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Optimization of power transformers based on operative service conditions for improved performance

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SUMMARY

Utilities are demanding nowadays that power transformers manufacturers comply with different performance and reliability requirements in order to provide a good service to electricity consumers in terms of quality of supply in addition to other requirements in line with modern society needs of environment protection.

There is an increased trend in recent years to legislate and regulate in energy efficiency, noise emissions and other environmental related aspects that are driving utilities and manufacturers to work together in different stages of the transformer life. One important goal of this collaborative effort is to achieve an optimized definition and transformer design by adapting the main requirements and specifications to the actual service conditions.

This paper presents some concepts that can be used to specify, define and optimize power transformers looking at the most common service conditions where they will spend the majority of their operative life.

The main associated advantages for the utilities are related to improved asset utilization (rationalized use of transformer materials with longer life expectancy because of a more balanced hot spot temperature across the regulating range, additional overload capabilities) , energy efficiency and environmental benefits (optimized losses with less auxiliary consumption, reduced sound levels).

Power transformers and autotransformers are typically defined and specified looking at the operative needs of a particular utility considering the adequate power rating, impedance, regulation range and using the international standards as a reference when coming to performance, tolerances, test and final acceptance.

The transformer design is optimized based on the requirements and specification (losses, operating temperatures, sound level) and considering the most restrictive operative and testing conditions (i.e.. in an extreme tap changer position, maximum ambient temperature), normally without evaluating in detail the performance at the most common service conditions.

Under this traditional approach, the transformers will spend most of their operative lives working at the typical service conditions that are different to those used for transformer optimization.

In this paper, some guidelines are presented to optimize the transformers looking at their typical working conditions exemplified with two case examples. The first one focused on the thermal balance between windings and the second related to the optimization of the cooling system and sound level, that will serve to illustrate the main advantages of the concept:

- Increased life expectancy because of a balanced hot spot in all operating conditions.
- Improved overloading capabilities.
- Reduced noise levels in typical service conditions.
- Rationalized use of transformer materials.
- Reduction of overall cooling equipment power consumption.
- Increased redundancy of cooling equipment.

KEYWORDS

Power transformer, energy efficiency, design optimization, hot spot, thermal balance, ageing, noise, ODAN, service conditions.

1. - INTRODUCTION

Power transformers and autotransformers are typically defined and specified using a conventional approach based on international standards, being the final acceptance criteria normally referred to factory test requirements as per those standards.

The transformer design based on that approach is normally optimized (i.e. total losses and operating temperatures and noise) focused mainly at the worst testing or service conditions (for example related to position of tap changer or ambient temperatures) in some cases without considering and looking in detail to the most common service conditions.

The result of this traditional approach is that some transformers could be operating most of their service life at the typical service condition, not being those for what were specifically optimized.

A design optimization of power transformers looking at the service and operative conditions, on top of complying with the requirements of the international standards, is then a useful tool for the end users to guarantee an optimum and efficient operation and an improved transformer performance.

The operational factors that are specifically considered in this study are power rating, tap changer position and cooling system operation. The main performance characteristics of the transformer considering those factors are losses, winding temperatures and hot spots and sound level. These characteristics are directly related to the transformer direct cost, the capitalized cost and the total cost of ownership and to its environmental impact.

When considering the regulating range of the transformers operating on the transmission and distribution systems, it is normally defined within ±8% and ±15%. The tap changer regulation range implies that one of the main windings will be defined for a fixed rated voltage and the other for a voltage variation from 16% to 30% in percentage.

The transformer nominal rated power is normally applicable in all the regulating range with no power decrease between the different positions. The transformer will be then optimised for the worst loading condition, which is normally one of the extreme tap changer position (usually the minimum voltage position associated to higher current rating). In this worst loading condition, the transformer will have the highest losses, hot spot temperatures and sound level and the design considerations will be limited by that.

If the most typical operating condition is close to the central tap or other tap position, meaning that the transformer will spend most of the time in other positions than the extremes, different from the optimum design condition, that will imply:

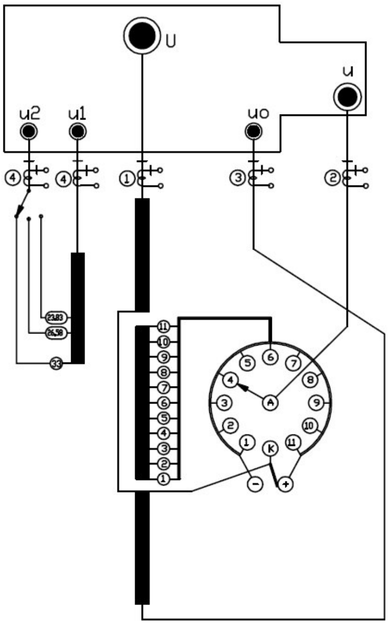
- → Higher losses per unit copper weight (higher losses (kW per kg), not rationalising the transformer use of materials.
- → Unbalanced operating temperatures between windings and different thermal ageing between them.
- → Non optimized sound level and auxiliary power consumption.

This paper presents two case examples of service condition optimized solutions considering the typical tap changer operating range, the load profiles, overload requirements and expected performance of the transformer from the user perspective.

2. – CASE I: THERMAL BALANCE OPTIMIZATION

An evaluation of the transformers thermal balance across all regulation range to optimize the design is presented applied to a 600MVA, 400/230kV standardized transformer of the Spanish HV transmission system owned by REE (Red Eléctrica de España is also the system operator of the Spanish high voltage system).

The units are single phase autotransformers rated 200 MVA, 50Hz, with on load tap changer regulation located in line of the low voltage side meaning a constant flux regulation design. The regulating range is ±15% with all taps having the nominal rating of 200MVA.



VOLTAGE & CURRENT RATING								
HIGH VOLTAGE 200MVA		LOW VOLTAGE 200 MVA TAP CHANGER Nº. ??????					TERTIARY 40 MVA	
NOMINAL VOLTAGE VOLTS	NOMINAL CURRENT AMPS	TAP POSITION	TAP SELECTOR	DIVERTER SWITCH	NOMINAL VOLTAGE VOLTS	NOMINAL CURRENT AMPS	NOMINAL VOLTAGE VOLTS	NOMINAL CURRENT AMPS
230940	866	21	11	–	152709	1310	33000	1212
		20	10	–	150717	1327		
		19	9	–	148725	1345		
		18	8	–	146734	1363		
		17	7	–	144742	1382		
		16	6	–	142750	1401		
		15	5	–	140758	1421		
		14	4	–	138766	1441		
		13	3	–	136774	1462	26580	1505
		12	2	–	134782	1484		
		11c	1	–	132791	1506		
		11b	K	– +	132791	1506		
		11a	11	+	132791	1506		
		10	10	+	130799	1529		
		9	9	+	128807	1553		
		8	8	+	126815	1577	23830	1679
		7	7	+	124823	1602		
		6	6	+	122831	1628		
		5	5	+	120839	1655		
		4	4	+	118848	1683		
		3	3	+	116856	1702		
		2	2	+	114864	1741		
		1	1	+	112872	1772		

Figure 1 : Name plate for CASE 1 autotransformer

Those transformers are specified to comply with IEC standards. Therefore, the operating temperature limits (hot spot, average winding and top oil) and the design are conditioned and limited considering the maximum losses condition, that will be the operating position for the heat run test.

This assumption is the worst condition, but not the typical working condition of this kind of unit (the testing condition is the minimum voltage tap and the typical working position is the central position of the regulating range).

The result of thermally optimizing the transformer for the testing condition from a theoretical approach implies that:

- → In the non regulating winding: The hot spot temperature rise is constant along the regulating range and is optimized to the maximum admissible value.
- → In the regulated winding: The hot spot temperature rise is not constant along the regulating range and is optimized at the maximum losses position for the maximum admissible value.

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The following figure illustrates this traditional design optimization presenting the hot spot temperature rise over the ambient and the hot spot gradient over the top oil temperature for the HV (common) and LV (series) windings in the subject transformer across all the regulating range:

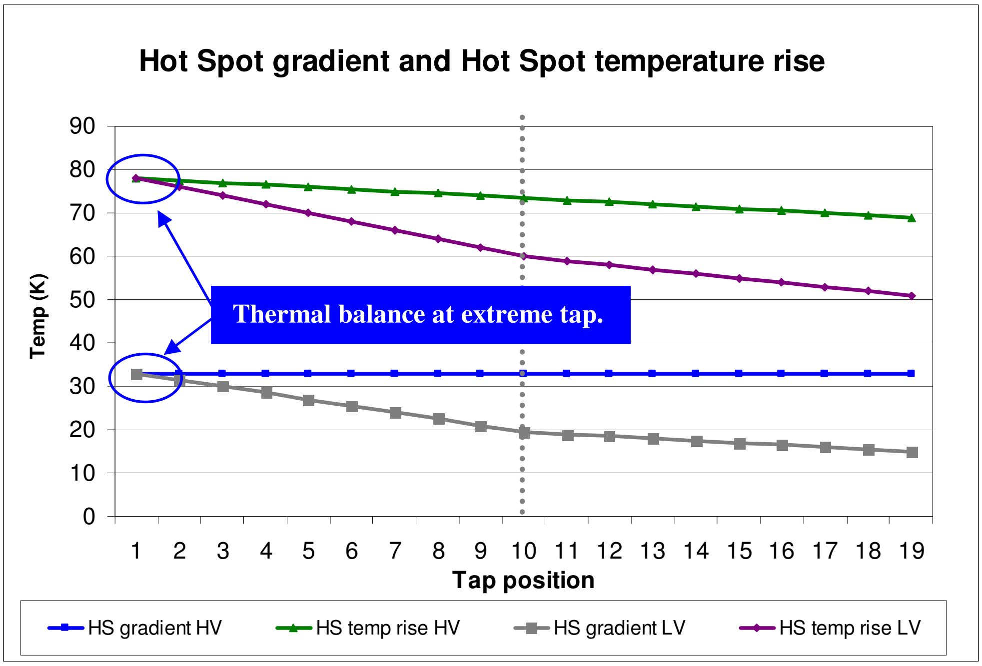

Figure 2 : Hot spot calculated in HV and LV winding.

The figure 2 illustrates that balance between the hot spots of the two main windings in the testing condition, which is the extreme tap, where the transformer has the maximum losses.

This traditional design approach optimizes the transformer from the point of view of the heat run test condition. One consequence is that the temperature between windings and their associated ageing will differ (since is only equivalent at the extreme tap position). The ageing of both windings will be not balanced since the typical working position is closer to the central tap position.

At the central tap position, there is a difference of 15K between hot spots that provides four times difference in the windings ageing (IEC 60076-7, thermally upgraded paper), meaning that for a unitary ageing of the non regulated winding, the regulated winding ageing per unit is 0.25.

Different assumptions about tap changer operating positions and relative loads have been evaluated looking at different working conditions of the autotransformers.

Three different assumptions have been considered to establish interesting scenarios and exemplify the case, changing the time spent at each tap position (time distribution) and the load profile (load distribution):

→ **Assumption #1:**
- Time distribution in each different tap: Uniform.
- Load distribution: Uniform (100% in all the taps).

→ **Assumption #2:**
- Time distribution in each different tap: Close to a Gauss distribution centred in central tap.
- Load distribution: Uniform distribution (100% in all the taps).

→ **Assumption #3:**
- Time distribution in each different tap: Close to a Gauss distribution centred in central tap.
- Load distribution: close to a Gauss distribution centred in central tap.

Figure 3 represents the product of the time and load distributions at the different tap positions for the above mentioned assumptions.

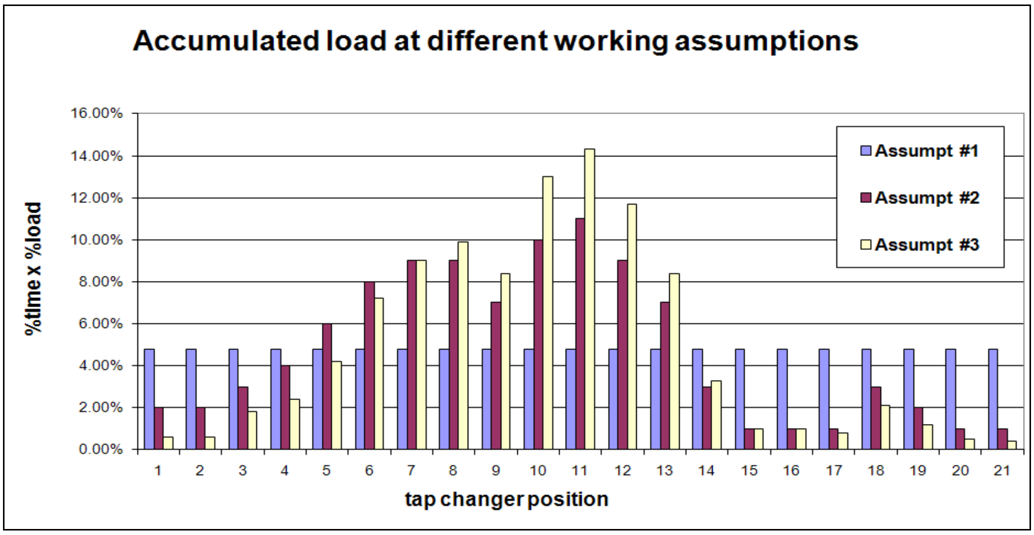

Figure 3 : Compared accumulated load at different service assumptions.

The accumulated load mentioned in Figure 3 has been determined as the product or the integral of the load and time distribution in different tap positions.

Three different transformer designs have been optimized considering the following three concepts:

→ **Design Concept #1:**
- Thermal balance at the heat run test tap changer position (extreme tap).
- Hot spot temperature rise limited to 78K at the heat run test condition in HV and LV windings, according to IEC standards.

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→ **Design Concept #2:**

- Thermal balance at service conditions (central tap).
- Hot spot temperature rise limited to 78K at the testing conditions in HV and LV windings, according to IEC standards.

→ **Design Concept #3:**

- Thermal balance at service condition (central tap).
- Hot spot temperature rise limited to 78K at the central tap, with an overall loss of life of 1 or less for the load profile, according IEC standards.

To illustrate the three design concepts, figures 4, 5 and 6 show the hot spot temperature rises for the main windings (HV and LV) in all the range of tap changer positions and rated power following the three different designs criteria:

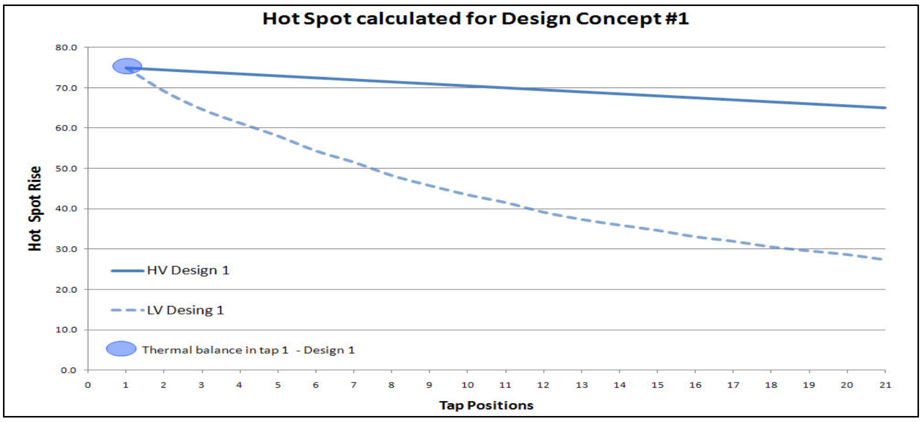


Figure 4 : Design Concept #1 Hot Spot temperature rise

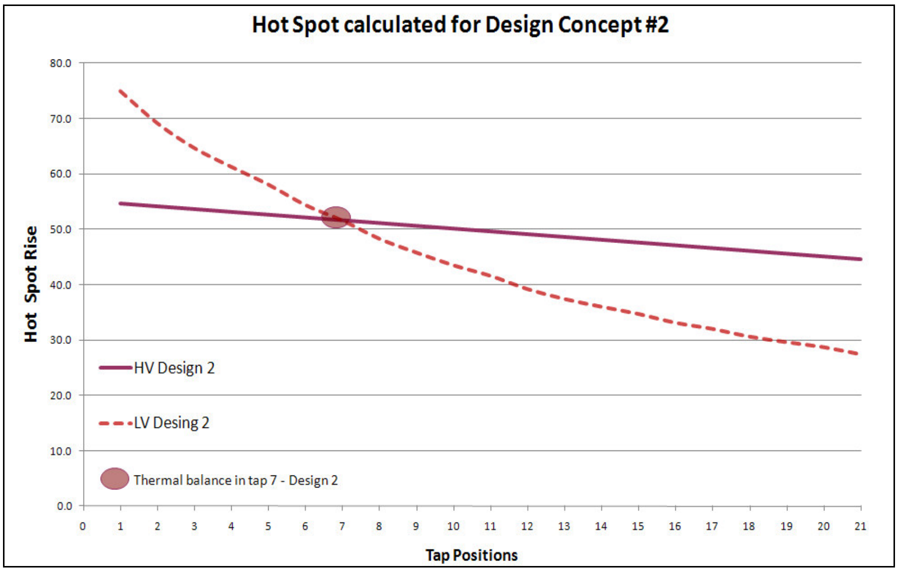


Figure 5 : Design Concept #2 Hot Spot temperature rise

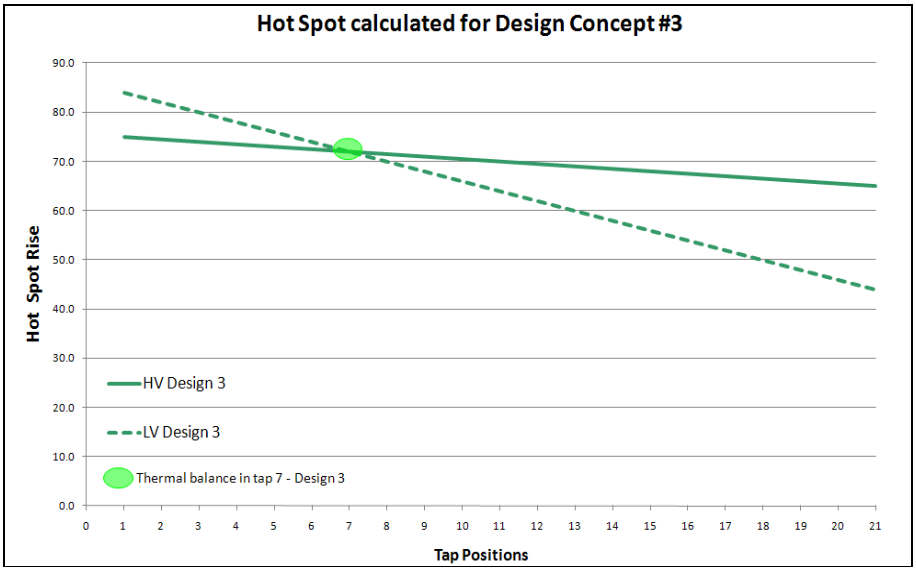


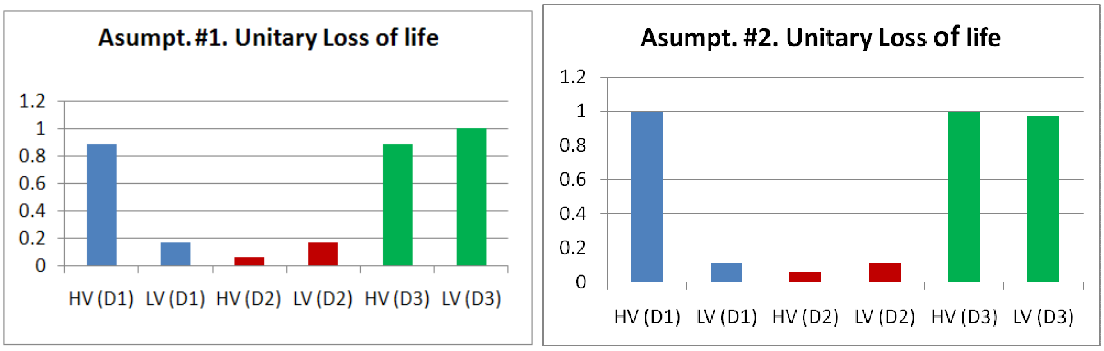
Figure 6 : Design Concept #3 Hot Spot temperature rise

The impact of these three different design concepts in the weights and performance characteristics referred to the unit with the lowest weight is the following:

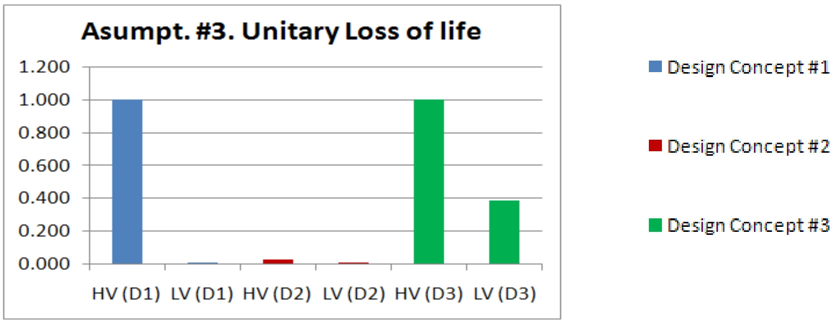
	Core (kg)	No-load losses (kW)	Cu (kg)	Load losses (kW)
Design 1	102%	52,7	113%	234,2
Design 2	106%	55,2	132%	205,9
Design 3	100%	51,8	100%	267,6

Table 1 : Design Concept performance data

The differences between the three different optimized designs from the thermal perspective can be evaluated calculating their loss of life following IEC standards. Figures 7.1, 7.2 and 7.3 present the calculated loss of life for the HV (series) and LV (common) windings in the three designs in per unit referred to the highest loss of life in the three service condition (loading-tap changer profile) assumptions.



Figures 7.1-7.2-7.3 : Unitary loss of life in service in the three service assumptions



Figures 7.1-7.2-7.3 : Unitary loss of life in service in the three service assumptions

An analysis of the compared unitary loss of life for the three different design concepts under the three different service assumptions is presented below:

Service assumption #1:

1. In the cases where the thermal balance is optimized for the central tap (#2 and #3) the loss of life is driven by the regulated winding (the LV, common winding).

2. In the design case #1 balanced at the extreme tap position, the loss of life is driven by the non regulated winding, so it is not related to the operation of the unit and only depends on the load.

3. The ratios for the loss of life between windings in the three cases are:

Case #1	5.3
Case #2	0.4
Case# 3	0.9

There is a clear improvement in the loss of life when a thermal balance between windings is applied closer to the central tap.

4. The design of the regulated winding in concepts #1 and #2 is the same, meaning that the loss of life is the same for the regulated windings in both cases. Due to their different thermal performance of the non regulated winding, the loss of life is driven in a more efficient way in concept #2.

5. In absolute terms, the design concept #2 provides a tremendous improvement in terms of loss of life. This is normal because of having lower temperatures, lower losses and more material. When comparing the loss of life between design concepts #1 and #3, they have similar loss of life ratios although the losses and temperatures are significantly higher in case #3, implying a clear advantage associated to having thermally balanced windings looking at the service conditions.

Service assumption #2:

The ratios for the loss of life between windings in the three cases are:

Case #1	8.9
Case #2	0.6
Case# 3	1.0

There is a clear improvement of the loss of life when the thermal balance is applied and optimized closer to the central tap.

Service assumption #3:

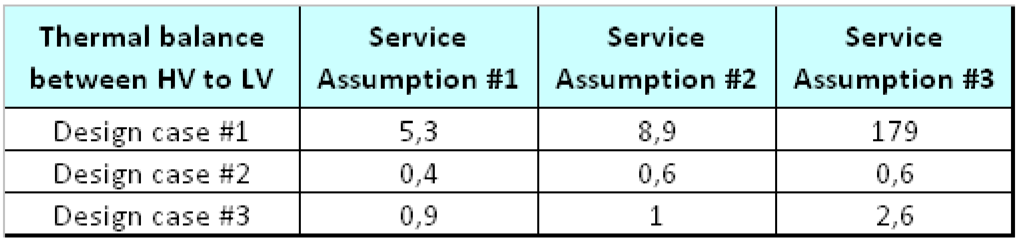
The loss of life in the three design cases is driven by the non regulated winding (HV, series winding). The ratios of the loss of life between windings in the three cases are extremely uncompensated, specially for design case #1 based in the thermal balance focus at the testing condition.

Case #1	179
Case #2	4.5
Case# 3	2.5

There is a clear improvement in the balance between the loss of life of the windings when the thermal optimization is applied closer to the central tap.

The main conclusions after the analysis of the three cases are:

The transformer with a thermally balanced design concept at the central tap (the most common operating condition) has a much better balanced ageing between windings compared to a thermal balance at the extreme tap.



Thermal balance between HV to LV	Service Assumption #1	Service Assumption #2	Service Assumption #3
Design case #1	5,3	8,9	179
Design case #2	0,4	0,6	0,6
Design case #3	0,9	1	2,6

Table 2 : Thermal balance ratio between windings (regulated – non regulated)

Table 2 presents the thermal balance between windings calculated for the three design concepts at the different service assumptions. The figures are the ratio between the unit loss of life of each winding.

A design optimization strategy based on a thermal balance at the central taps (or those taps where the transformer is normally operated) meaning a more balanced ageing between windings provides a better rationalization of the use of the transformer materials.

Table 3 presents the relative loss of life in per unit per row , the lower the value the lower the loss of life and the higher the life expectancy (the case with relative loss of life 1 per row is the one having the shortest life expectancy).

Table 4 evaluates the efficiency of the material use compared to the life expectancy by presenting the ratio between the unitary loss of life of table 3 and the amount of material used in each case.

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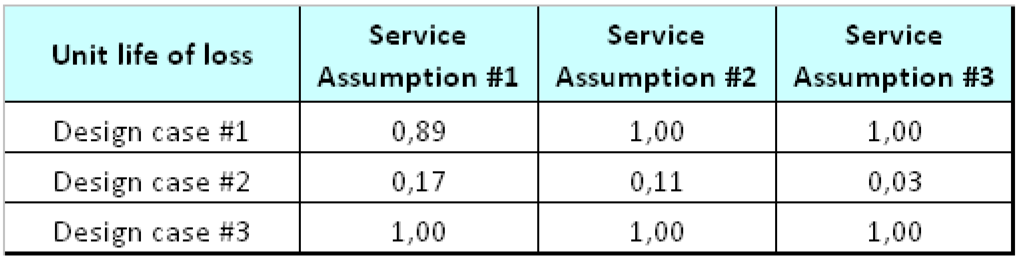
Looking to both tables (3 and 4) the following conclusions are observed:

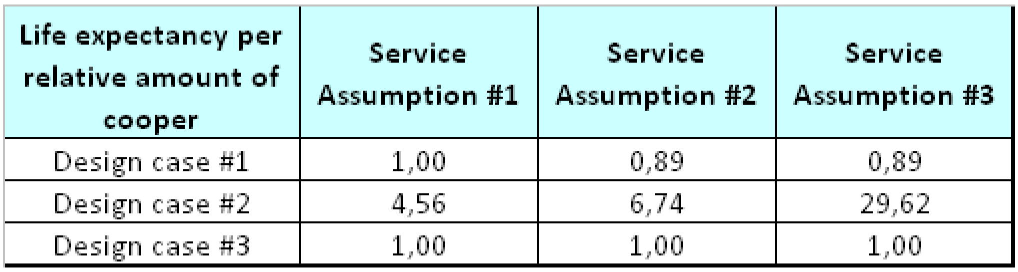
- Comparing design cases #1 to #3 we obtain a similar life expectancy with a reduction of material of 13% in design case #.3 where the thermal balance has been applied. Also load losses are reduced in 23%, which means a decrease in the transformer capitalized cost.

- In the same way, comparing design cases #1 to #2 an increase of material of 15% provides an improvement in life expectancy of 9.5 times, taking the average of the three service assumptions.



Unit life of loss	Service Assumption #1	Service Assumption #2	Service Assumption #3
Design case #1	0,89	1,00	1,00
Design case #2	0,17	0,11	0,03
Design case #3	1,00	1,00	1,00

Table 3 : Unitary loss of life



Life expectancy per relative amount of cooper	Service Assumption #1	Service Assumption #2	Service Assumption #3
Design case #1	1,00	0,89	0,89
Design case #2	4,56	6,74	29,62
Design case #3	1,00	1,00	1,00

Table 4 : Life expectancy per relative amount of copper

The main advantages of the presented design optimization based on an overall thermal balance at the typical service conditions are:
- Rationalized use of transformer materials.
- Increased life expectancy because of a balanced hot spot in all operating conditions.
- Improved overloading capabilities.

The thermal balance concept can be used to reduce the total owning cost of the transformer taking advantage of a design optimization looking at the actual operative conditions (load profile, tap changer operating positions...etc.).

This thermal balance optimization can be used to rationalize the transformer use of materials by equalizing the operating temperatures between the windings across all the regulating range.

This can be achieved either by:
- Increasing the expected life expectancy of the transformer, with higher overall weight and reducing the losses: This improves the asset utilization, lowering the total owning cost because of the lower losses and the longer life.
- Maintaining the same level of life expectancy using less amount of materials with higher losses: This reduces the transformer first cost, depending the total ownership cost on the losses capitalization.

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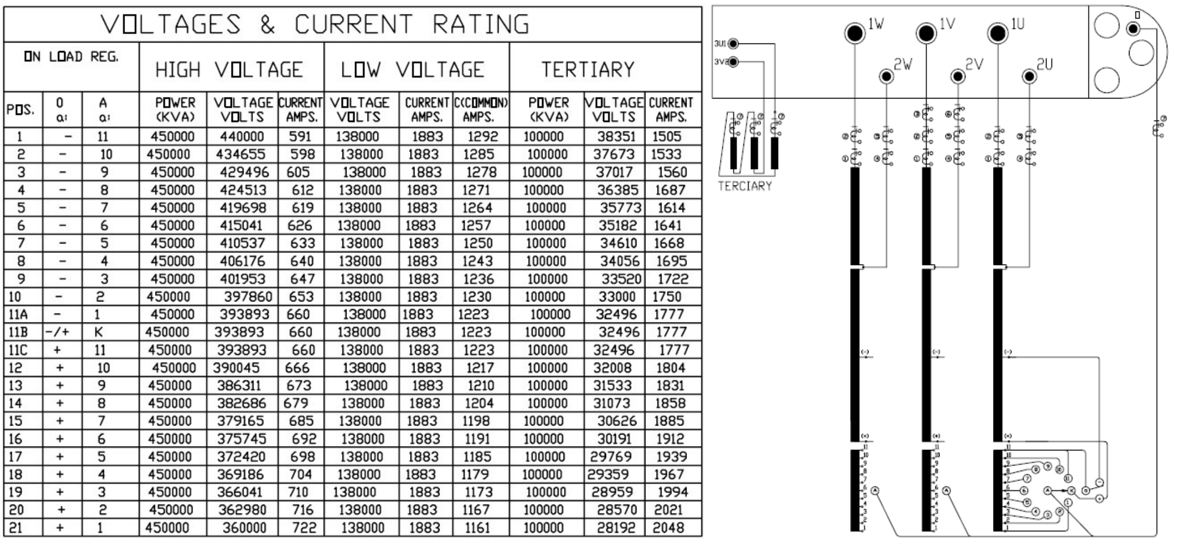
3. – CASE II: OPTIMIZATION OF NOISE EMISSION

This second case example is an evaluation of the transformer optimum cooling equipment performance to achieve suitable levels of noise according to the user specifications.

This case is based on a three phase autotransformer 450 MVA, 400/138 kV 50 Hz with ±10% in the HV side achieved with variable flux regulation. This autotransformer is owned by Iberdrola and installed close to a large urban area, requiring a low noise performance.



VOLTAGES & CURRENT RATING

ON LOAD REG.			HIGH VOLTAGE			LOW VOLTAGE			TERTIARY		
POS.	0 a:	A a:	POWER (KVA)	VOLTAGE VOLTS	CURRENT AMPS.	VOLTAGE VOLTS	CURRENT AMPS.	C(COMMON) AMPS.	POWER (KVA)	VOLTAGE VOLTS	CURRENT AMPS.
1	–	11	450000	440000	591	138000	1883	1292	100000	38351	1505
2	–	10	450000	434655	598	138000	1883	1285	100000	37673	1533
3	–	9	450000	429496	605	138000	1883	1278	100000	37017	1560
4	–	8	450000	424513	612	138000	1883	1271	100000	36385	1687
5	–	7	450000	419698	619	138000	1883	1264	100000	35773	1614
6	–	6	450000	415041	626	138000	1883	1257	100000	35182	1641
7	–	5	450000	410537	633	138000	1883	1250	100000	34610	1668
8	–	4	450000	406176	640	138000	1883	1243	100000	34056	1695
9	–	3	450000	401953	647	138000	1883	1236	100000	33520	1722
10	–	2	450000	397860	653	138000	1883	1230	100000	33000	1750
11A	–	1	450000	393893	660	138000	1883	1223	100000	32496	1777
11B	–/+	K	450000	393893	660	138000	1883	1223	100000	32496	1777
11C	+	11	450000	393893	660	138000	1883	1223	100000	32496	1777
12	+	10	450000	390045	666	138000	1883	1217	100000	32008	1804
13	+	9	450000	386311	673	138000	1883	1210	100000	31533	1831
14	+	8	450000	382686	679	138000	1883	1204	100000	31073	1858
15	+	7	450000	379165	685	138000	1883	1198	100000	30626	1885
16	+	6	450000	375745	692	138000	1883	1191	100000	30191	1912
17	+	5	450000	372420	698	138000	1883	1185	100000	29769	1939
18	+	4	450000	369186	704	138000	1883	1179	100000	29359	1967
19	+	3	450000	366041	710	138000	1883	1173	100000	28959	1994
20	+	2	450000	362980	716	138000	1883	1167	100000	28570	2021
21	+	1	450000	360000	722	138000	1883	1161	100000	28192	2048

Figure 8 : Name plate for CASE II autotransformer

Nowadays, an increasing number of transformers require low sound levels to minimise the noise impact and to meet local regulations.

The main sources of noise in a transformer are the core, the windings and the cooling equipment. The noise coming from core and windings is mainly related with the core induction and geometrical aspects of the core and windings (the major driver of the noise produced in the active part (core and windings) is associated to)the core induction. The other main source of noise is the cooling equipment and is produced by the air fans and oil pumps (being the noise coming from the air fans several times higher than the noise from the pumps).

Conventionally the cooling system is designed with different stages dependant on the load, namely:

ONAN	Oil Natural Air Natural
ONAF	Oil Natural Air Forced
OFAF	Oil Forced Air Forced
ODAF	Oil Forced and Directed Air Forced
ODAN	Oil Forced and Directed Air Natural

This case example will illustrate how to achieve a required sound level by using an optimal and efficient cooling equipment configuration having negligible differences in terms of transformer cost, dimensions or weights.

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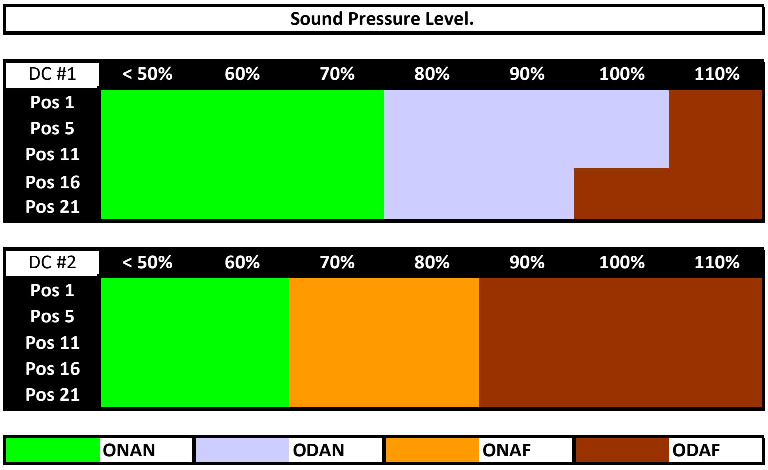
Two design approach examples have been evaluated:

- Design Concept #1: Optimized design introducing an ODAN stage, looking at specific performance depending on the tap position (the transformer is designed to provide 100% of load in the central tap within the ODAN stage)
    - Cooling Stages:
        - 1st stage: ONAN, 70% of the load.
        - 2nd stage: ODAN, 90% of the load (100% at the central tap).
        - 3rd stage ODAF, 100% of the load.
- Design Concept #2: Conventional design approach in terms of cooling equipment.
    - Cooling Stages:
        - 1st stage: 60% of the load ONAN cooled.
        - 2nd stage: 80% of the load ONAFcooled.
        - 3rd stage 100% of the load ODAF cooled.

The following mapping is showing the sequence of each cooling stage as a function of the tap position and load for the two cases:



Sound Pressure Level.

DC #1	< 50%	60%	70%	80%	90%	100%	110%
Pos 1	🟩	🟩	🟩	🟪	🟪	🟪	🟫
Pos 5	🟩	🟩	🟩	🟪	🟪	🟪	🟫
Pos 11	🟩	🟩	🟩	🟪	🟪	🟪	🟫
Pos 16	🟩	🟩	🟩	🟪	🟪	🟫	🟫
Pos 21	🟩	🟩	🟩	🟪	🟪	🟫	🟫

DC #2	< 50%	60%	70%	80%	90%	100%	110%
Pos 1	🟩	🟩	🟧	🟧	🟫	🟫	🟫
Pos 5	🟩	🟩	🟧	🟧	🟫	🟫	🟫
Pos 11	🟩	🟩	🟧	🟧	🟫	🟫	🟫
Pos 16	🟩	🟩	🟧	🟧	🟫	🟫	🟫
Pos 21	🟩	🟩	🟧	🟧	🟫	🟫	🟫

🟩 ONAN 🟪 ODAN 🟧 ONAF 🟫 ODAF

Table 5 : Cooling Stages distribution per Design Concept

The next step of the evaluation includes a calculation and analysis of the sound level of both designs in different conditions considering the effect of the load and the tap position (maximum, nominal and minimum).

Figure 9 shows three graphs representing the noise level at different loading at different tap positions. The noise level is represented by the covered areas implying that the differences in area are differences in sound level.

Figure 9.1: The noise level is slightly lower in case #1 up to 90% of the load. In average, the design case #1 has 4 dB lower noise that is a 6.1% noise reduction. The largest difference is at 70% load with 11.5 dB.

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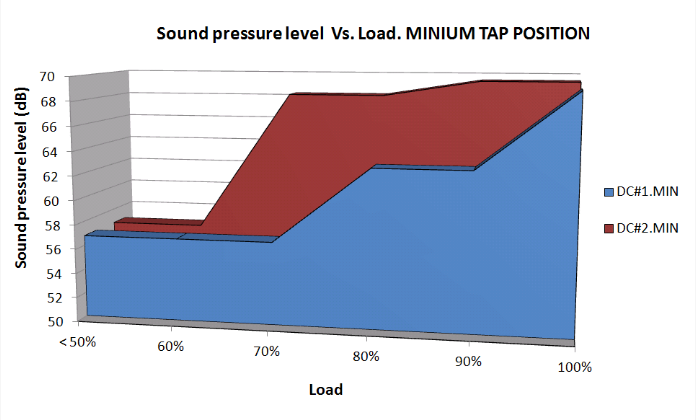

Figure 9-1: Sound level distribution at different loads in minimum tap position

Figure 9.2: The noise level is slightly lower in case #1 at all the range above 60% load. In average, the design case #1 has 4.4 dB lower noise that is a 6.6% noise reduction. The largest difference is at 70% load with 8.3 dB.

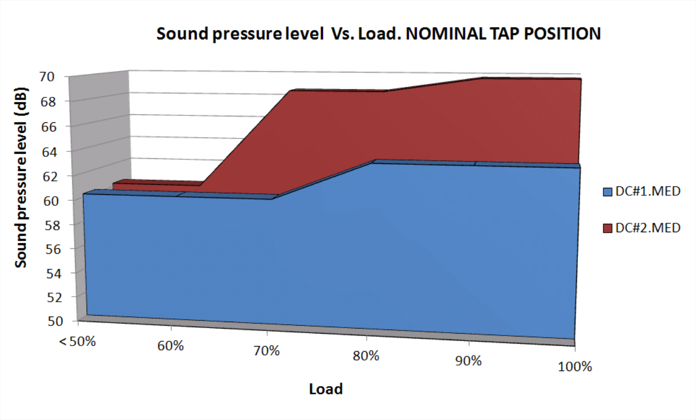

Figure 9-2: Sound level distribution at different loads in medium tap position

Figure 9.3: The difference is negligible due to the fact that the noise from the core is dominant at that tap position, so in this extreme condition there is no impact between the different cooling strategies.

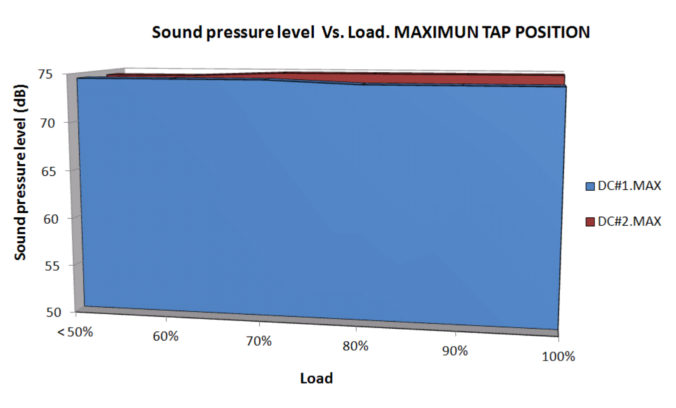

Figure 9-3: Sound level distribution at different loads in maximum tap position

The advantage of using the ODAN concept of case #1 to reduce noise in power transformers is illustrated in figures 9-1, 9-2 and 9-3,

An analysis of the maximum power output of each design concept can provide to achieve 65dB of sound level at the nominal position of the tap changer is presented in figure 10.

The ODAN concept #1 provides an additional 45% more output power (average) within the limit of 65 dB because the transformer can be operated without fans (as the main sound level contributor) in more than half of the tap changer positions.

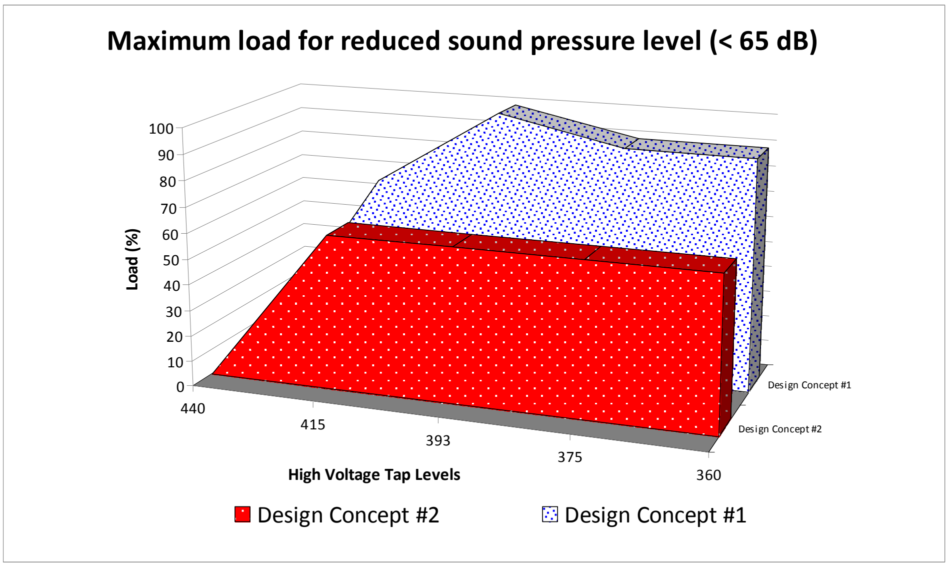

Figure 10 : Maximum power output at 65dB per Design Concept.

The main advantages of a transformer cooling arrangement with an ODAN cooling stage defined to dissipate the total losses at full load in the nominal tap are:

- The sound level at the nominal tap position is reduced by 4.4 dB (average) with a maximum reduction up to 8 dB at different loads.

- The differences in cost, weights or dimensions associated to the use of an intermediate ODAN stage solution compared to the traditional approach with intermediate stage ONAF are negligible.

- An intermediate ODAN solution provides a more rational use of the cooling equipment, reducing the noise emissions without additional material expense.

- This solution can be also enhanced in combination with direct hot spot measurements to manage the cooling equipment providing a more rationalized use of pumps and fans, additional noise reduction and reduced auxiliary losses.

CONCLUSIONS

This paper has presented some concepts that can be used to specify, define and optimize power transformers looking at the most common service conditions where they will spend the majority of their operative life.

The main associated advantages for the utilities are related to improved asset utilization (rationalized use of transformer materials with longer life expectancy because of a more balanced hot spot temperature across the regulating range, additional overload capabilities) , energy efficiency and environmental benefits (optimized losses with less auxiliary consumption, reduced sound levels).

Two case examples have been presented to illustrate the main advantages of optimizing the transformers looking at their typical working conditions. The first one is focused on the thermal balance between windings and the second is related to the optimization of the cooling system and sound level:

- Overall thermal balance between windings:

  The main advantages of a transformer design optimization considering an overall thermal balance between windings at the typical service conditions are:
  - Rationalized use of transformer materials.
  - Increased life expectancy because of a balanced hot spot in all operating conditions.
  - Improved overloading capabilities.

  The presented thermal balance concept can be used to reduce the total owning cost of the transformer taking advantage of a design optimization looking at the actual operative conditions (load profile, tap changer operating positions, etc…).

  The thermal balance optimization can be used to rationalize the transformer materials by equalizing the operating temperatures between the windings across all the regulating range.

  This can be achieved either:
  - Increasing the life expectancy of the transformer, with higher overall weight and reducing the losses: This improves the asset utilization, lowering the total owning cost because of the lower losses and the longer life.
  - Maintaining the same level of life expectancy using less amount of materials with higher losses: This reduces the transformer first cost, depending the total ownership cost on the losses capitalization.

- Optimization of the cooling system and sound level:

  The main advantages of a design optimization considering an alternative cooling strategy based in the typical service conditions, with an ODAN cooling stage defined to dissipate the total losses at full load in the nominal tap are:
  - Reduced average noise emission.
  - Reduced cooling equipment consumption.

Both examples illustrate the importance of the collaboration between utilities and transformer manufacturers. A collaborative effort to specify the requirements and to optimize the transformer design based on the service conditions is the key to provide improved performance characteristics and a reduced environmental impact.

BIBLIOGRAPHY

[1] IEC 60076-2. "Temperature rise for liquid immersed transformer" (Third Edition 2010-10).

[2] IEC 60076-7. "Loading guide for oil-immersed power transformers" (First Edition 2005-12).

[3] ANSI - IEEE C57.12.00.2006. "IEEE Standard for Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers" (Revision of IEEE Std 57.12.00-1999)