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A Study on the Assignment of the Vibration Classes to the Power Transformers in Operation (154[kV])

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Abstract

High reliability is essential for power transformers, and their fault causes are reportedly more related to mechanical causes than electrical ones. The transformer soundness judgment currently depends only on the electrical insulation characteristic and the chemical test of the insulation oil, so that there are few fundamental measures against the frequent mechanical damages and failures in transformers.

The mechanical soundness judgment techniques are conducted through processes that include structural analysis and vibration resistance treatment during the manufacturing process of each manufacturer, but the vibration is not tested during the design, manufacturing, and operating processes since there are no detailed technical standards and procedures on the vibration problem, which are important in terms of maintenance.

Therefore, in this study, vibration phenomena were measured from the 32 power transformers in operation in the substations under the Daejeon Power Transmission District Office of the Korean Electric Power Corporation (KEPCO). The vibration was measured at 24 sections (6x4) on one side, and only the maximum values were selected from the measured vibration values. This was because the maximum vibration values more significantly affect the soundness of the transformer than the average vibration values. The vibration classes were given considering the maximum vibration based on ISO 10816-1 (2001).

Key Words : Transformer, Vibration, Maintenance, Peak vibration value, Vibration Class

1. Introduction

Transformers require high reliability. There are cases with operation stops caused by various reasons, however, and the analysis of the fault causes show that they are reportedly more related to mechanical causes than electrical ones[1-5].

In particular, the resonance phenomena caused by vibration were found, which increased the vibration amplitude of the transformer. Because of the lack of technical measures on the problems caused by vibration in the transformer designing and manufacturing processes, the failures from mechanical damages caused by elapsed years of the transformer have not been decreasing[5].

The transformer soundness judgment depends only on the electrical insulation characteristic of

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the wiring and the chemical test of insulation oil, so that there are few fundamental measures against the mechanical damages and failures in transformers[6-9].

It is very difficult to find the cause of a mechanical failure since there is no mechanically operating sections in transformers. In Korea, there is no research result on mechanical soundness of the transformer. The mechanical soundness judgment of transformers is conducted through the processes including structural analysis and vibration resistance treatment during the manufacturing process, but the vibration is not tested during the designing, manufacturing and operating processes since there are no detailed technical standards and procedures on vibration problems, which are important in terms of maintenance.

Outside Korea, studies to detect the loosened iron cores or wirings in the transformer are underway using the vibration signals generated from the transformer. The mechanical soundness judgment technique, however, has not yet been established even outside Korea[10-11].

Therefore, this study was conducted to address this problem. For the 32 power transformers in operation (154[kV]) in substations under Daejeon Power Transmission District Office of KEPCO, vibration phenomena were measured, and only the average and maximum values were taken from the measured vibration values. Because the maximum vibration values have the highest impact on the transformers, they were analyzed and the vibration classes were assigned according to them based on ISO 10816-1 standard[12].

This study will be helpful in many ways because a guideline for the transformer operation can be established by classifying the transformer conditions into normal, maintenance-required and replacement-required conditions using the assigned vibration classes.

2. Vibration Test

In this study, the vibration level of the transformer in operation was measured in compliance with KS B 0714 (2001) standards[13].

The subjects in this study were 32 power transformers in nine substations under the Daejeon Power Transmission District Office of KEPCO. They were 154[kV]/60[MVA] power transformers with a voltage ratio of 154/23[kV] (YY connection). Their elapsed years were classified into less than 10 years (15 transformers), 10 years or more but less than 20 years (12 transformers), and 20 years or more but less than 30 years (five transformers).

The types and manufacturers of the transformers varied according to each substation's installation sequence, and phase A was set as the reference for the single-phase transformers. Only the accessible areas were measured, and the operating and installation conditions and the load capacity at the time of the measurement were also used to analyze the data. Figure 1 shows a diagram of the vibration measurement and analysis system for the transformers in operation.

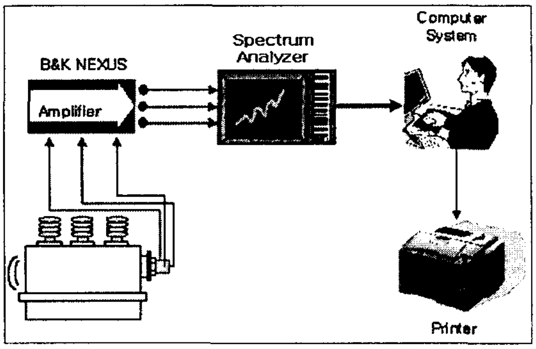

Fig. 1. Vibration measurement and analysis system

2.1 Measurement equipment and methods

The vibration speed ([mm/sec]) at the measurement positions of the transformers in operation were measured, with the measurement frequency range was 0-3.2[kHz] at 1[Hz] intervals. Table 1 shows the devices that were used for the measurement and analysis.

Table 1. Measurement of the transformer vibration

Equipment Name	Specifications
Pulse System	Model : 3039 (B&K) Frequency range : 0~51.2[kHz]
Charge Amplifier	Model : UV-06A (RION) Charge Sensitivity : 105[pC] Acceleration : 0.5~30,000[Hz]±10[%] : 1~15,000[Hz]±5[%] Velocity : 3~3,000 [Hz]±5[%]([mm/s]) Displacement: 3~500[Hz]±10[%]([mm]) 1~1,000 m/s2 (1~9.99[pC]/(m/s2)) 149(H)×33(W)×210(D)[mm], 700[g]
Accelero-meter	Model : PV-95 (RION) Charge Sensitivity : 0.765[pC]([m/s2]) Transverse Sensitivity : 3[%] Capacitance : 397[pF] Vib. range : 1~10,000 [Hz]

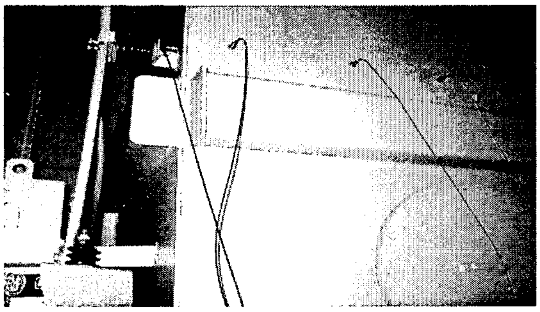

Fig. 2. Measurement of the transformer vibration

Figure 2 shows the vibration measurement on one side (divided in 6x4 sections) of the transformer in operation by attaching an accelerometer on it to ensure optimal conditions and minimum errors.

2.2 The subject transformers

Table 2 shows the specifications of the transformers the vibrations of which were measured. Letters A to I represent the substations. The sets of 32 transformers are represented as Nos. 1 and 2 or Nos. 1 to 4. Most of the transformers were single-phase transformers, but some were three-phase transformers. The three manufacturers are represented as manufacturers ⓐ, ⓑ, and ⓒ, and the years of manufacture were uniformly distributed from 1983 to 2007. The capacity refers to the operating capacity of the transformers at the time of the measurement.

Table 2. Transformers the vibrations of which were measured

Sub-st. Name	Bank Name	Capacity ([kV]/[MVA])	Phase	Company	Year
A	#1	154/60	3	ⓐ	2006
	#2	154/60	3	ⓐ	2006
B	#1	154/60	1	ⓐ	1992
	#2	154/60	1	ⓐ	1992
	#3	154/60	1	ⓑ	1996
	#4	154/60	1	ⓑ	1998
C	#1	154/60	3	ⓒ	1984
	#2	154/60	3	ⓒ	1987
D	#1	154/60	1	ⓐ	2002
	#2	154/60	3	ⓑ	1990
	#3	154/60	1	ⓐ	2005
	#4	154/60	3	ⓒ	1984

Sub-st. Name	Bank Name	Capacity ([kV]/[MVA])	Phase	Comp-any	Year
E	#1	154/60	3	ⓒ	1983
	#2	154/60	3	ⓒ	1983
	#3	154/60	3	ⓒ	1990
	#4	154/60	3	ⓐ	1991
F	#1	154/60	1	ⓐ	2001
	#2	154/60	1	ⓐ	2001
	#3	154/60	1	ⓑ	1996
	#4	154/60	1	ⓒ	2003
G	#1	154/60	3	ⓑ	1990
	#2	154/60	3	ⓑ	1993
	#3	154/60	1	ⓒ	1995
	#4	154/60	1	ⓒ	2004
H	#1	154/60	1	ⓐ	2001
	#2	154/60	1	ⓐ	2001
	#3	154/60	1	ⓐ	2004
	#4	154/60	1	ⓒ	2003
I	#1	154/60	3	ⓒ	1988
	#2	154/60	1	ⓐ	1996
	#3	154/60	1	ⓑ	2007
	#4	154/60	1	ⓑ	2007

3. Test Results

3.1 Measurement of the maximum vibration

Figure 3 shows the vibration of a transformer in operation that was measured with the vibration sensors at each position after dividing one side of the transformer at 1m-or-less equal lengths into a 6x4 matrix structure. At this time, the maximum vibration meant the highest vibration value among those from all the points.

When the position with the maximum vibration speed could already be estimated based on the measurement experiences, not all the positions had to be measured. When a smaller number of measurement positions had been considered in the acceptance or approval tests, however, a prior agreement had to be made with the manufacturer or client.

The structure of the relevant specific part and the installation conditions had to be known before accurate measurement positions could be selected, and the positions where the vibration converter could be properly attached had to be selected as the measurement positions.

The measurement had to be conducted in three orthogonal directions, with one of the measurements conducted in the vertical direction with reference to the transformer surface. The vertical direction with reference to the surface had to be indicated as the Z axis, and the horizontal directions, as the X and Y axes.

The vibration sensors had to be installed on flat and solid surfaces, and the accelerometers were preferably fixed tightly on the measurement positions without using additional mounting blocks. Further details on the installation were in compliance with KS B 0714 (2001)[13].

For the measurement, a transformer was excited with the rated voltage with a rated frequency regardless of the presence of the auxiliary cooler. When a voltage was abruptly applied to the transformer, it was desirable not to measure the vibration for a few minutes after the Sw2 was switched on. If there were additional vibration sources that might have had an impact on the transformer surface vibration, including forced air cooling auxiliary devices and hydraulic pumps, they had to be in operation at the time of the measurement. The subject transformer had to be supported using solid supports or flexible mounts so that they would not have an impact on the vibration of the transformer.

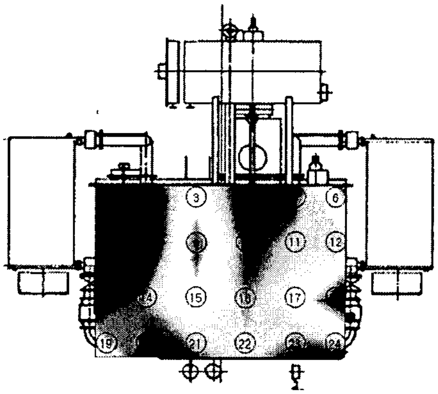

Fig. 3. Points for the transformer vibration measurement

3.2 Measurement results of the maximum vibration

Table 3 shows the maximum vibration measurement results for the single-phase transformers, and Table 4 shows those for the three-phase transformers. B1 refers to Transformer 1 in Substation B. The average vibration is the average of the vibration values of all the transformers [Vib. (avg)], and Vib. (the peak) is the maximum vibration of all the vibration values.

Table 3. Average and maximum vibrations of the single-phase transformers

TR Name	Year	Load ([MVA])	Vib. (avg)	Vib. (peak)
B1	1992	31.0	1.45	2.74
B2	1992	36.0	1.98	3.77
B3	1996	35.0	1.94	3.26
B4	1998	25.0	1.70	3.13
D1	2002	25.3	1.30	2.45
D3	2005	23.0	0.82	1.46
F1	2001	16.3	1.11	2.85
F2	2001	23.3	1.40	3.18
F3	1996	17.8	1.44	2.45
F4	2003	21.9	1.90	8.39
G3	1995	33.3	0.78	1.99
G4	2004	33.8	0.84	2.39
H1	2001	37.0	1.14	4.27
H2	2001	34.0	1.11	2.29
H3	2004	37.0	1.29	2.04
H4	2003	38.0	1.14	4.27
I2	1996	39.0	1.50	2.48
I3	2007	39.0	1.19	3.47
I4	2007	38.0	1.92	3.45

Table 4. Average and maximum vibrations of the three-phase transformers

TR Name	Year	Load ([MVA])	Vib. (avg)	Vib. (peak)
A1	2006	10.0	1.35	2.76
A2	2006	10.0	1.29	2.03
C1	1984	28.0	1.75	2.79
C2	1987	29.0	1.07	3.19
D2	1990	15.0	1.12	3.22
D4	1984	6.4	2.55	6.21
E1	1983	34.6	3.27	5.32
E2	1983	31.8	3.50	6.21
E3	1990	33.6	1.07	1.70
E4	1991	34.5	1.90	8.39
G1	1990	24.6	1.53	3.03
G2	1993	33.8	1.10	2.31
I1	1988	32.0	1.11	2.48

3.3 Analysis of the maximum vibration of the transformers

In assigning vibration classes to the transformers, only the maximum values of all the measured values were taken, according to KS B 0706-6 (2001). Therefore, the maximum vibration values, instead of the vibration values from each point or the frequency used, were used in the analysis, as follows[14].

The magnitude of the maximum vibration was more clearly analyzed by presenting the average values of all the transformers to analyze the maximum vibration values.

Figure 4 shows the average and maximum vibrations of the single-phase transformers, where the average and maximum values greatly differed. The maximum vibration values are local values and are not highly correlated with the average values.

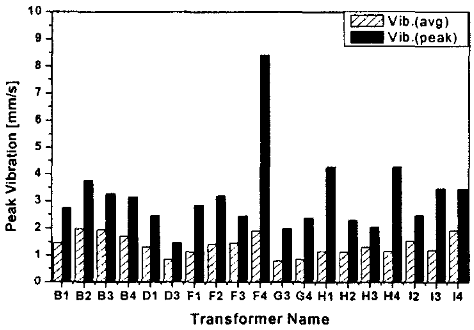

Fig. 4. Graph of the average and maximum vibrations of the single-phase transformers

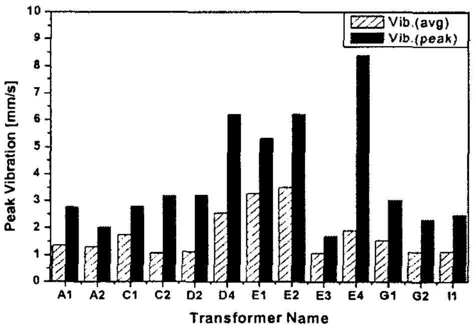

Fig. 5. Graph of the average and maximum vibrations of the three-phase transformers

Figure 5 shows the average and maximum vibrations of the three-phase transformers, where the maximum vibration values are not correlated with the average values, as in the case of the single-phase transformers.

The transformers with the greatest maximum vibration values were Bank 4 of Substation E and Bank 4 of Substation F. They had equal maximum vibrations of 8.39[mm/s].

4. Analysis of the Results

4.1 Classification of the transformer vibration

Table 5 shows the vibration classes for each area of the transformer based on KS B 0706-6. These value guidelines support the evaluation of the vibration severity that was applied to the transformer body and accessories. The vibration severity refers to all the vibration values, including the maximum, average, and rms value, and to a set of values or parameters. This may refer to the instantaneous value or the average value. This is also called the vibration seriousness.

The vibration class is generally classified into seven classes according to type, application, size, composition, flexibility, steel or iron nature, and speed, but in this study, it was classified into four groups considering the flexibility of the rotary machine and the transformer.

If the circumstances allow it, recommendations will be presented on the allowable guideline limits of the values according to the transformer types using this classification. Until then, the operating results or experiences can be used for specific classifications with the agreement of both the manufacturer and the customer. Table 6 shows the descriptions of the evaluation areas. The vibration values of the transformers had a more constant trend over their life than of the rotary machines, so that Classes A and B were combined in this table. It is expected that another set of guidelines for distinguishing Class A from Class B can be established after more experiences have been accumulated.

Table 5. Relationship between the transformer vibration classification and the evaluation area

Vib. Severity	Vibration Division			Evaluation dimension			
	Displacement [μm] (r.m.s)	Velocity [mm/s] (r.m.s)	Acceleration [m/s2] (r.m.s)	1	2	3	4
1.1	17.8	1.12	1.76	A	A	A	A
1.8	28.3	1.78	2.79	B	B	B	B
2.8	44.8	2.82	4.42	B	B	B	B
4.5	71.0	4.46	7.01	B	B	B	B
7.1	113	7.07	11.1	C	B	B	B
11	178	11.2	17.6	D	C	B	B
18	283	17.8	27.9	D	D	C	B
28	448	28.2	44.2	D	D	D	C
45	710	44.6	70.1	D	D	D	D
71	1125	70.7	111	D	D	D	D
112	1784	112	176	D	D	D	D
180				D	D	D	D

Table 6. Guidelines for determining the transformer vibration class

Class	Explain
A	Vibration area of newly installed transformers. It is assumed that most transformers belong to this area.
B	Long-term operation is conventionally allowed without limit.
C	Long-term operation is conventionally adjudged inappropriate. The transformer can generally be operated in this condition for a limited duration until there is a proper chance for maintenance.
D	The vibration is adjudged so severe as to damage the transformer.

4.2 Assignment of the transformer vibration class

Table 7 shows the vibration classes that were assigned based on the vibration classification and evaluation areas in Table 5, using the maximum values of the vibration values that were measured from the power transformers. The vibration classes were assigned with the evaluation areas divided into four areas, and they were organized so that they could be selected according to the circumstances[12].

There were no Class A transformers in the results of the vibration class assignment. This was because there were no newly installed transformers. Most of the transformers were classified as Class B transformers.

There were three Class C transformers in Area 1, and two in Area 2. These were the ones installed in the mid-1980s, which underwent deterioration with the passing of time, and were adjudged not suitable for continuous long-term operation. It seems that the transformer can generally be operated for a limited duration until there is a proper chance for maintenance.

There were only two Class D transformers in Area 1. It could not be concluded, however, that these two transformers deteriorated merely with the passing of time because they were installed in 1991 and 2003. They were adjudged as not satisfying transformer operation standards because of the circumstances that influenced the operating conditions. It seems that an immediate inspection of the transformers is needed, as the vibration was severe enough to damage the transformers.

Table 7. Assignment of the transformer vibration class

TR Name	Year	Phase	Load ([MVA])	Vib. (peak) [mm/s]	Evaluation dimension			
					1	2	3	4
A1	2006	3	10.0	2.76	B	B	B	B
A2	2006	3	10.0	2.03	B	B	B	B
B1	1992	1	31.0	2.74	B	B	B	B
B2	1992	1	36.0	3.77	B	B	B	B
B3	1996	1	35.0	3.26	B	B	B	B
B4	1998	1	25.0	3.13	B	B	B	B
C1	1984	3	28.0	2.79	B	B	B	B
C2	1987	3	29.0	3.19	B	B	B	B
D1	2002	1	25.3	2.45	B	B	B	B
D2	1990	3	15.0	3.22	B	B	B	B
D3	2005	1	23.0	1.46	B	B	B	B
D4	1984	3	6.40	6.21	C	B	B	B
E1	1983	3	34.6	5.32	C	B	B	B
E2	1983	3	31.8	6.21	C	B	B	B
E3	1990	3	33.6	1.70	B	B	B	B
E4	1991	3	34.5	8.39	D	C	B	B
F1	2001	1	16.3	2.85	B	B	B	B
F2	2001	1	23.3	3.18	B	B	B	B
F3	1996	1	17.8	2.45	B	B	B	B
F4	2003	1	21.9	8.39	D	C	B	B
G1	1990	3	24.6	3.03	B	B	B	B
G2	1993	3	33.8	2.31	B	B	B	B
G3	1995	1	33.3	1.99	B	B	B	B
G4	2004	1	33.8	2.39	B	B	B	B
H1	2001	1	37.0	4.27	B	B	B	B
H2	2001	1	34.0	2.29	B	B	B	B
H3	2004	1	37.0	2.04	B	B	B	B
H4	2003	1	38.0	4.27	B	B	B	B
I1	1988	3	32.0	2.48	B	B	B	B
I2	1996	1	39.0	2.48	B	B	B	B
I3	2007	1	39.0	3.47	B	B	B	B
I4	2007	1	38.0	3.45	B	B	B	B

5. Conclusion

In this study, 32 transformers (154[kV]/60 [MVA]) from KEPCO distribution substations in Daejeon and Chungcheongnam-do were selected for vibration measurement.

The measured vibration data were analyzed, and the vibration classes were assigned to the 32 transformers based on KS B 0706-6 by dividing the evaluation areas into four areas.

There were no Class A transformers. Most of the transformers belonged to Class B. There were three Class C transformers in Area 1, and two in Area 2. These transformers were adjudged as not suitable for continuous long-term operation. It seems that these transformers can generally be operated for a limited duration until there is a proper chance for maintenance. There were two Class D transformers only in Area 1. It could not be concluded, however, that these two transformers deteriorated merely with the passing of time because they were installed in 1991 and 2003. They were adjudged as not satisfying transformer operation standards due to the circumstances that influenced the transformers' operating conditions. It seems that their immediate inspection is needed, as the vibration was severe enough to damage them.

It is expected that the results of this study can be used to evaluate the soundness of transformers in operation as basic data. It is necessary, however, to first establish the KS standard for the classification of vibrations.

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Biography

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