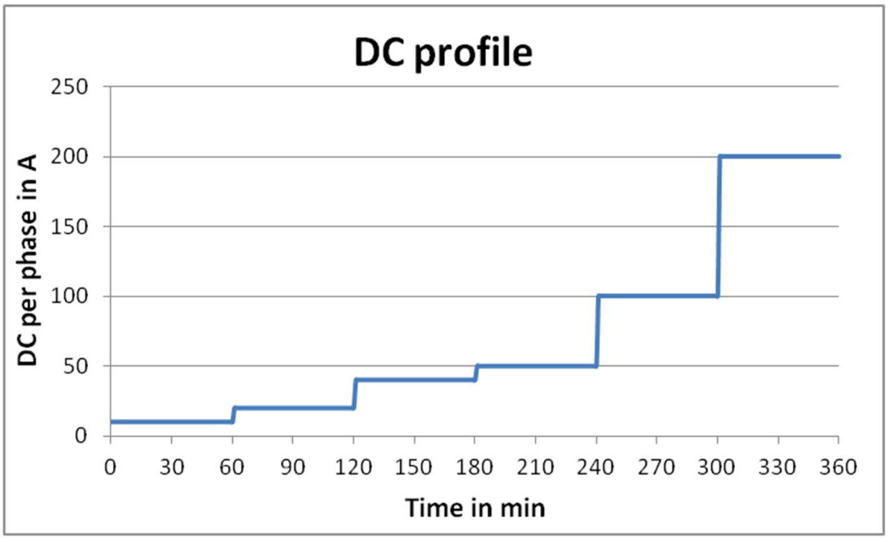


Figure 3: DC profile

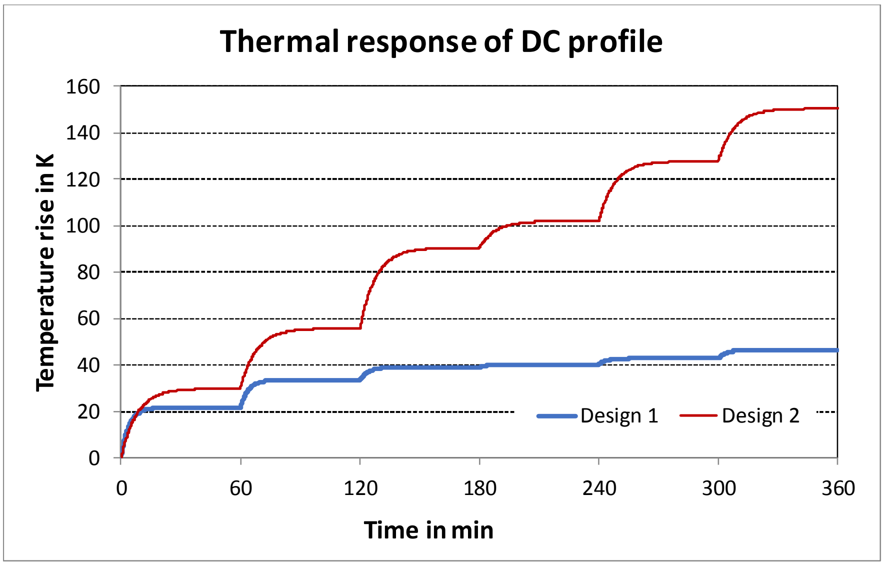


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T17

Content

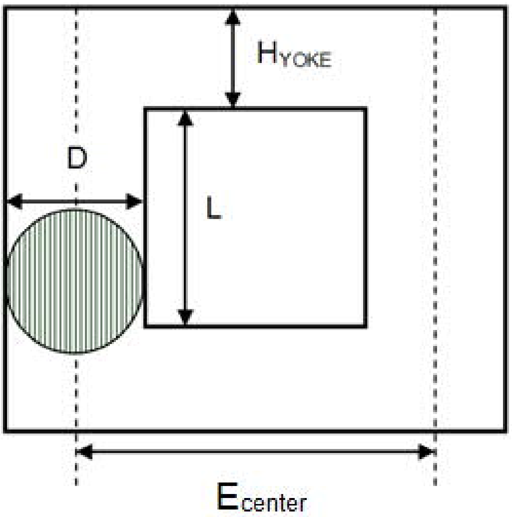
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T17
Transformer type	GSU
Rated power	94 MVA
Number of phases	1
Voltage levels	410/√3 kV // 15.75 kV
Winding affected by DC	HV
Core type	2



L [mm]	1830
D [mm]	926
H yoke [mm]	910
E center [mm]	1650
A limb [m2]	0.60413
A yoke [m2]	0.60477

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 1.005 H (per leg)

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] “Design 1”	Tie bar hot spot rise [K] “Design 2”
10	25.6	42.2
20	34.1	71.0
40	37.9	103.0
50	38.7	109.9
100	42.4	128.4
200	43.8	146.8

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

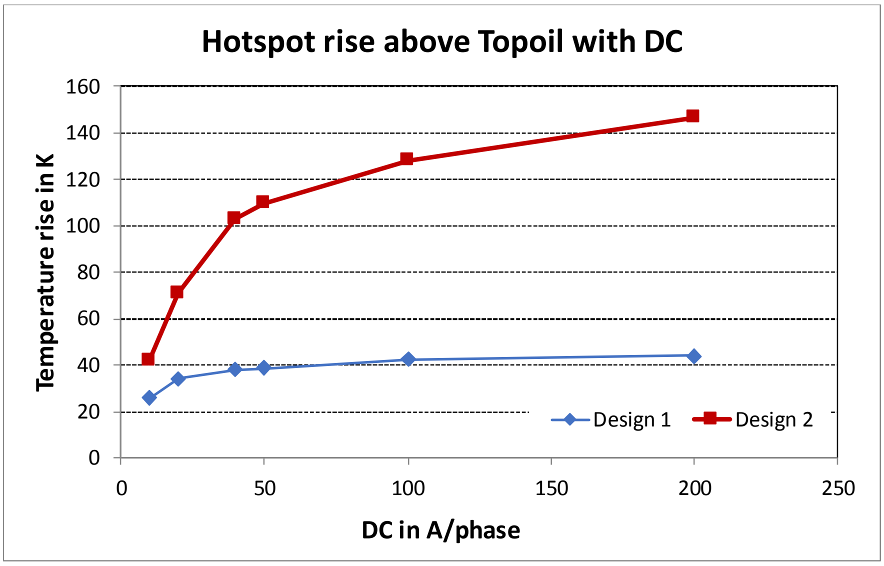


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

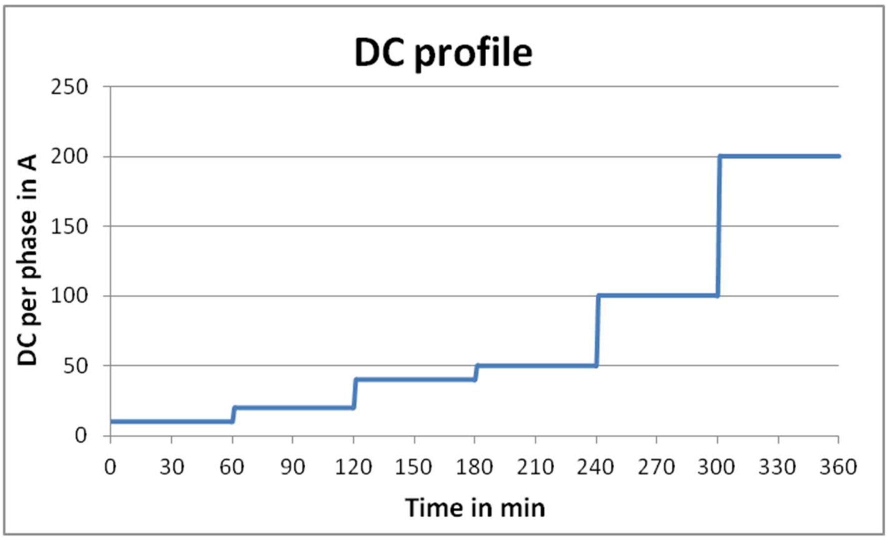


Figure 3: DC profile

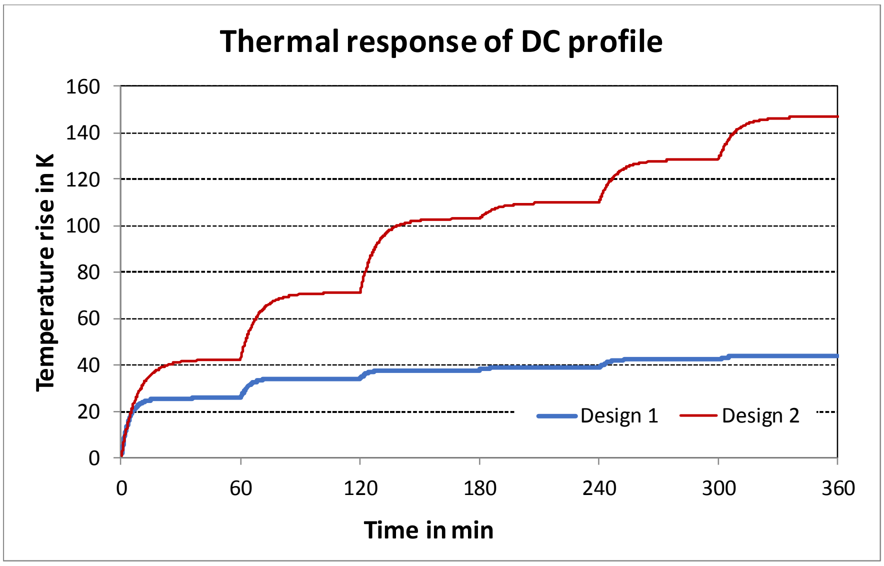


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T18

Content

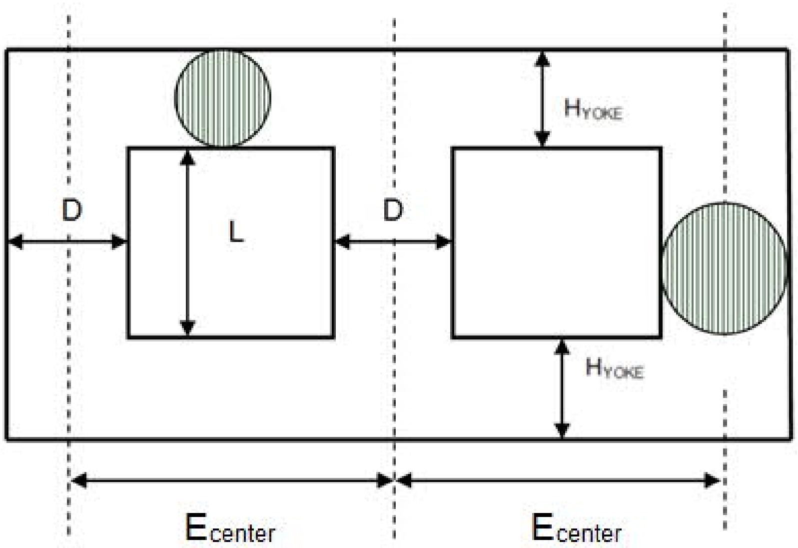
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T18
Transformer type	Auto
Rated power	750 MVA
Number of phases	3
Voltage levels	420 kV // 230 kV
Winding affected by DC	HV
Core type	3



L [mm]	1940
D [mm]	1156
H yoke [mm]	1140
E center [mm]	2348
A limb [m2]	0.956643
A yoke [m2]	0.956643

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.5017 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	0.0	0.0
20	0.3	0.1
40	13.9	21.1
50	24.3	49.6
100	37.7	116.8
200	42.1	154.1

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

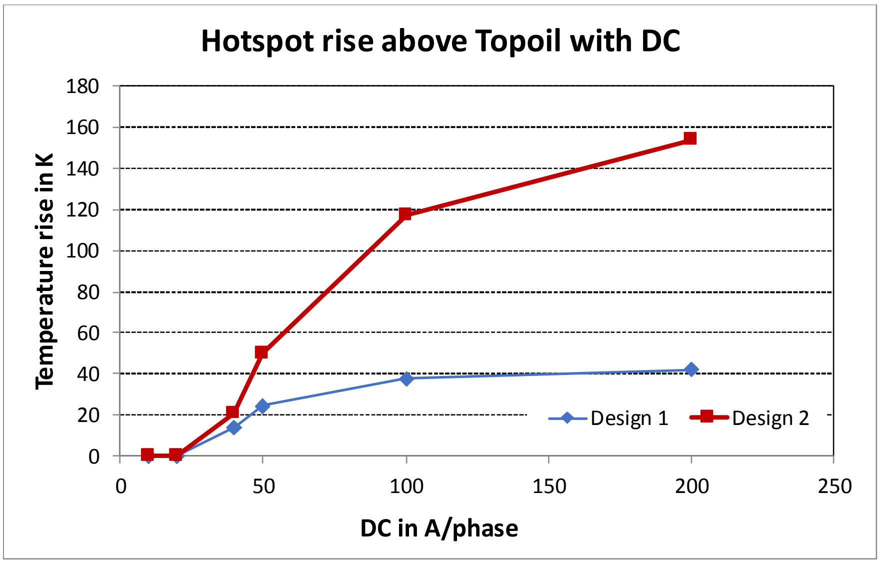


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

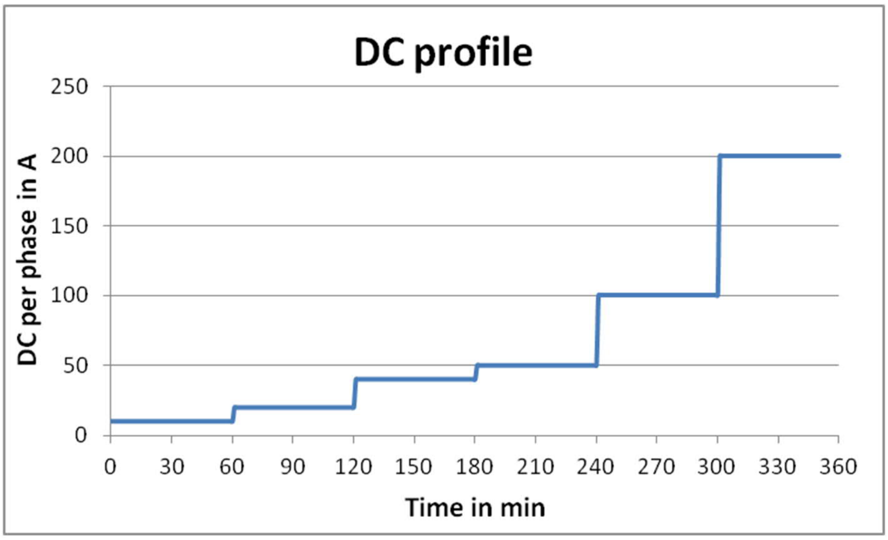


Figure 3: DC profile

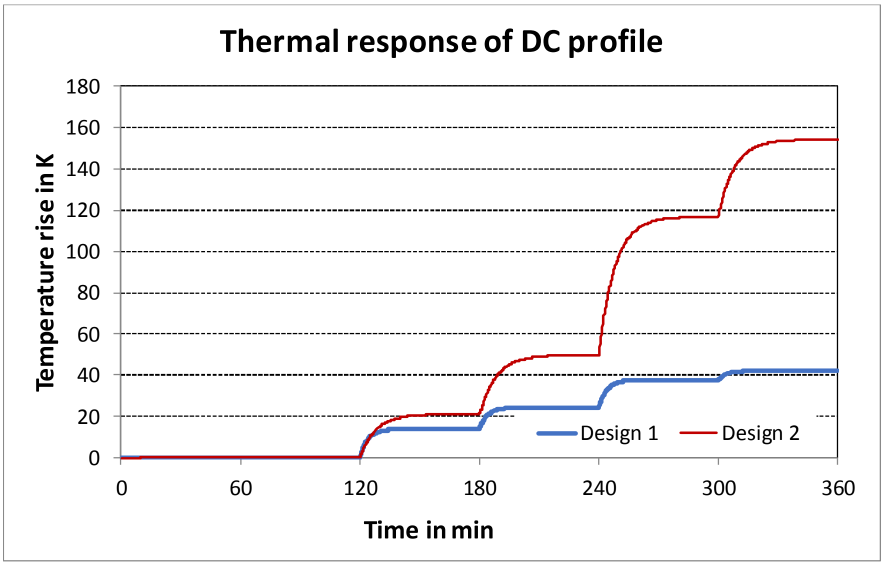


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T19

Content

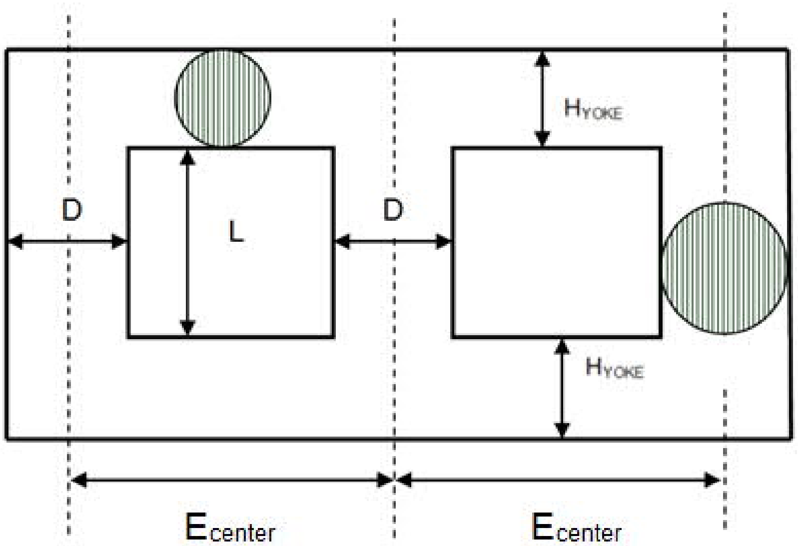
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T19
Transformer type	GSU
Rated power	160 MVA
Number of phases	3
Voltage levels	400 kV // 15 kV
Winding affected by DC	HV
Core type	3



L [mm]	2177
D [mm]	848
H yoke [mm]	820
E center [mm]	1496
A limb [m2]	0.522987
A yoke [m2]	0.523457

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.8207 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] “Design 1”	Tie bar hot spot rise [K] “Design 2”
10	0.1	0.1
20	6.9	8.6
40	38.8	75.1
50	41.9	90.4
100	47.1	110.9
200	51.9	126.2

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

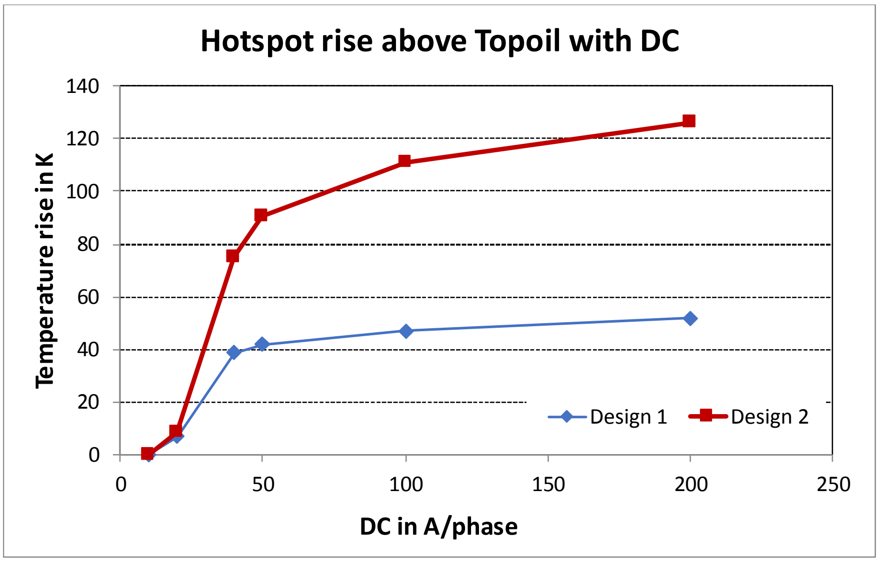


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

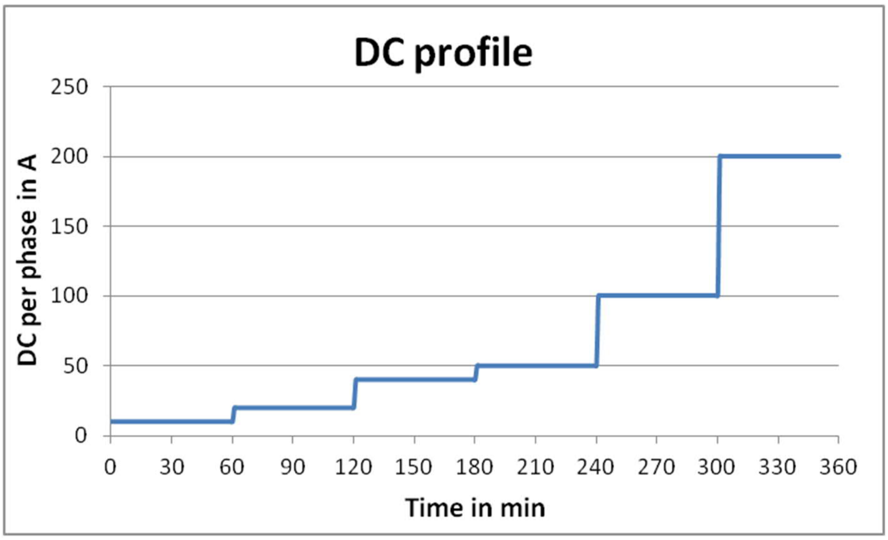


Figure 3: DC profile

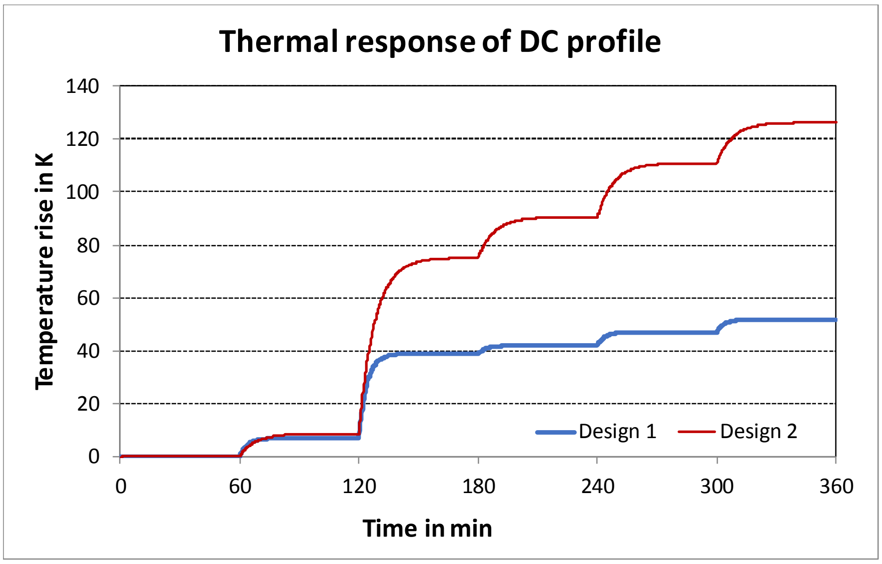


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T20

Content

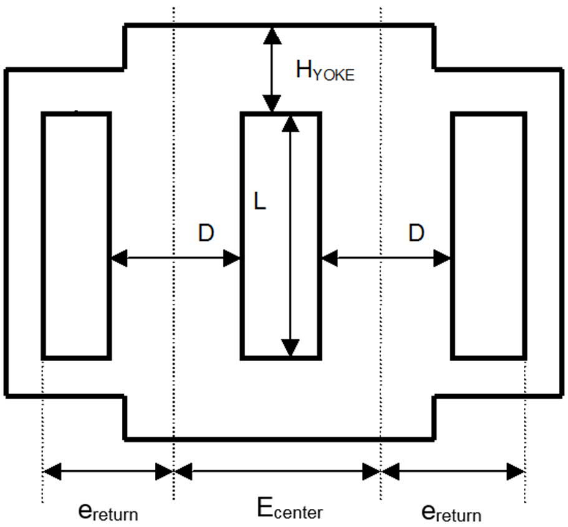
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T20
Transformer type	GSU
Rated power	570 MVA
Number of phases	1
Voltage levels	405/√3 kV // 20 kV
Winding affected by DC	HV
Core type	4



L [mm]	2755
D [mm]	1280
H yoke [mm]	680
E center [mm]	2475
A limb [m2]	1.161042
A yoke [m2]	0.716691
A return [m2]	0.444187
e return [mm]	1341

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.2539 H (per leg)

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] “Design 1”	Tie bar hot spot rise [K] “Design 2”
10	8.9	13.2
20	16.8	27.2
40	27.7	56.8
50	31.1	68.2
100	36.7	101.3
200	40.1	126.6

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

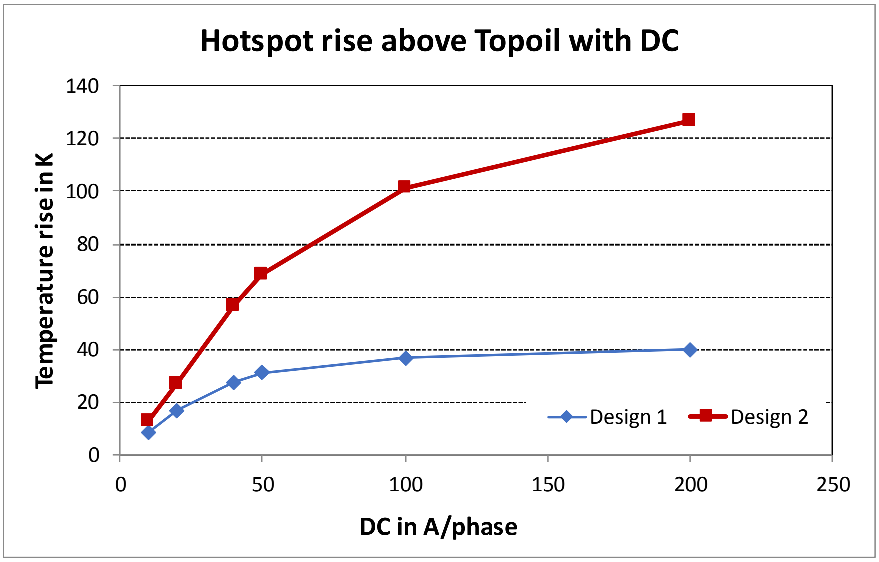


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

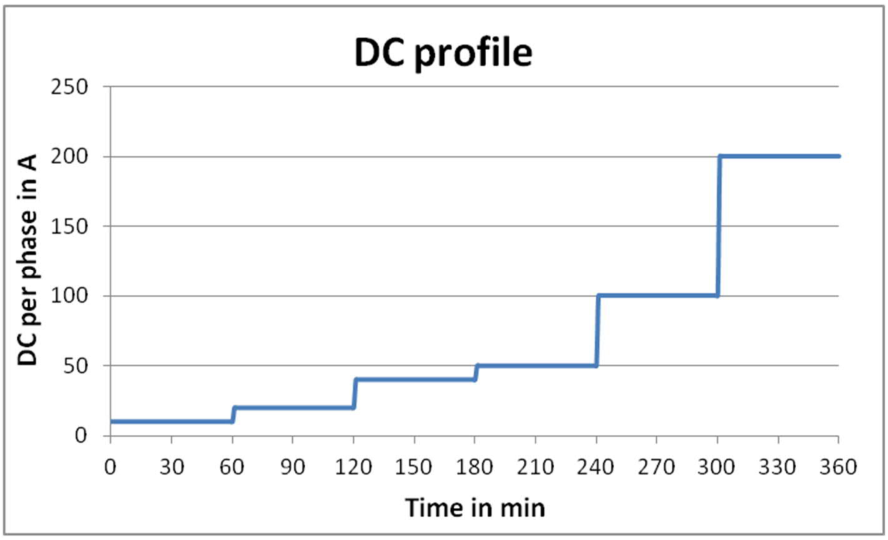


Figure 3: DC profile

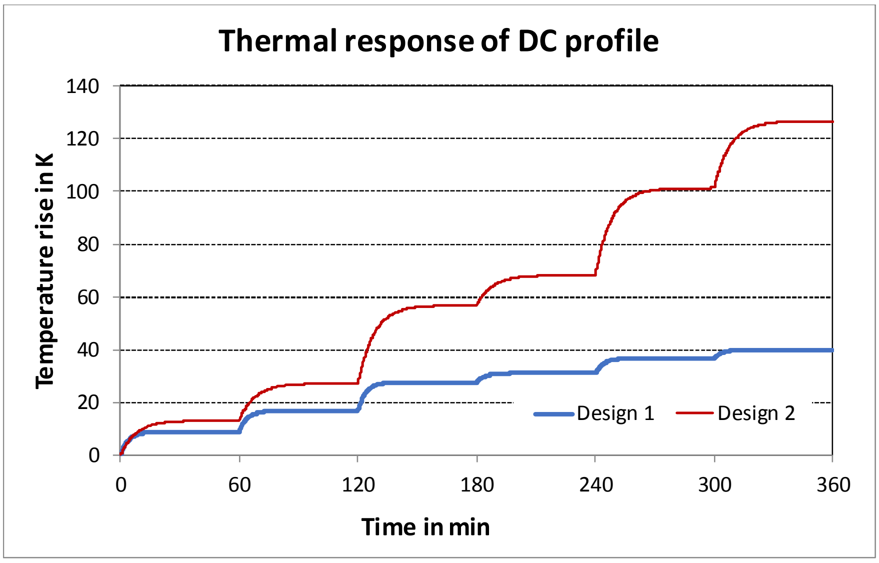


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T21

Content

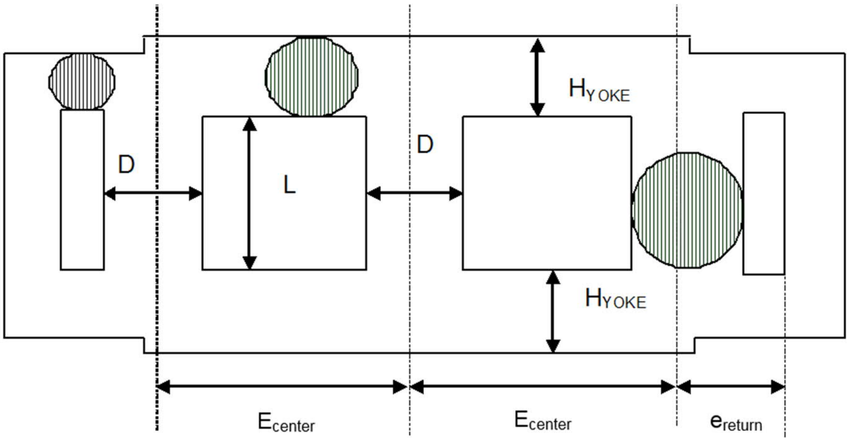
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T21
Transformer type	TRA
Rated power	450 MVA
Number of phases	3
Voltage levels	405 kV // 230 kV // 21 kV
Winding affected by DC	HV
Core type	5



L [mm]	2790
D [mm]	1232
H yoke [mm]	700
E center [mm]	2578
A limb [m2]	1.088957
A yoke [m2]	0.621221
A return [m2]	0.547751
e return [mm]	1332

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.4508 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] “Design 1”	Tie bar hot spot rise [K] “Design 2”
10	13.1	17.4
20	23.4	33.4
40	37.8	56.0
50	41.8	64.7
100	48.1	92.2
200	51.6	108.3

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

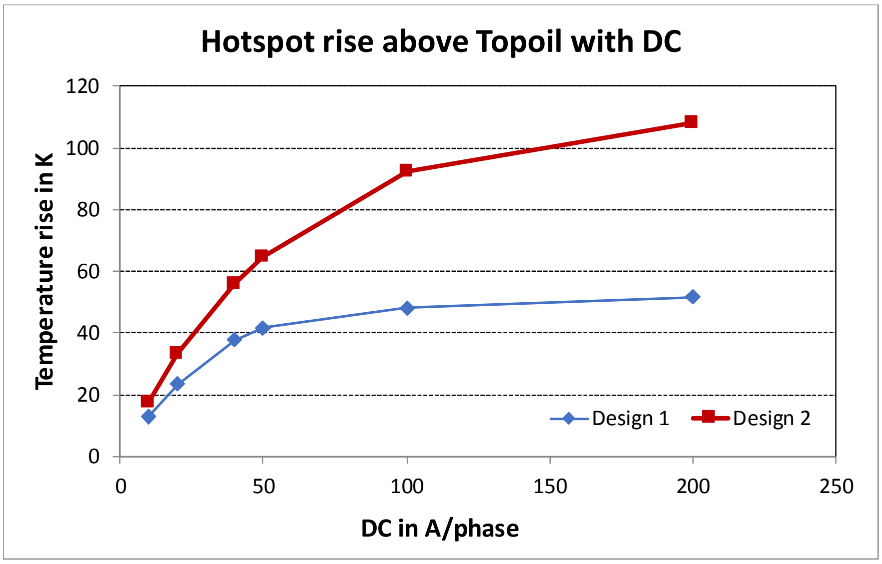


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

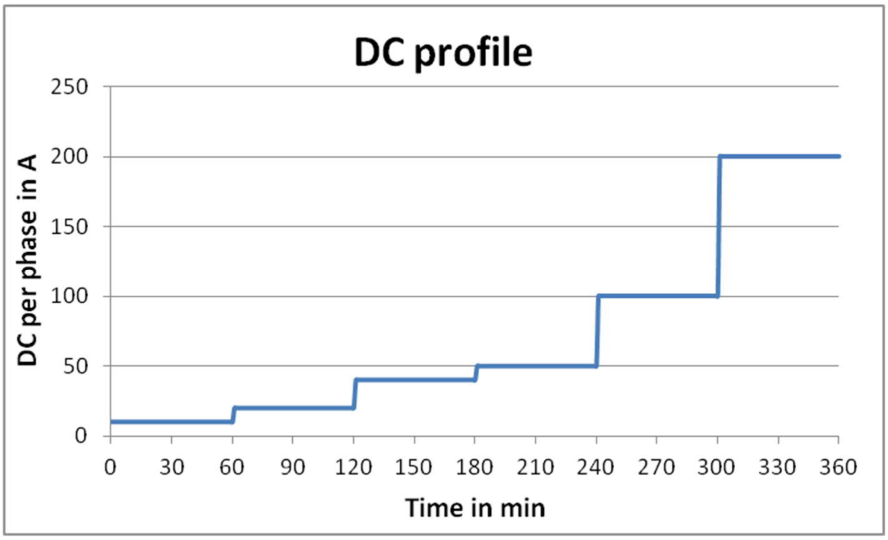


Figure 3: DC profile

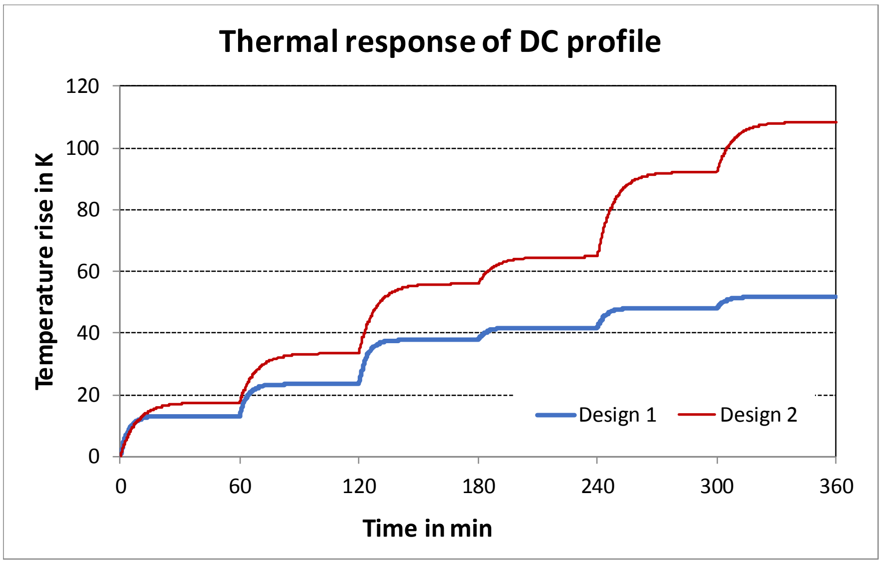


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T22

Content

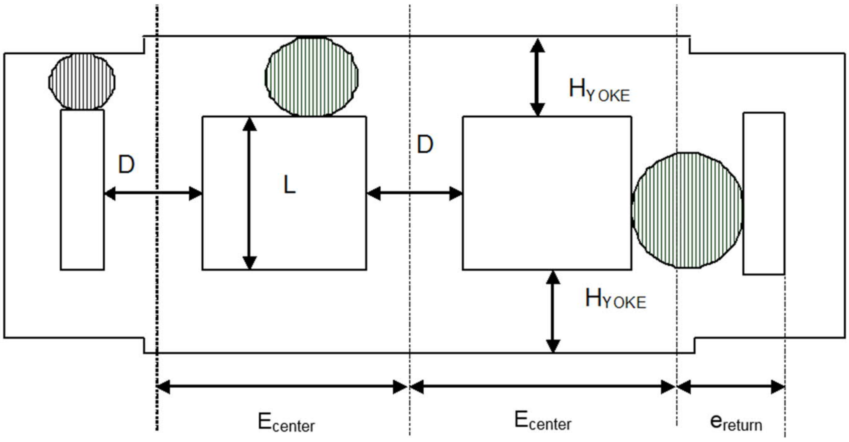
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T22
Transformer type	GSU
Rated power	310 MVA
Number of phases	3
Voltage levels	400 kV // 11 kV
Winding affected by DC	HV
Core type	5



L [mm]	2270
D [mm]	1236
H yoke [mm]	670
E center [mm]	2102
A limb [m2]	1.08331
A yoke [m2]	0.617512
A return [m2]	0.540706
e return [mm]	1067

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.2804 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	16.7	24.8
20	30.0	49.0
40	37.4	81.0
50	38.7	92.2
100	42.7	119.7
200	44.6	139.9

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

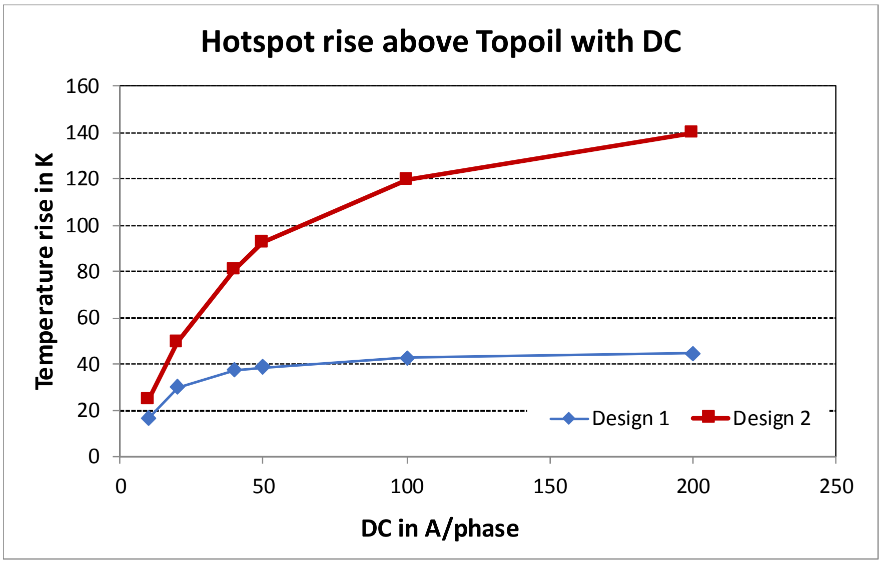


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

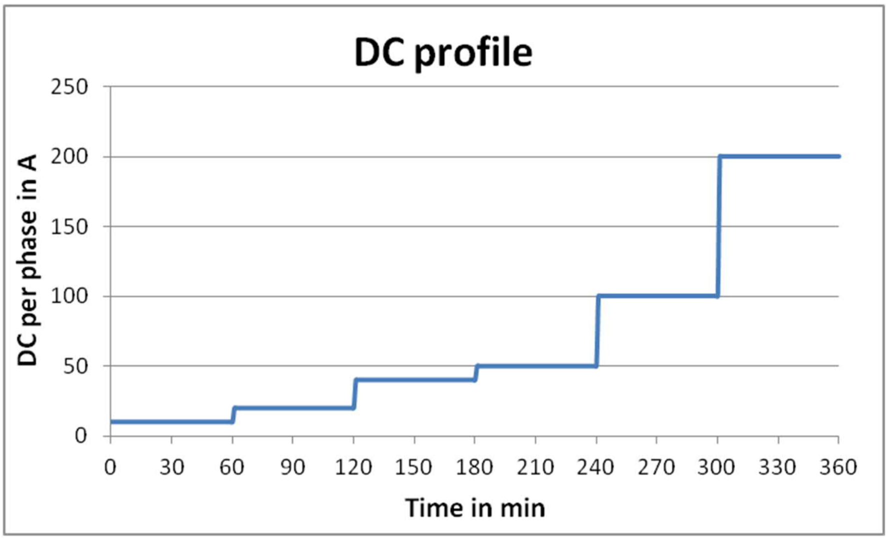


Figure 3: DC profile

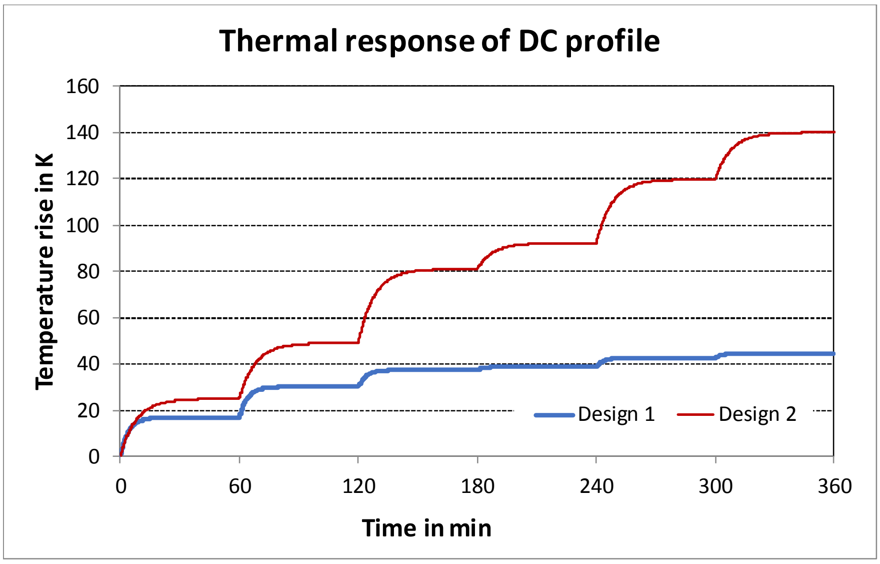


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T23

Content

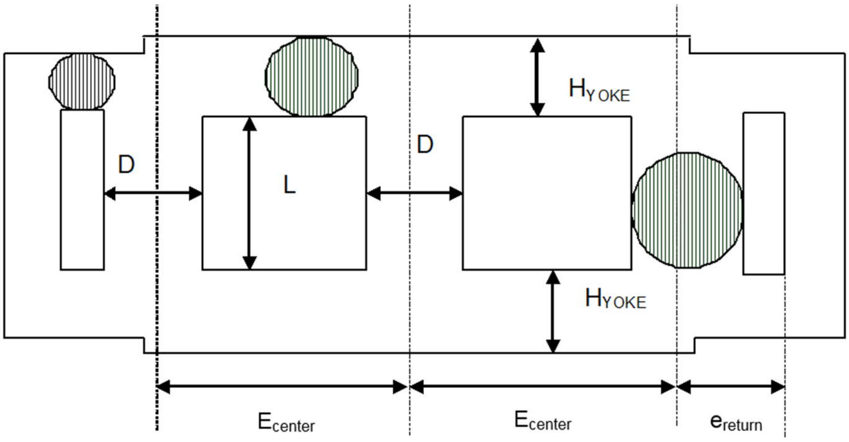
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T23
Transformer type	GSU
Rated power	910 MVA
Number of phases	3
Voltage levels	420 kV // 22 kV
Winding affected by DC	HV
Core type	5



L [mm]	3276
D [mm]	1218
H yoke [mm]	680
E center [mm]	2416
A limb [m2]	1.061416
A yoke [m2]	0.605097
A return [m2]	0.532685
e return [mm]	1230

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.2094 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	14.2	20.2
20	25.1	40.5
40	35.9	74.6
50	37.8	86.1
100	42.3	118.0
200	45.0	146.6

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

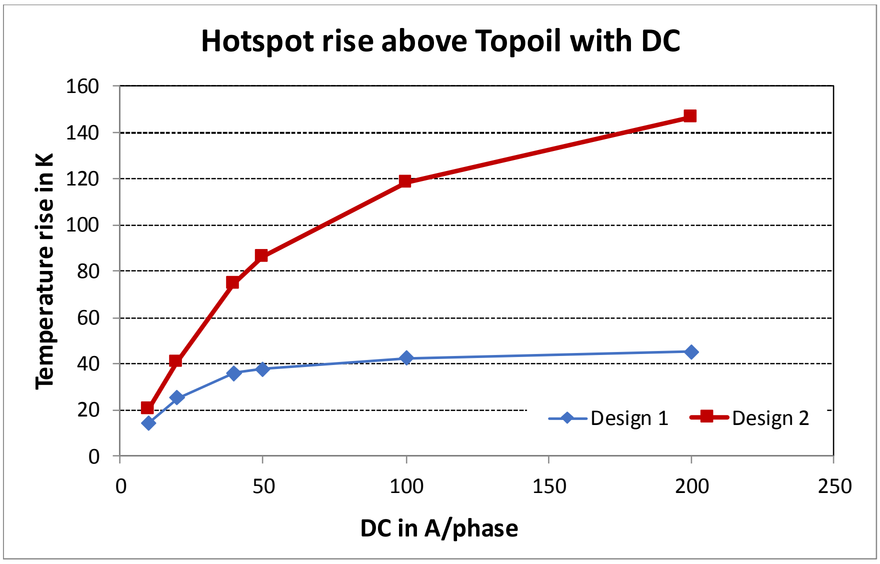


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

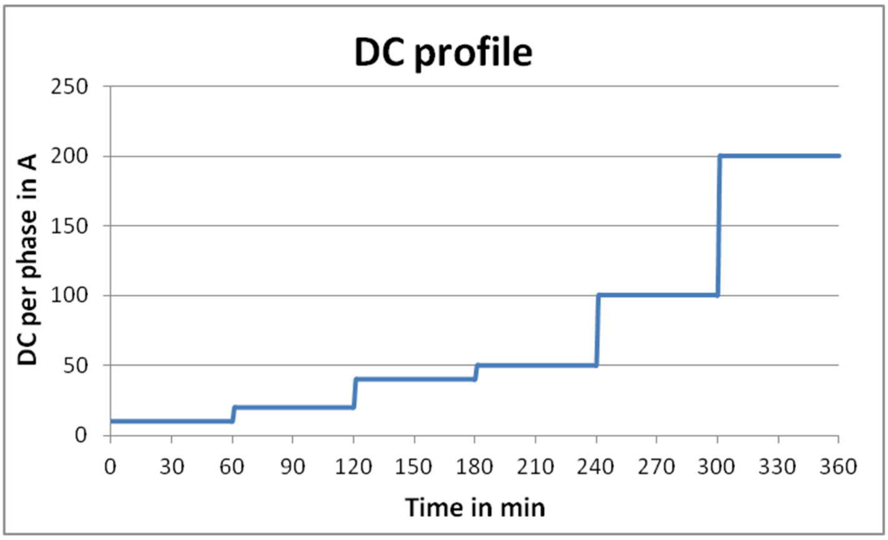


Figure 3: DC profile

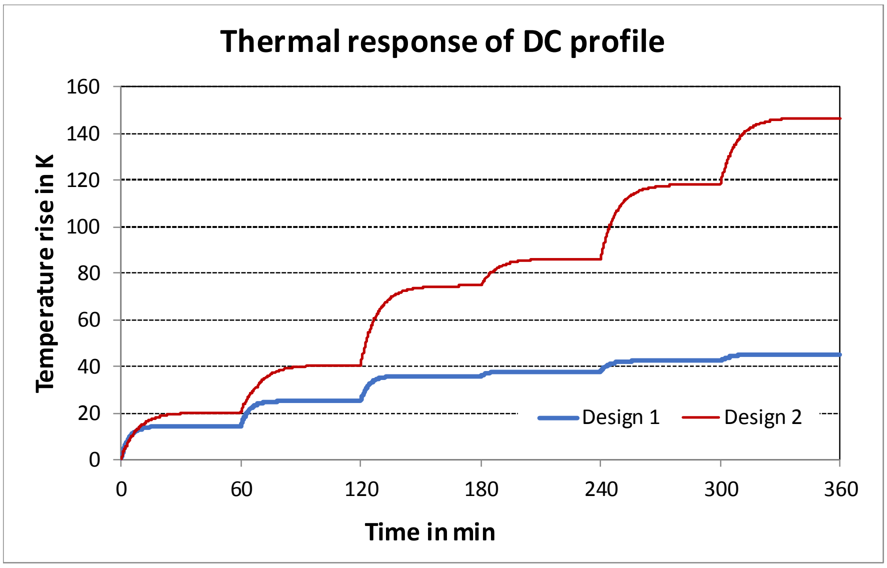


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T24

Content

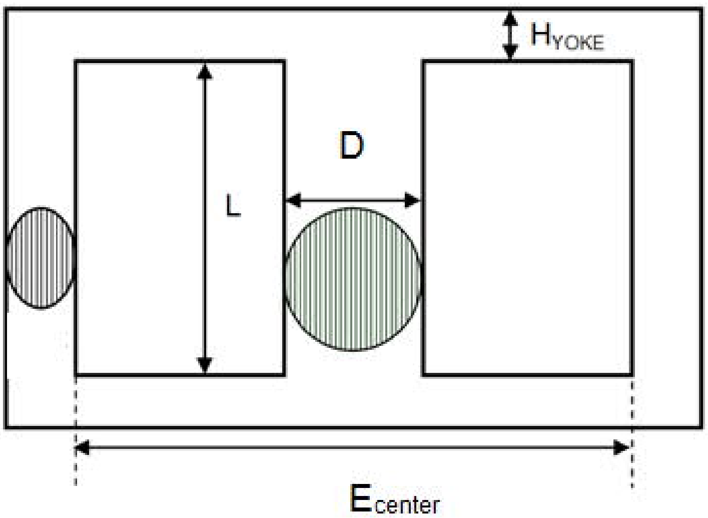
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T24
Transformer type	Auto
Rated power	100 MVA
Number of phases	1
Voltage levels	335/√3 kV // 136/√3 kV // 13.8 kV
Winding affected by DC	HV
Core type	1



L [mm]	2276
D [mm]	644
H yoke [mm]	320
E center [mm]	2060
A limb [m2]	0.286286
A yoke [m2]	0.144462

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.9352 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	35.5	110.5
20	38.4	140.5
40	41.8	173.5
50	45.7	188.0
100	46.6	230.0
200	53.1	296.6

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

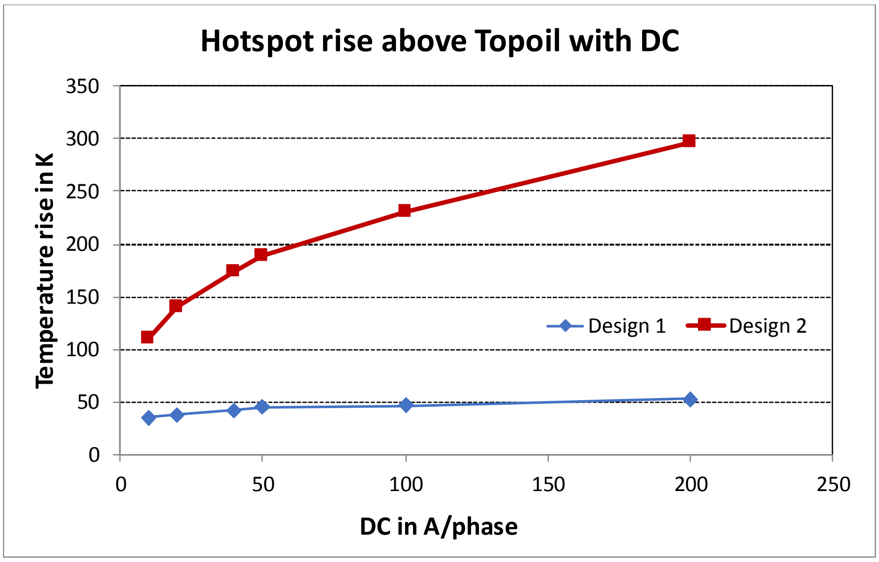


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

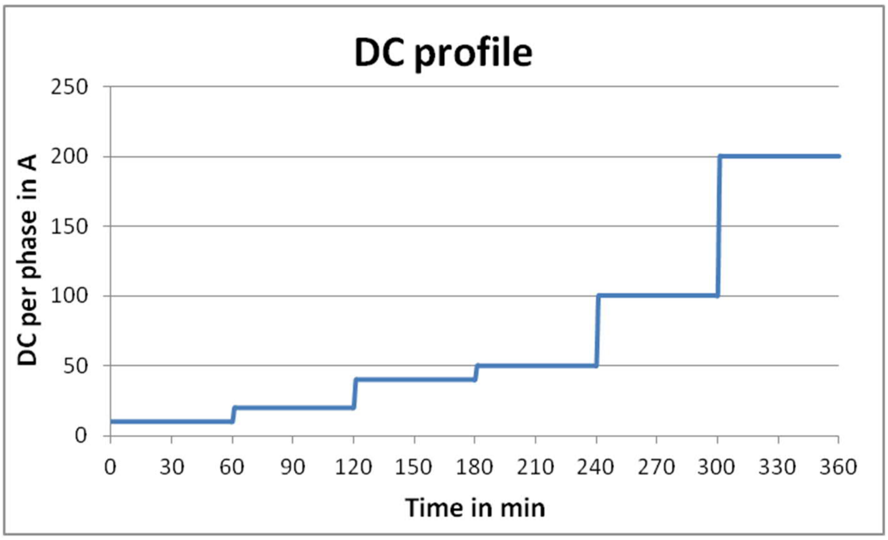


Figure 3: DC profile

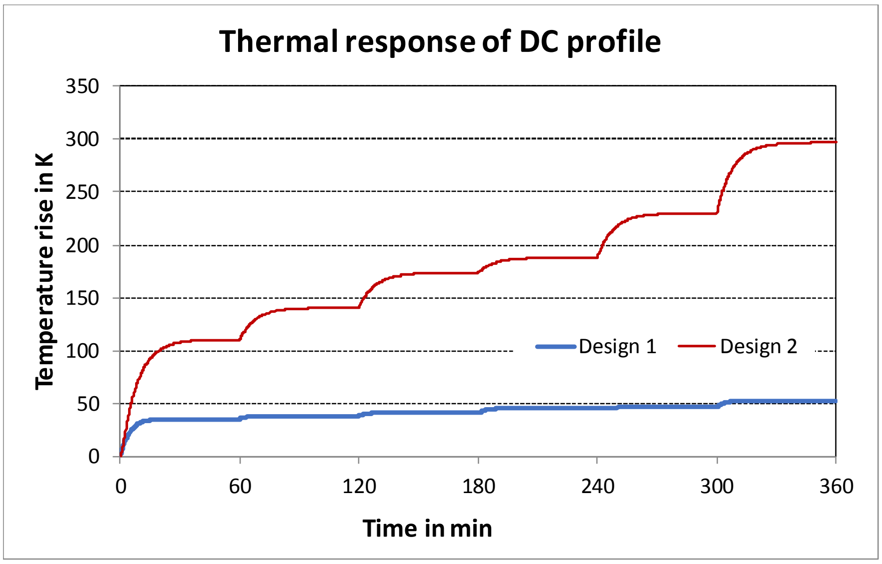


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T25

Content

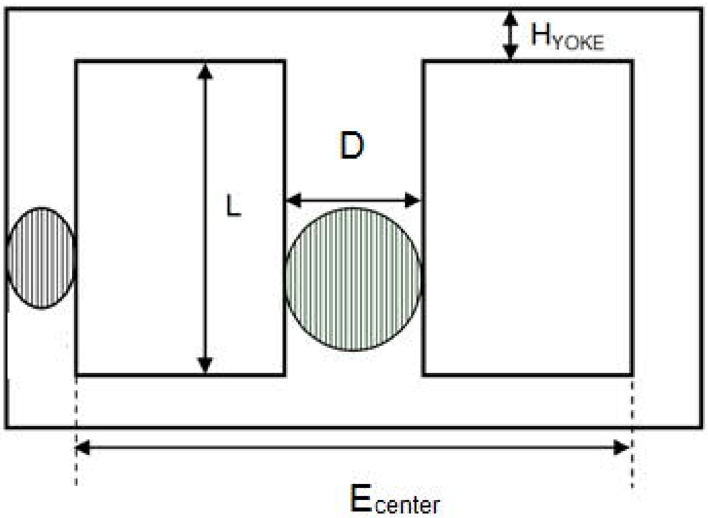
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T25
Transformer type	Auto
Rated power	133.33 MVA
Number of phases	1
Voltage levels	345/√3 kV // 230/√3 kV // 138/√3 kV // 115/√3 kV // 14.4 kV
Winding affected by DC	HV
Core type	1



L [mm]	1980
D [mm]	740
H yoke [mm]	370
E center [mm]	2108
A limb [m2]	0.386419
A yoke [m2]	0.195154

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.7786 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	31.2	93.5
20	37.1	127.0
40	40.6	154.0
50	41.3	166.8
100	42.7	206.2
200	47.5	259.9

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

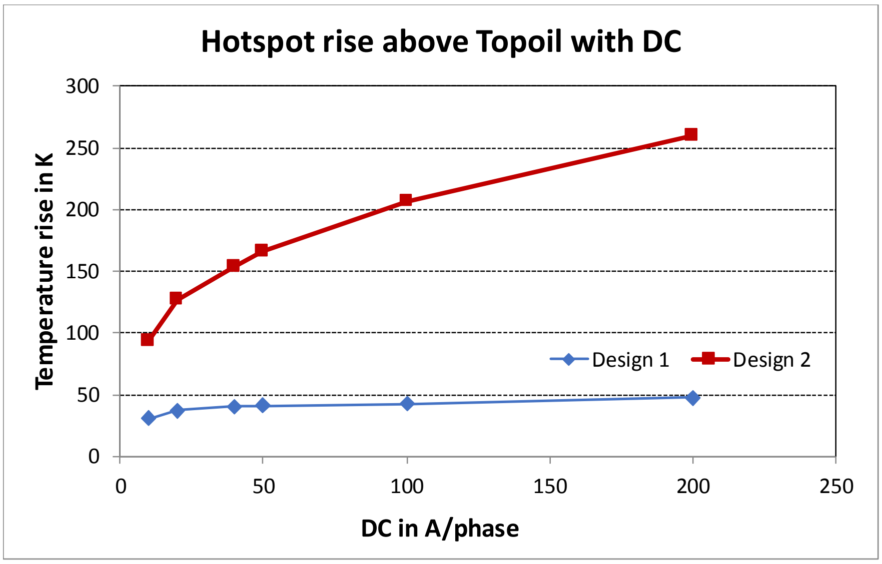


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

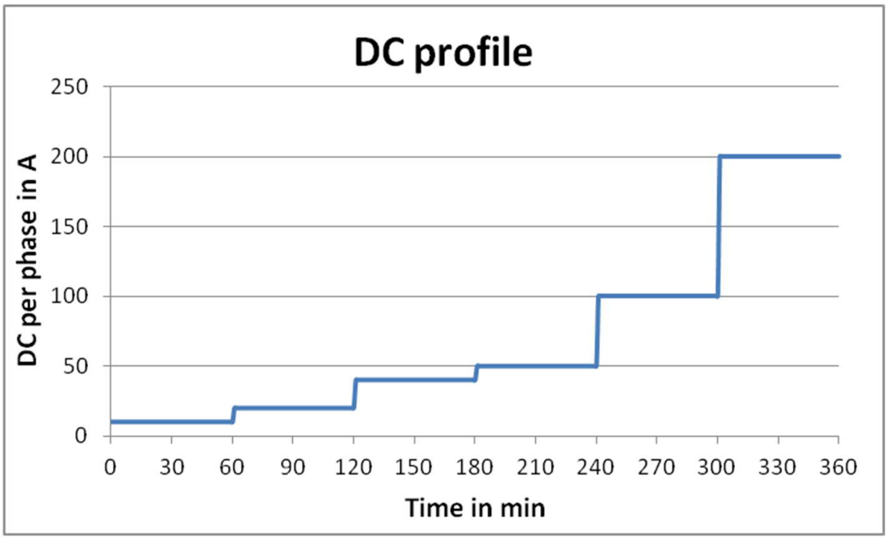


Figure 3: DC profile

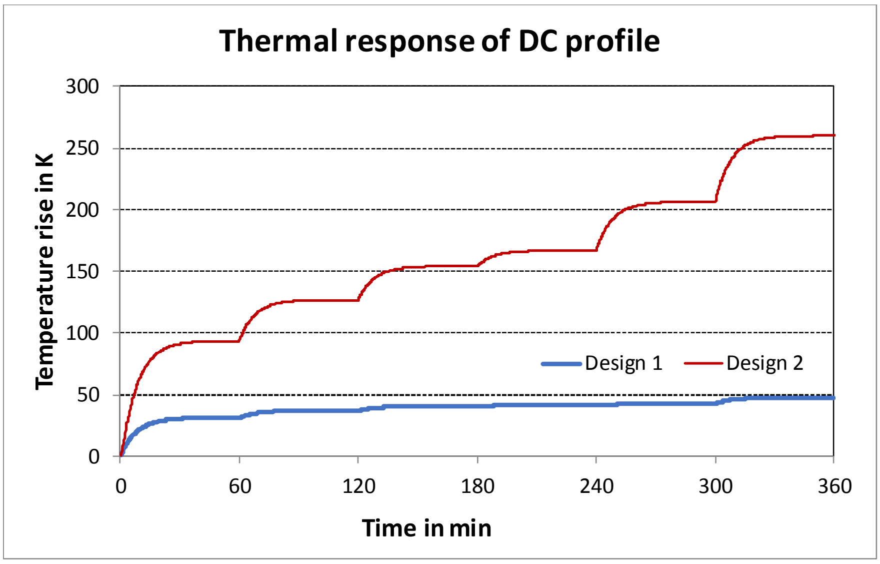


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T26

Content

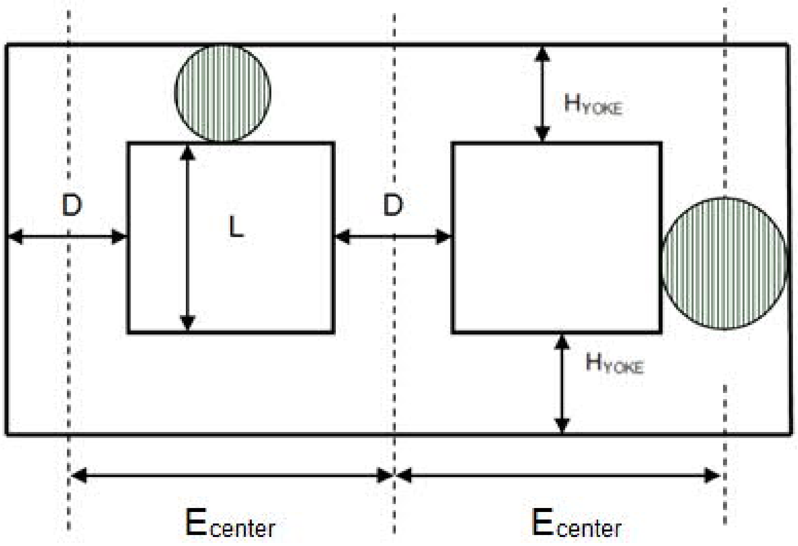
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T26
Transformer type	TRA
Rated power	120 MVA
Number of phases	3
Voltage levels	275 kV // 33 kV
Winding affected by DC	HV
Core type	3



L [mm]	1800
D [mm]	732
H yoke [mm]	720
E center [mm]	1662
A limb [m2]	0.384427
A yoke [m2]	0.384639

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 1.1103 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	0.0	0.0
20	4.9	4.3
40	31.2	74.3
50	33.7	91.7
100	37.3	122.2
200	37.6	151.8

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

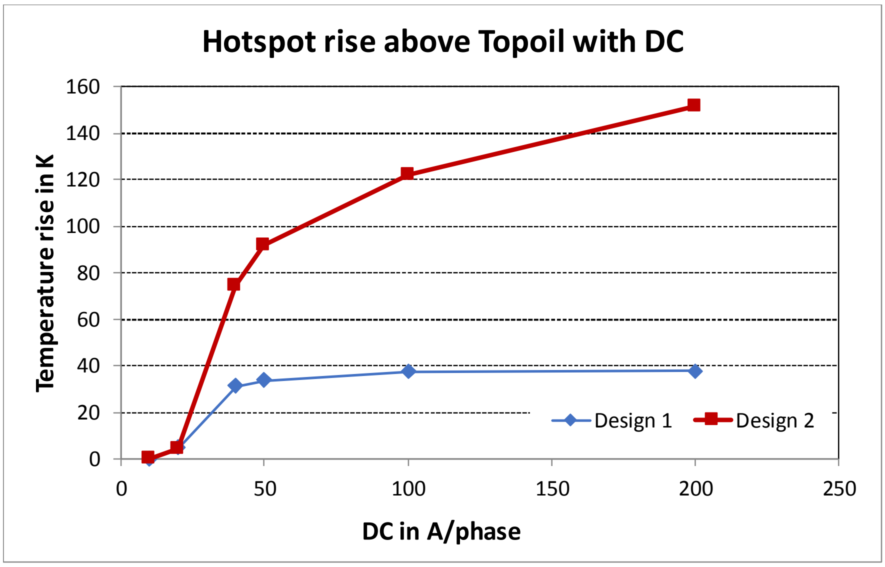


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

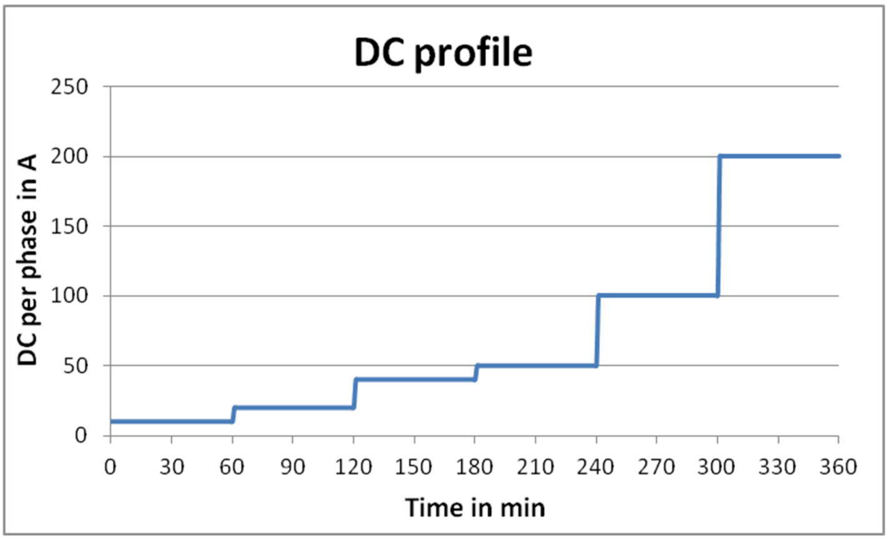


Figure 3: DC profile

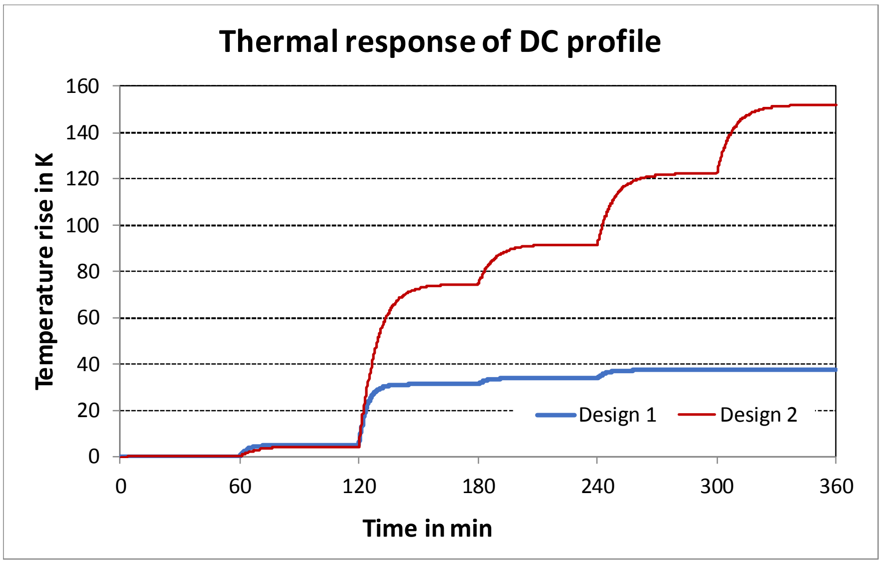


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T27

Content

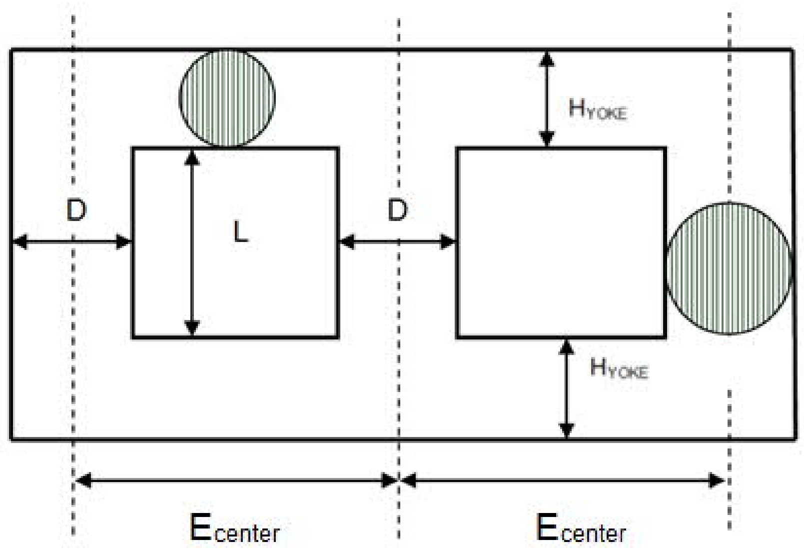
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T27
Transformer type	Auto
Rated power	500 MVA
Number of phases	3
Voltage levels	275 kV // 132 kV // 22 kV
Winding affected by DC	HV
Core type	3



L [mm]	2880
D [mm]	908
H yoke [mm]	890
E center [mm]	1890
A limb [m2]	0.578036
A yoke [m2]	0.578438

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.2475 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	0.3	0.1
20	9.1	13.2
40	30.9	66.5
50	35.5	86.4
100	40.5	122.8
200	45.2	156.7

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

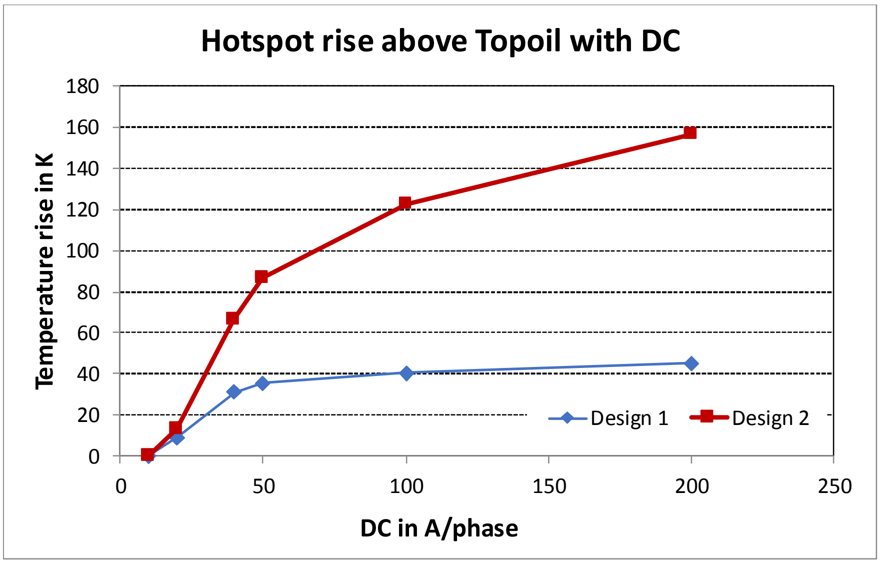


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

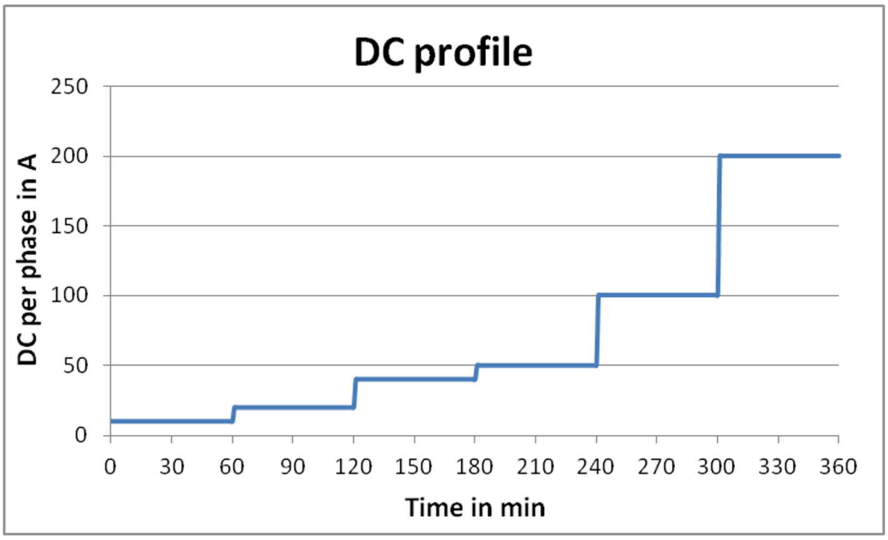


Figure 3: DC profile

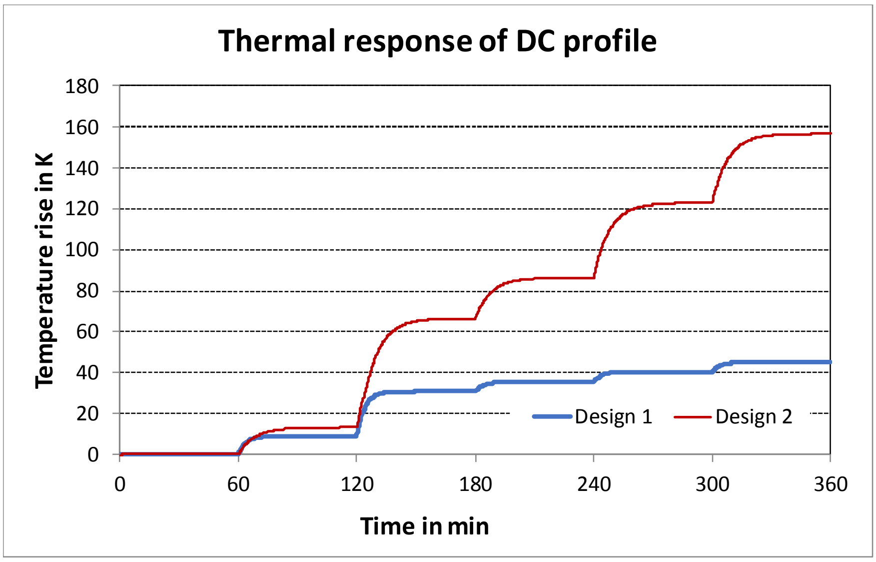


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T28

Content

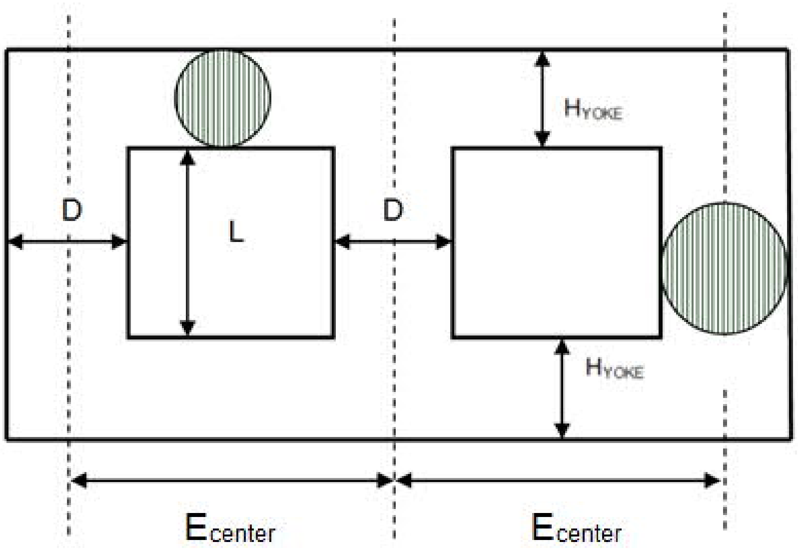
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T28
Transformer type	Auto
Rated power	200 MVA
Number of phases	3
Voltage levels	330 kV // 138.6 kV // 11 kV
Winding affected by DC	HV
Core type	3



L [mm]	1600
D [mm]	854
H yoke [mm]	840
E center [mm]	2000
A limb [m2]	0.514929
A yoke [m2]	0.515137

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.8302 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	2.7	2.2
20	22.7	53.1
40	33.2	108.8
50	34.2	118.9
100	36.5	158.5
200	38.7	209.3

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

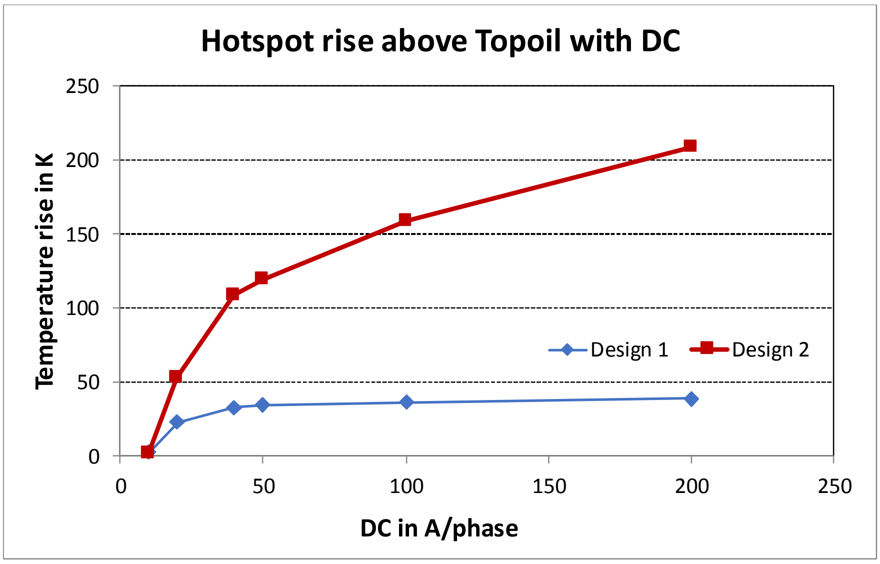


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

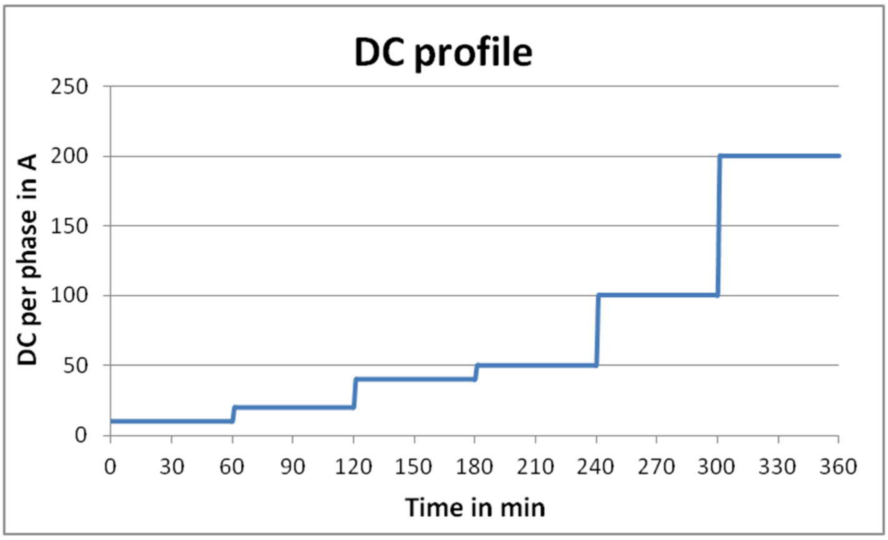


Figure 3: DC profile

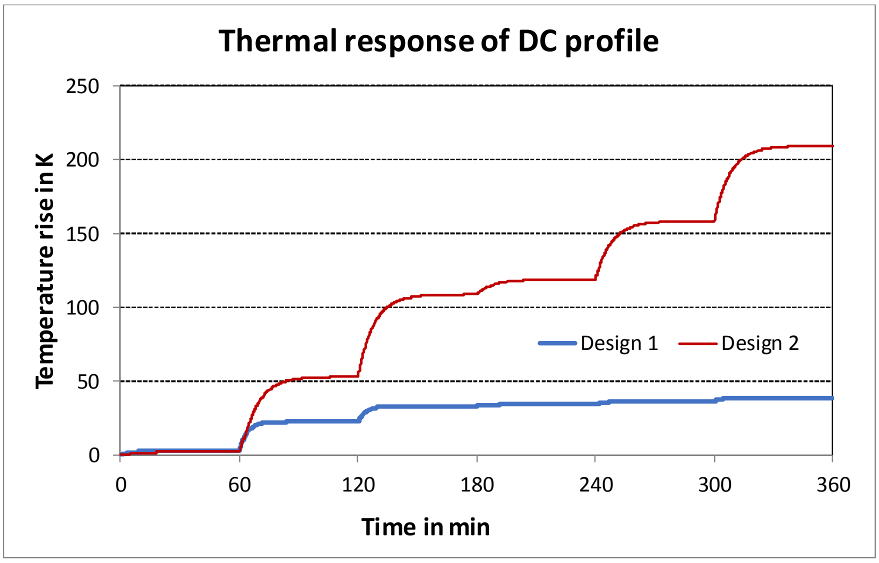


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T29

Content

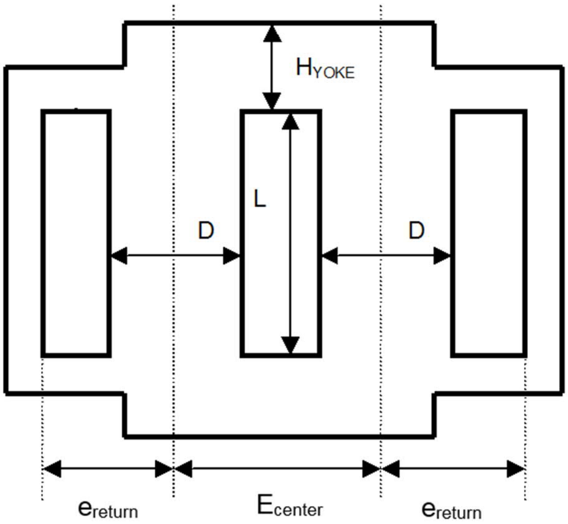
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T29
Transformer type	GSU
Rated power	500 MVA
Number of phases	1
Voltage levels	345/√3 kV // 24.5 kV
Winding affected by DC	HV
Core type	4



L [mm]	2150
D [mm]	1234
H yoke [mm]	720
E center [mm]	2502
A limb [m2]	1.07495
A yoke [m2]	0.716356
A return [m2]	0.357762
e return [mm]	1270

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.2311 H (per leg)

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] “Design 1”	Tie bar hot spot rise [K] “Design 2”
10	8.3	11.4
20	15.8	24.8
40	27.4	52.9
50	31.5	64.7
100	37.5	100.9
200	41.8	128.8

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

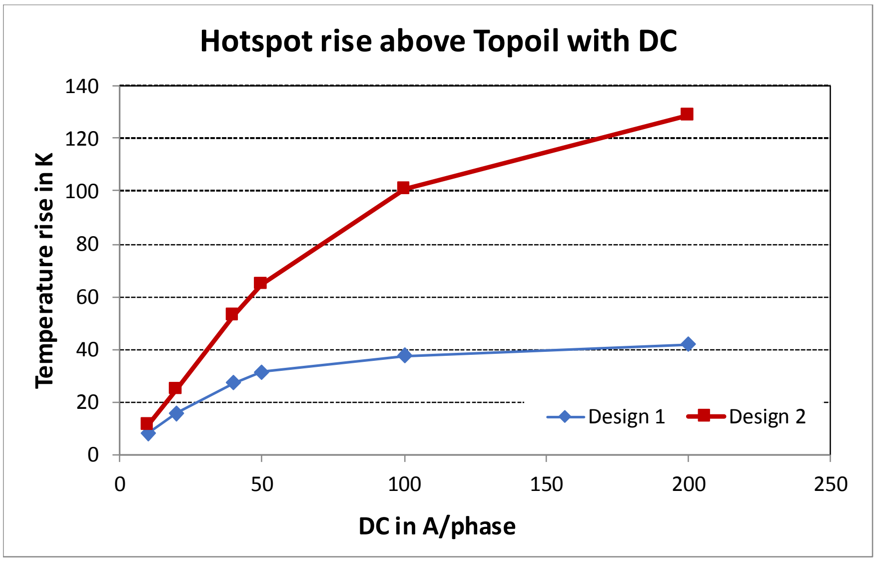


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

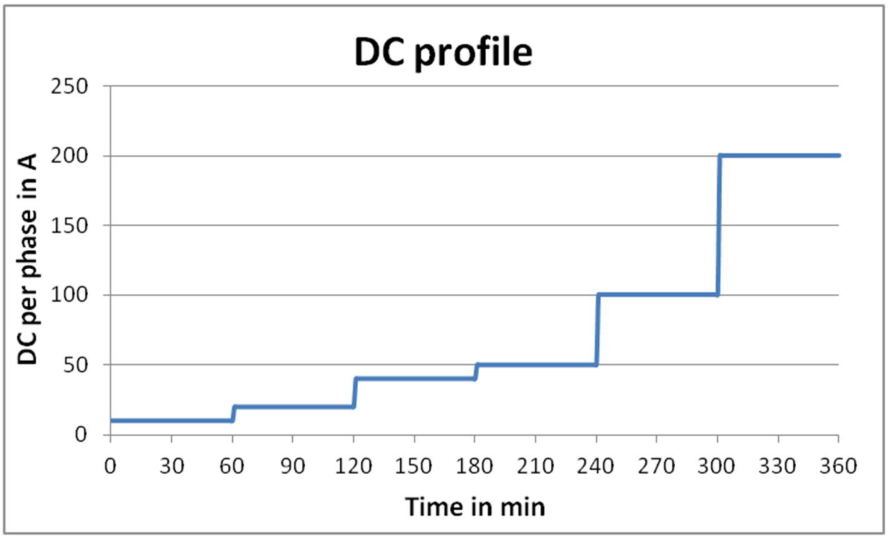


Figure 3: DC profile

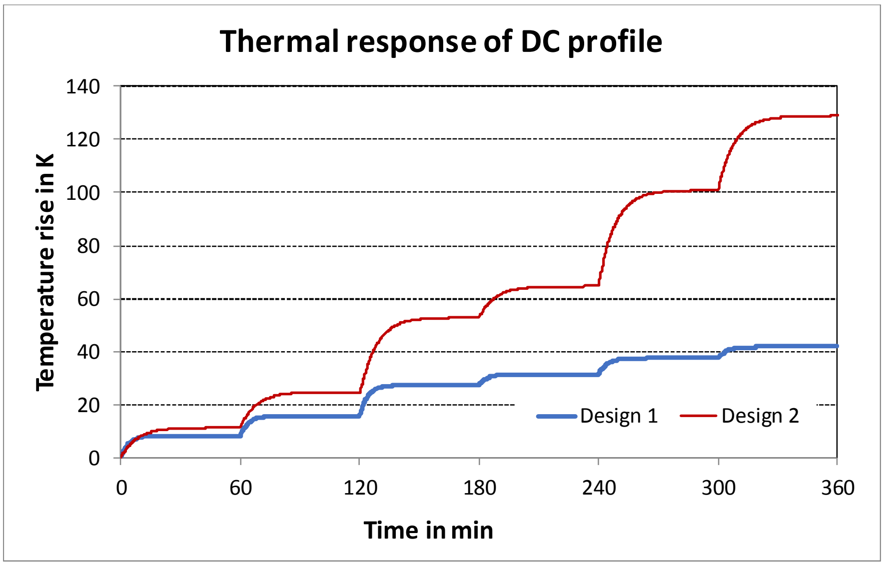


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T30

Content

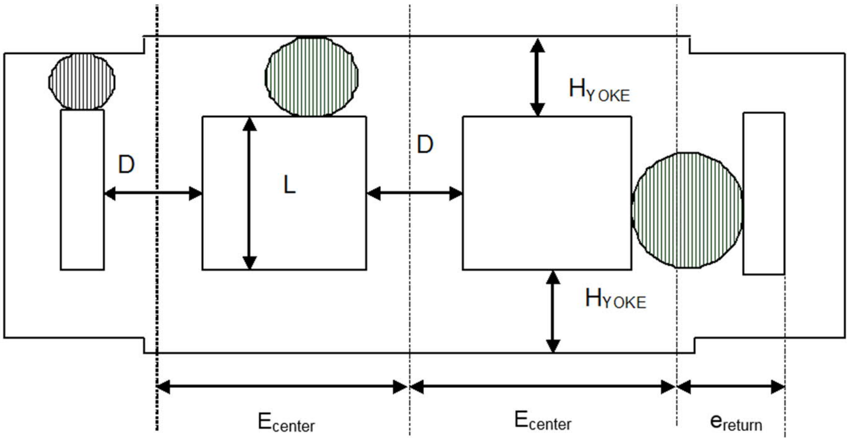
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T30
Transformer type	Auto
Rated power	500 MVA
Number of phases	3
Voltage levels	345 kV // 138 kV // 24.9 kV
Winding affected by DC	HV
Core type	5



L [mm]	2870
D [mm]	904
H yoke [mm]	510
E center [mm]	1840
A limb [m2]	0.578636
A yoke [m2]	0.330188
A return [m2]	0.28989
e return [mm]	950

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.2275 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	22.3	31.8
20	35.8	64.0
40	44.4	103.1
50	46.1	115.6
100	50.5	146.1
200	53.1	182.0

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

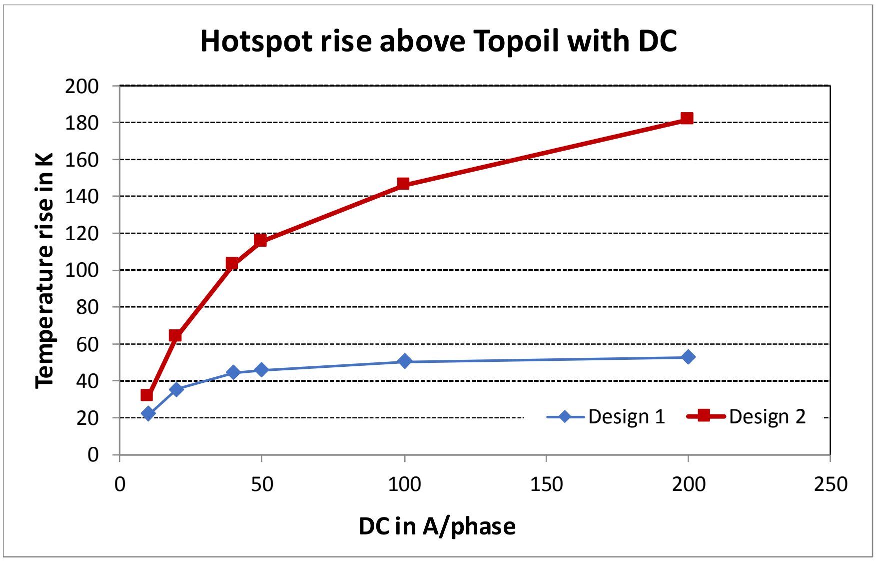


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

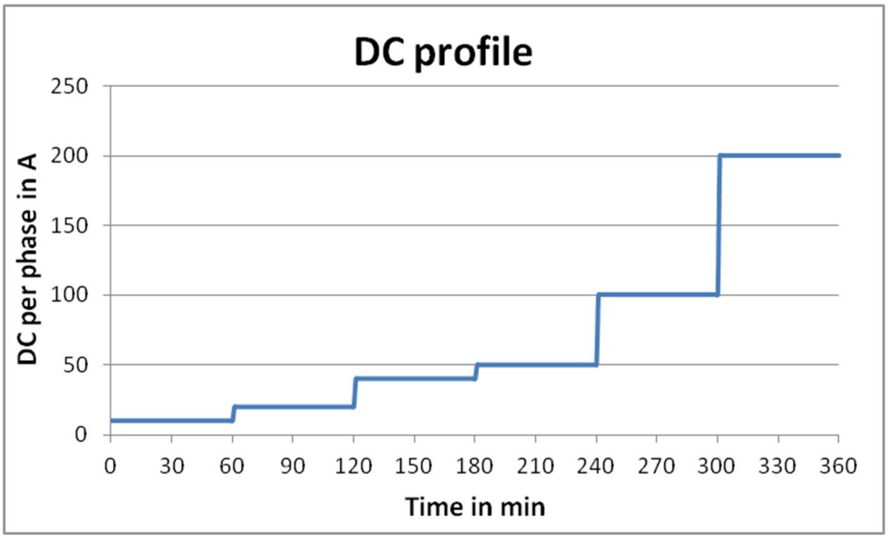


Figure 3: DC profile

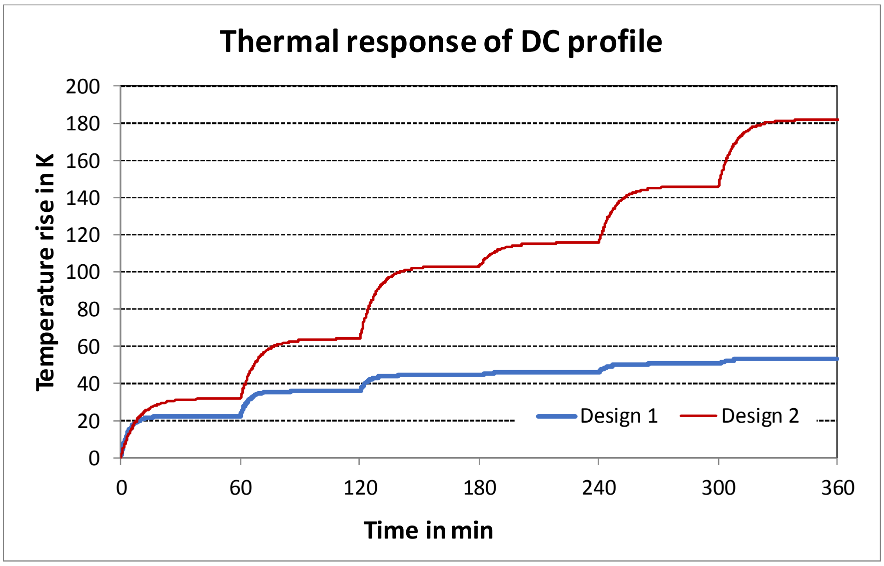


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T31

Content

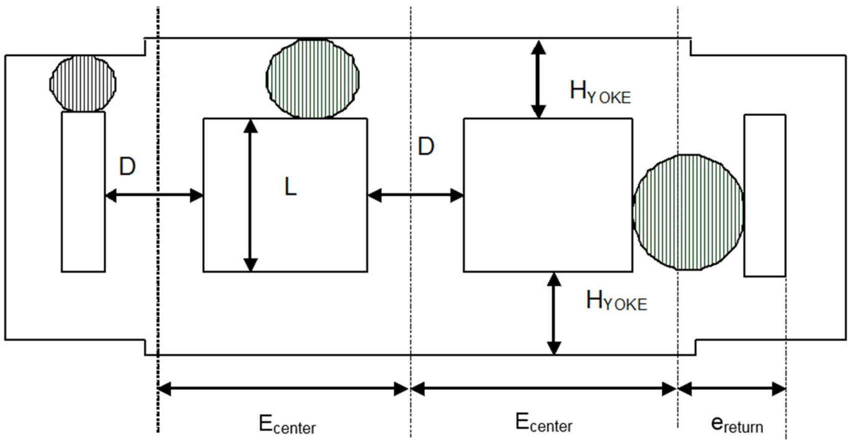
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T31
Transformer type	Auto
Rated power	800 MVA
Number of phases	3
Voltage levels	345 kV // 143 kV // 23 kV
Winding affected by DC	HV
Core type	5



L [mm]	2525
D [mm]	1122
H yoke [mm]	630
E center [mm]	2068
A limb [m2]	0.902604
A yoke [m2]	0.514265
A return [m2]	0.454251
e return [mm]	1054

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.1527 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	16.5	22.8
20	30.1	47.4
40	42.0	85.6
50	44.0	98.1
100	47.9	134.1
200	51.5	167.9

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

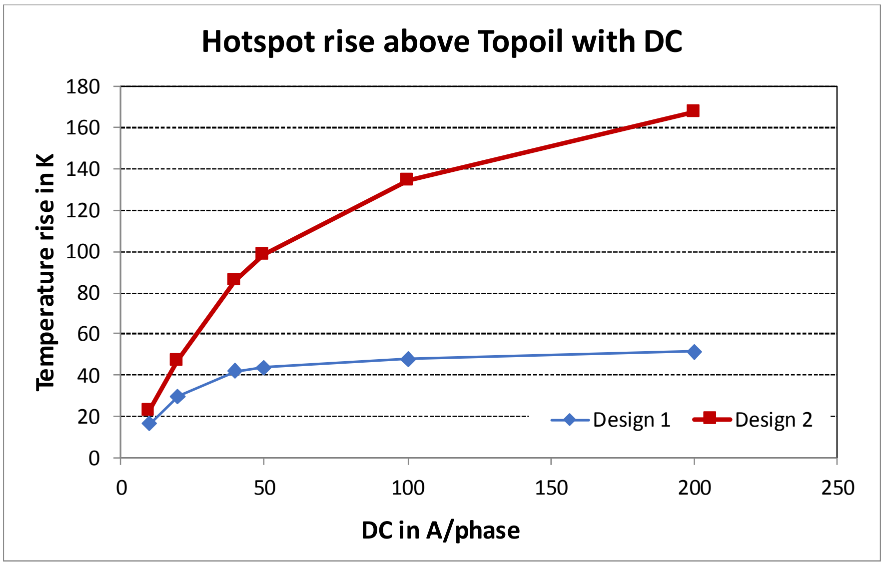


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

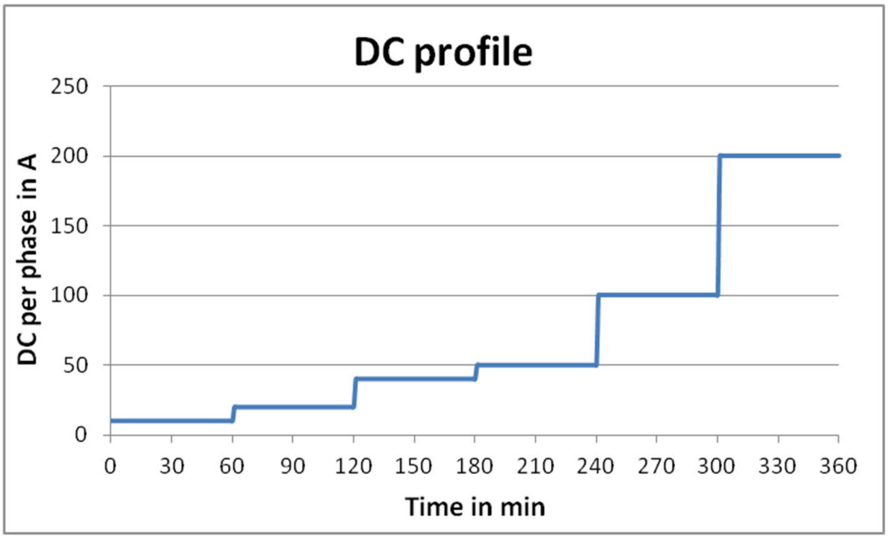


Figure 3: DC profile

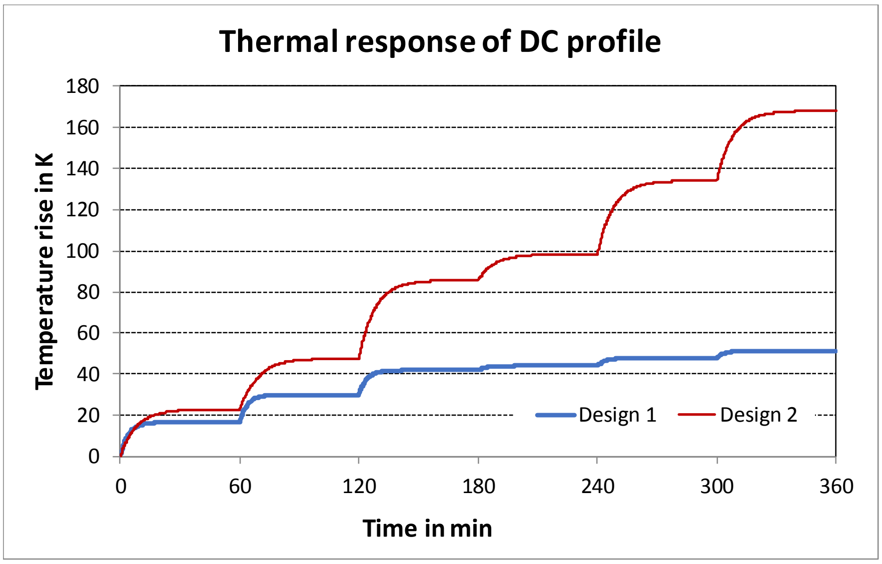


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T32

Content

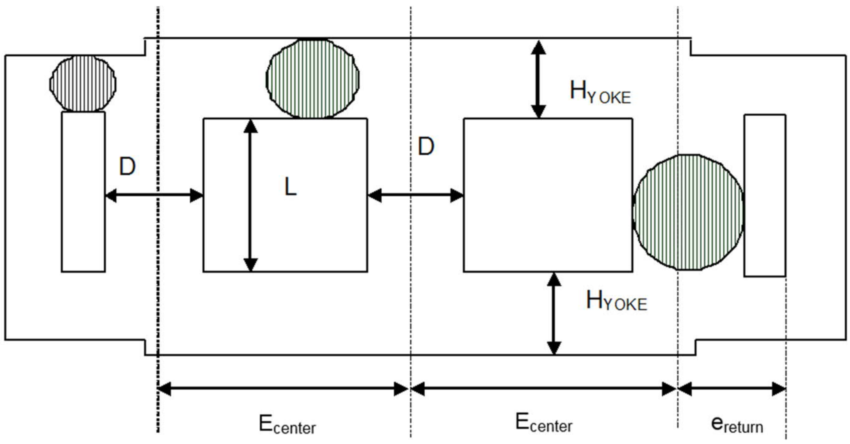
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T32
Transformer type	GSU
Rated power	315 MVA
Number of phases	3
Voltage levels	345 kV // 21.25 kV
Winding affected by DC	HV
Core type	5



L [mm]	2680
D [mm]	1016
H yoke [mm]	570
E center [mm]	1920
A limb [m2]	0.734245
A yoke [m2]	0.418206
A return [m2]	0.368232
e return [mm]	985

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.1689 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	14.4	20.3
20	26.0	42.4
40	39.1	81.2
50	41.1	94.1
100	45.8	132.7
200	48.7	168.8

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

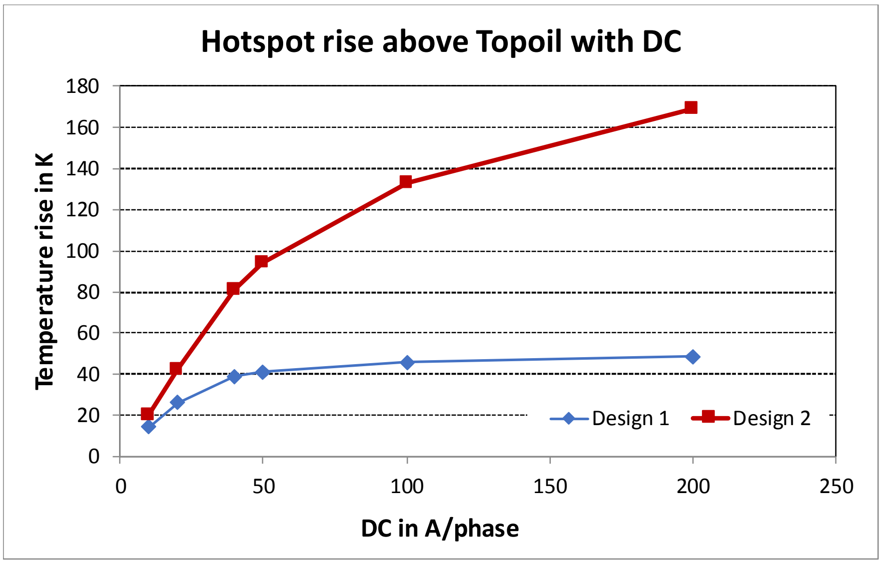


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

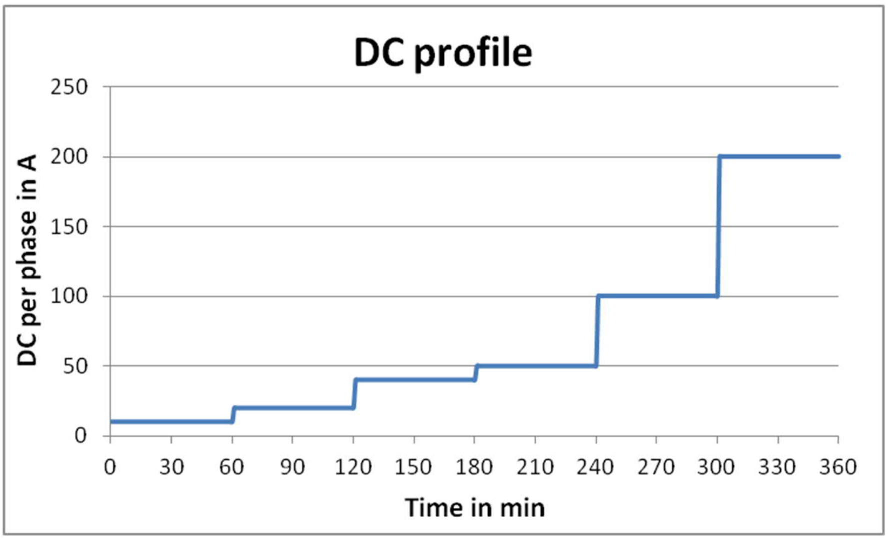


Figure 3: DC profile

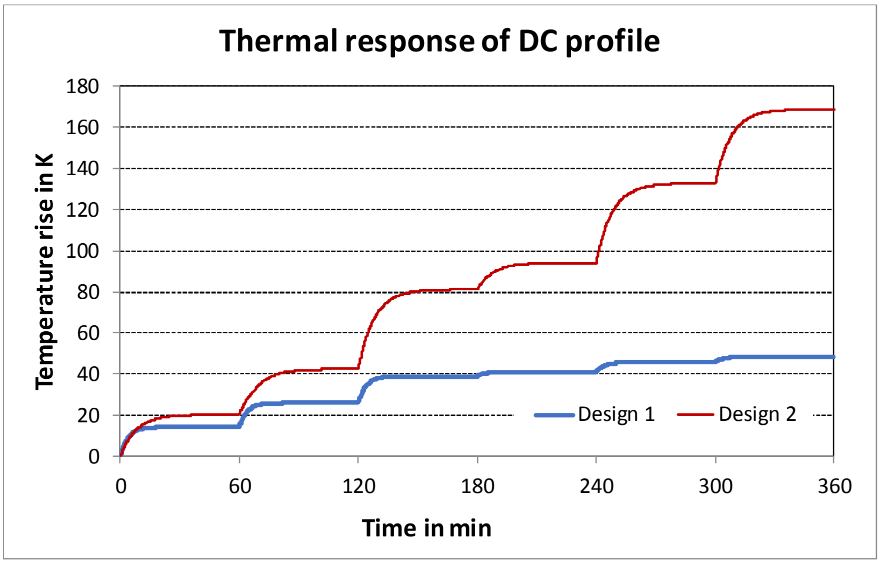


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T33

Content

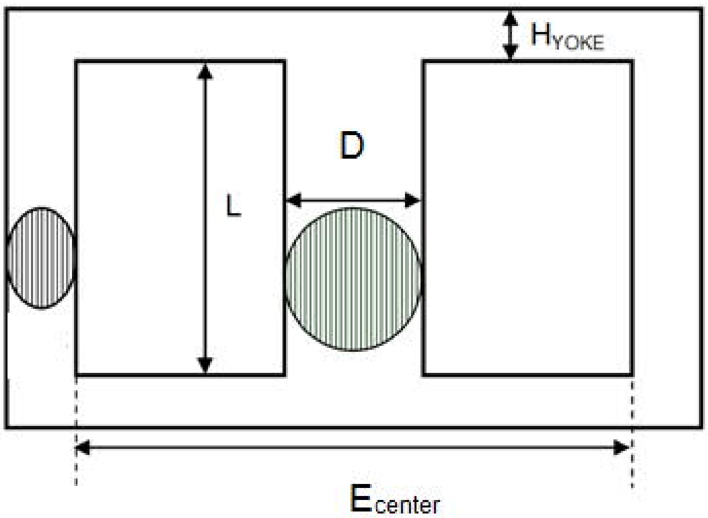
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T33
Transformer type	Auto
Rated power	133.33 MVA
Number of phases	1
Voltage levels	230/√3 kV // 115/√3 kV // 13.2 kV
Winding affected by DC	HV
Core type	1



L [mm]	2496
D [mm]	754
H yoke [mm]	370
E center [mm]	1740
A limb [m2]	0.394473
A yoke [m2]	0.19852

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.2176 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	25.3	43.6
20	37.5	80.6
40	42.9	121.5
50	44.6	130.8
100	46.9	165.7
200	51.3	213.4

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

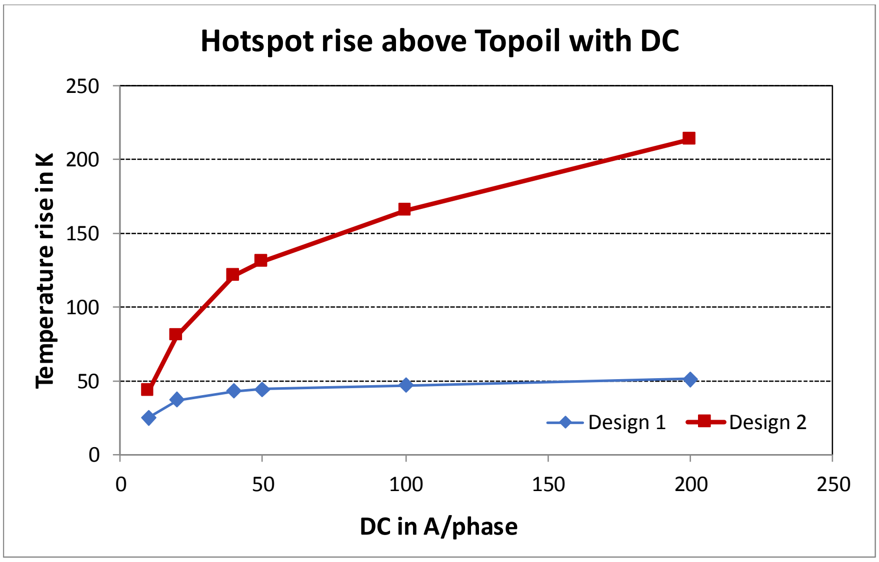


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

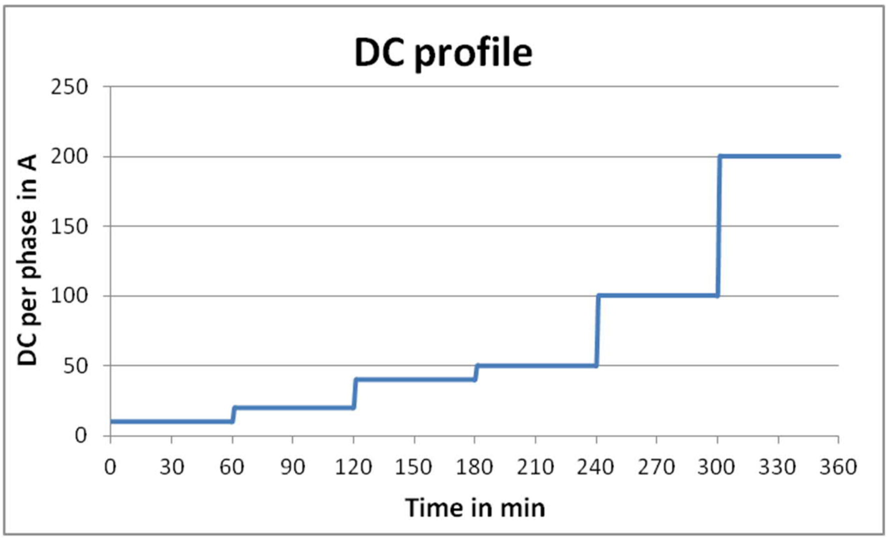


Figure 3: DC profile

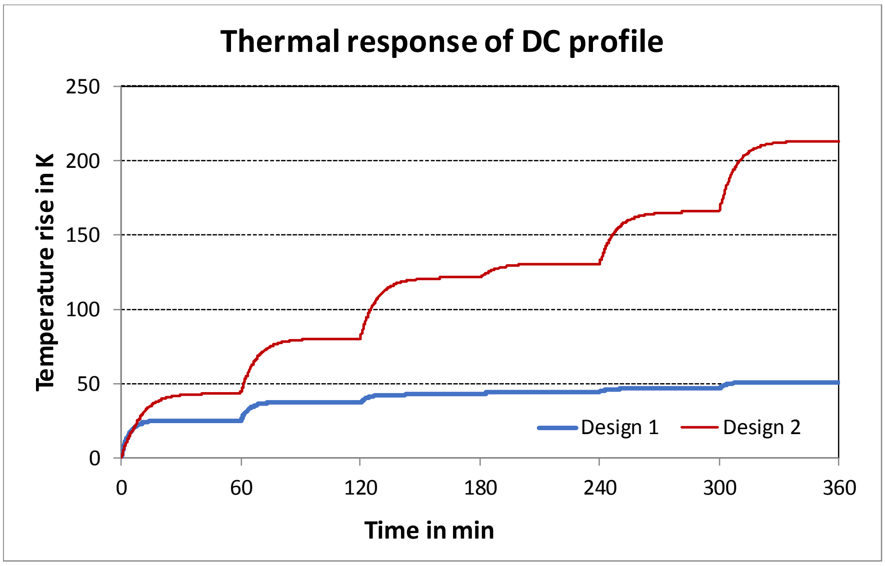


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T34

Content

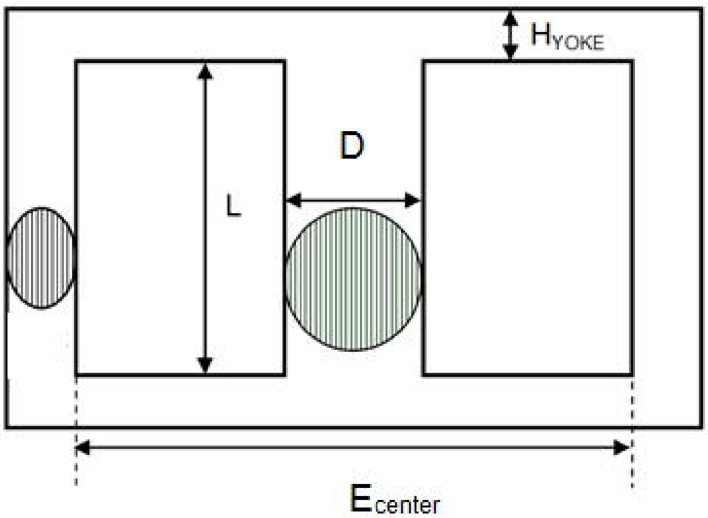
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T34
Transformer type	Auto
Rated power	66.6 MVA
Number of phases	1
Voltage levels	231/√3 kV // 121/√3 kV // 10.5 kV
Winding affected by DC	HV
Core type	1



L [mm]	2970
D [mm]	732
H yoke [mm]	360
E center [mm]	1770
A limb [m2]	0.37933
A yoke [m2]	0.19185

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.3042 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	30.2	55.6
20	39.5	95.8
40	43.9	125.5
50	44.9	133.1
100	48.7	162.2
200	49.9	204.4

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

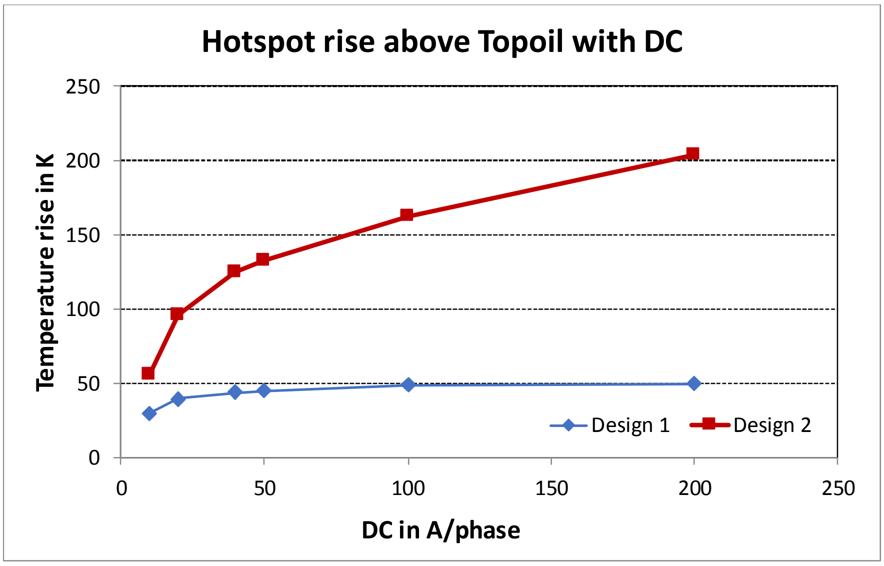


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

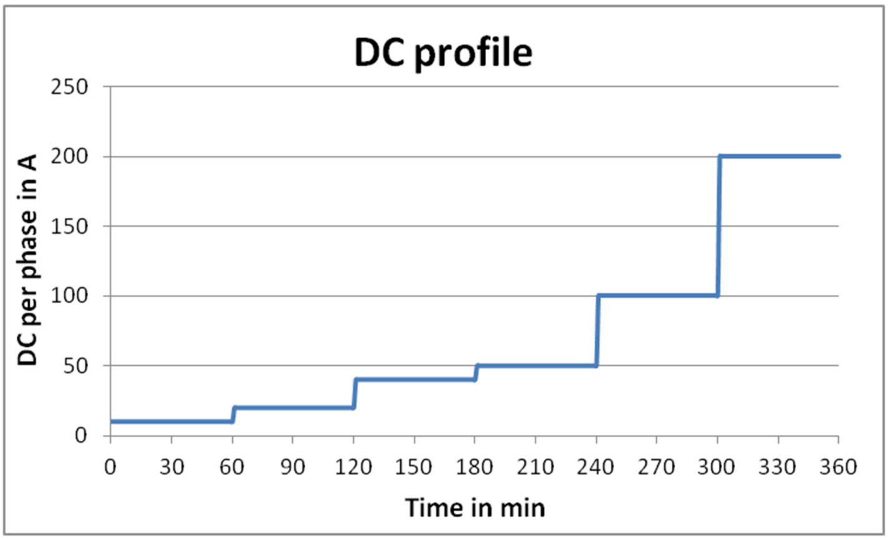


Figure 3: DC profile

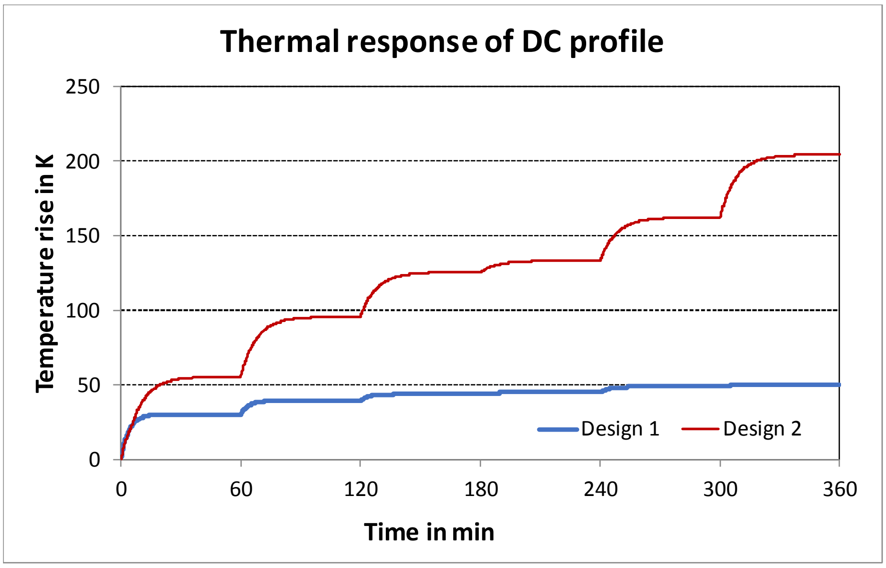


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T35

Content

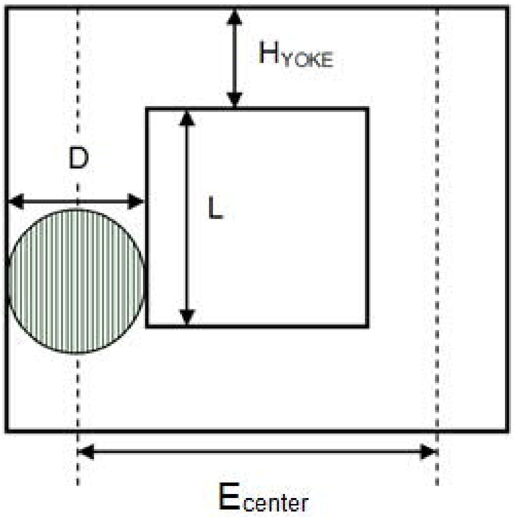
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T35
Transformer type	GSU
Rated power	100 MVA
Number of phases	1
Voltage levels	230/√3 kV // 23 kV
Winding affected by DC	HV
Core type	2



L [mm]	1902
D [mm]	852
H yoke [mm]	840
E center [mm]	1444
A limb [m2]	0.5246
A yoke [m2]	0.52474

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.3944 H (per leg)

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	18.8	27.0
20	30.6	52.5
40	36.6	88.0
50	37.9	99.7
100	40.6	125.5
200	43.3	145.8

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

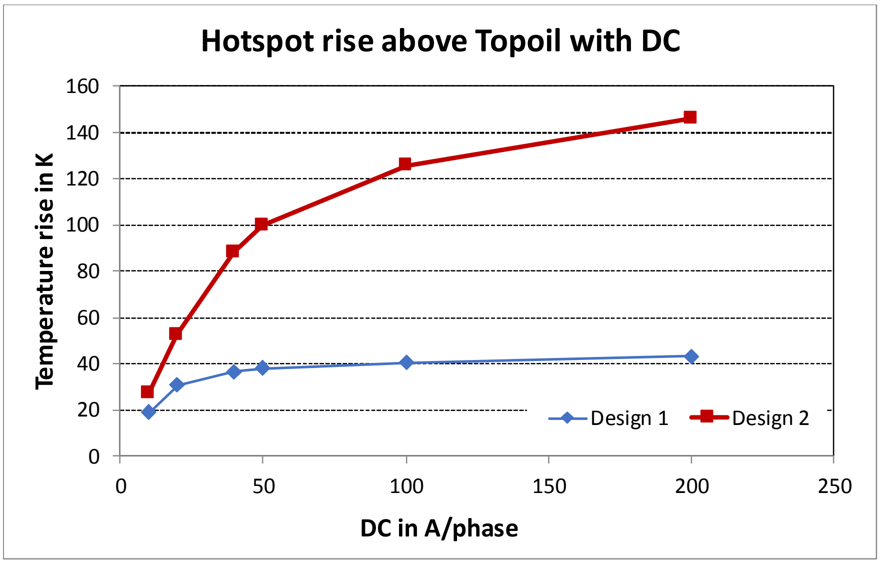


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

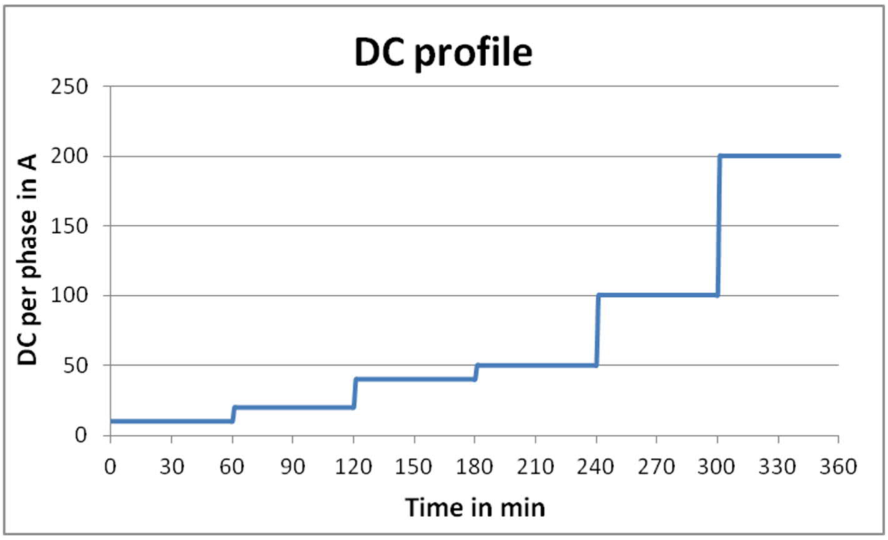


Figure 3: DC profile

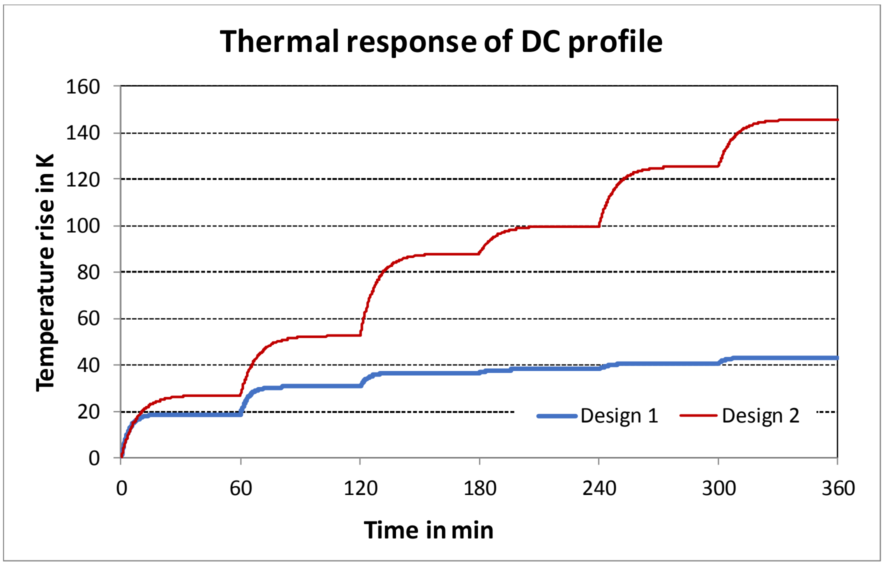


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T36

Content

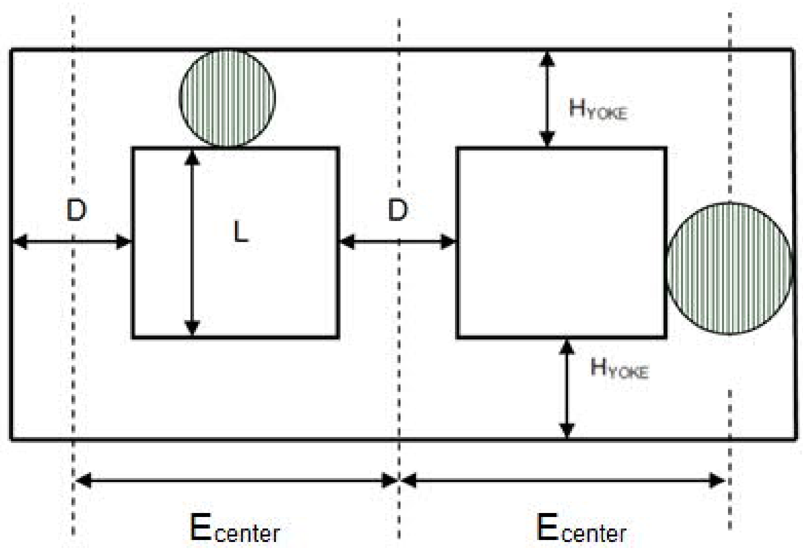
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T36
Transformer type	Auto
Rated power	160 MVA
Number of phases	3
Voltage levels	230 kV // 115 kV // 13.2 kV
Winding affected by DC	HV
Core type	3



L [mm]	2180
D [mm]	550
H yoke [mm]	540
E center [mm]	1264
A limb [m2]	0.211731
A yoke [m2]	0.211924

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.5103 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	19.7	28.8
20	39.0	91.3
40	44.8	138.8
50	46.9	154.4
100	49.3	196.4
200	51.3	256.5

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

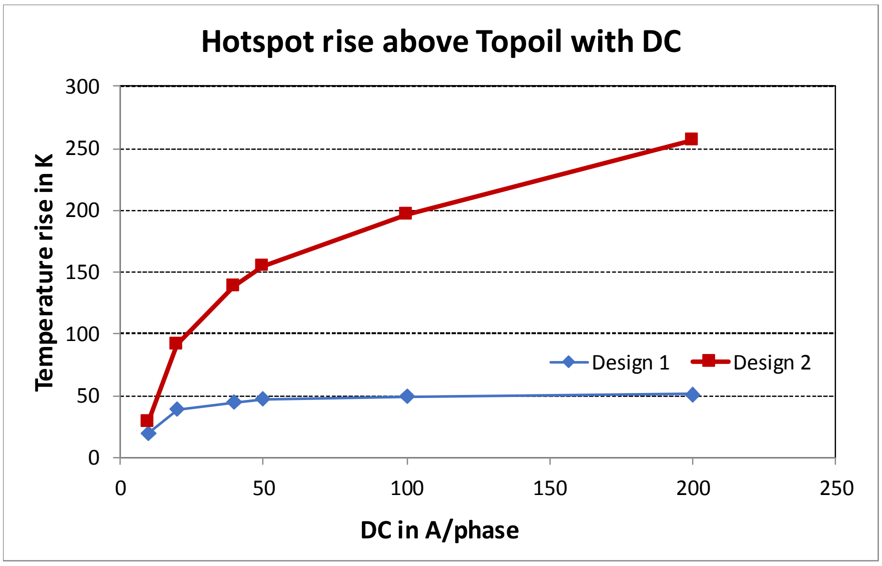


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

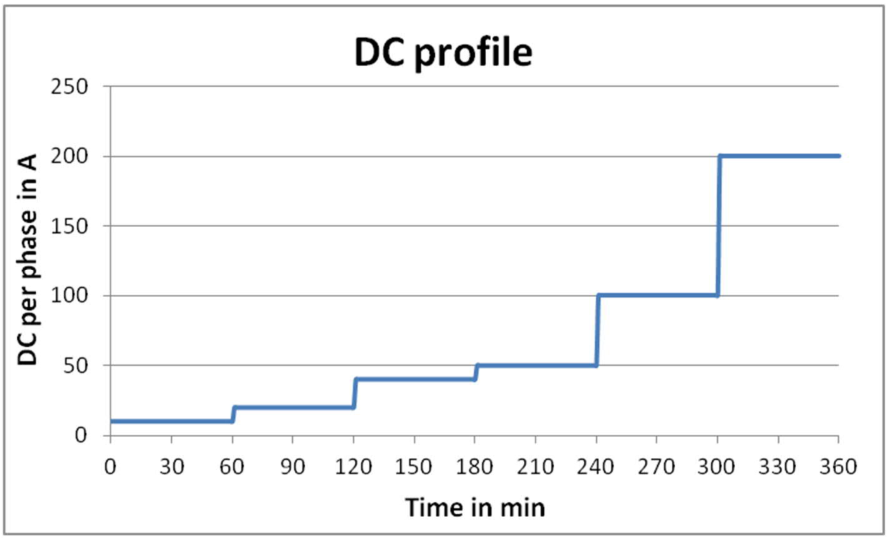


Figure 3: DC profile

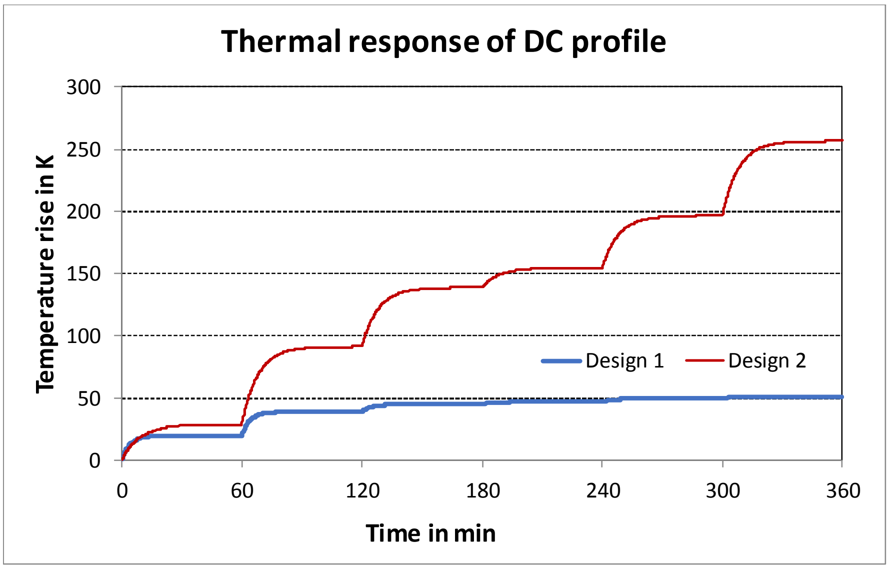


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T37

Content

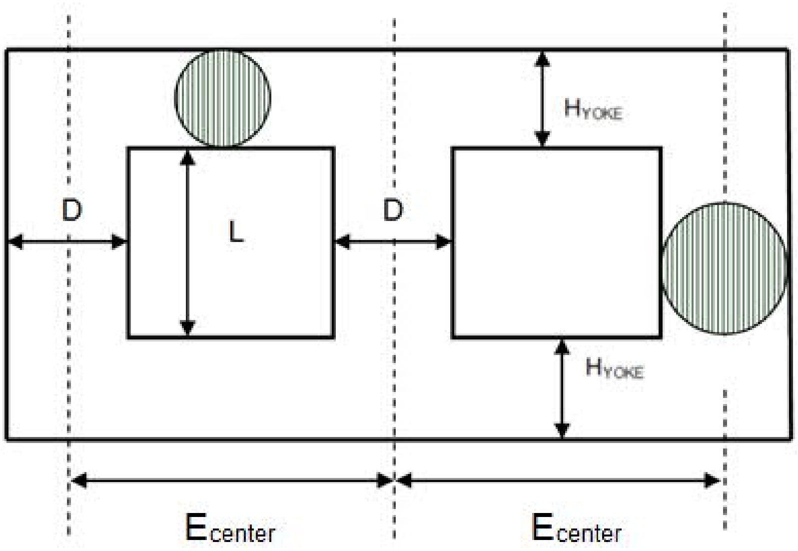
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T37
Transformer type	GSU
Rated power	290 MVA
Number of phases	3
Voltage levels	230 kV // 18 kV
Winding affected by DC	HV
Core type	3



L [mm]	2150
D [mm]	974
H yoke [mm]	970
E center [mm]	1732
A limb [m2]	0.675203
A yoke [m2]	0.67611

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.1518 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	0.1	0.0
20	0.2	0.1
40	5.4	4.5
50	12.4	15.4
100	43.0	80.0
200	51.4	135.0

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

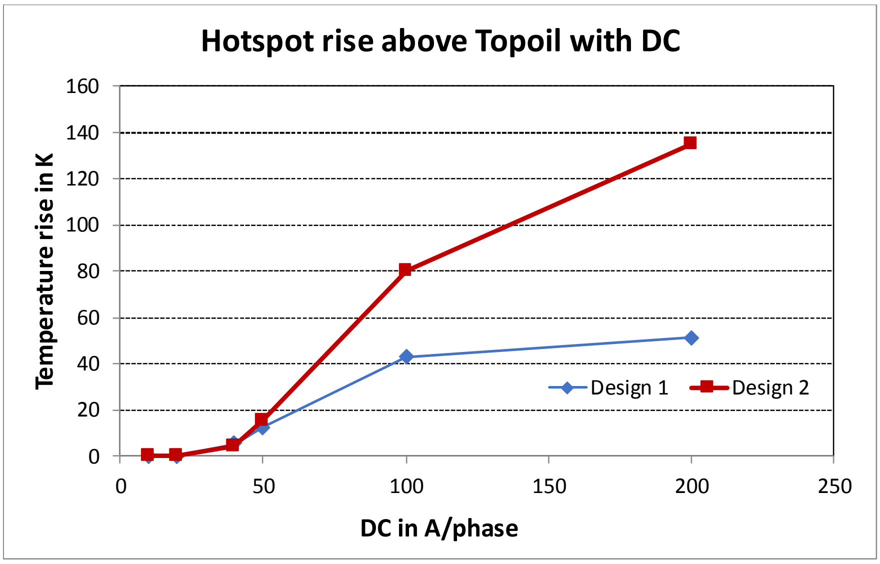


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

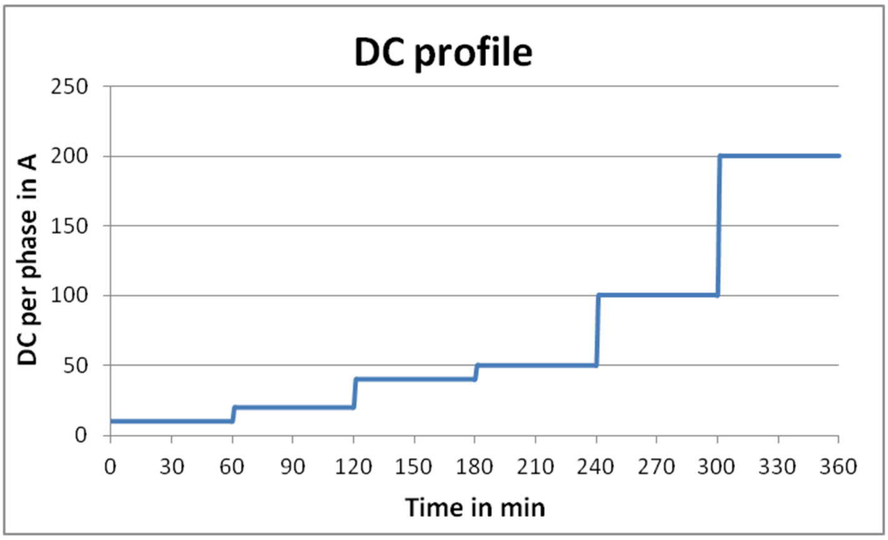


Figure 3: DC profile

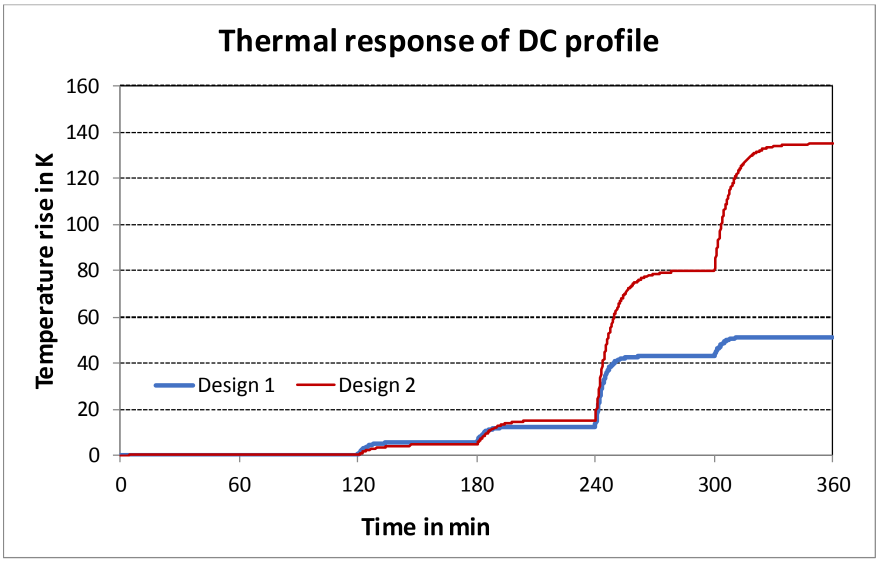


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T38

Content

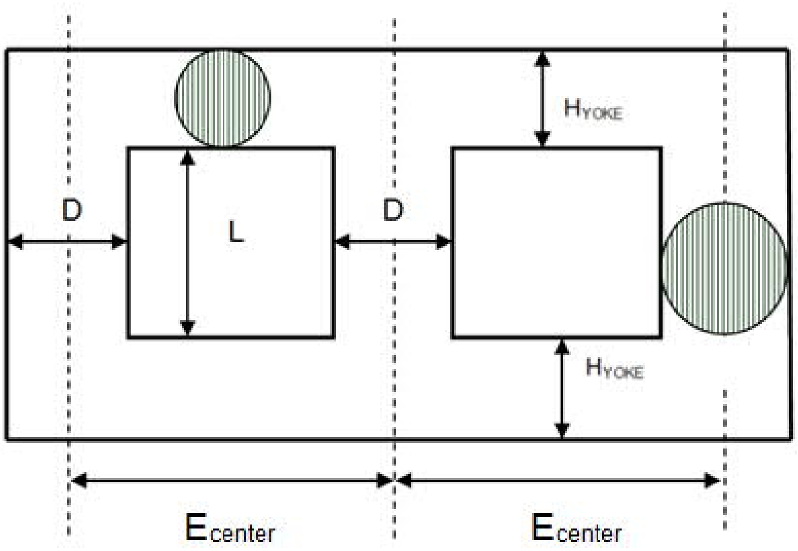
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T38
Transformer type	Auto
Rated power	420 MVA
Number of phases	3
Voltage levels	230 kV // 121.4 kV // 13.2 kV
Winding affected by DC	HV
Core type	3



L [mm]	2422
D [mm]	890
H yoke [mm]	880
E center [mm]	2034
A limb [m2]	0.556753
A yoke [m2]	0.557204

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.2475 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	0.0	0.0
20	0.0	0.0
40	3.5	3.0
50	12.7	19.1
100	37.7	102.5
200	43.5	144.3

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

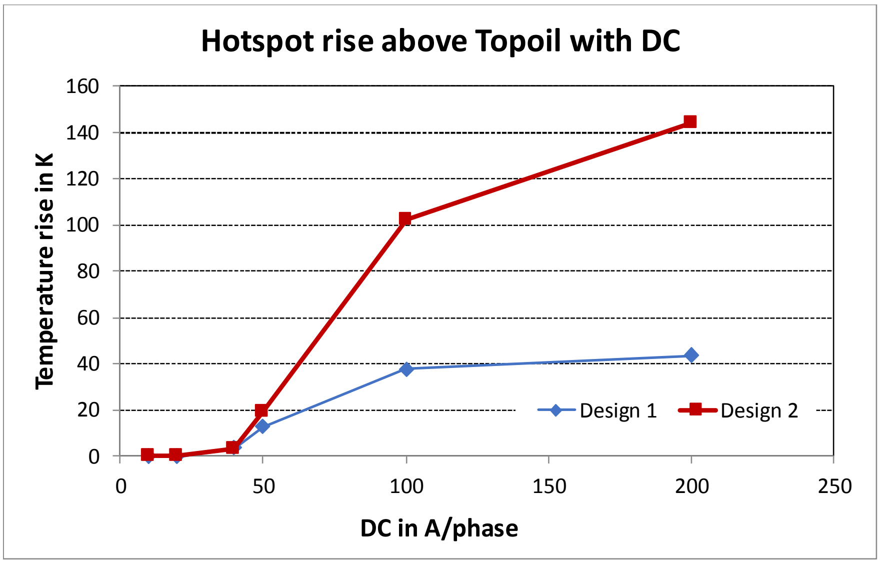


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

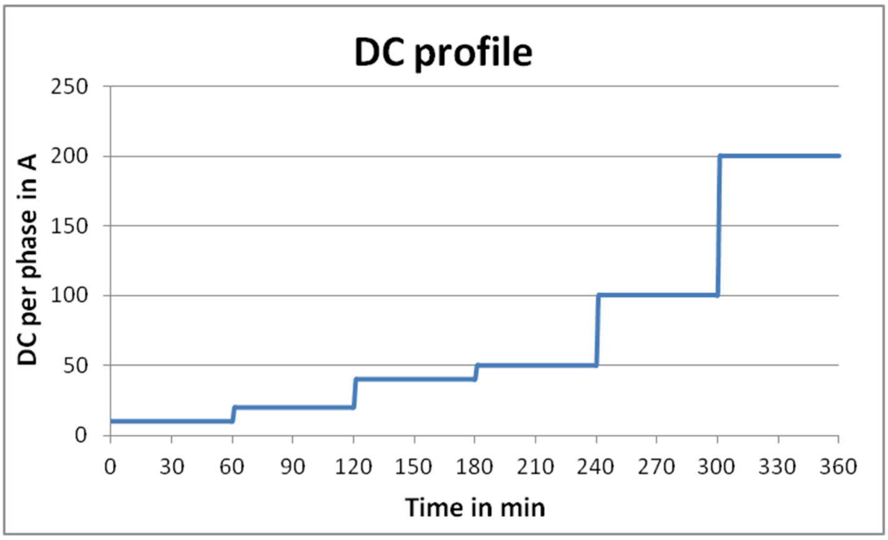


Figure 3: DC profile

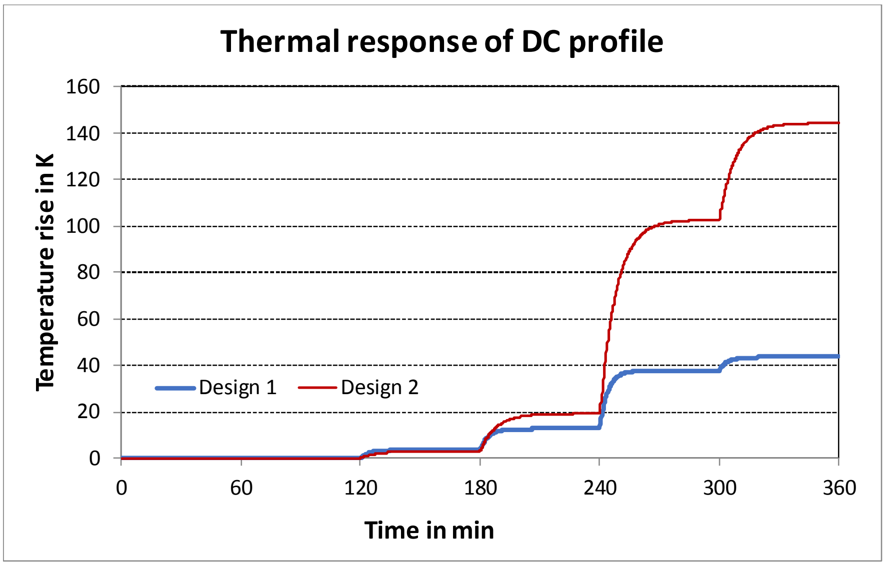


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T39

Content

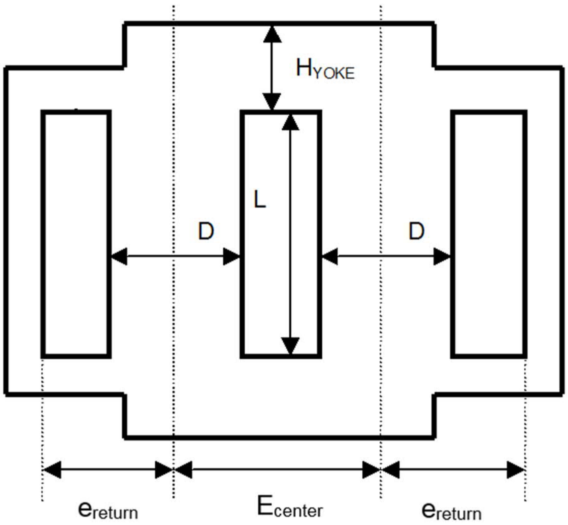
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T39
Transformer type	GSU
Rated power	300 MVA
Number of phases	1
Voltage levels	242/√3 kV // 25 kV
Winding affected by DC	HV
Core type	4



L [mm]	3120
D [mm]	922
H yoke [mm]	560
E center [mm]	1530
A limb [m2]	0.592307
A yoke [m2]	0.422582
A return [m2]	0.169966
e return [mm]	816

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.1318 H (per leg)

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] “Design 1”	Tie bar hot spot rise [K] “Design 2”
10	13.0	14.9
20	24.6	31.4
40	40.6	56.4
50	45.1	66.2
100	52.3	101.6
200	57.5	127.8

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

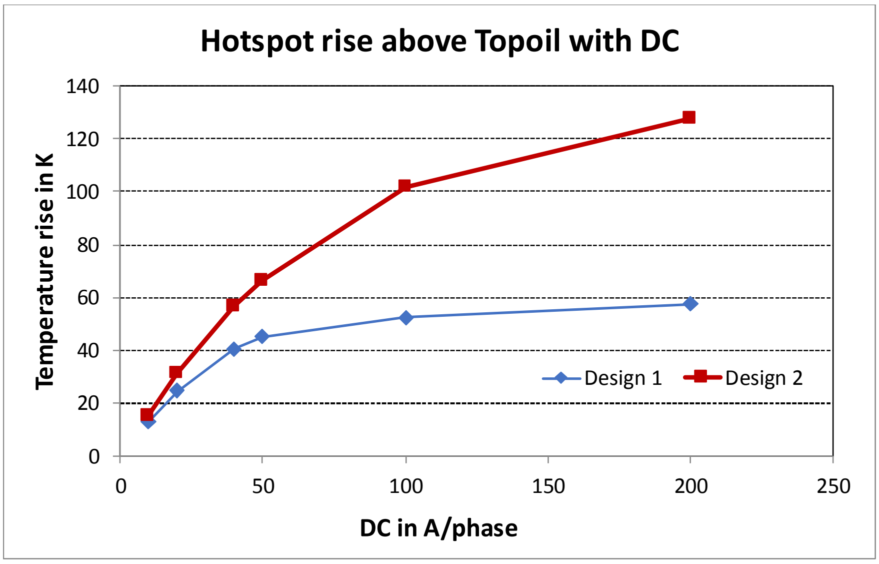


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

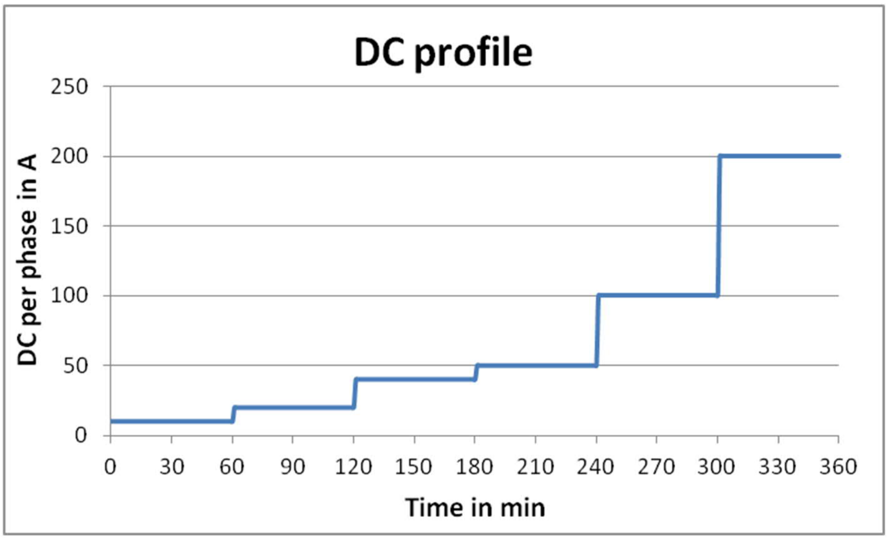


Figure 3: DC profile

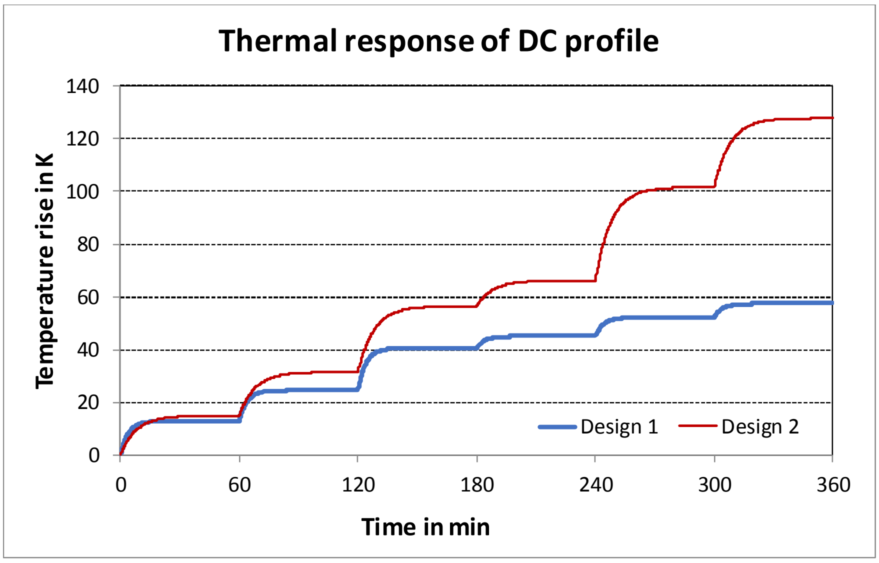


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T40

Content

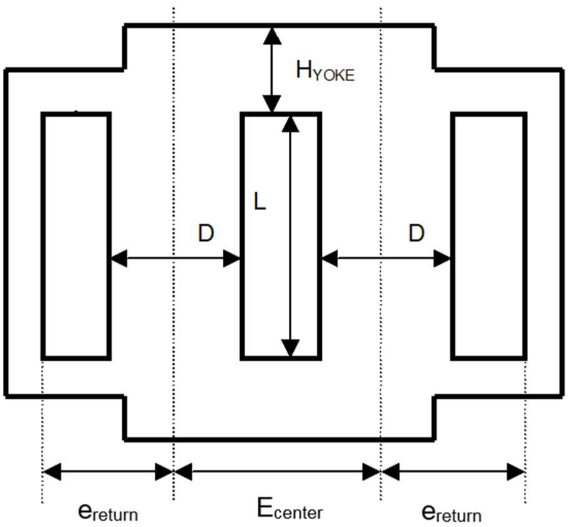
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T40
Transformer type	GSU
Rated power	466 MVA
Number of phases	1
Voltage levels	240/√3 kV // 25 kV
Winding affected by DC	HV
Core type	4



L [mm]	2780
D [mm]	1330
H yoke [mm]	750
E center [mm]	2048
A limb [m2]	1.26565
A yoke [m2]	0.83568
A return [m2]	0.429652
e return [mm]	1066

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.0572 H (per leg)

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	4.2	3.3
20	10.8	13.4
40	21.2	30.2
50	25.8	37.6
100	40.8	65.8
200	47.4	101.4

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

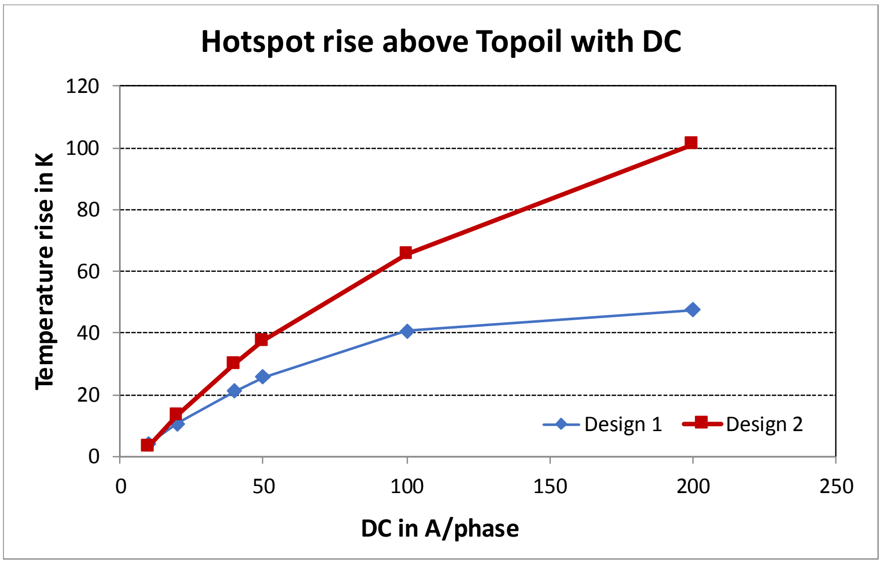


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

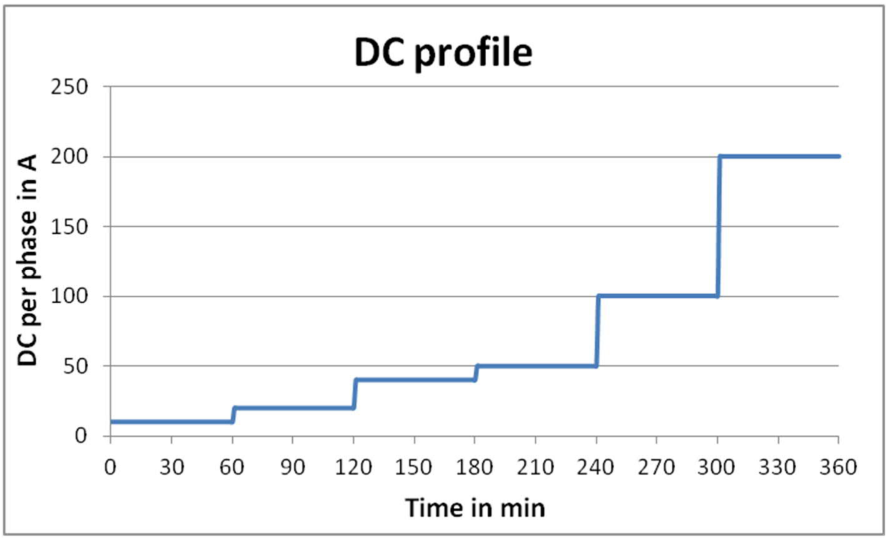


Figure 3: DC profile

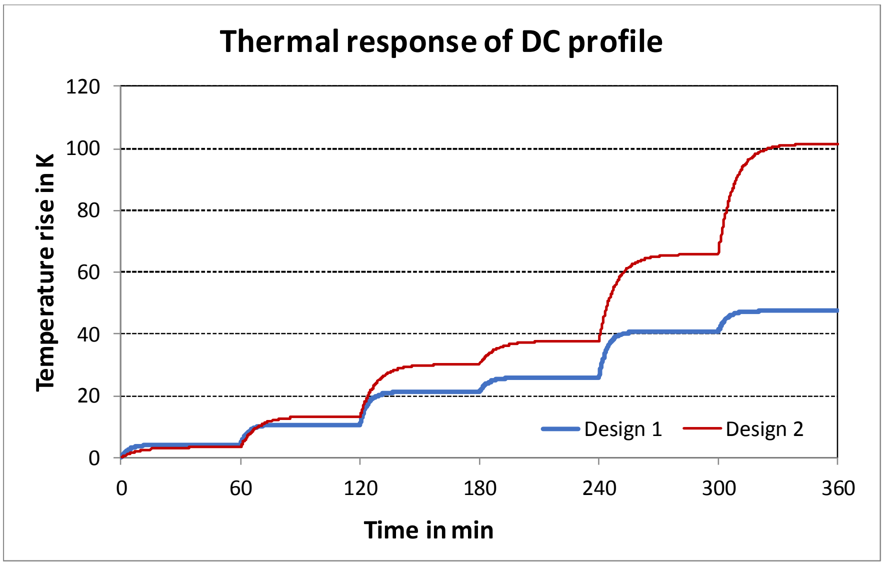


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T41

Content

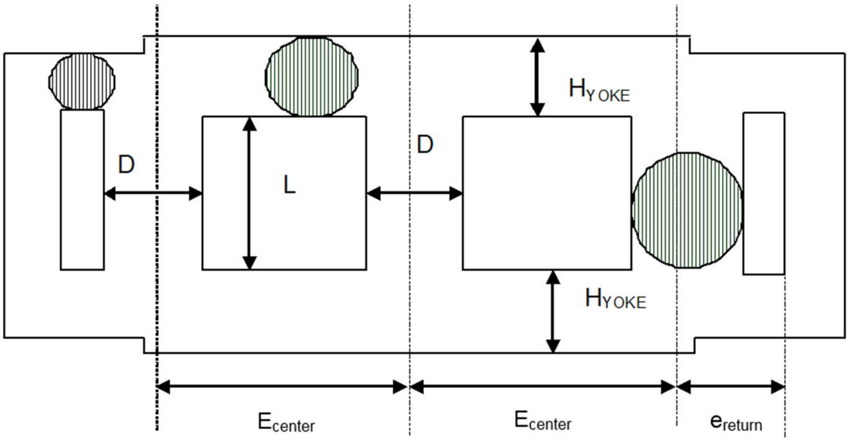
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T41
Transformer type	GSU
Rated power	240 MVA
Number of phases	3
Voltage levels	225 kV // 15.5 kV
Winding affected by DC	HV
Core type	5



L [mm]	2490
D [mm]	1016
H yoke [mm]	580
E center [mm]	1930
A limb [m2]	0.742116
A yoke [m2]	0.4226
A return [m2]	0.37374
e return [mm]	1001

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.1518 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] “Design 1”	Tie bar hot spot rise [K] “Design 2”
10	12.7	18.0
20	24.3	37.8
40	35.0	66.7
50	36.4	76.9
100	39.9	108.0
200	43.3	127.5

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

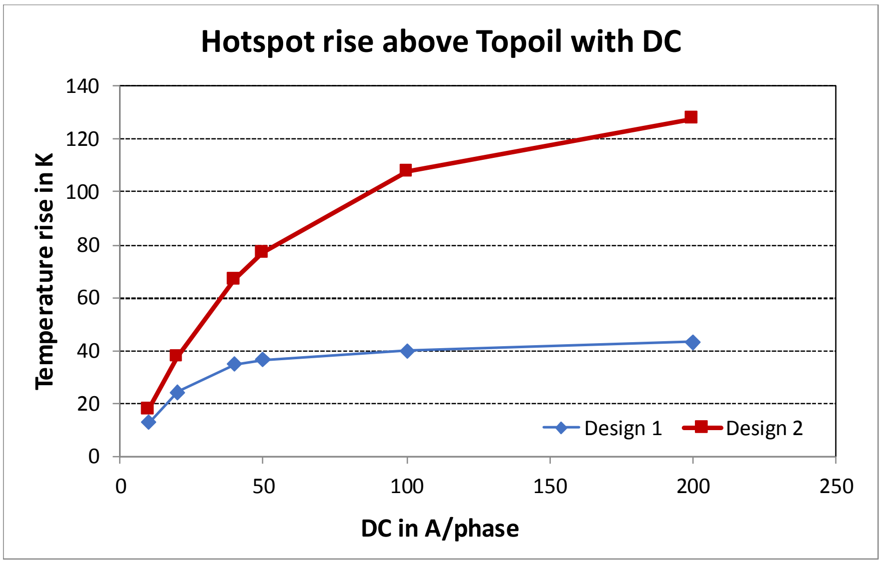


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

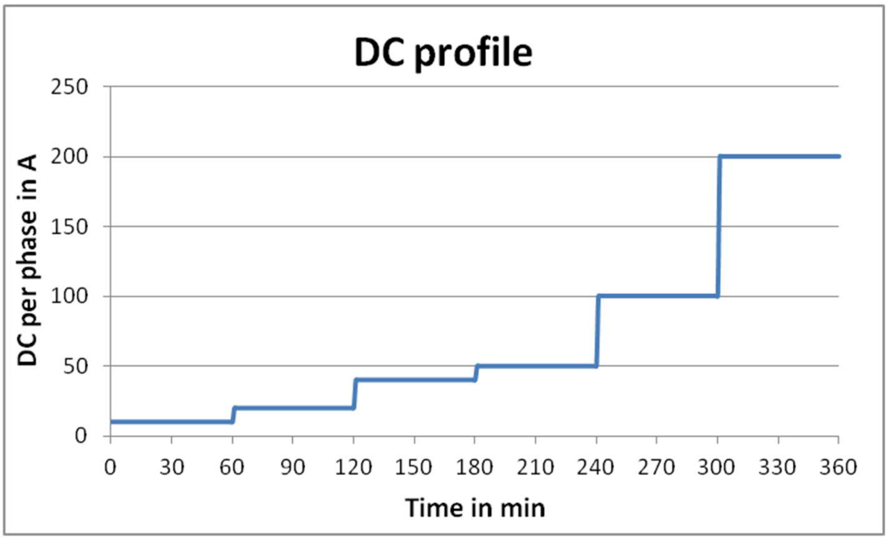


Figure 3: DC profile

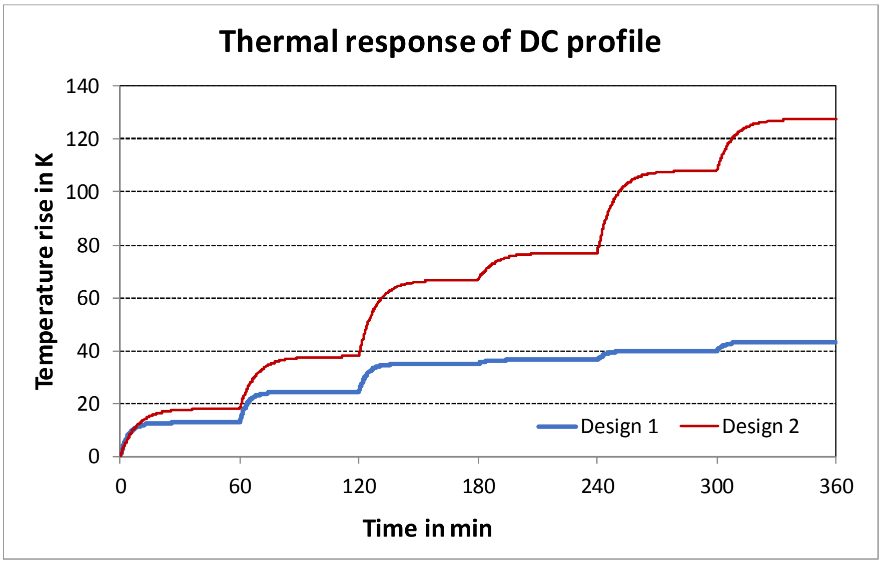


Figure 4: Thermal response of DC profile

DC Capability study – Tie bars

Transformer T42

Content

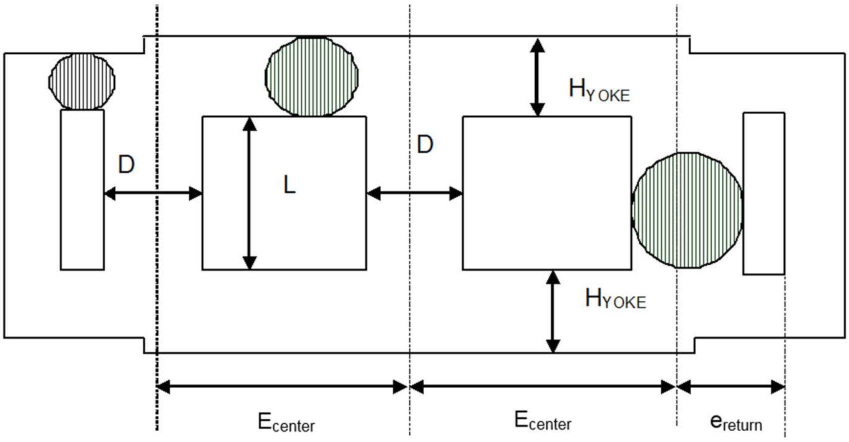
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T42
Transformer type	Auto
Rated power	560 MVA
Number of phases	3
Voltage levels	230 kV // 138 kV // 13.2 kV
Winding affected by DC	HV
Core type	5



L [mm]	2840
D [mm]	952
H yoke [mm]	540
E center [mm]	2060
A limb [m2]	0.616472
A yoke [m2]	0.350407
A return [m2]	0.309138
e return [mm]	1050

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.1466 H

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	10.9	14.5
20	20.3	30.1
40	34.0	64.7
50	36.8	77.0
100	42.2	111.6
200	44.6	139.4

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

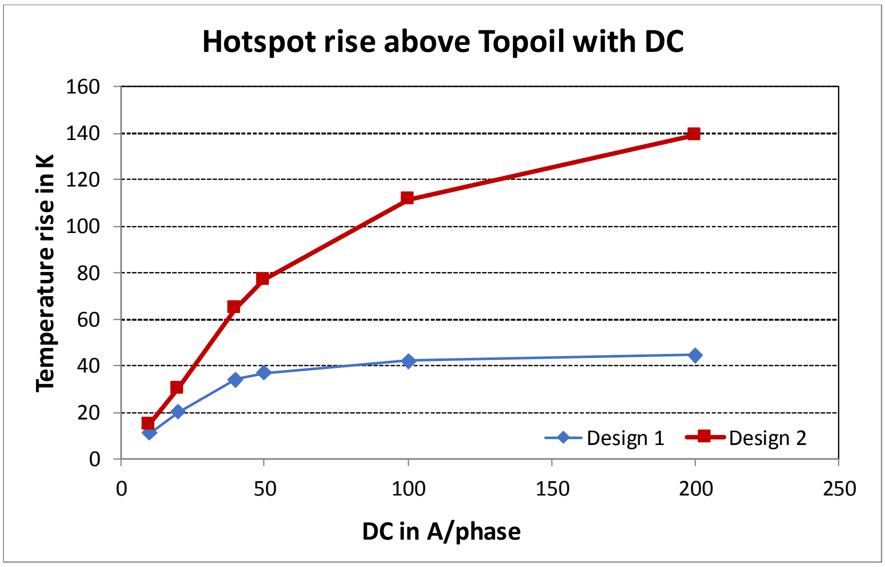


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

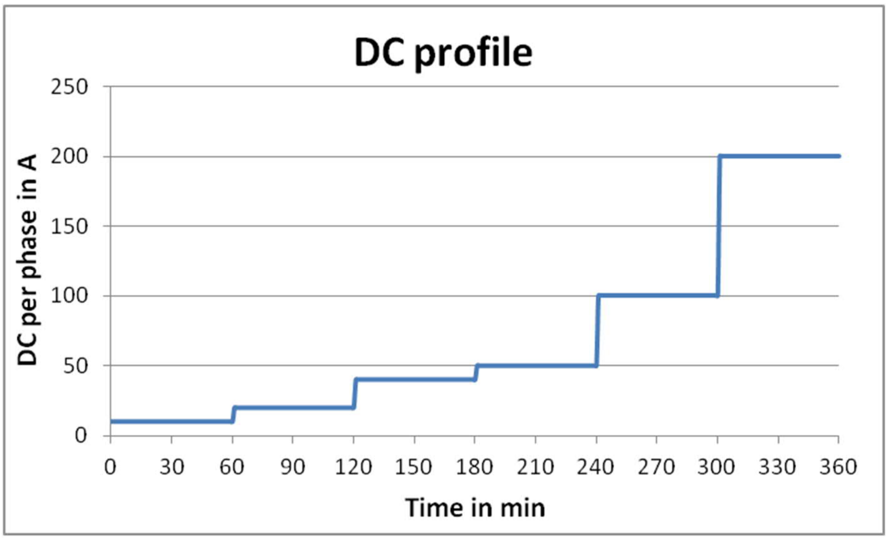


Figure 3: DC profile

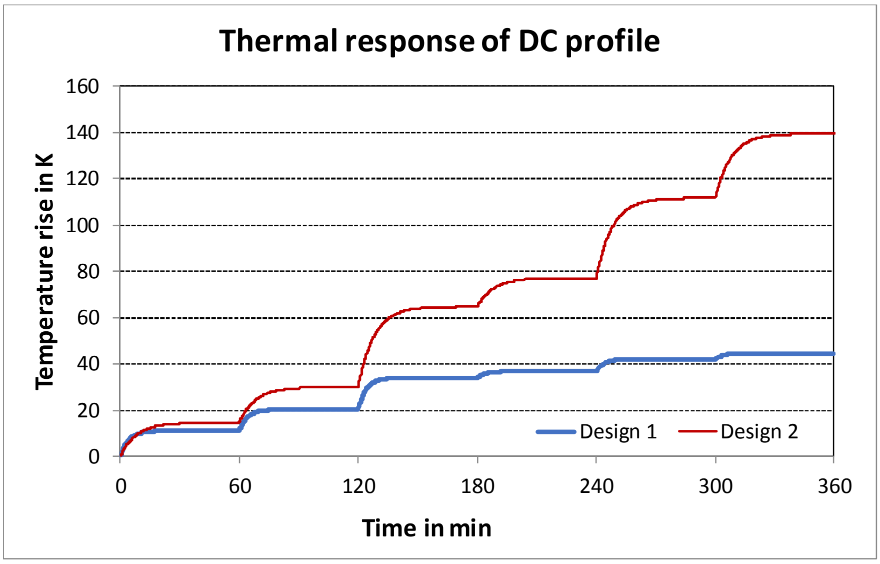


Figure 4: Thermal response of DC profile

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