Diagnostics of Mechanical Faults in Power Transformers - Vibration Sensor Network Design under Vibration Uncertainty

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ABSTRACT

Power transformer is a critical component in energy transmission, and its failure can cause catastrophic social loss. Among many techniques to prevent the transformer failures, ones using vibration signals show good capability of detecting the mechanical faults. For on-site power transformers, numerous vibration sensors are installed to take into account vibration uncertainty which comes from sizable and complex transformers and random operating condition. It, however, brings about the high maintenance cost of sensing system as well as superfluous data obstructing precise diagnostics. This study proposes sensor positioning to detect mechanical faults of power transformers. Thirty six on-site power transformers in nuclear power plants were employed. Their vibration signals are processed based upon the principles of transformer vibration. Vibration characteristics are analyzed in terms of spectrum analysis, vibration contour plot and high vibration locations. Then the sensor network design framework is proposed which adjusts the number of sensors and their locations to measure high vibration signals robustly under vibration uncertainty. It is demonstrated that the designed sensing system evaluates the health status of the power transformers successfully with the significantly reduced number of sensors.

1. INTRODUCTION

Power transformer, used in a transmission network to step-up or–down a voltage with above 200MVA rating, is the one of key components in power plants. It is also one of the most frequently failed components due to the harsh operating condition such as high temperature, high electric loads, nonstop operation, and outdoor installation. Moreover, deterioration and being high capacity increase the failure rate even more. As the unexpected failure of power transformers can cause the plant shut down with tremendous capital loss, the power transformer should be monitored and maintained properly.

For this purpose, enormous researches have been investigated and these were reviewed by Wang, Vandermaar, and Srivastava (2002), Duval (2002) and Saha (2003). The commonly used techniques are (1) dissolved gas analysis (DGA), (2) power factor analysis, (3) internal temperature measurement, (4) thermography, (5) partial discharge testing (PD), (6) degree of polymerization, and (7) frequency response analysis test (FRA). Among them, the diagnostics using vibration signals is one of the most effective methods to detect mechanical faults such as joint loosening, winding/core movement, wear crack and high vibration. According to Lee, Jung, and Yang (2003), the mechanical failures are important because of their high portion of total failures (about 40% in Korean nuclear power plants) with little researches against them compared with the other chemical and electrical failures. In order to diagnose the transformers, Ji, Cheng, and Li (2005), Ji, Luo, and Li (2006) and Ji, Zhu, and Li (2011), used core vibration signals by analyzing the correlation between electrical signals and core vibration. Bartoletti, Desiderio, Di Carlo, Fazio, Muzi, Sacerdoti, and Salvatori (2004) classified the transformers health condition with health-related parameters from the spectrum of a transformer tank vibration. Garcia, Burgos, and Alonso (2006) proposed the tank vibration model which is a function of current, voltage and temperature. Hu, Wang, Youn, Lee, and Yoon (2012) proposed two health indices and a copula-based health grade system from tank vibration spectrum signals. Li, Zhao, Zhang, and Lou (2012) employed hidden Markov model to diagnose the mechanical faults of on-load tap changer (OLTC) and Borucki (2012) measured the vibration of transient state and analyze in time-frequency domain to distinguish the 4 health states.

Above researches have proven that the vibration signals are effective to detect the mechanical faults in transformers. In order to apply these researches to on-site power transformers, the one of things required is a sensor network (SN) design that is to design the type, number and locations of the sensors. In general, field experts install numerous vibration sensors on the transformer tank to cope with the vibration uncertainty coming from its large size, complexity and variant operating conditions. The sensing system with numerous sensors has high failure rate with low reliability and high install/maintenance cost. Also it may acquire health-irrelevant superfluous data obstructing precise transformer health assessment. Above researches suggested to install few sensors based upon a transformer structure and vibration mechanics without the quantitative analysis on transformer vibration characteristics. Only Garcia et al. (2006) install the sensor of which the vibration is most similar to that of inner winding. This method has limitations that 1) it is hard to be applied in the operating transformers of which the inner part is not accessible and 2) can be prone to measure a core vibration which is correlated with mechanical faults in core. Therefore this paper aims at developing the framework of SN design capable of detecting the mechanical faults of power transformers using the minimized number of sensors. The rest of this paper is organized as follows: Section 2 explains transformer vibration principle, employed target power transformers and data acquisition method; Section 3 analyzes the characteristics of power transformer vibration with acquired vibration data; Section 4 proposes the framework of SN design; Section 5 shows the diagnostics of mechanical faults in power transformers followed by the conclusions in Section 6.

2. OVERVIEW OF TRANSFORMER VIBRATION AND DATA ACQUISITION

2.1. Principles of transformer vibration

Transformer vibration originates from an inner core and winding shown in Fig. 1. Their vibrations are induced by magnetostriction and electromagnetic force respectively. Magnetostriction, shape changing of a ferromagnetic material due to alternating magnetic field, yields the core vibration. And electromagnetic force, interaction force between winding current and leakage flux, results in the winding vibration. Two forces are respectively proportional to the squared voltage and current of electrical signal. Therefore, the excitation frequency of the core and winding is twice frequency of alternating current. Additionally it is known that the core has higher harmonic frequencies due to the nonlinearity of core magnetostriction.

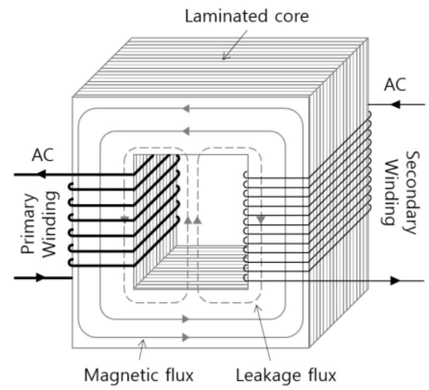


Figure 1. Core, winding and electromagnetic signals

2.2. Description on target power transformers

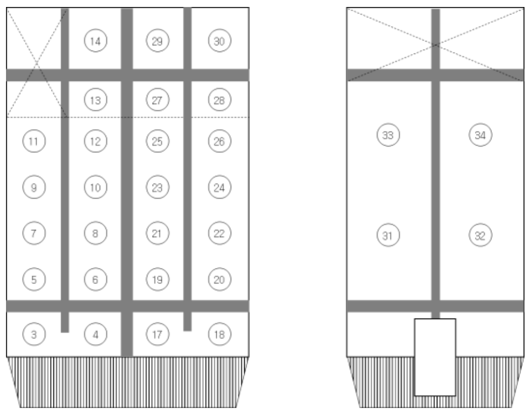
In this study, the thirty six power transformers in two nuclear power plants are employed. They are almost homogeneous in terms of a same manufacturer, same type (single phase, oil-filled, shell type), and similar power capacity. They are divided into six groups according to their tank surface structure and install year ranging from the oldest 1988 to the newest 2003. Table 1 summarizes the informations above with repair history and the number of installed sensors explained in next subsection. The power transformers operate at 100% full power and their electrical signals are overall steady with 60Hz frequency.

Table 1. Information about target power transformers

Group	1	2	3	4	5	6
Plant	α plant			β plant		
Unit #	1, 2	3, 4	5, 6	1, 2	3, 4	5, 6
Char.	single-phase, same manufacturer, oil-filled, shell type					
Capa. (MVA)	362*3	353*3	396*3	360*3	353*3	396*3
Install year	88	96	03	86	93	01
Replaced	O	X	X	O	O	X
# of sensors	44	48	48	44	36~40	38~40

2.3. Data acquisition

In order to measure the transformer vibrations, it is desirable to install sensors inside where the vibration originates from. However highly intense electromagnetic field, inner-filled oil and high temperature make it impossible. Instead, the sensors were installed on the tank surfaces of the power transformers. As the vibration of core and winding is transmitted to the surfaces through the inside oil, it is possible to measure the inner parts vibrations indirectly. The tank surface was reinforced with rib structures to reduce the vibration, thus the sensors were installed in the grids of the four side surfaces as shown in Fig. 2. According to the accessibility of the power transformers, the numbers of installed sensors are slightly different as shown in Table 1. In this study, B&K 4381 and PCB 357B33 charge type accelerometers and charge amplifiers (RION UV-06A) were used.



a) left side b) Front side

Figure 2. Sensor install on the a) left and b) front side tank surfaces of power transformer

Based upon the transformer vibration principle in Section 2.1, we know that the power transformer vibrates at low to medium frequency range and its spectrum data is informative to assess the condition of the core and winding where most mechanical failures occur. Thus, vibration velocities at every 1.25Hz up to 2000Hz were measured. Depending on the test availability of each transformers, the vibrations were measured for three times with the interval of 10 and 6 months. As a result, 108 measurements (=36 transformers*3 measurements) were conducted and each measurement include the spectrum data from multiple sensors.

3. POWER TRANSFORMER VIBRATION CHARACTERISTICS

This section analyzes the vibration characteristics of the power transformers in terms of spectrum signals, vibration signal trend, vibration contour plots and operation years. This helps the understanding of overall transformer behavior and the development of the SN design framework which the goal of this research.

3.1. Spectrum signal characteristic

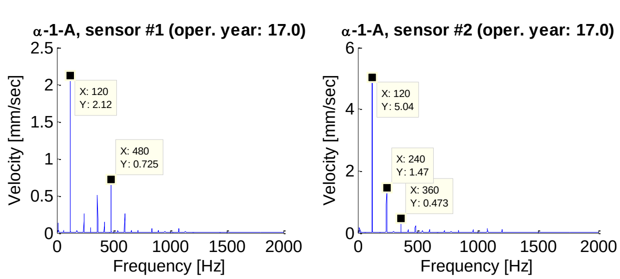
Fig. 3 shows the spectrum signals from the sensors #1 and 2 of unit #1 phase A transformer in plant α. This transformer is one of the oldest ones, and should be mainly concerned. The operation year in figure 3 is the duration from the transformer install to the measurement. The obervations are listed below.

- Peak signals occur at every 120Hz which is twice frequency of electrical signal (60Hz), highly according with Section 2.1.
- In general, 120Hz fundamental signals has the largest value and subsequent harmonic signals become smaller as shown in Fig.3 b). There are exceptions as well like Fig. 3 a).
- In Fig. 3, sensor 1 installed 30cm apart from sensor 2 has under half 120Hz amplitude of sensor 2. For 120Hz signals from whole sensors of the same transformer, the maximum and minumum values are 34.3 and 0.19 mm/sec. Therefore, it is concluded that the transformer vibration signals strongly depend on their sensor locations.

3.2. Vibration signal trend

Fig. 4 shows the 120 and 240Hz signals, representative of fundamental and harmonic signals, from the right-side sensors of the same transformer. The numbers in legend indicate the operation years.

- The signals do not increase as the operation year increases. This is because the measurement interval, maximum 1.3 years, is too short to observe transformer health degradation comparing to its design lifetime 30-50 years.
- Regardless of the operation years, signal are mixed up overall. It means that the vibration signals have randomness and high amplitude signals are robust to the randomness. The vibration randomness comes from uncertainty factors such as manufacturing defect,



a) sensor #1 b) sensor #2

Figure 3. Spectrum signals of unit #1 phase A transformer in α plant (group 1)

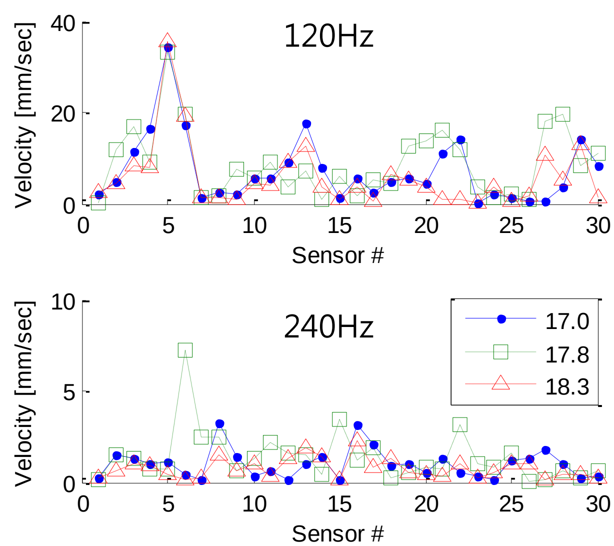


Figure 4. Sensor-wise 120 & 240Hz signals of unit #1 phase A transformer in α plant (group 1)

maintenance, measurement time (temperature & humidity), measurement error, electrical signal input.

- For the other uncertainty factors, it is known that sensor install position error is allowable within 5cm (Ji et al., 2011), the transformer temperature does not affect the vibration severely (Canadian electricity association, 1997), and the electrical signal input is highly steady.

3.3. Vibration contour plots

In order to analyze vibration aspect specifically, the normalized contour plots of 120 and 240Hz signals from the right-side sensors of unit #1 transformers in α plant is depicted in Fig. 5.

- Although three transformers have the exactly same tank surface structure, their vibration aspect are different. The difference comes from the uncertainty factors discussed in Section 3.2.
- For 120Hz, the high vibrations are concentrated on an upper region consistently.
- For 240Hz, whereas, the high vibrations are scattered in whole region and do not maintained through time flow. The reason why 240Hz signals have high randomness is

3.4. Aging effect on vibration

As the measurement interval is too short to observe the health degradation, whole 36 transformers are compared together. The Fig. 6 plots the root mean square (RMS) and maximum value of whole measurements along their operation time. It is found that the scale of maximum values are about three times that of RMS values meaning that each vibration measurement consists of small amplitudes values for the most part. That is, the transformer vibration can be characterized by the high amplitude values. This inference can be verified by the more obvious signal increase of 120Hz maximum value along the operation time compared with that of 120Hz RMS value. The reason why 240Hz signals do not increase as 120Hz ones is that it is only affected by the core health degradation whereas 120Hz by core, winding, joint loosening, and other mechanical faults.

4. SENSOR NETWORK DESIGN FRAMEWORK

This section propose the SN design framework in order to diagnose the mechanical faults in power transformers with the minimized number of sensors. The analyzed transformer vibration characteristics in Section 3 can be summarized as follows.

- The transformer vibration has the fundamental frequency of 120Hz and harmonic frequencies at every 120Hz.
- Many uncertainties prevail in the transformer vibration making vibration aspects in an identical transformer different and signals mixed up.
- Only few sensor points give high amplitude signals which are resistant to uncertainty factors and characterizing the vibration condition of transformers.
- High amplitude points are concentrated on upper surface region consistently for 120Hz and scattered for 240Hz.

Thus, the designed SN needs to (i) be robust to the vibration uncertainty such as moving high amplitude location and (ii) detect the high amplitude signals of 120Hz and 240Hz signals which are relevant to the mechanical health condition of power transformers. To make it realized, multiple sensors should be utilized, meanwhile their quantity can be minimized using the consistency of high vibration locations, especially for 120Hz. The procedures to design the SN are listed below.

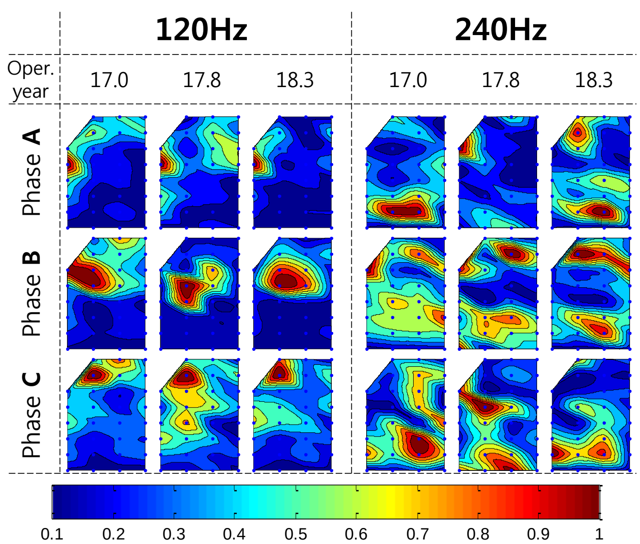


Figure 5. Normalized vibration contour plot unit #1 transformers in α plant (group 1)

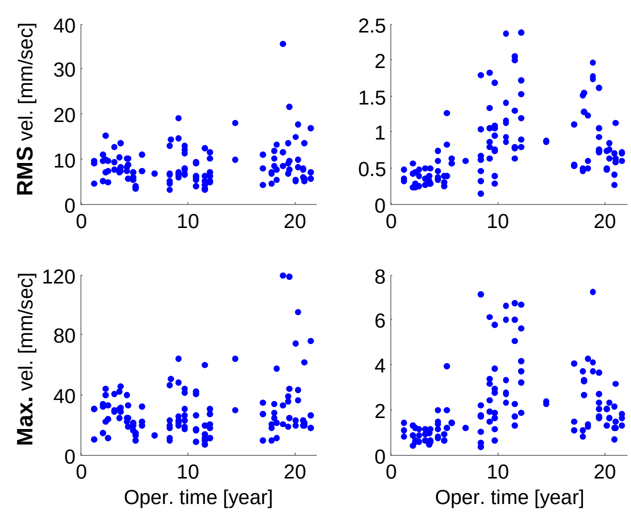


Figure 6. RMS and maximum values of whole vibration measurements

(1) Determine target relative signal levels δ_f for fundamental and 2nd harmonic frequencies respectively. In this study, $f = 120, 240$Hz.

(2) For all measurements and two frequencies, extract sensor locations sets $\{i\}_j^f$ measuring the signal above the target relative signal level δ_f.

$$\text{Find } \{i\}_j^f \text{ such that } \frac{S_{i,j}^f - \min_i S_{i,j}^f}{\max_i S_{i,j}^f - \min_i S_{i,j}^f} \geq \delta_f \qquad (1)$$

where $S_{i,j}^f$ indicates the signals at f frequency from ith sensor of jth measurement.

(3) Find an intersection sensor location set $\{k\}$ having at least one sensor location in common with the extracted sensor location sets $\{i\}_j^f$ in step (2).

$$\text{Find } \{k\} \text{ such that } N\left(\{k\} \cap \{i\}_j^f\right) \geq 1 \text{ for all } j \;\&\; f \qquad (2)$$

(4) In case of multiple intersection sensor location sets $\{k\}_l$, choose one set having the highest mean detectability which is the overall measure of detecting relatively high amplitude signals.

$$\underset{l}{\operatorname{argmax}} \; \underset{f,j}{\operatorname{mean}} \frac{\max_i S_{i=\{k\}_l,j}^f - \min_i S_{i,j}^f}{\max_i S_{i,j}^f - \min_i S_{i,j}^f} \qquad (3)$$

The designed SN is capable of measuring the relatively high signals above δ_f for all measurements, and has high probability of detecting the high amplitude signals in following new measurements, that is robust to the transformer vibration uncertainty. As the result of SN design, the number of used sensors for different target relative signal levels is plotted in Fig. 7. As the target relative signal level rises, the required number of sensors increase. The increment in the number of sensors is larger for 240Hz signals having more uncertainty compared with 120Hz signals. Fig. 8 show the designed sensor positioning for group 1 transformers at different target relative signal levels. For the low target level, the important sensor locations are selected first and then

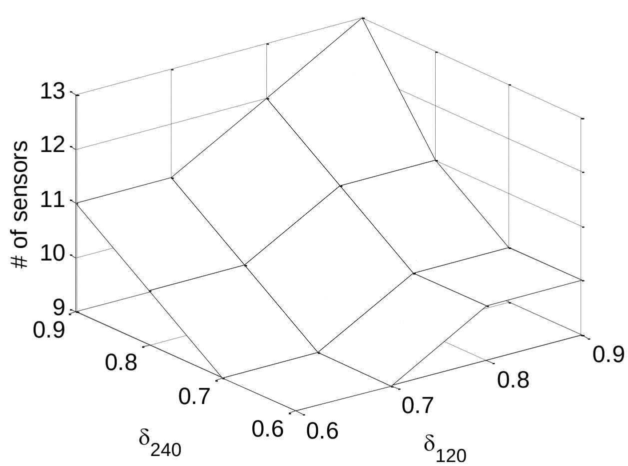
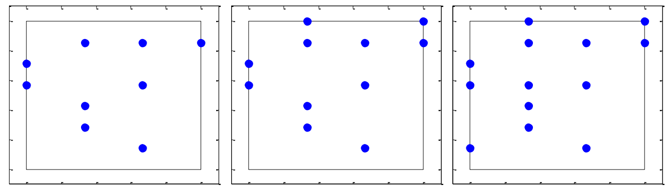


Figure 7. The number of sensors used in SN design for allocated target relative signal levels (group 1)



a) $\delta_{120}, \delta_{240} = 0.7$ b) $\delta_{120}, \delta_{240} = 0.8$ c) $\delta_{120}, \delta_{240} = 0.9$

Figure 8. Sensor positioning at different target relative signal level (group 1)

additional sensors are installed in other locations for the higher target level.

In order to demonstrate the performance of the designed SN, the maximum values from the whole sensors and the designed SN with $\delta_{120}, \delta_{240} = 0.7$ from 6 groups are plotted in Fig. 9. The designed SN can detects the 70% above signals for all measurements. With respect to the maximum amplitudes, it can detect 87.7% of 120Hz and 64.9% of 240Hz maximum values while reducing the number of sensors about 75%.

5. DIAGNOSTICS OF MECHANICAL FAULTS

This section shows the diagnostics of mechanical faults in power transformers based upon the designed SN. From Section 2 and 3, the high vibration signals at fundamental and 2nd harmonic frequencies are related to the mechanical health states. If the fundamental frequency signals increase only, the mechanical faults of the winding can be predicted. If the 2nd harmonic signals increase, that of the core can be predicted. And when both arise, both faults can be predicted as well.

In this study, the two health indices are proposed; fundamental health index (FHI) and harmonic health index (HHI) which are the maximum values of acquired signals at fundamental and 2nd harmonic frequencies respectively.

$$FHI = \max_{i \in \{k\}} S_i^{120} \qquad (4)$$

$$HHI = \max_{i \in \{k\}} S_i^{240} \qquad (5)$$

where $S_{i,j}^f$ is the signals at f frequency from ith sensor of jth measurement and $\{k\}$ is the sensor sets of designed SN. According to the vibration principles in Section 2,1, FHI is related to the health condition of the winding and core and HHI is related to that of the core. Fig. 10 plots two health indices of power transformers using the designed SN ($\delta_{120}, \delta_{240} = 0.7$). The diagnostics results are listed below.

- The newest transformers in two power plants (group 3 and 6) have low health indices.
- Group 4 in has high FHI without changing HHI, meaning that winding health condition has degraded. The transformers in group 4 were replaced by field experts due to its health degradation.

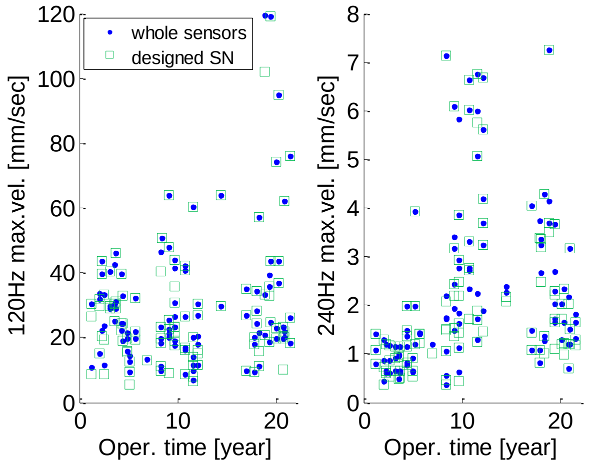


Figure 9. Comparison of maximum signals from whole sensors and designed SN ($\delta_{120}, \delta_{240} = 0.7$)

- Group 1 and 5 have high *HHI* and low *FHI* similar to that of the newest transformers group 3 and 6 are estimated to have the core in bad health condition. Those transformers were replaced by field experts due to its health degradation.
- The middle aged group 2 locates between the oldest group 1 and the newest group 3.

The diagnostic results coincide with the repair history and operating times, demonstrating the performance of the proposed SN design framework and two health indices.

6. CONCLUSIONS

This paper proposed the SN design framework for mechanical fault detection of power transformers. Using the acquired vibration that from the on-site power transformers in nuclear power plant, the characteristics of the power transformers are analyzed in various respects. The proposed SN design framework adjusts the number of sensors and their locations to be robust to the vibration uncertainty and detect high amplitude signals of fundamental and 2nd harmonic frequency relevant to the mechanical health condition of power transformers. The fault diagnostic of power transformers is conducted based upon the designed SN with the proposed two health indices, *FHI* and *HHI*. From the accordance of diagnostic results with the repair history and operating times, the proposed method are proved to be suitable for mechanical fault diagnostic for power transformers. Moreover, the designed SN consists of significantly reduced number of sensors, and this saves the data size by measuring health-relevant data and the cost of sensor install/maintenance.

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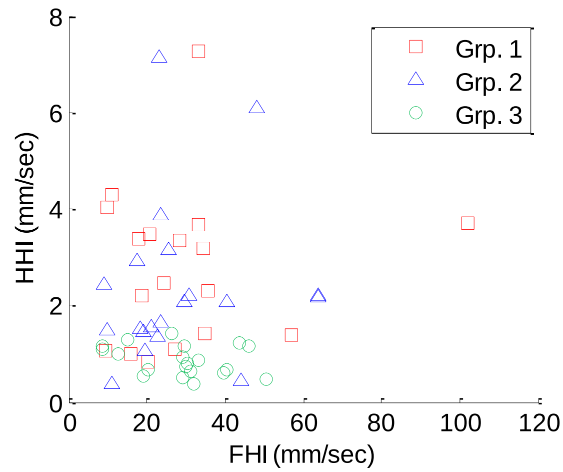
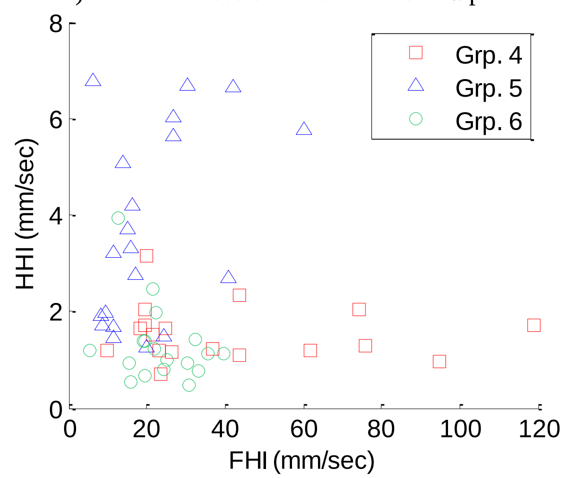


a) Health indices of transformers in α plant



b) Health indices of transformers in β plant

Figure 10. Health indices of power transformers using the design SN ($\delta_{120}, \delta_{240} = 0.7$)

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BIOGRAPHIES

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Mr. Wook-Ryun Lee received his Master's degree in Mechanical Engineering from Chungnam National University in 2004 and his Bachelor's degree from Yonsei University in 1997. He is currently a senior researcher in the Green Energy Laboratory of the Research Institute in the Korea Electric Power Corporation, Daejeon, Korea. His research interests are control of noise and vibration generated from power plants, and kinetic energy storage system such as flywheel energy storage, energy-harvesting etc.