Interpretation of Turn-to-Turn Insulation Fault by Dissolved Gas Analysis

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ABSTRACT

The purpose of dissolved gas analysis (DGA) in utilities is to help detect the presence of abnormality within transformer. When faults occur in transformers, transformer engineers need to determine the location and risk of the faults. Ultimately, they have to decide, based on DGA, whether to continue operating or not, perform internal inspection, or dispose the transformer. In this study, the fault and failure types in the transformer are suggested to determine the location and risk of the faults. In particular, turn-to-turn insulation faults are classified as degradation and breakdown. These faults are difficult to identify during internal inspection, and have a high possibility of failure. Urgent decision and action are thus required to avoid failure. In degradation of turn-to-turn insulation faults, failures may occur by generating thermal gases in paper during a long period of time. In breakdown of turn-to-turn insulation faults, thermal gases are not generated in paper, and failures are rather due to sudden breakdown of insulation. This study also presents a typical example of a turn-to-turn insulation fault. This example shows the progress of the fault from thermal to discharge, which is common phenomena in winding fault. Based on the findings of this work, transformer engineers can determine by DGA if transformers can be operated with or without internal inspection, or disposed when the fault has not been identified during internal inspection.

Index Terms — **dissolved gas analysis, power transformers, transformer winding, failure type, fault type**

1 INTRODUCTION

TRANSFORMER engineers determine whether faults are present in transformers with dissolved gas analysis (DGA). If the transformer is judged by DGA as presenting danger for its operation, transformer engineers determine the fault occurring in the transformer according to gases formed and inspection of its internal parts, in order to identify the faults. If faults are identified during internal inspection, the faults are repaired, and the transformer put back in operation. If the faults cannot be repaired, or if their repair would be too costly, the transformer is disposed. Deciding whether to dispose of the transformer or not is difficult when the faults cannot be identified during internal inspection. The transformer is, therefore, operated again after degassing oil, without having identified the fault locations (components) or causes, and the DGA oil sampling interval used to monitor the transformer is reduced.

Locations that cannot be identified during internal inspection of transformers are more likely to be inside core and winding. Most faults inside core are thermal fault, which seldom cause failure. However, most faults inside winding are discharge fault, which may lead to rapid failures according to KEPCO's experiences. The risk of failure in transformers is higher when oil has been degassed because gas concentrations need at least several months to reach previous levels. The reason why transformers are operated with a high risk of failure is that turn-to-turn insulation faults cannot be identified by traditional DGA methods.

IEEE C57.104 [1], IEC 60599 [2], and Electric Technology Research Association - Japan (ETRA) [3] are the main standards or criteria used for evaluating the faults in transformers from DGA. Michel Duval has developed the Duval Triangles and Duval Pentagons, and introduced the Duval Triangle in IEC 60599 [4-6], thus contributing to the evaluation of the faults in transformers [7]. Many researchers have improved the reliability of diagnosis using DGA because it is recognized as an effective method for the diagnosis of transformers. The fault types in transformers that can be detected with DGA are classified as thermal and discharge, using the key gas or gas ratio methods, among others. Thermal faults are classified as thermal in oil and thermal in paper, and discharge faults are classified as discharges in oil and discharges in paper.

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Table 1 shows the key gases according to the fault types in transformers. C_2H_6, CH_4, and C_2H_4 are key gases for thermal in oil of t < 300 °C (T1), 300 °C < t <700 °C (T2), and t > 700 °C (T3), respectively. H_2, C_2H_2 and C_2H_4 are key gases for corona partial discharges (PD), low energy discharges (D1), and high energy discharges (D2) in oil, respectively. CO and CO_2 are key gases for thermal in paper. However, for discharge in paper, no key gas has been presented. For faults in paper. CO and CO2 may also indicate that paper has deteriorated during a long period of time due to heat generated by the normal operation of aged transformers. However, most transformers that have not reached their end of life are replaced because of abnormal accidental failures rather than normal deterioration. Most of these failures are of discharge inside winding where paper is used, and the key gas is C_2H_2, seldom CO or CO_2. Moreover, because the fault types in transformers indicated in traditional standards are difficult to relate to the fault and failure types that occur in actual transformers, transformer engineers cannot easily estimate the fault and failure types in winding with DGA.

Table 1. Key gases according to fault types.

Fault Types	Key Gases
Thermal-oil	C_2H_6, CH_4, and C_2H_4
Discharge-oil	H_2, C_2H_2 and C_2H_4
Thermal-paper	CO and CO_2
Discharge-paper	**not clear currently**

In this study, the fault and failure types [2] in transformers are deduced from DGA to determine the location and risk of the faults. A total of 338 failed transformers and 141 internal inspected transformers where faults were identified have been used. In this study, the fault is defined as the internal components of transformers have the defect. The faults can cause overheat and discharge at the components and gases may be generated. In such faults, discharge in winding may progress to failure, and discharge in clamp bolts may not progress to failure. Some faults can also be repaired by internal inspection of the transformer in the field. The failure is defined as transformers can no longer be operated and must be removed because the fault has progressed to failure. Turn-to-turn insulation faults are classified as degradation and breakdown. These faults are difficult to identify during internal inspections. Thus, they have a high possibility of failure, and require urgent decision or action. This study also presents a typical example of a turn-to-turn insulation fault. This example shows the progress of the fault from thermal to discharge.

2 THE FAULT AND FAILURE TYPES OF TRANSFORMERS DETERMINED BY DGA

When faults in transformers are estimated by DGA, it is necessary to evaluate the fault according to gases formed and to determine whether or not to perform internal inspection. If faults cannot be identified by internal inspection, the transformer engineers should decide whether the transformer can still be operated, or should be disposed. In this study, in order to determine the location and risk of the faults in transformers, the fault and failure types in transformers are classified by DGA from failed and internal inspected transformers where faults were identified.

2.1 FAULT TYPES OF TRANSFORMERS DETERMINED BY DGA

Figure 1 shows the results of internal inspection and DGA of transformers at KEPCO. A total of 293 transformers are evaluated by DGA from 2001 to 2016. Faults were identified by internal inspection in 141 transformers, and not identified by internal inspection in 152 transformers.

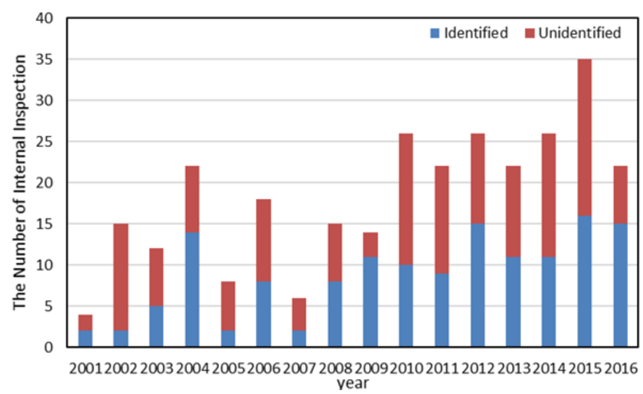

Figure 1. Internal inspection and DGA of transformers at KEPCO.

Table 2 shows the percentage of faults identified during internal inspection made at different DGA levels. As shown in Table 2, the higher the DGA level, the higher the percentage of faults identified by internal inspection. The percentage of internal inspection at DGA danger level, based at KEPCO on the level of C_2H_2 only [8], was 4% of all internal inspection made, but the percentage of faults identified by internal inspection was 85%. At Caution level 1, the percentage of internal inspection was 19%, but the percentage of faults identified by internal inspection was 20%.

Table 2. Percentage of faults in transformers identified by internal inspection as a function of DGA level.

DGA Level	The number of Internal Inspections by DGA	Percentage of Internal Inspections Made	Identified	Unidentified	Percentage of Faults Identified by Inspection
Danger	13	4%	11	2	85%
Abnormal	115	39%	73	42	63%
Caution 2	110	38%	46	64	42%
Caution 1	55	19%	11	44	20%

The faults inside winding are difficult to identify by internal inspection. Similarly, the thermal faults in core are difficult to identify. If the fault cannot be clearly identified by internal inspection, even a minor trace of gas may be mistaken as a fault. This can lead to major errors in determining whether the

Table 3. Percentage of fault location found and identified by internal inspection of transformers.

	Found and Identified			Unidentified	Total		
	Number of Fault Locations Found	Number of Faults Identified by Internal Inspection	Percentage of Faults Identified		Number of Faults		Percentage of Fault Locations Identified by Internal Inspection
Winding	45	30	67%	49	94	32%	32%
Bushing	12	10	83%		12	4%	83%
OLTC	11	10	91%		11	4%	92%
Core	62	19	31%	96	158	54%	12%
Clamp	3	3	100%		3	1%	100%
Oil	8	8	100%	7	15	5%	53%
Total	141	80	57%	152	293	100%	27%

transformer can be kept in operation, should be repaired, or should be disposed. Table 3 shows the percentage of fault locations found and identified by internal inspection.

As shown in Table 3, the number of faults in core was 158. However, the percentage of faults identified by internal inspection was only 12%, because of the difficulty of identifying faults during internal inspection. The number of faults in winding was 94, and the percentage of faults identified was 32%. Faults in bushing, OLTC tap selector, and clamp, which can more easily be identified by internal inspection of transformers, had high percentages of faults identified. There were 15 faults in oil, and the percentage of faults identified was 53%, due to stray gassing of oil. These values indicate that the locations, in transformers where faults are difficult to identify by internal inspection, are core and winding.

As shown in Table 3, total percentage of faults identified by DGA was only 27%. The reason why faults could not be accurately identified is that fault locations in transformers cannot be identified precisely by DGA. Many studies have classified the failure types (FMEA) in transformers [10-12]. However, these studies do not address the relation between the locations of failures and DGA. Moreover, only a few studies have classified the fault types not reaching to failure. The fault types can be classified as those progressing from fault to failure and those not progressing to failure but are generating gases. For example, discharges in winding are likely to rapidly progress to failure, but discharges in bolts are unlikely to progress to failure and only generate gases. Therefore, transformers with discharges in bolts can continue to operate, but internal fault must be inspected during the scheduled internal inspection period. Stray gassing does not require internal inspection. However, discharges in winding or OLTC tap selector contacts are likely to lead to failure and should be inspected immediately.

Therefore, classifying the fault types of transformers is necessary to determine the locations and likelihood of failure occurrence in transformers by DGA. In this study, 293 transformers that were internally inspected are analyzed to classify the fault types by DGA. Fault locations are classified as winding, bushing, OLTC, core, clamp, and oil, as shown in Table 4. Winding faults are classified as faults in paper and leads. A winding fault was expected to cut winding conductors because of through faults or lightning, but this situation does not occur in actual transformers. Paper faults were expected to be of the thermal or discharge. In this study, turn-to-turn insulation faults are classified as the degradation and breakdown. These faults are difficult to identify by internal inspection, and have a high possibility of failure. Therefore, they require urgent decision or action. Degradation lead to failure by generating thermal gases in paper during a long period of time. In breakdown, thermal gases are not generated in paper but result in the sudden breakdown of insulation. Bushing faults are classified as faults in corona shield and terminals. Corona shield faults are classified as of the discharge and thermal. Terminal faults are classified as of the discharge and thermal in loose bolts. OLTC faults are classified as faults in the diverter S/W cylinder and tap selectors. Diverter cylinder faults are classified as the thermal when oil is communicating with the main tank oil by cracking of the cylinder. Tap selector faults are classified as faults in terminals and contacts, all of which involve loose bolts. Tap selector contact faults are classified as the discharge and thermal. Core faults are classified as faults in multiple grounds, loose stud bolts, and core. Multiple grounds are classified as the thermal, loose stud bolts as the discharge, and core as the T1, T2, and T3, respectively, depending on temperature. Clamp faults are classified as the discharge in loose bolts of the pressure ring. Oil faults are classified as oxidation of uninhibited oil and partial discharge by particle and stray gassing [9].

Table 4. The fault types in transformers determined by DGA.

Component1	Component2	Component3	Causes	Results
Winding	Insulation	Turn to Turn		Degradation
				Breakdown
	Lead	Insulation paper		Discharge
Bushing	Corona Shield			Discharge
				Thermal
	Terminal	Bolts	Loose bolts	Discharge
				Thermal
OLTC	Diverter S/W	Cylinder	Crack	Inflow Oil
	Tap Selector	Terminals	Loose bolts	Discharge
		Contacts	Loose bolts	Discharge
				Thermal
Core	Ground		Multiple grounds	Thermal
	Stud Bolts		Loose bolts	Discharge
				Thermal
Clamp	Pressure Ring	Bolts	Loose bolts	Discharge
Oil			Uninhibited oil	Oxidation
			Particle	Discharge
			Stray Gassing	Discharge

2.2 FAILURE TYPES OF TRANSFORMERS DETERMINED BY DGA

In this study, 1,030 transformers that tripped by operating circuit breaker or relay from 1981 to 2014 are analyzed. The locations of faults in transformers are given in percentages, with winding at 20%, OLTC at 10%, bushing at 3%, accessories at 22%, and others at 45%. Among the 1,030 tripped transformers, 338 units showed failures of winding, OLTC, and bushing that affected DGA. The failures of accessories and others did not relate to DGA. In accessory failures, transformers tripped due to malfunctions of the relays, such as the sudden pressure relay and the pressure relief valve. Other failures occurred because transformers tripped due to T/L and D/L through faults and workmanship errors. In this study, the failure that could be identified by DGA are classified as faults in winding, bushing, and OLTC, as shown in Table 5.

Table 5. The fault types in transformers determined by DGA.

Component1	Component2	Component3	Causes	Results
Winding	Insulation			Turn-to-Turn Degradation
				Turn-to-Turn Breakdown
Bushing	Corona Shield			Discharge
OLTC	Tap Selector	Contacts	Loose bolts	Discharge

In the literature [10-12], transformer failures are classified as occurring in winding, core, clamp, mechanical support, oil, bushing, OLTC, tank, fan, pump, radiator, and conservator. Winding failures are classified as occurring in the conductor, insulation, lead, mechanical structure, barrier, and binding in the literature. However, in actual transformers, winding failures occur only in the insulation. Therefore, considering the fault types classified in Section 2.A, turn-to-turn insulation faults are classified as the degradation and breakdown. Bushing failures are classified as occurring in condenser, gasket, corona shield, and porcelain in the literature, but only failures in the corona shield occur in actual transformers. Therefore, this fault is classified as of the discharge. OLTC failures are classified as faults in the diverter S/W, tap selector, drive shaft, and contacts in the literature. However, in actual transformers, failures occur only in the tap selector contacts and are classified as the discharge.

Table 6. Failure types of transformers.

Parts	Classification of fault in the literature	KEPCO experience
Winding	conductor, insulation, lead, mechanical structure, barrier, and binding	insulation
Bushing	condenser, gasket, corona shield, and porcelain	corona shield
OLTC	diverter S/W, tap selector, drive shaft, and contacts	tap selector contacts
Core	steel insulation and ground	
Clamp	workmanship errors, transportation failure, and operating vibration	
mechanical support	wedges and woods	
Oil	moisture, oxygen, and particle	
tank,	tank and gaskets	
fan, pump	motor, bearings, and impeller	
radiator	plate, flange, and valve	
conservator	tank, piping, and gaskets	

3 EXAMPLE OF TURN-TO-TURN INSULATION FAULT

3.1 DGA HISTORICAL DATA OF THE TRANSFORMER

In this study, turn-to-turn insulation faults are classified as the degradation and breakdown. This study presents a typical example of a turn-to-turn insulation fault. This example shows the progress from thermal fault to discharge, which is common phenomenon in winding fault. The transformer is 154/23 kV, 1 phase, 60 Hz, 15/20 MVA, and ONAN/ONAF cooling with OLTC.

This transformer was manufactured in May 2001 and had been in operation since June 2001. As shown in Table 7, C_2H_4 was at Caution 1 level from June 2009. Therefore, the DGA sampling interval was reduced. C_2H_4 and TCG were at Caution 1 level from January 2010. CH_4 also was at Caution 1 level from June 2011. However, because C_2H_4, CH_4, and TCG were all at Caution 1 level, the DGA sampling interval was maintained at six months. Gas concentrations significantly increased in January 2016. H_2 and C_2H_6 were at Caution 1 level,

Table 7. DGA historical data (ppm).

Date	H_2	C_2H_2	C_2H_4	C_2H_6	CH_4	TCG	CO	CO_2	Decision
08/14/01							22	82	Normal
06/04/02			6		3	9	50	505	Normal
06/18/03			18		7	25	180	1,451	Normal
06/03/04	6		29	5	14	54	183	402	Normal
07/06/05			19		14	48	142		Normal
09/01/06			36	42	21	99	45	835	Normal
08/07/07			44	41	18	103	228	1,876	Normal
10/21/08			67	53	55	223	151	1,635	Normal
06/24/09	9		128	92	128	439	547	2,314	Caution 1
01/05/10	11		146	112	145	512	309	1,778	Caution 1
06/25/10	9		193	135	147	592	532	1,809	Caution 1
12/07/10	4		151	120	140	516	288	2,159	Caution 1
06/02/11	9		173	128	169	578	353	1,911	Caution 1
02/14/12	9		176	132	166	591	244	1,484	Caution 1
08/17/12	8		167	129	156	565	246	2,105	Caution 1
04/12/13	7		173	132	174	587	244	2,182	Caution 1
09/05/13	8		174	157	179	631	295	2,075	Caution 1
04/08/15			185	181	162	653	165	1,912	Caution 1
01/08/16	34	1	180	85	97	518	25	382	Caution 1
01/15/16	256		835	204	602	2,197	27	416	Abnormal
02/02/16	587	4	1,886	459	1,404	4,986			Danger
02/03/16	Internal Inspection								
02/16/16			15	8					Normal
03/17/16			22	24	10				Normal
04/20/16			40	86	25				Normal
05/30/16			43	80	35	206			Normal
08/01/16	337	3	1,220	372	926	3,239	47	547	Danger
08/08/16	Internal Inspection								
01/23/17	Disassemble Inspection at the Factory								

CH_4 and TCG at Caution 2 level, and C_2H_4 was at Abnormal level. After 15 days, C_2H_4 increased from 835 ppm to 1,886 ppm, and H_2 increased from Caution 1 to Caution 2 level. TCG reached danger level from the abnormal level, and the other gases increased by more than twice. Therefore, the transformer was determined as requiring internal inspection.

3.2 ESTIMATION OF THE FAULT

The fault was estimated before internal inspection of the transformer based on the methods proposed by IEEE C57.104, IEC 60599, and ETRA. Table 8 shows the identification of the fault using IEEE C57.104, IEC 60599, and ETRA. The key gas method of IEEE C57.104 indicated C_2H_4 as the key gas and thermal fault in oil as the fault types. The Doernenburg ratio method indicated thermal decomposition, and Roger's ratio method thermal > 700 °C. Basic gas ratios and the Duval Triangle of IEC 60599 indicated a T3 (thermal fault, t > 700 °C). The gas pattern of ETRA indicated C_2H_4-A, which is a thermal fault in oil. The gas composition ratio indicated a thermal fault > 700 °C. Therefore, the fault in the transformer in this study was estimated to be a thermal fault, t > 700 °C. IEEE C57.104 provides no specific information about the typical causes of thermal faults of t > 700 °C. In IEC 60599, the typical causes of thermal faults are insufficient cooling, excessive currents circulating in adjacent metal parts (as a result of bad contacts, eddy currents, stray losses, or leakage flux), excessive currents circulating through the insulation dielectric losses, thermal runaway, overheating of internal winding or bushing connection lead, and overloading. In addition, the typical causes of T3 are presented as large circulating currents in the tank and core, and minor circulation currents in tank walls created by a high uncompensated magnetic field and shorting links in core steel laminations. In ETRA, the typical causes of high temperature thermal are large circulating currents in tank and core, closed loops in core, overheating of winding, and bad contacts of OLTC tap selector. Typical fault examples for C_2H_4 suggest bad contacts of OLTC, circulating currents in core, and short circuits between core laminations and bad contacts.

Table 8. Identification results of the fault.

DGA Interpretation Methods		Results of DGA Interpretation	Fault
IEEE C57.104	Key gas	C_2H_4	Thermal oil
	Doernenburg ratio	R1 (2.4), R2 (0), R3 (0), and R4 (0)	Thermal decomposition
	Roger's ratio	R2 (0), R1 (2.4), and R5 (4.15)	Thermal>700℃
IEC 60599	Basic gas ratios	C_2H_2/C_2H_4 (0), CH_4/H_2 (2.4), and C_2H_4/C_2H_6 (4.1)	T3 (thermal fault, t >700 ℃)
	Duval Triangle		T3 (thermal fault, t >700 ℃)
ETRA	Gas Pattern	C_2H_4-A	Thermal-Oil
	Gas Ratio	C_2H_2/C_2H_4 (0), C_2H_2/C_2H_6 (0), and C_2H_4/C_2H_6 (4.1)	Thermal>700℃

3.3 INTERNAL INSPECTION OF THE TRANSFORMER

The transformer was internally inspected to find the fault. External inspections and electrical tests were performed before internal inspection of the transformer. The external inspections, which included the OLTC driving unit, OLTC oil filtering unit, lightning arrester, fans and pump motors, radiator, bushing, conservator, temperature indicators, local panel, mechanical protection devices, oil preservation system, and oil leakage, were all good. Insulation resistance between winding and ground was more than 2,000 MΩ, and the results of the electrical tests were good.

The transformer was de-energized, and the external parts of winding, core, clamps, bolts, bushing lead, support wood, and OLTC tap lead were inspected, but thermal or carbonization marks were not found. Local thermal traces were also not found in core. However, as shown in the results of the evaluation of the fault, arc traces at OLTC tap selector contacts were found (Figure 2). Therefore, OLTC tap selector contacts were replaced. The fault in the transformer was considered to have been repaired, and voltage applied on the transformer in February 2016. After applying the load, DGA results measured every month from March 2016 were all normal.

(a) + Tap (b) – Tap

Figure 2. Arc traces at OLTC tap selector.

3.4 GAS GENERATION AND ANOTHER INTERNAL INSPECTION

Six months after replacing OLTC tap selector contacts, danger level of DGA was again reached, as shown in Table 7, in August 2016. DGA had the same pattern as before. This indicated that the fault had not been repaired by replacing OLTC tap selector contacts. Therefore, the transformer was subjected to another internal inspection. External inspections and electrical tests were performed again before internal inspection of the transformer. Test results were all good. Internal inspection of the transformer was carried out again in August 2016. Thermal or carbonization marks were not found in any visible parts, such as winding, core, bushing lead, OLTC tap winding leads, and OLTC tap selector.

3.5 ESTIMATION OF THE FAULT BASED ON THIS STUDY

The fault was re-estimated because IEEE C57.104, IEC 60599, and ETRA did not match internal inspection results of the transformer. The transformer in this study was considered not to have reached its end of life after 15 years of operation. Therefore, paper was less likely to have generated gases due to load-related thermal faults. Transformers that have not reached their end of life are likely to generate gases due to discharge in winding paper. The deterioration caused by discharges in winding paper leads to failure due to arcing between turn-to-turn winding. At this moment, a fault in winding starts with partial discharge of low energy, and it develops into serious discharge of high energy and arcing. Windings are covered with paper. Therefore, if partial discharge occurs between windings, paper will begin to deteriorate due to weak discharge at first, and gases will be generated due to local thermal degradation of paper due to partial discharge. When the deterioration of paper advances and the amount of discharge charge increases, the paper will be carbonized due to local overheating by discharge. Gas concentrations will increase as paper deteriorates. As the deterioration of paper further increases, a direct discharge (arc discharge) will occur between windings as paper punctures, and gases will be generated by arc discharge in oil rather than in paper. As a result, H_2 will be generated. As the arc discharge increases further, C_2H_2 will be generated.

Therefore, paper begins to deteriorate due to partial discharge at first, and C_2H_4 and CH_4 are generated by the local overheating of paper by partial discharge. As paper deterioration and amount of partial discharges increase, C_2H_4 and CH_4 increase, and H_2 occurs due to partial discharge. Therefore, the transformer in this study can be interpreted as being in a state in which partial discharge in turn-to-turn winding increase considerably due to the progress of paper deterioration. However, arc discharge did not progress because C_2H_2 was low. That was, this transformer corresponds to the typical example of the degradation of turn-to-turn insulation fault classified in Section 2.A.

3.6 DISASSEMBLED INSPECTION OF THE TRANSFORMER AT THE FACTORY

As a result of the fault thus evaluated, the transformer was considered dangerous to operate. The transformer was moved to the factory in December 2016 and disassembled clamp, core and winding to identify the fault in January 2017. After disassembling windings, carbonized traces were found between sections #46 and #47 in the bottom of the medium-voltage winding, as shown in Figure 3, possibly due to discharges but more likely to the hot spot T3.

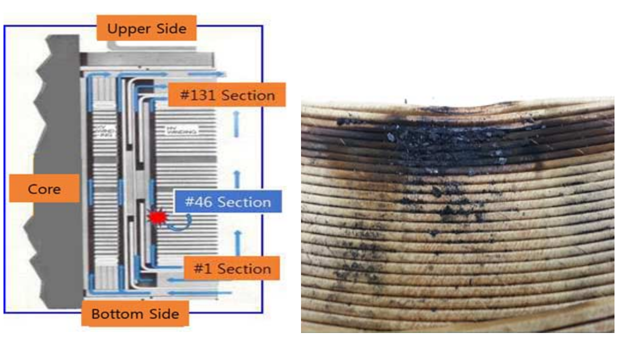

Figure 3. Carbonization in the medium-voltage winding.

4 CONCLUSIONS

In this study, the fault and failure types in transformers are deduced from DGA to determine the location and risk of the faults. A total of 338 failed transformers and 141 internal inspected transformers where faults were identified have been used. Turn-to turn-insulation faults are classified as degradation and breakdown. These faults are difficult to identify during internal inspection, and have a high possibility of failure. Therefore, urgent decision or action are required to avoid failure. In degradation of turn-to-turn insulation faults, failures may occur by generating thermal gases in paper during a long period of time. In breakdown of turn-to-turn insulation faults, thermal gases are not generated in paper, and failures are rather due to sudden breakdown of insulation. This study also presents a typical example of a turn-to-turn insulation fault. This example shows the progress of the fault from thermal to discharge, which are common phenomena in winding fault. The identification of the fault using IEEE C57.104, IEC 60599, and ETRA indicated a thermal fault, $t > 700$ °C. However, the results of twice internal inspections of the transformer did not match with the fault identified by traditional DGA standards. The fault presented in this study was degradation of turn-to-turn insulation fault. Paper deterioration considerably progressed. The fault proposed in this study has been determined by disassembling the transformer at the factory and confirming that carbonization occurred as a result of significant thermal or discharge faults between windings. Based on the results of this study, transformer engineers can determine by DGA if transformers can be operated without internal inspection, should be internally inspected, or should be disposed when the fault has not been identified during internal inspection.

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