Feasibility Study on Condition Monitoring of Power Network Asset Using PMU Measurements

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***Abstract*—Current asset management for distribution networks has adopted a passive strategy - either run to failure or perform field inspection of limited assets within a fixed period. This paper aims to study the feasibility of using high-resolution data recorded by phasor measurement units (PMUs) for real-time asset monitoring. Accelerated ageing experiment on a laboratory transformer and the insulator pollution experiment have been performed. The PMU measurements collected from both experiments are used to evaluate the asset health conditions by examing the standard deviation of the signal to noise ratio (SNR) after the statistical analysis and noise segregation of the original PMU measurements. A comparative study between the traditional condition assessment method and the proposed method demonstrates the feasibility of using the PMU data to evaluate the asset health conditions.**

Keywords—Asset condition monitoring, PMU, transformer ageing, insulator failure, signal to noise ratio

I. Introduction

The rapid deployment of distributed generators (e.g., solar photovoltaic-PV) has created many new challenges to distribution power networks due to the bi-directional power flow and PV power fluctuations. These new issues will accelerate the ageing and deterioration of electrical assets which were originally designed to be operated under a uni-directional and slow-changing power flow [1]. The accelerated deterioration will stress the aged distribution networks. For example, in the Australian Queensland distribution network, a large amount of equipment in distribution systems has aged more than its designed life, which poses a substantial risk to reliable electricity supply.

Traditionally, one way of monitoring assets such as transformers that use insulation paper and oil samples is to test dissolved gases in the oil. This is known as dissolved gas analysis (DGA)[2]. In DGA method, the rate of change in gas concentrations can be an early indicator of faults and the absolute gas concentrations can be correlated to the overall ageing of the transformer insulation paper. The Duval triangle method is usually used to process the dissolved gases concentration and identify different fault types (e.g., thermal faults and discharge faults) from DGA[3]. There are some disadvantages for this DGA-based approach such as the requirement of specialised skills to collect oil samples and the impracticality of taking oil samples frequently from the tank which makes monitoring the development of dissolved gas concentrations less time effective. An alternative approach is to install online DGA monitoring instrumentation into the transformer tank, which is comparatively expensive. There are a vast number of assets (e.g., transformer) in distribution networks. It is noneconomical and almost impractical to continuously monitor all these assets. Therefore, current asset management for distribution networks has adopted a passive strategy - either run-to-failure or performing field inspection of limited assets within a fixed period [4]. As a result, such a passive strategy can lead to totally unprepared outages or unexpected failures between inspections. This presents an opportunity for leveraging real-time measurements as an alternative for the condition monitoring of distribution network assets.

Considering the above challenges in the existing power utility practice, PMUs synchronised by Global Positioning System (GPS) provide an opportunity to monitor equipment conditions in a proactive manner. This could be achieved by investigating the characteristics of the PMU measurements over a period of time and determining possible relationships between asset conditions and PMU data variation features. Therefore, the development of the PMU-based condition monitoring approach is important to provide an economical and reliable alternative to traditional techniques.

An attempt has been made in [5] to identify the incipient failure of a past catastrophic transformer explosion with the variation band of the signal to noise ratio (SNR) of voltage and current signals. The preliminary results in [5] do show a promising potential usage of PMU data for transformer incipient failure prediction. However, there is no solid demonstration and theoretical explanation on why the faulty transformer can cause the SNR variation band to increase. Therefore, this research aims to investigate the possibility of using PMU measurements to evaluate the health condition of two types of power assets (i.e., oil-immersed transformer and silicone rubber insulator) through experiment demonstration. Specifically, both extensive transformer ageing experiment and insulator pollution experiment were conducted using a specially designed facility in the laboratory along which the PMU data were continuously collected for asset condition monitoring.

The main contributions of this paper are shown below:

- Dedicated experiment design to collect the PMU measurements for PMU-based asset condition monitoring.

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- Feasibility study of the standard deviation of the SNR for the evaluation of transformer ageing conditions and the insulator erosion situations.
- Linking the standard deviations of the SNR to the actual ageing conditions of the studied asset.

II. Methodology for Asset Condition Evaluation

A. Traditional Transformer Condition Monitoring

The traditional transformer condition monitoring is performed through the DGA on transformer oil and the degree of polymerization (DP) measurement on insulating paper. In this paper, the DGA and transformer operating analysis results will be the benchmark for the results from the SNR-based asset condition monitoring method.

The transformer's operational year can be estimated by DP value using (1) [6].

$$Operational\ Year = 20.5 \cdot \log \left(\frac{1100}{DP}\right) \tag{1}$$

The Duval Triangle method is employed to determine the fault that occurred inside the transformer. The schematic for the Duval Triangle method is shown in Fig.1. The equations to evaluate the fault type are shown below.

$$\begin{cases} \%C_2H_2 = 100 \cdot \dfrac{x}{(x+y+z)} \\ \%C_2H_4 = 100 \cdot \dfrac{y}{(x+y+z)} \\ \%CH_4 = 100 \cdot \dfrac{z}{(x+y+z)} \end{cases} \tag{2}$$

where x, y, z are the concentration of three types of gases C_2H_2, C_2H_4, CH_4, respectively.

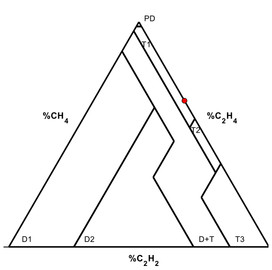

Fig. 1 Fault detection by Duval triangle

Fault types identified by Duval triangle:
- D1: Discharge fault with low energy
- D2: Discharge fault with high energy
- DT: Fault caused by electrical and thermal stress
- PD: Partial discharge faults
- T1: Thermal Fault at Temperature < 300°C
- T2: Thermal Fault at Temperature> 300 °C and < 700 °C
- T3: Thermal Fault at Temperature > 700 °C

B. SNR-based Asset Condition Monitoring Using PMU Data

The flowchart for the proposed method is shown in Fig. 2. To analyse the SNR of PMU measurements, noise must be segregated from the raw data. A median filter is used to segregate the noise from the original PMU data. The order of the median filter is selected using the trial and error method. The noise distribution and the normalized auto-correlation coefficients (NACC) are used to evaluate the filter performance [7]. If the filter order is properly selected, the noise will follow the Normal distribution and the NACC will be less than 0.1. After the noise segregation from the measurements, the SNR can be further determined. Then the SNR standard deviation will be calculated to evaluate the asset conditions.

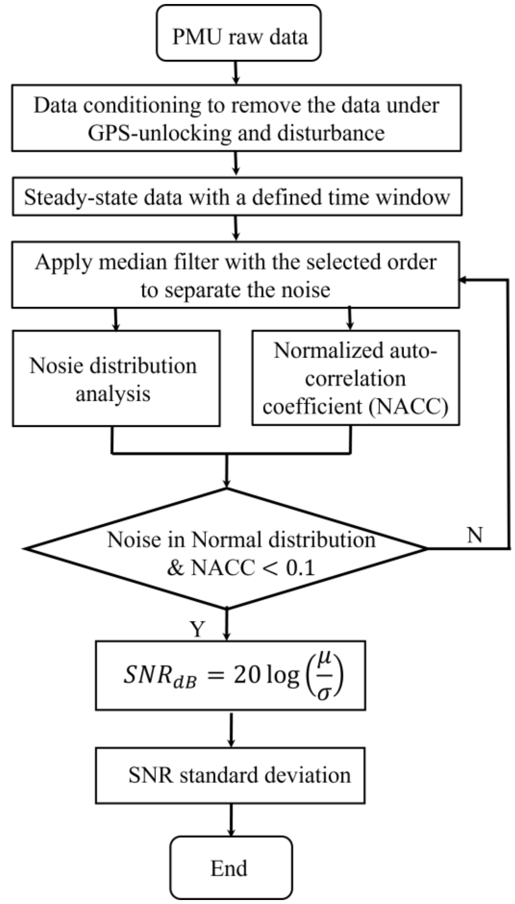

Fig. 2 Flowchart of SNR-based asset condition monitoring using PMU data

The normalized auto-correlation calculation r_{xx} is calculated by (3) to determine whether the filtered noise samples are independent or correlated [7].

$$r_{xx}(l) = \frac{\sum_{n=1}^{N} \eta(n) \cdot \eta(n-l)}{\sum_{n=1}^{N} \eta(n)^2} \tag{3}$$

where N is the total number of samples. l is the delay. $l = [(-N+1), (-N+2), \ldots, -1, 0, 1, 2, \ldots, (N-2), (N-1)]$.

The average NACC of γ_{xx}^{AVG} at all the lags are calculated based on (4). It needs to be noticed that a small value of average NACC is reasonable to show the statistical dependence of the filtered noise is minimal.

$$\gamma_{xx}^{AVG} = \frac{1}{N-1} \sum_{l=1}^{N-1} |\gamma_{xx}(l)| \tag{4}$$

Once the noise is subtracted from the raw data, the SNR in dB can be calculated by (5).

$$SNR_i = 20 \log \left(\frac{\mu}{\sigma}\right) \tag{5}$$

where μ is the mean value of the true signal and the σ is the standard deviation of the noise.

The standard deviation of the SNR δ is obtained by (6).

$$\delta = \sqrt{\frac{1}{M}\sum_{i=1}^{M}(SNR_i - \frac{1}{M}\sum_{i=1}^{M}SNR_i)^2} \qquad (6)$$

where δ is the standard deviation of the SNR, M is the total number of the SNR in the defined time period for the standard deviation calculation. Based on the study, the SNR standard deviation is better than the absolute value of SNR to evaluate the conditions of the asset. Their comparative study will be discussed in Section IV.

III. Experiment System Introduction

A. Transformer Aging Experiment System

In this study, the extensive ageing experiment is performed on a single-phase laboratory transformer which is a scaled-down prototype of a real power transformer [8]. The rated capacity of the experimental transformer is 5kVA with a ratio of 240V/2000V. The winding of the experimental transformer is a shell type. Fig. 3 shows the diagram of the ageing experiment where a PMU was installed to monitor the voltage, current and frequency of the transformer. Given the small current flowing through the transformer winding which may not be able to generate sufficient heat for the ageing experiment, a controllable heater was installed on the bottom of the prototype transformer to boost the temperature of the transformer and accelerate its ageing process. In addition, fibre optical sensors were also deployed at different positions along the winding to record the temperature distribution of the transformer. With these setups, the temperature of the prototype transformer can be fully controlled to emulate different thermal ageing conditions.

The ageing experiment is conducted on the laboratory transformer for an equivalent of 56 days. During the ageing, the transformer is kept at 85 ºC with a 30A load current. Oil samples and cellulose paper were regularly collected to measure the dissolved gas concentration in transformer oil and DP value as well as the moisture content of the insulating paper.

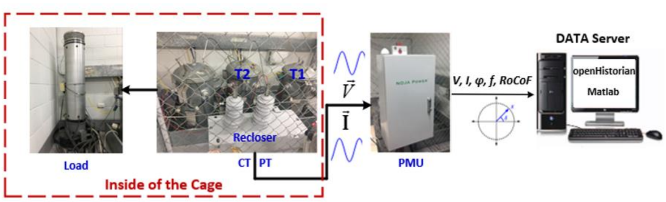

Fig. 3 Transformer ageing experiment platform

B. Insulator Pollution Experiment System

The aim of this experiment is to investigate the feasibility of using low-resolution PMU measurements for insulator arcing detection due to the pollution on its surface. Firstly, the experiment system was established as shown in Fig. 4. The pollution of the insulator was accelerated by spraying the salt solution on its surface in the salt fog chamber at NOJA Power testing laboratory. This aims to imitate the polluted environment of the insulator installed at the feeder near the coastal area. The artificial pollution experiment is conducted based on the IEEE standard [9]. Two types of devices, including the Power Quality Meter (PQM) and PMU, are used to record the voltage/current at high-voltage (HV) and low-voltage (LV) windings, respectively. As shown in Fig. 4 (b), the HV side of the transformer is open-circuit when there is no arcing fault during the experiment. Thus, the current of HV winding is also zero and the measured signal by PMU only contains voltage (9.9kV). At the same time, the LV current measured by PQM is zero as well. As the experiment continues, arcing faults occurred on the insulator surface. Then, voltage drop was recorded by PMU while current surge was measured by PQM. Therefore, the current waveform recorded by PQM with 1024 samples per cycle and the voltage data recorded by PMU with 1 sample per cycle are used for the condition assessment. The effective days for the analysis are 54.

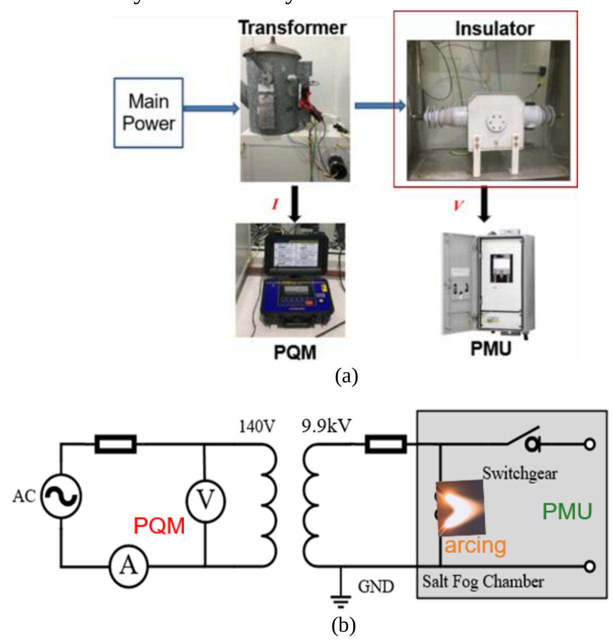

Fig. 4 (a) Insulator pollution experiment system and (b) schematics digram.

IV. Results Analysis and Discussions

A. DGA and DP Results from Transformer Aging Experiment

Table I summarises DGA measurements and DP values of transformer ageing experiment at different ageing stages. The transformer insulation paper and oil analysis results will be the baseline of SNR analysis results. Fig. 5 shows the correlation between the measured DP values and the operation year of the transformer as determined by (1). It shows the equivalent age of the transformer is 9.5-year before the ageing experiment and it reaches 12.9 years after 56 days of ageing, which means the transformer insulation is still in very good condition.

TABLE I. Dissolved Gas Concentrations and DP Values at Each Ageing Stage

Ageing days	*DP*	*CH_4 (ppm)*	*C_2H_4(ppm)*	*C_2H_2(ppm)*
1	690	11	11	0
19	649	10	8	0
38	605	12	8	0
56	586	7	4	0

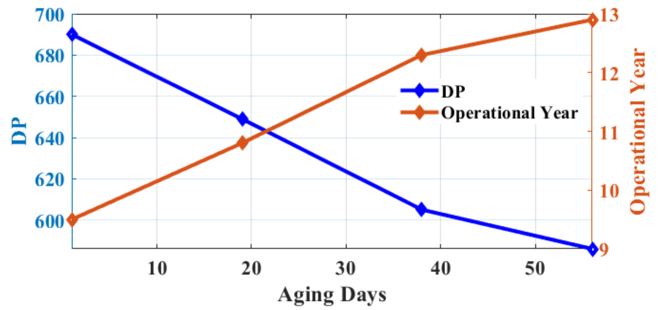

Fig. 5 DP and estimated operational year of the transformer in the experiment

Based on the collected gas concentration in Table I, Duval triangle method is employed to identify the incipient faults of the transformer, which is shown in Fig. 6. The red dots indicate the transformer was subjected to thermal faults with a temperature lower than 300°C at all ageing stages. This fault is caused by the thermally accelerated ageing experiment. Therefore, there is no other fault occurred inside of the transformer during the experiment.

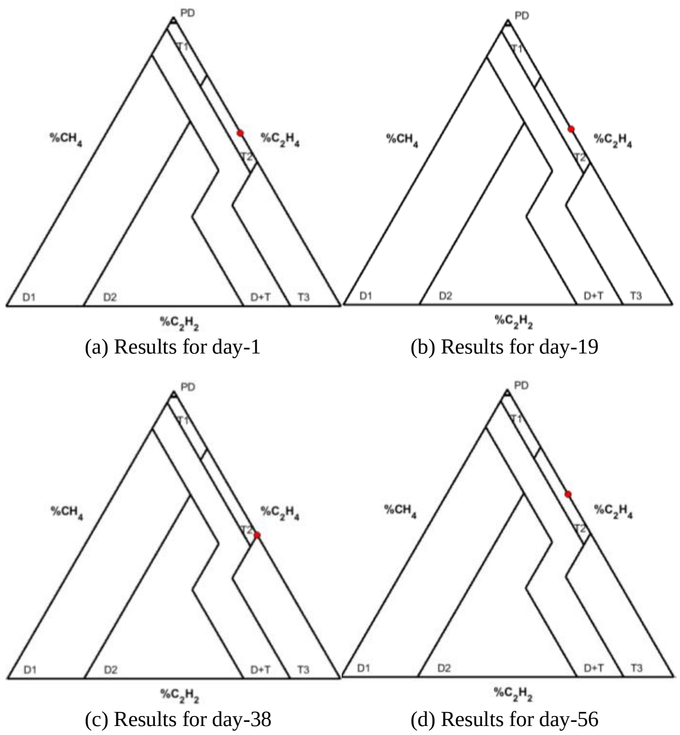

Fig.6 Incipient faults identified by Duval triangle method at each ageing stage

The analysis results from the DP and DGA will be used as the baseline to validate the feasibility of the SNR standard deviation of PMU data for the asset condition monitoring.

B. PMU Results from Transformer Ageing Experiment

In this section, the original time-series PMU measurements are scanned using a moving window with a length of 10s. For the PMU data within the window, a median filter with order 41 is used for noise segregation. One example of the noise distribution, NACC results, and noise segregation are shown in Fig. 7. It is observed that the NACC of the extracted noise are all less than 0.1 and the extracted noise generally follows Gaussian distribution. Hence, the extracted noise signal is considered as the true noise signal. Then, the extracted noise signal and the true signal are used for SNR calculation.

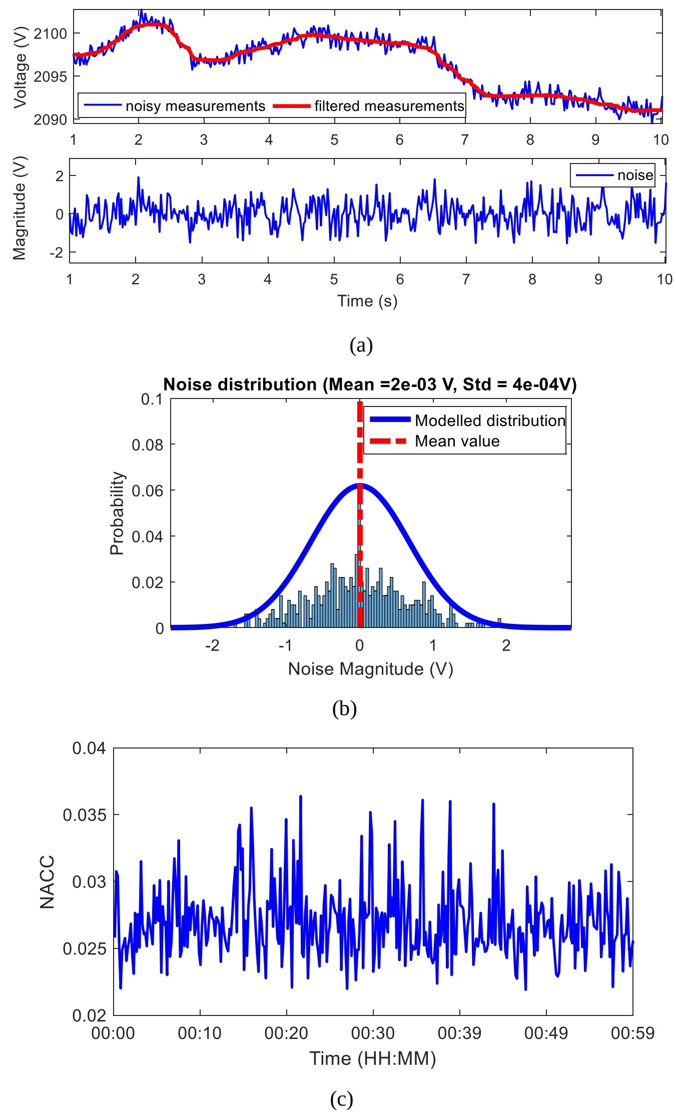

Fig. 7 (a) Original 10-second PMU data and extracted noise using the median filter (b) noise distribution (c) NACC of one-hour voltage measurements

The SNR and its standard deviation for voltage measurements during the 56-day ageing experiment are shown in Fig. 8. The density presents the distribution of the different SNRs each day. The average value of SNR is 69 dB. It is hard to see the trend of the SNR variation based on the direct SNR values, while the increasing trend can be observed from the standard deviation of the SNR. Although the SNR standard deviations with very high density are mainly concentrated within 1 dB, the overall trend of the SNR standard deviation increased with the ageing of the transformer. The correlation between the equivalent operational year and the standard deviation is summarised in Table II. Based on these results, the ratio between SNR standard deviation and the operational year is 0.35 dB/year. Therefore, the SNR standard deviation can be used as a feature to estimate the actual operational year of the transformer.

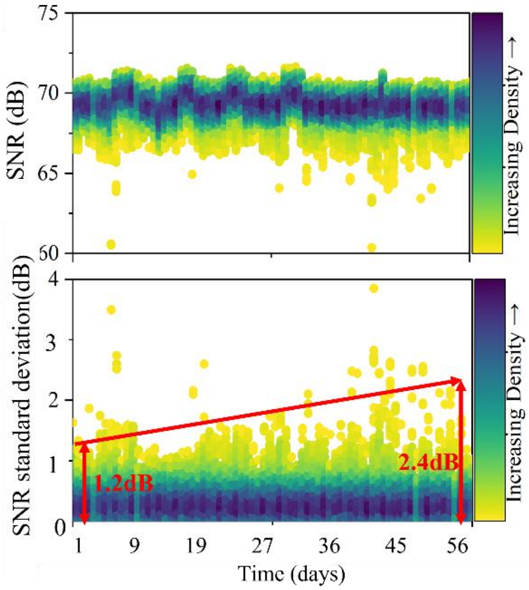

Fig. 8 (a) SNR of voltage measurement and (b) Standard deviation of SNR on different ageing days in transformer ageing experiment

TABLE II. CORRELATION BETWEEN OPERATIONAL YEAR AND SNR STANDARD DEVIATION ON DIFFERENT AGEING DAYS

	Day-1	Day-56
Operational year (year)	9.5	12.9
Standard deviation (dB)	1.2	2.4

C. PMU Results of Insulator Pollution Experiment

Similarly, the voltage SNR and SNR standard deviation from the insulator pollution experiment are as shown in Fig. 9. The average voltage SNR is 60dB which is 9dB lower than that of the transformer ageing experiment. In other words, the calculated noise level in the insulator experiment is much higher than that in the transformer experiment. Furthermore, the SNR standard deviation is much bigger than that of the transformer experiment and the density is almost evenly distributed between 0 to 17.5dB.

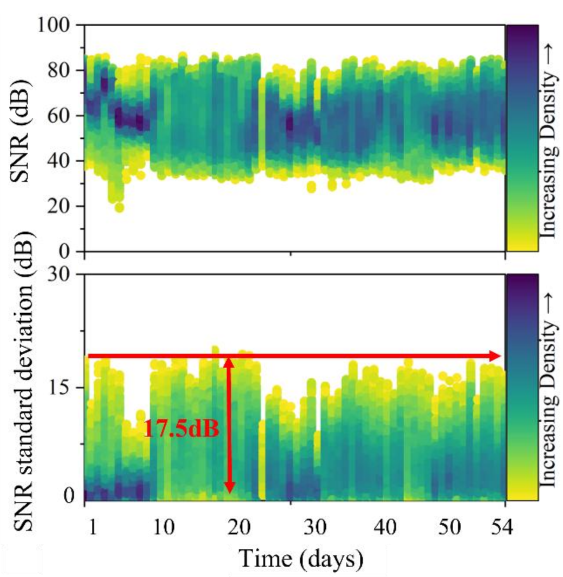

Fig. 9 (a) SNR of voltage measurement and (b) Standard deviation of SNR in insulator pollution experiment

To further investigate the difference in noise level between the transformer ageing experiment and the insulator experiment, the current waveform data from the PQM is collected which is shown in Fig. 10. Extensive arcing faults occurred during the insulator pollution experiment. Based on the statistical analysis the duration for the majority of arcing faults is 4 cycles (i.e., 80ms) and every second has arcing faults. Therefore, the SNR are not reliable for assessing the condition of assets with numerous faults. In this case, the fault data should be removed from the original PMU measurements before the SNR analysis. Further research will investigate the relationship between the insulator erosion conditions and the arcing occurring density to explore the underlying relationship between these two types of data and determine whether the arcing fault density can be one feature for the insulator erosion condition evaluation.

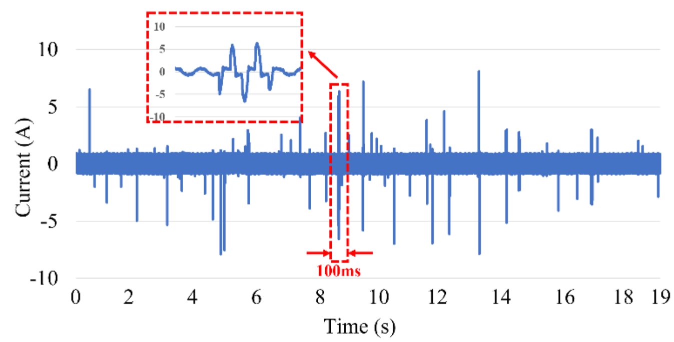

Fig. 10 Arcing faults during the insulator pollution experiment based on PQM

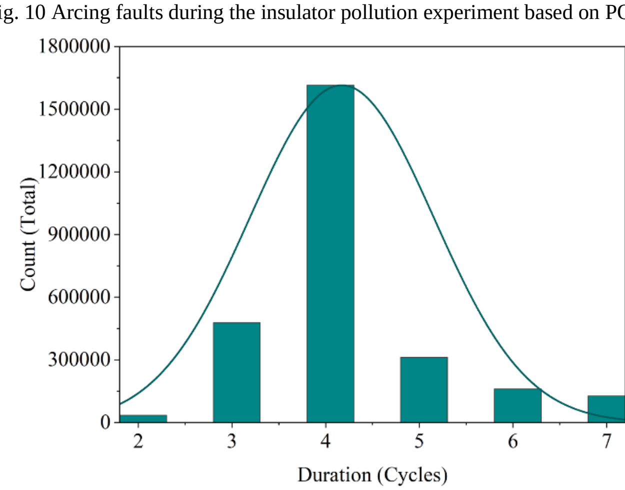

Fig. 11 Statistical analysis of arcing faults during the insulator pollution experiment based on PQM

V. CONCLUSION

PMU has provided a new direction for asset health condition monitoring. This paper investigates the feasibility of using the SNR of PMU data to evaluate the asset health conditions through laboratory experiments on transformer ageing and insulation pollution. The results demonstrate that the SNR standard deviation acts as a good indicator to estimate the transformer ageing conditions. The transformer ageing experiment could be continued to further study the feasibility of using the PMU data to estimate the impending failure of the transformer. In terms of the insulator pollution experiment, there are too many arcing faults that create significant transients in the waveform. The SNR standard deviation is much bigger and the noise can not be accurately removed from the original PMU measurements. Therefore, SNR is not suitable for insulator erosion condition assessment. Further studies will be conducted based on actual PMU data with the gradual erosion of insulators and arcing density will be analysed for insulator erosion level evaluation.

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