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Harmonic components of leakage current as a diagnostic tool to study the aging of insulators

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Abstract

This paper presents a harmonic component monitoring technique to study the aging of toughened glass insulators. Harmonic analysis theories and the principles of statistical analysis are applied in this finding. Both new and aged insulators are tested for harmonic components with a 240 V_{rms} AC voltage input. The power spectrum obtained from experiment is analyzed for the potential harmonic component as an indicator of aging in toughened glass insulators. The new and aged toughened glass insulators' power spectrums are compared to obtain the desired result. The level of confidence for the obtained result is determined by using statistical analysis. It is found that the fundamental, third, fifth and seventh harmonic components have positive results (i.e. the power consumed by these harmonic components increases with the age of the toughened glass insulator). The experimental results show that the third harmonic component is an indicator of the aging of toughened glass insulators.

Keywords: Aged and new glass insulators; Leakage current; Harmonic components; Fourier analysis and *F*-test in ANOVA

1. Introduction

Toughened glass insulators are widely used by Malaysia's power utilities in their transmission lines. However, the life expectancy of the insulators still remains uncertain. In Malaysia, these lines are operated at three levels of voltage— that is, 132, 275 and 500 kV. In the state of Selangor alone, the 132, 275 and 500 kV systems comprise a total of 370 tension towers and 4463 suspension towers with a total number of 535,704 glass-insulator pieces being used. A total of 19 cap-and-pin glass insulators (type M92, standard profile) were used in this experiment. The insulators were received from Tenaga Nasional Berhad (TNB), the Malaysian national power company. Fifteen were field-aged and four were brand new. The field-aged insulators were removed from 132 kV lines in Kapar power station located along the coast in the state of Selangor, Malaysia. These insulators have been in service for more than a decade.

Toughened glass insulators can become contaminated due to long service periods and this may cause leakage currents to flow through it and along the surfaces. The leakage currents may lead to intense head, electrical discharges as well as flashover. Many researchers have studied the aging effect of insulators using different approaches such as leakage current pattern, pulse, waveform monitoring [1,2], etc. Presently, the new approach of monitoring the leakage current's harmonic components is used for finding the aging effect of the insulator. This approach assumes that there will be some harmonic component(s) of leakage current, which will serve to indicate the aging of the insulator. El-Hag et al. [3–5] have completed different types of research using a low-frequency harmonic component monitoring technique.

The first research uses the low-frequency harmonic components of leakage current to study the aging of silicone rubber insulators in salt-fog condition [3]. In this research, three different shape designs of silicone rubber

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insulators are used as test samples. The aim of this research is to use the third and fifth harmonic components of leakage current as an indication of dry band arcing and hence as a measure of aging in silicone rubber insulators. The research concluded that the low-frequency harmonic component of leakage current could be a better indication of arcing, and hence aging, than the fundamental component. The second research is using low-frequency harmonic component of leakage current to detect arcing on high-temperature vulcanized (HTV) silicone rubber in salt-fog condition [4]. In this research, the HTV silicone rubber rods are used as test samples. The main objective of this research is to find a correlation between the low-frequency harmonic component of leakage current and the aging of HTV silicone rubber rods. This research shows that the third and fifth harmonic components of leakage current increase significantly with the increase in the electric field, which enhances the dry band arcing. The third research uses fundamental and low-frequency harmonic component of leakage current to study the aging of RTV and HTV silicone rubber in salt-fog conditions [5]. The test samples used in this research are fiberglass-reinforced plastic (FRP) rods, coated with HTV or room-temperature vulcanized (RTV) silicone rubber. Again, the third and fifth harmonic components of leakage currents increase with increase in dry band activity. The conclusion of this research is that both the fundamental and low-frequency harmonic components of leakage current can effectively be used to study the aging of silicone rubber insulators in a salt-fog test.

2. Background theory

The relationship between the power spectrum and harmonic components of the leakage current of an insulator can be related using a few basic Fourier transform theorems. The equality of power spectrum and harmonic component of leakage current in representing the harmonic content of a signal can easily be proven using these theorems for engineering applications, particularly in the study of aging of toughened-glass insulators.

2.1. Power spectrum

There are functions, $f(x)$, which are not square, integrable and so do not have an energy spectrum, satisfying the following limit condition:

$$\left\langle |f(x)|^2 \right\rangle = \lim_{X\to\infty} \frac{1}{2X}\int_{-X}^{+X} |f(x)|^2 \mathrm{d}x < \infty \left\langle |f(x)|^2 \right\rangle = \lim_{X\to\infty} \frac{1}{2X}\int_{-X}^{+X} |f(x)|^2 \mathrm{d}x < \infty. \quad (1)$$

These functions are often called finite power signals, since a finite mean rate of energy transfer in a system is often represented by such a function. Periodic signals such as sine or cosine functions as well as step function fall into this category. For functions that satisfy Eq. (2), a quality called the power spectrum, $S_f(y)$, is defined, which plays a role in finite power signals.

2.2. Parseval's theorem

In mathematics, Parseval's theorem usually refers to the result that the Fourier transform is unitary; loosely, that the sum (or integral) of the square of a function is equal to the sum (or integral) of the square of its transform. It originates from a 1799 theorem about the series by Marc-Antoine Parseval that was later applied to the Fourier series. Although the term "Parseval's theorem" is often used to describe the unitary property of any Fourier transform [6], especially in physics and engineering, the most general form of this property is more properly called the Plancherel theorem. Parseval's theorem, a special case of the Plancherel theorem, states that

$$\sum_{n\in Z} |c_n(f)|^2 = \frac{1}{2T}\int_{-T}^{T} |f(x)|^2 \mathrm{d}x. \quad (2)$$

Eq. (2) can be restated with the real Fourier coefficients as [6,7]

$$\frac{a_0^2}{4} + \frac{1}{2}\sum_{n=1}^{\infty}(a_n^2 + b_n^2) = \frac{1}{2T}\int_{-T}^{T} |f(x)|^2 \mathrm{d}x. \quad (3)$$

These theorems may be proven using the orthogonal relationships. They can be interpreted physically by saying that writing a signal as a Fourier series does not change its energy.

2.3. Rayleigh's theorem

The integral of the squared modulus of a function is equal to the integral of the squared modulus of its spectrum, that is

$$\int_{-\infty}^{\infty} |f(x)|^2 \,\mathrm{d}x = \int_{-\infty}^{\infty} |F(s)|^2 \,\mathrm{d}s. \quad (4)$$

Eq. (4) is similar to the following equation:

$$\int_{-\infty}^{\infty} f(x) f*(x)\,\mathrm{d}x = \int_{-\infty}^{\infty} F(s) F*(s)\,\mathrm{d}s. \quad (5)$$

The theorem, which corresponds to Parseval's Theorem for Fourier series, was first used by Rayleigh in his study of black-body radiation. In this, as in other connections, each integral represents the amount of energy in a system, one integral taking over all values of a coordinate and the other overall spectral components. The theorem is sometimes referred to in mathematical circles as Plancherel's theorem, after M. Plancherel, who established this theorem in 1910. The theorem is true if both the integrals exist.

2.4. Power theorem

The equation of the Power theorem is the same as that for Rayleigh's theorem when f^* is replaced by g^*

and F^* by G^*:

$$\int_{-\infty}^{\infty} f(x)g^*(x)\,\mathrm{d}x = \int_{-\infty}^{\infty} F(s)G^*(s)\,\mathrm{d}s. \tag{6}$$

In many physical interpretations, each side of Eq. (6) represents energy or power. Two different approaches may be used to evaluate the energy or power. In one approach the instantaneous or local power or energy is evaluated as the product of a pair of canonically conjugate variables (electric and magnetic fields, voltage and current, force and velocity) integrated over time or space.

3. The relationship between power spectrum and harmonic component of leakage current

According to Parseval's theorem, the power spectrum, which is the integral of the mean square value of a function $f(x)$, is equal to the sum over the entire range of harmonics of the square of the absolute value of its spectrum. If $f(x)$ represents a voltage or a current and a load of 1 Ω pure resistance is assumed, the mean power consumed is the sum of all the powers contributed by the harmonics into which the voltage or current wave has been resolved. Parseval's theorem states that the power spectrum of a function is equal to the integral of the mean square value of a function. While Rayleigh's theorem states that the integral of a mean square of a function is equal to the integral of the product of the function and its conjugate, according to the power theorem, the conjugate of a function can be replaced with a conjugate of another function given the new function is canonically conjugate with the original function. The power or energy is evaluated as the product of a pair of canonically conjugate variables (voltage and current, electric and magnetic field, force and velocity) integrated over time or space. Therefore, the power spectrum is capable of representing the harmonic components of a leakage current.

3.1. Level of confidence

The levels of confidence for the experimental outcomes have been calculated using statistical methods. Two methods are used to test the level of confidence of the obtained data that are hypothesis tests involving differences of two population means and the *F*-test in analysis of variance (ANOVA). The *F*-test or *F*-statistic can be used to determine whether the difference between two sample variances is significant enough to suggest that the populations would have different variances [8]. In performing an *F*-test for variances, the null hypothesis states that they are unequal.

3.1.1. Hypothesis test involving differences of two population means, $\mu_1 - \mu_2$ ($n_1 \geqslant 30$, $n_2 \geqslant 30$)

This process uses sample data and is a statistical procedure to decide whether or not to reject a hypothesis about a population parameter value [9]. The population variances σ_1^2 and σ_2^2 are unknown. If $n_1 \geqslant 30$ and $n_2 \geqslant 30$, the test statistic to be used is

$$Z_{\text{test}} = \frac{\bar{X}_1 - \bar{X}_2 - \mu_0}{\sqrt{(S_1^2/n_1) + (S_2^2/n_2)}}. \tag{7}$$

If $n_1 < 30$ and $n_2 < 30$ then the test statistic to be used is

$$t_{\text{test}} = \frac{\bar{X}_1 - \bar{X}_2 - \mu_0}{\sqrt{(S_1^2/n_1) + (S_2^2/n_2)}}, \tag{8}$$

$$v = \frac{\left((s_1^2/n_1) + (s_2^2/n_2)\right)^2}{\frac{(s_1^2/n_1)^2}{n_1 - 1} + \frac{(s_2^2/n_2)^2}{n_2 - 1}}, \tag{9}$$

where $\bar{X}_1$ is the sample mean power of aged toughened glass insulator for each harmonic component, $\bar{X}_2$ the sample mean power of new toughened glass insulator for each harmonic component, S_1 the standard deviation of aged toughened glass insulator for each harmonic component, S_2 the standard deviation of new toughened glass insulator for each harmonic component, n_1 the numbers of aged toughened glass insulators sample used in the experiment and n_2 the numbers of new toughened glass insulators sample used in the experiment.

4. *F*-test in ANOVA

In statistics, ANOVA is a collection of statistical models, and their associated procedures, in which the observed variance is partitioned into components due to different explanatory variables. This method [9,10] is used to test whether there is a significant change or effect in the harmonic power level between new and aged toughened glass insulators. This method is applied to all 10 harmonic components for the significance of power escalation in each harmonic. The statistical parameters are shown in Table 1.

The formulae can be written as follows:

$$N = n_i + n_k, \tag{10}$$

$$SST = \sum_{i=1}^{k} \sum_{j=1}^{n} y_{ij}^2 - \frac{Y_{..}^2}{N}, \tag{11}$$

$$SST_{rt} = \sum_{i=1}^{k} \frac{Y_{i.}^2}{n_i} - \frac{Y_{..}^2}{N}, \tag{12}$$

Table 1
Statistical parameters for aged and new insulators

	Aged insulator	New insulator	
Power of *n*th harmonic (μW)	y_{i1}	y_{k1}	
	y_{i2}	y_{k2}	
	–		
	–		
	y_{in}	y_{k2}	
Total	Y_i	y_{k2}	$Y_{..}$

$$SSE = SST \times SST_{rt}, \tag{13}$$

$$MST_{rt} = \frac{SST_{rt}}{k-1}, \tag{14}$$

$$MSE = \frac{SSE}{N-k}. \tag{15}$$

The sum of squares, degree of freedom, mean square and calculated frequency are shown in Table 2.

5. Experimental setup

In this paper, a measurement circuit is designed to measure and amplify the leakage current of the toughened glass insulator. This measurement circuit provides the amplified signal of the leakage current to the oscilloscope. A little trial and error is needed during the design process in order to reduce the noise level as well as to obtain the amplified signal. For the experiment, the flow chart is shown in Fig. 1.

Table 2
ANOVA parameters

Sum of squares	Degrees of freedom	Mean square	Calculated f
SST_{rt}	$k-1$	$MST_{rt} = \frac{SST_{rt}}{k-1}$	$f = \frac{MST_{rt}}{MSE}$
SSE	$N-k$	$MSE = \frac{SSE}{N-k}$	
SST	$N-1$		

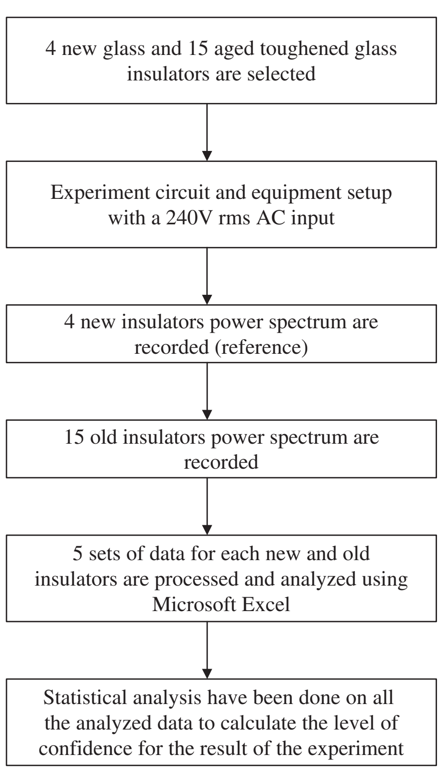

Fig. 1. Flowchart of the experiment.

In the experiment, four new toughened glass insulators and 15 aged toughened glass insulators are selected as the test samples. The experiment circuit and equipment is setup with a 50 Hz, 240 V_{rms} single-phase low-voltage AC input through variac. Initially, an aged toughened glass insulator sample is placed at the frame where the test circuit is connected. Approximately 5–10 min of time is required for the waveform and power spectrum of the sample to become stable after switching on the power input. After that, five sets of power spectrum data are obtained from the oscilloscope. The same experiment is carried out on all new and aged toughened glass insulator samples. The four new toughened glass insulators' power spectrums are recorded as a neutral reference. The 15 aged toughened glass insulators power spectrums are also recorded as the subject to be analyzed. The five sets of data for each new and aged toughened glass insulators are processed and analyzed using Microsoft Excel. Finally, statistical analysis has been done on all the analyzed data to calculate the level of confidence for the results of this experiment.

Firstly, the main power supply is attached to the variac. The function of the variac is to adjust the input voltage as well as for safety purposes. The variac is then connected to the toughened glass insulator sample, which hangs isolated at the wooden frame as shown in the Fig. 2. The input voltage is adjusted to 240 V_{rms} and the other end of the insulator is attached to the measuring circuit as shown in the Fig. 2. The leakage current measurement circuit is used to transfer the leakage current signal to the LeCroy oscilloscope.

The voltage measured and the power spectrum of the toughened glass insulator sample can be shown in the oscilloscope. A differential probe is used to measure the

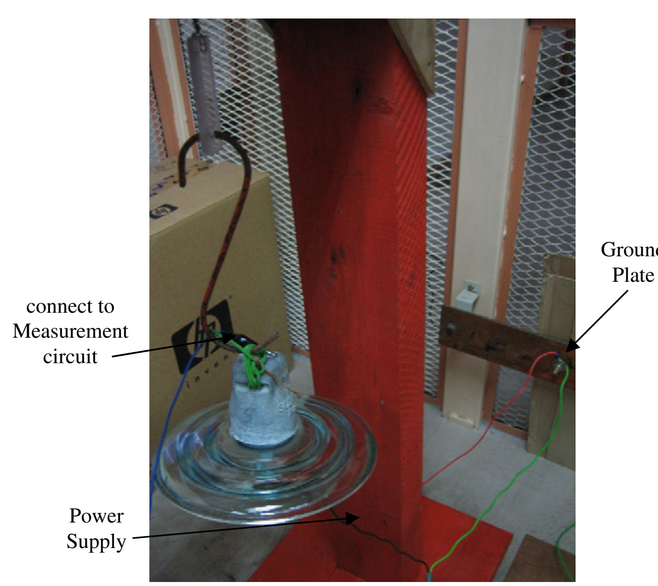

Fig. 2. Insulator sample with supply voltage.

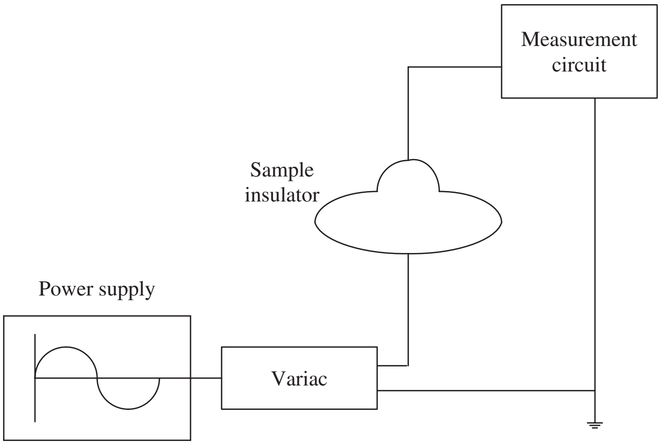

Fig. 3. Equivalent experimental circuit.

voltage with reference to the ground. The differential probe is capable of viewing the small signal in the presence of a large DC offset and other common-mode signal, and the accuracy that can be achieved in looking at these signals. The equivalent experimental circuit is shown in Fig. 3.

6. Experimental results

The power spectrum obtained from the oscilloscope during the experiment in units of dB_m is converted to watt using the following equation:

$$dB_m = 10\log\left(\frac{P}{1\times 10^{-3}}\right), \tag{16}$$

where dB_m is the power measured in decibel referenced to 1 mW, and P is the power measured in unit watt (W).

The voltage data taken from the oscilloscope can be used to calculate the leakage current of each sample of toughened glass insulator. The voltage obtained is a peak voltage, which needs to be converted to an rms voltage using the following equation:

$$V_{rms} = \frac{V_{peak}}{\sqrt{2}}. \tag{17}$$

The leakage current of the toughened glass insulator samples can be obtained using the following equation:

$$I_{rms} = \frac{V_{rms}}{R}, \tag{18}$$

where I_{rms} is the rms leakage current of the toughened glass insulator sample, V_{rms} the voltage obtained from oscilloscope, R the resistance of the measured circuit, 680 kΩ.

The total harmonic distortion can be calculated using the following equation:

$$THD = \frac{\sum \text{harmonic powers}}{\text{fundamental frequency power}}, \\ = \frac{P_2 + P_3 + P_4 + \cdots + P_n}{P_1}, \tag{19}$$

where P_n is the power of the nth harmonic.

The power escalation difference between new and aged toughened glass insulator samples is calculated using the equation as follows:

$$\%\ \text{difference} = \frac{\overline{X}_1 - \overline{X}_2}{\overline{X}_2} \times 100\%. \tag{20}$$

7. Comparison of mean power for each harmonic component between the insulators

At first, the data obtained from the experiment are converted to power in units of watts using Eq. (16). The mean power for each harmonic component of new and aged insulators is calculated using Eq. (1). The power escalation percentages of new and aged toughened glass insulators are calculated using Eq. (16). The results are shown in Tables 3 and 4, respectively.

7.1. Leakage current and total harmonic distortion of both insulators

The leakage current of both new and aged toughened glass insulators is calculated using Eqs. (17) and (18).

Table 3
Mean power for each harmonic component of new and aged toughened glass insulators

Harmonic component	Frequency (Hz)	Mean power of aged insulators, $\bar{X}_1$ (μW)	Mean power of new insulators, $\bar{X}_2$ (μW)
0	0	0.0203	0.0191
1	50	81,813.3507	77,283.2898
2	100	0.1440	0.1433
3	150	4.3448	0.1542
4	200	0.2375	0.2076
5	250	45.5092	36.0872
6	300	0.1729	0.2600
7	350	49.7116	35.0190
8	400	0.1099	0.0989
9	450	11.9239	11.3019
10	500	0.0940	0.0770

Table 4
Power escalation percentage for each harmonic component of new and aged toughened glass insulators

Harmonic component	Frequency (Hz)	Percentage of power difference (%)
0	0	6.24
1	50	5.86
2	100	0.53
3	150	2716.97
4	200	14.40
5	250	26.11
6	300	−33.50
7	350	41.96
8	400	11.20
9	450	5.50
10	500	22.03

The total harmonic distortions of new and aged toughened glass insulators are calculated using Eq. (19). The results are shown in Tables 5 and 6.

7.2. *Level of confidence of each harmonic component as an indicator of aging in insulator*

For the level of confidence of this experiment's result, statistical methods are used. The standard deviation used in this method is shown in Table 7. The result of the hypothesis test involving differences of two population means, $\mu_1 - \mu_2$ ($n_1 \leqslant 30$, $n_2 \leqslant 30$), is shown in Table 8. The analysis conditions of the collected data are as follows:

1. $n_1 = 15$, $n_2 = 4$.
2. Significance level $= \alpha = 1\%$.
3. Null hypothesis is H_0: $\mu_1 = \mu_2$.
4. Alternative hypothesis is H_1: $\mu_1 > \mu_2$.
5. Reject H_0 if $Z_{\text{test}} > Z_\alpha$.

The result of *F*-test in ANOVA is shown in Table 9. The analysis conditions of the collected data are as follows:

1. $n_i = 15$, $n_k = 4$.
2. $N = 19$, $k = 2$.

Table 5
Leakage current and total harmonic distortion of new toughened glass insulators

New insulator samples	Leakage current, I_{rms} (μA)	Total harmonic distortion (%)
Sample 1	2.9896	0.1083
Sample 2	2.9896	0.1067
Sample 3	2.9896	0.1113
Sample 4	2.9896	0.1051
Mean		0.1074

Table 6
Leakage current and total harmonic distortion of aged toughened glass insulators

Aged insulator samples	Leakage current, I_{rms} (μA)	Total harmonic distortion (%)
Sample 1	3.1846	0.1420
Sample 2	3.0546	0.1690
Sample 3	3.1196	0.1296
Sample 4	3.1846	0.1222
Sample 5	3.0546	0.1359
Sample 6	3.1196	0.1388
Sample 7	3.0546	0.1240
Sample 8	3.2496	0.1359
Sample 9	3.1846	0.1184
Sample 10	3.1846	0.1467
Sample 11	3.1846	0.1488
Sample 12	3.0546	0.1443
Sample 13	3.2496	0.1310
Sample 14	3.0546	0.1581
Sample 15	3.2496	0.1152
Mean		0.1346

Table 7
Standard deviation of the power for each harmonic component

Power of each harmonic (μW)	Standard deviation (s)	
	Aged insulator	New insulator
0	0.0022	0.0000
1	3781.7401	1486.1970
2	0.1199	0.0422
3	3.7166	0.0594
4	0.1136	0.0934
5	4.5678	3.4444
6	0.0743	0.0891
7	8.5894	2.6510
8	0.0390	0.0378
9	1.9254	1.5775
10	0.0373	0.0330

Table 8
Standard deviation of the power for each harmonic component

Power of each harmonic (μW)	v	$t_{a,\,v}$ (calculated)	t_{test} value	Result
0	14	2.6240	2.0758	$\mu_1 = \mu_2$
1	17	2.5670	3.6919	$\mu_1 > \mu_2$
2	16	2.5830	0.0203	$\mu_1 = \mu_2$
3	14	2.6240	4.3647	$\mu_1 > \mu_2$
4	13	2.6500	0.5422	$\mu_1 = \mu_2$
5	14	2.6240	4.5139	$\mu_1 > \mu_2$
6	8	2.8960	−1.7962	$\mu_1 = \mu_2$
7	16	2.5830	5.6866	$\mu_1 > \mu_2$
8	10	2.7640	0.5169	$\mu_1 = \mu_2$
9	13	2.6500	0.6672	$\mu_1 = \mu_2$
10	12	2.6500	0.8889	$\mu_1 = \mu_2$

Table 9
Result of *F*-test in ANOVA

Harmonic	*f* value	Result
1	5.3260	Positive treatment effect
2	0.0002	No treatment effect
3	4.8745	Positive treatment effect
4	0.2320	No treatment effect
5	14.5430	Positive treatment effect
6	4.0299	No treatment effect
7	10.9954	Positive treatment effect
8	0.2573	No treatment effect
9	0.3499	No treatment effect
10	0.6789	No treatment effect

3. Significance level $= \alpha = 5\%$.
4. H_0: $\alpha_1 = \alpha_2 = 0$ vs. H_1: $\alpha_i \neq 0$.
5. Reject H_0 if f value $> f_{\alpha;k-1,N-k} = f_{0.05;1,17} = 4.45$,

where α_I is the ith treatment effect.

8. Analysis

Fig. 4 shows the mean power spectrum for both new and aged toughened glass insulators. The graph shows the third

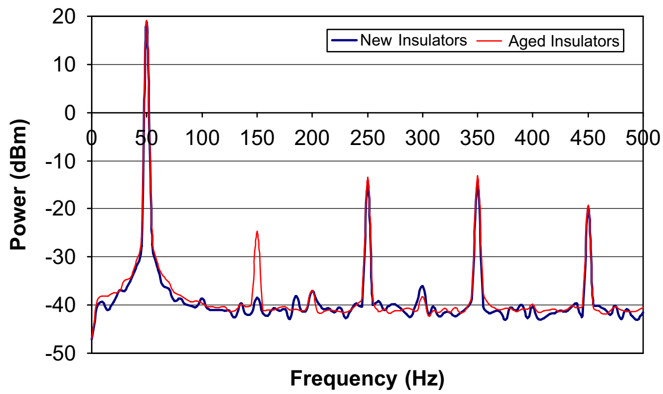

Fig. 4. Mean power spectrum for new and aged toughened glass insulators.

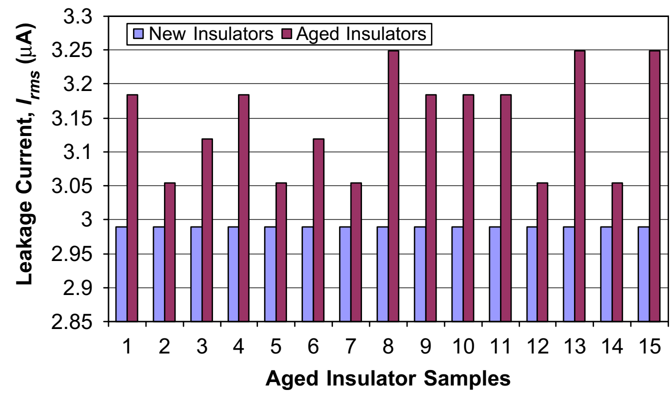

Fig. 6. Leakage current comparison of new and aged toughened glass insulators.

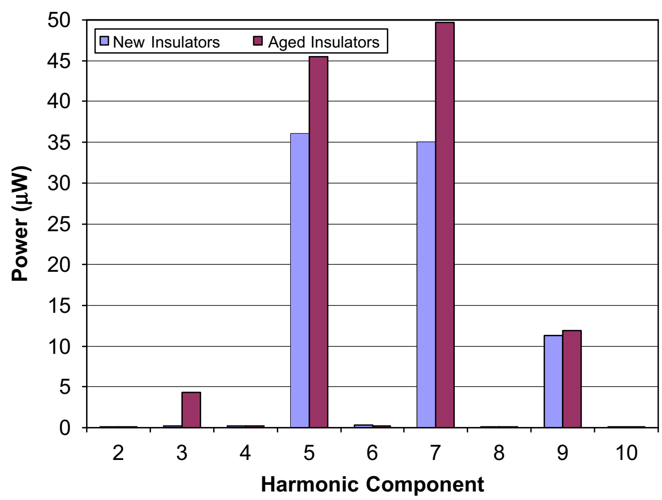

Fig. 5. Mean power versus harmonic component of new and aged toughened glass insulators.

harmonic component is a useful indicator of aging in toughened glass insulator as it can be seen that the third harmonic appears very obviously different for aged toughened glass insulators. There are also slight increases in the magnitudes of the fifth and seventh harmonic components for aged toughened glass insulator samples compared with new insulator samples.

The comparison of mean powers for both new and aged toughened glass insulators is shown in Fig. 5. The harmonic components included in Fig. 5 range from the second to the 10th harmonic components. The power increase in the third, fifth and seventh harmonic component is very noticeable in Fig. 5. Therefore, the third, fifth and seventh harmonic components may become indicators of aging in toughened glass insulators.

Fig. 6 shows the comparison of leakage currents for both new and aged toughened glass insulators. Based on the results of experiments shown in Tables 5 and 6, the assumption is made that the leakage currents for all new toughened glass insulators are the same in value. This graph also shows that the leakage current of all aged toughened glass insulators are higher compared with new toughened glass insulators. There are four levels of leakage current for aged toughened glass insulators shown in Fig. 6.

Based on the experimental results shown in Table 4, the power escalation percentage between new and aged toughened glass insulators is high for the third, fifth and seventh harmonic components, which is above 25% compared with the new toughened glass insulators power level. This is especially shown in the third harmonic component, which is more than 27% higher compared with the new toughened glass insulator power level.

The comparison of power levels for both new and aged toughened glass insulators shows that the third, fifth and seventh harmonic components will consume more power when the insulators' toughened glass is aged. Therefore, the third, fifth and seventh harmonic components are capable of showing signs of aging in toughened glass insulators.

The power consumed by these harmonic components will also cause an increase in total harmonic distortion, as given in Eq. (19). The assumption is made that the aging of toughened glass insulators will cause an increase in the power consumed by harmonic frequencies higher than the fundamental. The conclusion can be made that the total harmonic distortion of aged toughened glass insulators will be higher compared with new toughened glass insulators.

It is seen from the results shown in Tables 5 and 6 that the total harmonic distortions increase when the toughened glass insulator is aged. The new toughened glass insulators' total harmonic distortion ranges between 0.1% and 0.11% with a mean of 0.1078%, whereas the aged toughened glass insulators' total harmonic distortion ranges from 0.11% to 0.17% with a mean of 0.1372%. Although the increase in total harmonic distortion is small in value, it has shown signs of diminishing the insulator's performance. The total harmonic distortion increases when the power consumed by all the harmonic components above the fundamental component increases. The mean power and standard deviation of new and aged toughened glass insulators for second to tenth harmonic components are shown in Fig. 7. The mean powers of the third, fifth and seventh harmonic

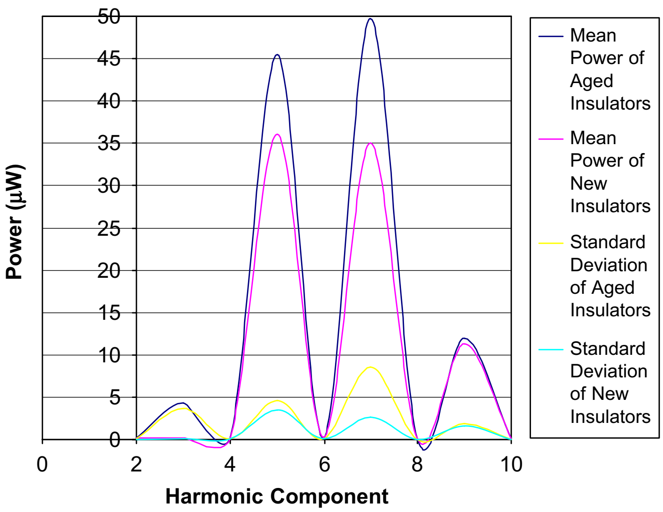

Fig. 7. Mean power and standard deviation of new and aged toughened glass insulators for the second to tenth harmonic components.

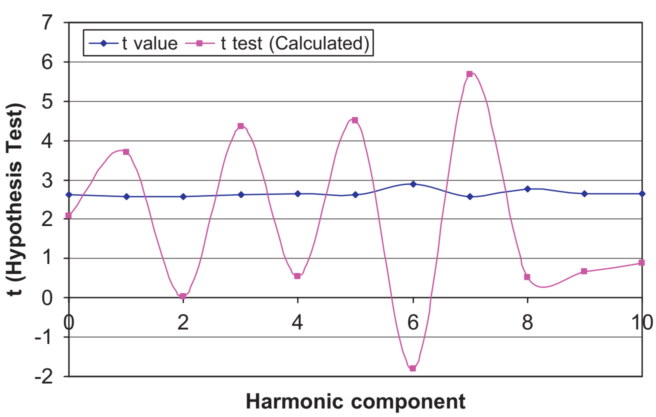

Fig. 8. Comparison of $t_{\alpha,\,\upsilon}$ and t_{test} (calculated) for hypothesis test.

components are visibly higher for the aged toughened glass insulators. The standard deviations of the third, fifth and seventh harmonic components are also higher for the aged toughened glass insulators. This shows that these harmonic components are capable of showing signs of aging in toughened glass insulators.

Fig. 8 shows a comparison of $t_{\alpha,\upsilon}$ and t_{test} (calculated) for the hypothesis test. The t_{test} (calculated) of the fundamental, third, fifth and seventh harmonic components is higher than $t_{\alpha,\upsilon}$ as shown in Fig. 8.

This indicates that the fundamental, third, fifth and seventh harmonic components satisfy the test with a 1% significance level, which means that these harmonic components are capable of indicating signs of aging in toughened glass insulators at 99% level of confidence.

As seen based on the result of the hypothesis test, the fundamental, third, fifth and seventh harmonic components are capable of indicating aging in toughened glass insulators. Fig. 9 shows the comparison of f value and $f_{\alpha;k-1,N-k}$ (calculated) for F-test in ANOVA. The $f_{\alpha;k-1,N-k}$ (calculated) of the fundamental, third, fifth and seventh

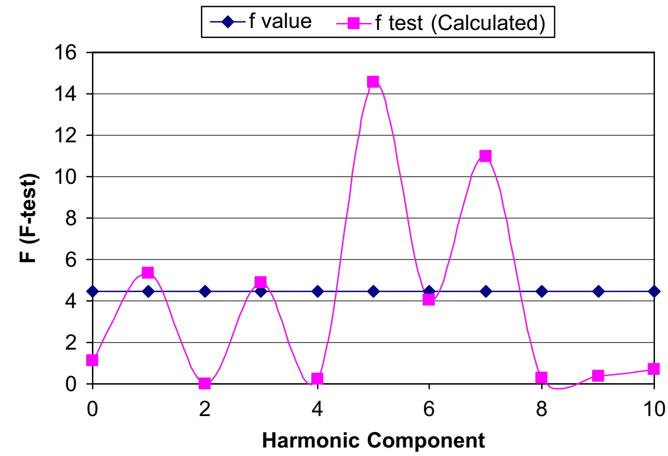

Fig. 9. Comparison of f value and $f_{\alpha;k-1,N-k}$ (calculated) for F-test in ANOVA.

harmonic components is higher than f value as shown in Fig. 9.

This indicates that the fundamental, third, fifth and seventh harmonic components satisfy the test with a 5% significance level, which means these harmonic components are capable of showing signs of aging in toughened glass insulators at a 95% level of confidence. Based on the result of F-test in ANOVA, the same comments as the hypothesis test can be made.

9. Conclusion

From the experimental results, it has been observed that the third harmonic component appears only in aged toughened glass insulator samples. It may be concluded that the third harmonic component is an indicator for aging of toughened glass insulators. However, there are also slight increases in the magnitude of the fifth and seventh harmonic components for aged toughened glass insulator samples compared with new toughened glass insulator samples. Therefore, the final conclusion can be made that the harmonic components of leakage current monitoring determined by this research are capable of becoming a technique or tool for power utility companies to use for toughened glass insulator quality monitoring in the future.

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