Health indexes for power transformers: A case study

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Summary

It seems essential that a health index for a power transformer should take into account the age of the transformer and its loading in service.

1. Introduction

Proper operation of power transformers is critical to ensuring transmission and distribution of electrical power. Most transformers have an electrical insulation system based on oil and paper. The state of the insulation system is the major factor influencing the state of the transformer.

During service the dielectric materials within the transformer deteriorate, and small concentrations of impurities such as water, carbon monoxide, carbon dioxide and furan compounds accumulate in the oil. Since it is easy to obtain oil samples from power transformers, the information most commonly collected by transformer fleet managers relates to the physical and dielectric properties of the oil. These properties include dielectric strength, dissipation factor, color and interfacial tension, and concentrations of dissolved gases, furans, acids and moisture.

Using these properties it is possible to determine whether a transformer has developed certain specific faults, e.g., partial discharges, arcing, sparking, overheating, etc. On the other hand, various health indexes have been proposed in order to characterize the general condition of a transformer [1] - [3]. The factors taken into account in these indexes by these indicators vary, and are given different statistical weightings depending on their influence on the general condition of the transformer.

In this article we evaluate the condition of a fleet of operating power transformers, using two recently-proposed health indexes, and compare the results.

2. Transformers fleet

The fleet consisted of 52 industrial transformers whose insulation systems consisted of Kraft paper and mineral oil. The power range of the transformers was 1.6 - 135 MVA, and the voltage range was 12 - 220 kV. The most common cooling systems were ONAN, ONAF and OFWF. They were divided into five main groups, with average years-in-service of 10, 20, 30, 40 and 50 years. The transformers came from three different manufacturers.

3. Experimental

The physical properties of the oil in the transformers were measured periodically, in accordance with the following standards: water content (IEC 60814), dielectric strength (IEC 60156), color (ASTM D1500), interfacial tension (ASTM D971-12) acidity (ASTM D-664) and dielectric loss (IEC 61620). The concentrations of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4) and acetylene (C_2H_2) accumulating in the oil were also measured periodically, in accordance with IEC 60567. (The interpretation of these concentrations and the ratios of the concentrations of certain pairs of gases are given in IEC 60599). The concentrations of furan compounds in the oil were also measured periodically, in accordance with IEC 61198.

4. Health index analysis

As stated above, a single health index can be used to characterize the overall condition of a power transformer. Many health indexes have been proposed by different authors [1]-[8]. Some of these indexes use subjective parameters, e.g., tank corrosion, cooling equipment, connectors, and protection equipment, which are difficult to evaluate. However, two health indexes based on the values of clearly defined quantities, routinely measured by power transformer owners, have recently been proposed [7], [8]. The main difference between them is that only one [8] considers the real age and the load regime of the transformer. The aim of the present work was to determine which of the two indexes studied provided the more accurate measure of transformer overall condition.

4.1 Health index 1 [7]

The first health index, I_1, takes into account three health subindexes corresponding to oil quality [7]. These are:
(1) $I_1(1)$, based on dielectric strength, dissipation factor, acidity, moisture, color and interfacial tension of the oil.
(2) $I_1(2)$, based on dissolved gas content of the oil.
(3) $I_1(3)$, based on furans content of the oil.

Subindex $I_1(1)$ can have values 0, 1, 2, 3 and 4, depending on the condition of the oil, as shown in Table 1. The corresponding data for subindex $I_1(2)$ are identical to those shown in Table 1.

Table 1. Subindex $I_1(1)$ of oil condition (based on [7]).

State	Range	$I_1(1)$
Very good	$HI_1(1) < 1.2$	4
Good	$1.2 \le HI_1(1) < 1.5$	3
Regular	$1.5 \le HI_1(1) < 2$	2
Bad	$2 \le HI_1(1) < 3$	1
Very bad	$HI_1(1) \ge 3$	0

The factor $HI_1(1)$ in Table 1 is defined as:

$$HI_1(1) = \frac{\sum_{j=1}^{6} s_j \cdot w_j}{\sum_{j=1}^{6} w_j} \quad [1]$$

where the summation is over the six physical and dielectric properties of the oil. The scores s_j and weights w_j are given in Table 2.

Table 2. Scores (s_j) and weights (w_j) for the six physical and dielectric properties of the oil (based on [7]).

	U ≤ 69 kV	69 kV < U < 230 kV	U ≥ 230 kV	s_j	w_j
Dielectric strength [kV]*	≥ 45	≥ 52	≥ 60	1	3
	35 – 45	47 – 52	50 – 60	2	
	30 – 35	35 – 47	40 – 50	3	
	≤ 30	≤ 35	≤ 40	4	
Interfacial tension [mN/m]	≥ 25	≥ 30	≥ 32	1	2
	20 – 25	23 – 30	25 – 32	2	
	15 – 20	18 – 23	20 – 25	3	
	≤ 15	≤ 18	≤ 20	4	
Acidity [mg KOH/g]	≤ 0.05	≤ 0.04	≤ 0.03	1	1
	0.05 – 0.1	0.04 – 0.1	0.03 – 0.07	2	
	0.1 – 0.2	0.1 – 0.15	0.07 – 0.1	3	
	≥ 0.2	≥ 0.15	≥ 0.1	4	
Moisture [ppm]	≤ 30	≤ 20	≤ 15	1	4
	30 – 35	20 – 25	15 – 20	2	
	35 – 40	25 – 30	20 – 25	3	
	≥ 40	≥ 30	≥ 25	4	
Color scale [ASTM D-1500]	≤ 1.5			1	2
	1.5 – 2.0			2	
	2.0 – 2.5			3	
	≥ 2.5			4	
Dissipation factor	≤ 0.1			1	3
	0.1 – 0.5			2	
	0.5 – 1			3	
	≥ 1			4	

*** Assuming an electrode separation of 2.5 mm (IEC 60156)**

The factor $HI_1(2)$ is defined as:

$$HI_1(2) = \frac{\sum_{j=1}^{7} s_j \cdot w_j}{\sum_{j=1}^{7} w_j} \quad [2]$$

where the summation is over the seven dissolved gases. The scores s_j and weights w_j are given in Table 3.

Table 3. Scores and weights for the dissolved gases in the oil (based on [7]).

Gas (ppm)	Score (s_j)						w_j
	1	**2**	**3**	**4**	**5**	**6**	
H_2	≤ 100	100 – 200	200 – 300	300 – 500	500 – 700	> 700	2
CH_4	≤ 75	75 – 125	125 – 200	200 – 400	400 – 600	> 600	3
C_2H_6	≤ 65	65 – 80	80 – 100	100 – 120	120 – 150	> 150	3
C_2H_4	≤ 50	50 – 80	80 – 100	100 – 150	150 – 200	> 200	3
C_2H_2	≤ 3	3 – 7	7 – 35	35 – 50	50 – 80	> 80	5
CO	≤ 350	350 – 700	700 – 900	900 – 1100	1100 – 1400	> 1400	1
CO_2	≤ 2500	2500 – 3000	3000 – 4000	4000 – 5000	5000 – 7000	> 7000	1

Subindex $I_1(3)$ can take five different values, corresponding to the furan concentration in the oil, as shown in Table 4.

Table 4. Values of the subindex $I_1(3)$ as a function of the furan concentration in the oil (based on [7]).

2FAL (ppb)	$I_1(3)$
0 – 100	4
100 – 250	3
250 – 500	2
500 – 1000	1
> 1000	0

The overall health index I_1 is given by

$$I_1 = \frac{\sum_{i=1}^{3} k_i \cdot I_1(i)}{4 \cdot \sum_{i=1}^{3} k_i} \quad [3]$$

where the weights k_1 (physical and dielectric properties), k_2 (dissolved gases content) and k_3 (furan content) are 8, 10 and 5 respectively. I_1 lies in the range 0 - 1.00. The overall condition of the transformer, based on the value of I_1, is listed in Table 5.

Table 5. Transformer condition as a function of health index I_1 (based on [7]).

I_1	Condition
0.85 – 1.00	Very good
0.70 – 0.85	Good
0.50 – 0.70	Fair
0.30 – 0.50	Poor
0.00 – 0.30	Very poor

4.2.- Health index 2 [8]

The second index I_2 consists of four subindexes.

The first subindex $I_2(1)$ is concerned with the state of the insulating paper in the transformer, and consists of two factors. The first of these, $HI_2(C,O)$, is concerned with the concentrations of CO and CO_2 dissolved in the transformer oil, and the second, $HI_2(fur)$, is concerned with the concentrations of furans in the oil. $HI_2(C,O)$ is one-third of the sum $F_1 + F_2 + F_3$, where the values of F_1, F_2 and F_3 are expressed in the form ax + b ; a and b are constants and x is the concentration of the relevant gas, as shown in Table 6.

Table 6. Values of F_1, F_2 and F_3 (based on [8]).

Gas	Concentration range x (μL/L)	a	b	F
CO	0 – 300	0.0067	0	F_1 = ax + b
	300 – 900	0.0017	1.5	
	900 – 1000	0.020	-4.97	
	1000 – 1400	0.0125	-7.50	
	> 1400	-	-	F_1 = 10
CO_2	0 – 2400	0.0008	0	F_2 = ax + b
	2400 – 3000	0.0033	-6.0	
	3000 – 5000	0.0005	2.4	
	5000 – 10000	0.0008	0.9	
	10000 – 13000	0.0003	5.9	
	> 13000	-	-	F_2 = 10
CO + CO_2	0 – 3000	0.00067	0	F_3 = ax + b
	3000 – 10000	0.00014	1.59	
	10000 – 170000	0.000033	2.66	
	170000 – 350000	$9.44 \cdot 10^{-6}$	6.65	
	> 350000	-	-	F_3 = 10

$HI_2(fur)$ is given by

$$\mathrm{HI}_2(\mathrm{fur}) = 3.344 \cdot \left(C_{fur}\right)^{0.413} \quad [4]$$

where C_{fur} is the furan concentration in the oil expressed in ppm. Finally

$$I_2(1) = 0.3 \cdot \mathrm{HI}_2(\mathrm{C,O}) + 0.7 \cdot \mathrm{HI}_2(\mathrm{fur}) \quad [5]$$

The second subindex $I_2(2)$ is concerned with the concentrations of five gases dissolved in the oil, namely H_2, CH_4, C_2H_6, C_2H_4, and C_2H_2, and is given by

$$I_2(2) = \sum_{j=1}^{5} w_j \cdot F_j \quad [6]$$

where the values of F_1 through F_5 are expressed in the form ax + b, where x is the concentration of the relevant gas, as shown in Table 7.

Table 7. Values of F_1 through F_5 (based on [8]).

GAS	Concentration range x(μL/L)	a	b	F
H_2	≤ 30	0	0	F_1 = ax + b
	30 – 50	0.1	-3	
	50 – 100	0.06	1	
	100 – 500	0.0125	3.75	
	> 500			F_1 = 10
CH_4	≤ 10	0	0	F_2 = ax + b
	10 – 15	0.4	-2	
	15 – 125	0.0727	0.9	
	> 125			F_2 = 10
C_2H_6	≤ 5	0	0	F_3 = ax + b
	5 – 20	0.1333	-0.6667	
	20 – 35	0.2	-2	
	35 – 70	0.125	0.625	
	> 70			F_3 = 10
C_2H_4	≤ 10	0	0	F_4 = ax + b
	10 – 30	0.1	-1	
	30 – 50	0.15	-2.5	
	50 – 75	0.04	3	
	> 175			F_4 = 10
C_2H_2	≤ 0.5	0	0	F_5 = ax + b
	0.5 – 3	0.8	-0.4	
	3 – 5	1.5	-2.5	
	5 – 35	0.1667	4.167	
	> 35			F_5 = 10

The weights w_j assigned to each gas are given in Table 8.

Table 8. Weight (w_j) for each of the five dissolved gases (based on [8]).

Gas	w_j
H_2	0.2310
CH_4	0.2306
C_2H_6	0.0772
C_2H_4	0.2301
C_2H_2	0.2312

The third subindex $I_2(3)$ is based on acid content of the oil (expressed as the mass of KOH required to neutralize 1g of oil), its dielectric strength, moisture content and dielectric loss, as given in eq.(7).

$$I_2(3) = \sum_{j=1}^{4} w_j \cdot F_{oil(j)} \quad [7]$$

Values of the four F_{oil} factors are given in Tables 9-12, and the statistical weights in Table 13.

Table 9. Values of F_{oil} (1) (acid content of the oil) (based on [8]).

U ≤ 69 kV		69 kV < U < 230 kV		U > 230 kV	
x(mg KOH/g)	F_{oil} (1)	x(mg KOH/g)	F_{oil} (1)	x(mg KOH/g)	F_{oil} (1)
x ≤ 0.015	0	x ≤ 0.015	0	x ≤ 0.015	0
0.015 < x ≤ 0.1	25.53.x - 0.353	0.015 < x ≤ 0.1	25.53.x - 0.353	0.015 < x ≤ 0.05	51.14.x - 0.857
0.1 < x ≤ 0.2	20.x	0.1 < x ≤ 0.25	40.x - 2	0.05 < x ≤ 0.2	40.x
0.2 < x ≤ 0.3	40.x - 4	x > 0.25	10	x > 0.2	10
x > 0.3	10				

Table 10. Values of F_{oil} (2) (dielectric strength of the oil) (based on [8]).

U ≤ 69 kV		69 kV < U < 230 kV		U > 230 kV	
x(kV)*	F_{oil} (2)	x(kV) *	F_{oil} (2)	x(kV) *	F_{oil} (2)
x > 45	0	x > 52	0	x > 60	0
43 < x ≤ 45	-x + 45	50 < x ≤ 52	-x + 52		
40 < x ≤ 43	0.667.x + 30.68	47 < x ≤ 50	0.667.x + 35.35	40 < x ≤ 60	-0.4.x + 24
30 < x ≤ 40	-0.4.x + 20	40 < x ≤ 47	-0.286.x + 17.44		
x ≤ 30	10	35 < x ≤ 40	-0.4.x+ 22	x ≤ 40	10
		x ≤ 35	10		

*** Assuming an electrode separation of 2.5 mm (IEC 60156)**

Table 11. Values of F_{oil} (3) (moisture content of the oil) (based on [8]).

U ≤ 69 kV		69 kV < U < 230 kV		U ≥ 230 kV	
x(mg/kg)	F_{oil} (3)	x(mg/kg)	F_{oil} (3)	x(mg/kg)	F_{oil} (3)
x ≤ 20	0	x ≤ 10	0	x ≤ 10	0
20 < x ≤ 30	0.2.x - 4	10 < x ≤ 20	0.2.x - 2	20 < x ≤ 30	0.4.x - 4
30 < x ≤ 45	0.4.x - 10	20 < x ≤ 35	0.4.x - 6	x > 30	10
x > 45	10	x > 35	10		

Table 12. Values of F_{oil} (4) (dielectric loss of the oil) (based on [8]).

tan δ	F_{oil} (4)
x ≤ 0.05	0
0.05 < x ≤ 0.15	20.x - 1
0.15 < x ≤ 0.5	5.714.x + 1.143
0.5 < x ≤ 1.5	4.x + 2
x > 1.5	10

Table 13. Weight (w_j) for each of the four factors F_{oil} (based on [8]).

Physical property	w_j
Acidity	0.2598
Dielectric strength	0.1452
Moisture	0.4565
Loss factor	0.1386

The fourth subindex $I_2(4)$ is concerned with the age and loading of the transformer, and is given by eq.(8),

$$I_2(4) = HI_2(0) \cdot e^{B\cdot(t_2-t_1)} \quad [8]$$

where $HI_2(0)$ is an initial factor, B is an aging coefficient, t_1 is the year in which $HI_2(0)$ was evaluated, and t_2 is the year in which the state of the transformer is now being evaluated. $HI_2(0)$ is related to the condition of the transformer when it entered service, and its value is usually 0.5, whereas it is about 6.5 when the transformer reaches the end of its service lifetime. Given that the expected service lifetime of the transformers involved in this study is 40 years, when operating below 40% of rated load, as quoted by the manufacturers, it follows that B = (ln (13)) / 40 = 0.064 $year^{-1}$ under such loading. However, the expected service lifetime decreases with increasing loading of the transformer, and therefore at higher percentage loadings B is increased by a load factor f_{load}, as given in Table 14.

Table 14. Values of load factor f_{load} (based on [8]).

Loading (%)	Load factor f_{load}
0 – 40	1
40 – 60	1.05
60 – 70	1.1
70 – 80	1.25
80 – 150	1.6

The overall health index I_2 is given by

$$I_2 = \sum_{i=1}^{4} k_i \cdot I_2(i) \qquad [9]$$

where the weights k_1 (state of the insulating paper), k_2 (concentrations of five dissolved gases in the oil), k_3 (acid content of the oil) and k_4 (age and loading of the transformer) are 0.2661, 0.0946, 0.0699 and 0.5695 respectively. I_2 lies in the range 0 - 10. The overall condition of the transformer, based on the value of I_2, is listed in Table 15.

Table 15. Transformer condition as a function of the health index I_2 (based on [8]).

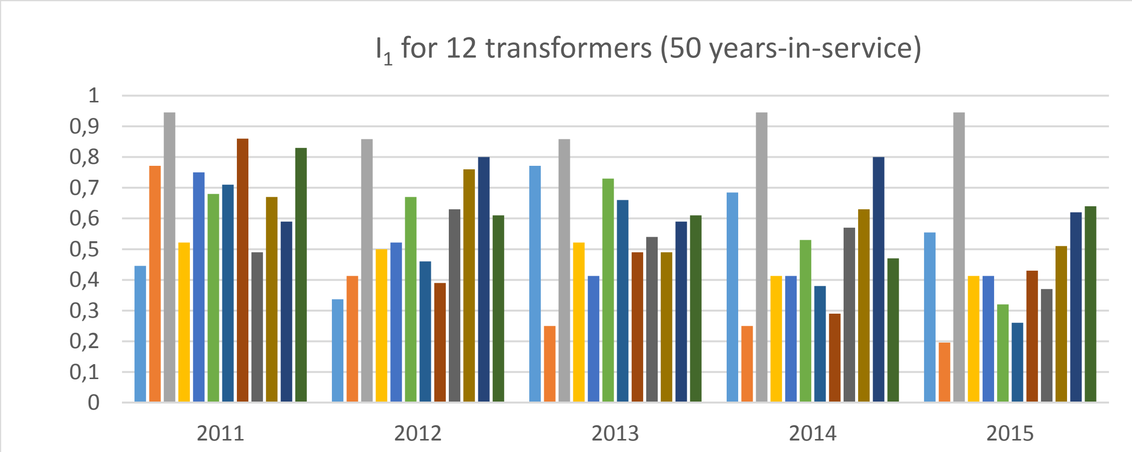
I_2	Condition
0 – 3.5	Very good
3.5 – 5.5	Good
5.5 – 7	Bad
7 – 10	Very bad

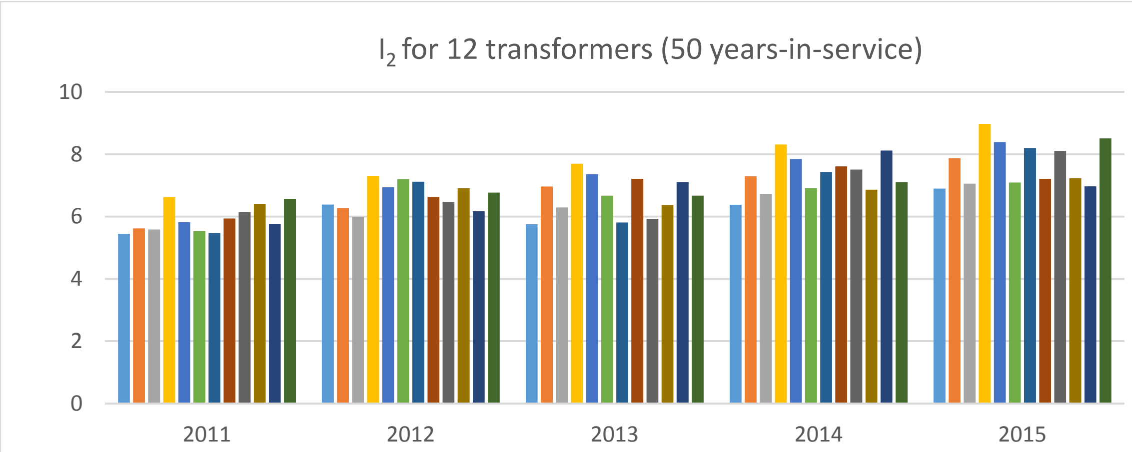
4.3. Comparison of I_1 and I_2 for 52 transformers

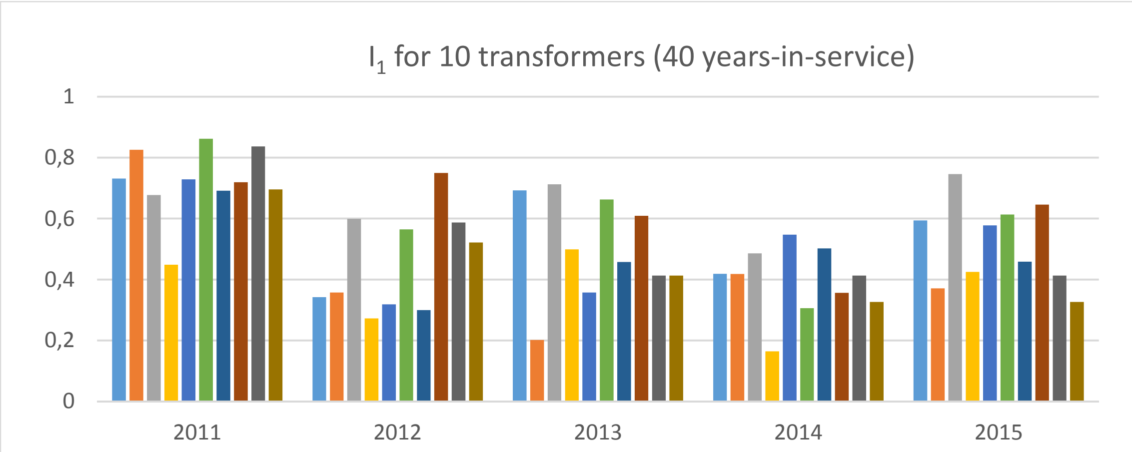
Figure 1 shows the indexes I_1 and I_2 for each of the 52 transformers, evaluated annually from 2011 to 2015. The transformers have been grouped according to their average time-in-service, i.e., 10 transformers with average time-in-service of 10 years, 10 transformers with 20 years, 10 transformers with 30 years, 10 transformers with 40 years, and 12 transformers with 50 years.

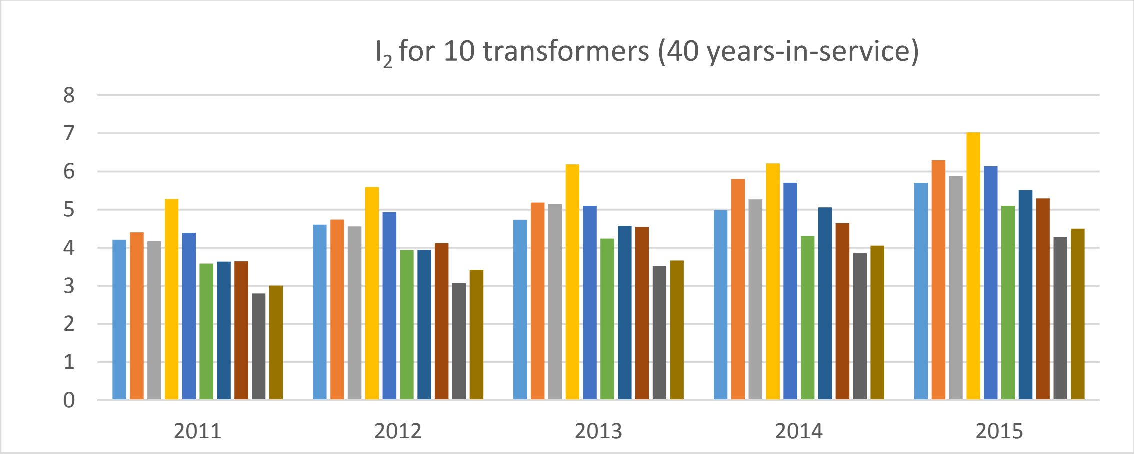
It will be seen that the minimum value of I_1, for the twelve transformers with average time-in-service of 50 years, was 0.2 over the five year period, and the maximum value was around 0.9. The corresponding minimum and maximum values for the ten transformers with average time-in-service of 10 years were 0.35 and 0.9 respectively. These unexpectedly large variations within a transformer group almost certainly occurred because some parameters used to estimate I_1 varied considerably with time, e.g., the concentrations of moisture, CO, CO_2 and 2FAL, as a result of variations in the environments in which these parameters were measured. In climates with high atmospheric moisture content, collection of oil samples must be carried out very carefully, in order to avoid contamination. Consequently the observed variation of I_1 almost certainly does not accurately reflect the true state of the solid insulation of the transformers, which is expected to age monotonically with time in service.

On the other hand, I_2 tends to increase gradually for each transformer within the same two groups, as expected. The values for the 50 year transformers range from around 5 in 2011 to around 8 in 2015, the corresponding range for the 10 year transformers being 1-2.

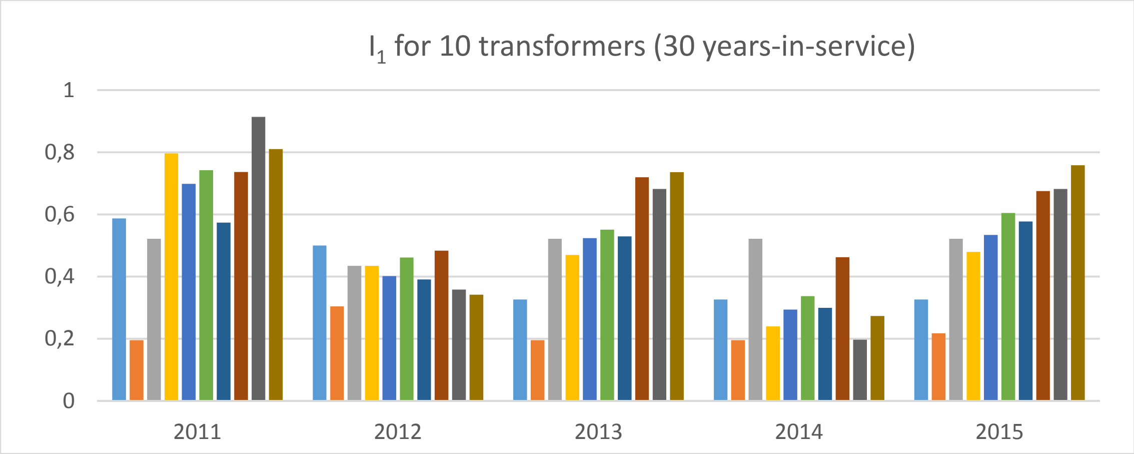




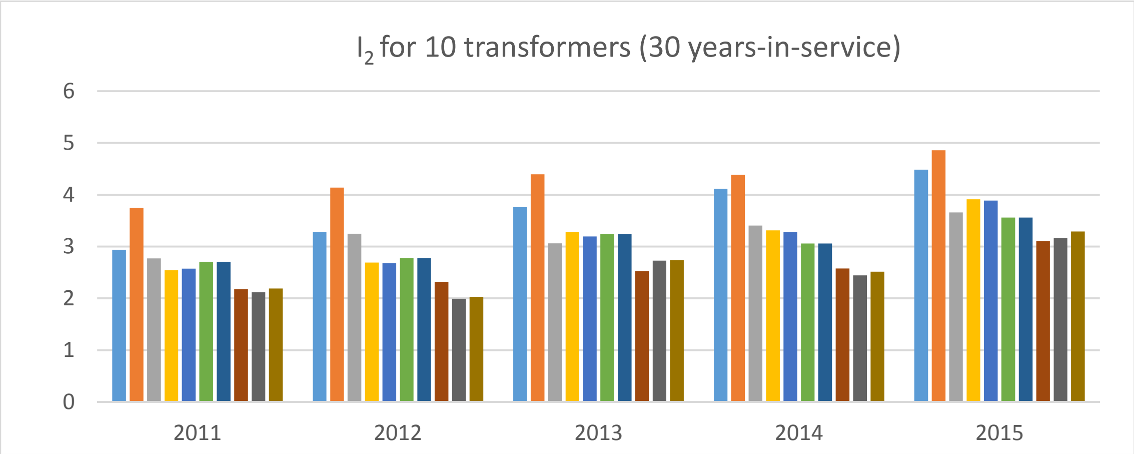




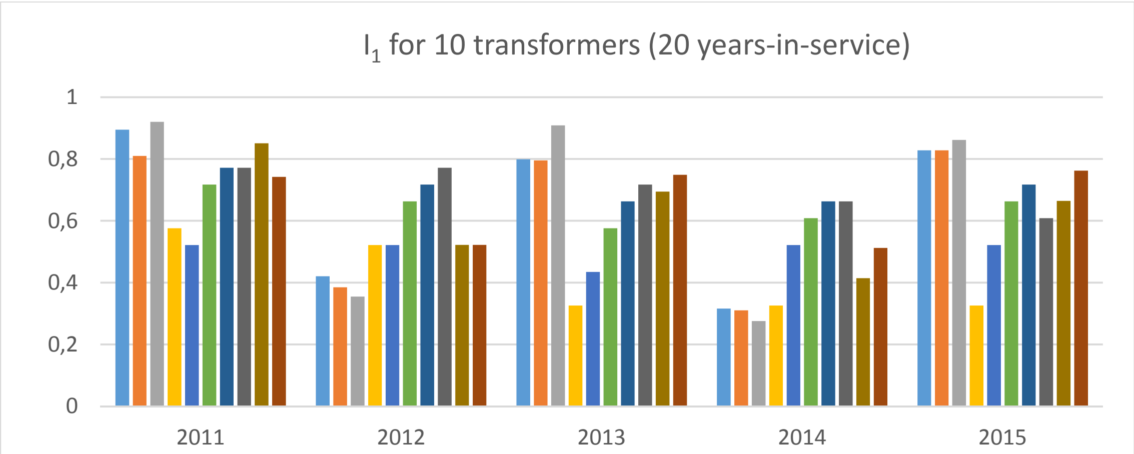
I_2 for 10 transformers (40 years-in-service)
8
7
6
5
4
3
2
1
0
2011
2012
2013
2014
2015



I_1 for 10 transformers (30 years-in-service)
1
0,8
0,6
0,4
0,2
0
2011
2012
2013
2014
2015



I_2 for 10 transformers (30 years-in-service)
6
5
4
3
2
1
0
2011
2012
2013
2014
2015



I_1 for 10 transformers (20 years-in-service)
1
0,8
0,6
0,4
0,2
0
2011
2012
2013
2014
2015

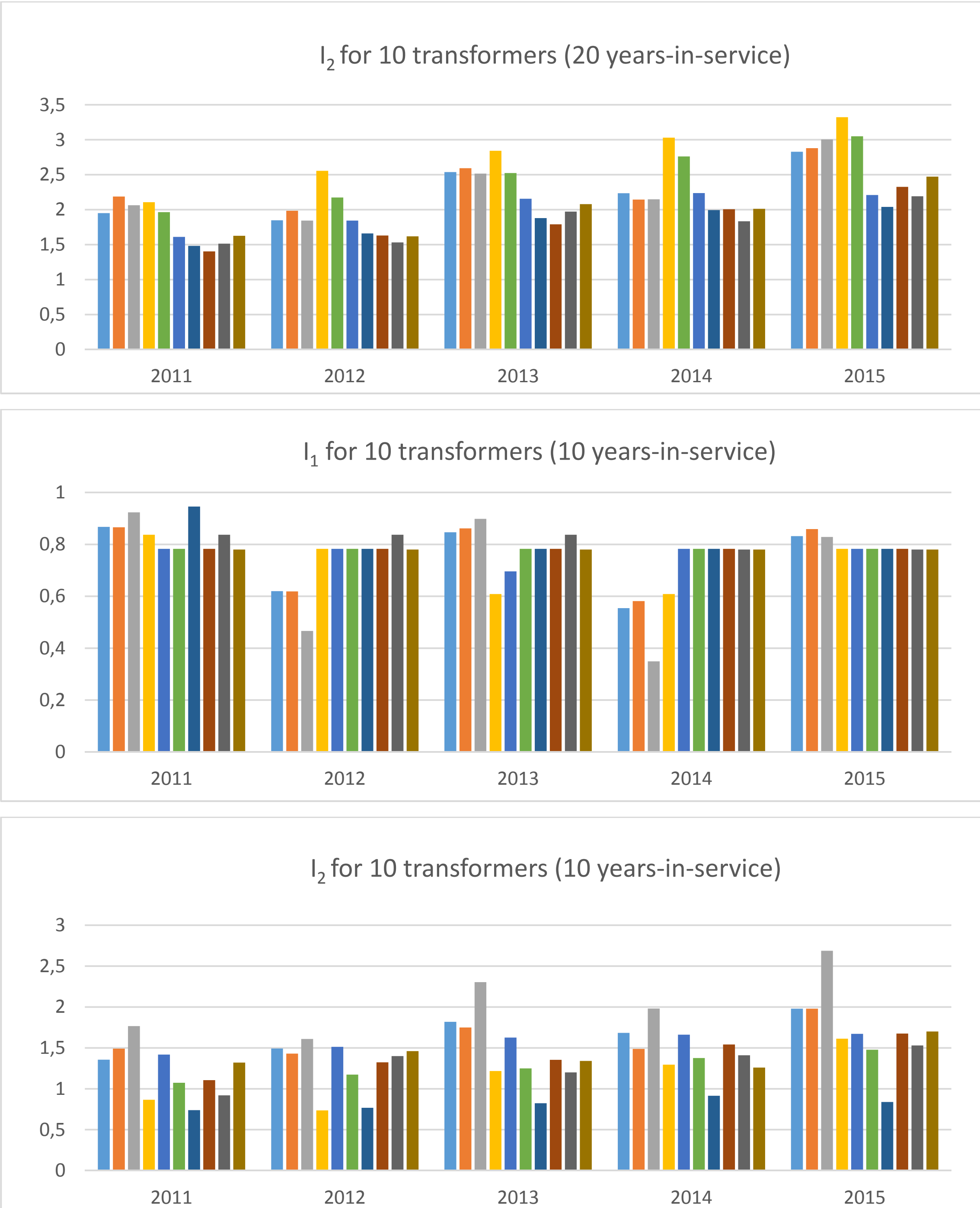


Figure 1. I_1 and I_2 for transformers in five years-in-service groups, evaluated over the last five years.

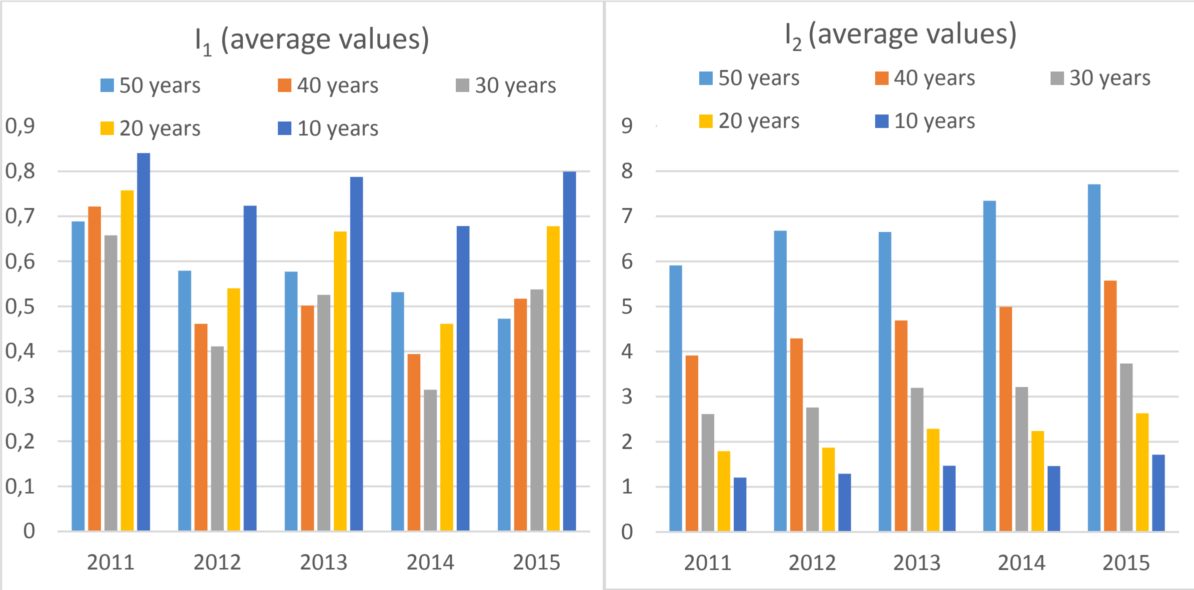


Figure 2. Values of I_1 and I_2 averaged within each of the five years-in-service groups, over the last five years.

Figure 2 shows the average values of I_1 and I_2 for the five groups of transformers with average times-in-service of 10, 20, 30, 40 and 50 years. The average values of I_2 show the same ordering between groups in each of the five years, while the average values of I_1 vary in an almost random fashion.

The following aspects of the data presented in Figures 1 and 2 should be noted:

- The average values of I_1 and I_2 both show that, in each of the five measurement years, the 10 year group of transformers is in better condition than each of the other groups, as would be expected. I_2 consistently shows that the younger the transformers the better their condition, as would be expected. The same is not true of I_1.
- A marked decrease in I_1 between two consecutive measurements could indicate the presence of a fault. On the other hand, a marked increase could be due to regeneration or replacement of the oil. A clear example of the latter can be observed for the first transformer (light blue colour) in the 50 year group, in which the oil was regenerated in 2012. I_1 increase markedly in 2013, and then decreases in 2014 and 2015. I_2 shows the opposite effect, as would be expected, but to a much lesser extent.
- The index I_2 is probably a more reliable indicator of overall transformer health than the index I_1. The main reason seems to be that I_2 takes into account the time for which a transformer has been in service and the extent to which it has been loaded; I_1 does not do so. The remaining service lifetime of a transformer is determined mainly by the condition of its paper insulation, which usually deteriorates gradually with time.
- Collection of uncontaminated oil samples for analysis is essential if the health index I_1 is to be accurately evaluated. However, it seems unlikely that more careful sample collection would render I_1 more reliable than I_2.

5. Conclusions

We conclude that health index I_2 is a more reliable indicator of transformer overall health than health index I_1. Although both make use of the same physical data, e.g., acid content of the oil, dissolved gas content of the oil, breakdown voltage and dielectric loss, only I_2 takes into account the time for which a transformer has been in service and the extent to which it has been loaded. The latter two factors seem to be essential to ensure that the health index reflects the expected monotonic deterioration in the condition of the transformer insulation with time in service. However, health index I_1 is probably a clearer indicator of a significant change in overall transformer health since the last measurement.

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BIOGRAPHIES

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