Mean life estimation of metal oxide surge arresters under harmonic distortion

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***Abstract*—In this paper, similar metal oxide-based arresters are tested using accelerated ageing tests with low and high total harmonic distortion content in the AC voltage stress. The extrapolated ageing times obtained are modelled using the three-parameter Weibull statistical distribution. The hypothesis testing based on the likelihood ratio test is invoked in order to ensure no possibility of equal probability density functions, which are therefore applied to estimate or predict the mean life of MOSA under distorted ac voltage stress. The results obtained indicate that the likelihood ratio test is found to be -1.2855 and the mean life obtained for MOSA samples aged with a total harmonic distortion content of 8.5% in the voltage stress is reduced by 30.13%.**

keywords- Metal oxide surge arrester, mean life, accelerated ageing, harmonic-distortion, weibull probability density function.

I. INTRODUCTION

Metal Oxide Surge Arresters (MOSA) are prone to electrical ageing or degradation as a result of constant AC or DC conduction [1-7]. With the advent of power electronic components in modern electrical and electronic systems, AC voltage and/or current usually appear to be distorted and therefore consist of harmonic frequency components superimposed to the basic wave or the fundamental. The influence of such harmonics on the ageing of MOSA units is completely overlooked in the literature [8, 9]. Therefore, the probability of reduced life and therefore of lower reliability, when MOSA devices are continuously subjected to long-term distorted ac voltage consists of important knowledge to both manufacturers and consumers of these transient overvoltage devices. In this study, two sets of 60 MOSA having similar physical and electrical properties are tested using accelerated ageing tests with and without harmonics injection in the applied voltage stress, and a constant thermall stress of 135^{o}C for a time duration of 96 hours. The ageing times measured are statistically modelled on the basis of the three-parameter Weibull distribution. Prior to conduct the reliability-based estimation or prediction of the mean life of MOSA devices aged with and without harmonics injection, the likelihood ratio test is applied in order to rule out any possibility of similar ageing time distributions under both test conditions. The results obtained ruled out any probability of similar ageing pattern and therefore indicate significant reduction in the mean life of MOSA devices subjected to accelerated ageing test with injection of harmonics.

II. METHODOLOGY

In order to achieve the objectives of this study the accelerated ageing test facility, which is aimed at simulating real life component degradation [10, 11], and the Weibull statistical analysis techniques are essentially required.

A. Accelerated Ageing Test

This test is implemented with the aid of the following components: the Nabertherm P330 or heat chamber, the $TDGC_2$ 1 kVA/50 Hz variable AC voltage regulator, the triac-based voltage controller, the high-temperature conductors and the data acquisition units. The Naberthem P330 consists of 9 resettable heating courses and 40 time-segments, and is able to provide constant thermal stress up to 3000^{o}C for a particular set time [12]. The test temperature was set at 135^{o}C for a time-period of 96 hours. The $TDGC_2$ 1 kVA/50 Hz variable AC voltage source is used to provide constant voltage stress across MOSA samples for the entire test time. This unit is synchronised with the Nabertherm P330 so that both AC voltage and thermal stresses are experienced simultaneously. The fundamental AC voltage supplied across MOSA units consisted of 85% of the rated AC breakdown voltage of the samples [13, 14]. The triac-based voltage controller represents the external source of harmonic distortion, which when required in the test is switched on to draw non-linear currents and thus distorting the AC voltage across the samples. The total harmonic distortion (THD) measured before and after the operation of the AC voltage controller is 1.5% and 8.5%, respectively. The high-temperature conductors used in this test consisted of single-core silicon cables capable of withstanding a maximum temperature of 180^{o}C [15]. These conductors are used to supply current to the MOSA units mounted inside the Nabertherm P330. The data acquisition units consisted of the 3-channel K5020 and the 2-channel MT 250 voltage/current data loggers as well as the TDS 1001B Tektronix digital scope meter. These units are used to record the voltage and current through the tested units each 30 seconds of time. The test set up of the accelerated ageing test is shown in figure 1.

B. Data Adequacy to the Weibull Distribution

The failure or ageing times recorded from data loggers are extrapolated to standard operating condition times using Arrhenius time accelerating model described in [16, 17].

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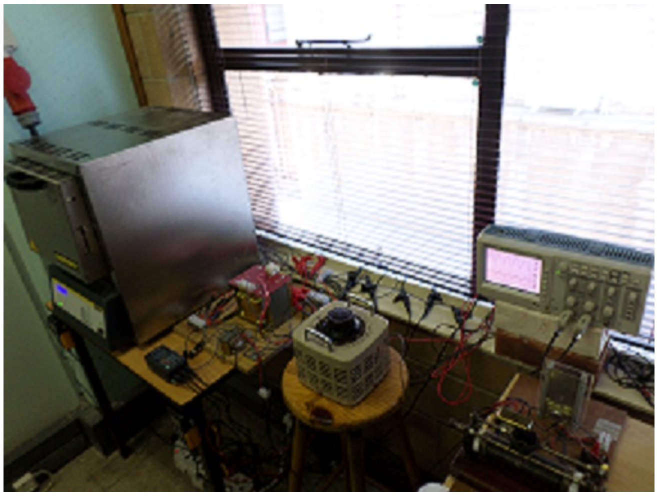

Fig. 1. Accelerated degradation test set up

The resulting cumulative probability of ageing is determined on the basis of the White's approximation [18 - 20]. Therefore, the extrapolated ageing times and the cumulative probability of ageing thus obtained are used to plot the Weibull cumulative density function (CDF), which is subsequently verified on the basis of the comparison between the correlation factor of the obtained CDF versus the critical coefficient value to be read off figure 2.

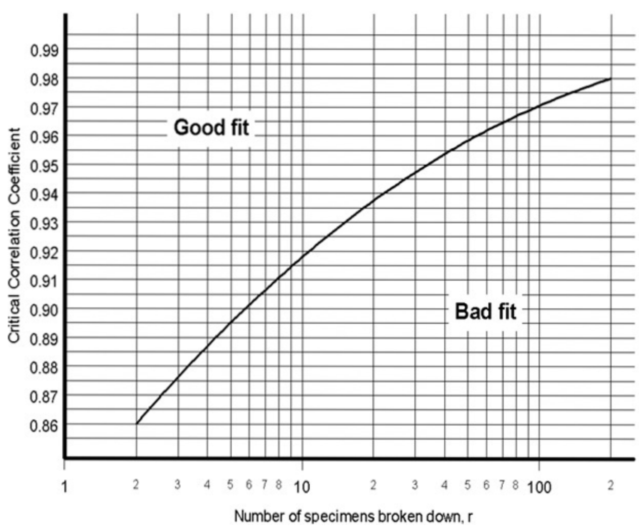

Fig. 2. Critical Correlation Values [21]

The extrapolated ageing times are therefore obtained using the following equation (Arrhenius Time Accelerating Model):

$$t_{eq.} = t_F \times 2.5^{\frac{(T_{test}-T_{std})}{10}} \tag{1}$$

Where: t_{eq} is the extrapolated ageing time expressed in hours corresponding to standard operating conditions of MOSA devices, T_{test} is the test temperature and T_{std} is the standard operating temperature. t_F is the failure time such as recorded during the accelerated ageing test. For the purpose of this study the considered standard operating temperature for MOSA devices is 40^{o}C. The cumulative probability of ageing is determined using the following approximation (White's Approximation):

$$F(i,p) \approx \left(\frac{i-0.44}{p+0.25}\right) \times 100 \tag{2}$$

Where, $F(i,p)$ is the cumulative probability of ageing, i is the ranking of aged MOSA devices and p is the number of MOSA samples subjected to accelerated ageing test.

The correlation factor of the CDF curves is therefore verified using the following equation:

$$\sigma = \frac{\sum (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum (x_i - \overline{x})^2 \cdot \sum (y_i - \overline{y})^2}} \tag{3}$$

Where: $x_i = \ln\left[-\ln\left(1 - \frac{F(i,n)}{100}\right)\right]$, $\overline{x} = \frac{\sum x_i}{r}$, $y_i = \ln t_{eq}$ and $\overline{y} = \frac{\sum y_i}{r}$. σ and r are the correlation factor and the number of aged MOSA samples, respectively.

C. Estimation of the Parameters

In order to estimate the parameters (the scale and the shape) of the Weibull distribution obtained, the least squares regression method is applied. The shape parameter is therefore expressed as follows:

$$\beta = \frac{\sum (x_i - \overline{x})^2}{\sum (x_i - \overline{x}) \cdot (y_i - \overline{y})} \tag{4}$$

Where: β is the estimated shape parameter of the Weibull distribution.

The scale parameter is estimated using the following equation:

$$\frac{1}{\lambda} = \exp\left[\overline{y} - \frac{\sum (x_i - \overline{x}) \cdot (y_i - \overline{y})}{\sum (x_i - \overline{x})^2} \cdot \overline{x}\right] \tag{5}$$

Where: $\frac{1}{\lambda}$ is the estimated scale parameter of the Weibull distribution.

D. Likelihood Ratio Test

The likelihood ratio test is used as the test statistic of the hypothesis testing methodology in order to validate either the null or the alternative hypothesis. These hypothesis refer to the probability of similar or distinct ageing time models under the test conditions described above. The statements to be tested are therefore as follows:

1) The null hypothesis: $H_o : f_1(t) = f_2(t)$
2) The alternative hypothesis: $H_a : f_1(t) \neq f_2(t)$

Where: $f_1(t)$ is the PDF of MOSA subjected to low THD voltage waveform and $f_2(t)$ is the PDF of MOSA subjected to high THD voltage waveform.

The test statistic is based on the likelihood ratio test which is expressed as:

$$z = -2\ln \frac{\prod\limits_{\gamma_1}^{t} \{f_1(t)\}}{\prod\limits_{\gamma_2}^{t} \{f_2(t)\}} = -2\ln \frac{\prod\limits_{\gamma_1}^{t} \{h_1(t) \cdot R_1(t)\}}{\prod\limits_{\gamma_2}^{t} \{h_2(t) \cdot R_2(t)\}} \quad (6)$$

Where: z is the likelihood ratio test, γ_1 is the location parameter for $f_1(t)$ and γ_2 is the location parameter for $f_2(t)$. $h_1(t)$ and $R_1(t)$ are the ageing rate and reliability functions when the THD of the voltage stress is low. $h_2(t)$ and $R_2(t)$ are the ageing rate and reliability functions when the THD of the voltage stress is high.

Therefore, the null hypothesis may be deemed valid if the following condition is observed: $z \geq \chi^2_{0.01}$ [22, 23], where $\chi^2_{0.01}$ is the chi-square distribution at 0.01 significance level and with 1 degree of freedom (df). These values are provided in [24].

E. Ageing Times Modeling and Mean Life Prediction

The Weibull probability density function (PDF) could be used in order to model the ageing times distribution obtained. Applying the estimated parameters, the ageing time model is therefore expressed as follows:

$$f(t) = \beta\lambda\left[\lambda(t-\gamma)\right]^{\beta-1} \cdot \exp\left[-\lambda(t-\gamma)\right]^{\beta} \quad (7)$$

Where: $f(t)$ is the three-parameter Weibull probability density function of the ageing time.

To predict the mean life of MOSA operating under distorted AC voltage, the following equation is applied:

$$\mu = \int_0^{\infty} t \cdot f(t)\, dt = \int_0^{\infty} R(t))dt \quad (8)$$

Where: μ is the mean life and $R(t)$ is the reliability function.

Since the parameters obtained in the ageing times model are estimates, the likelihood ratio test - based hypothesis testing methodology is conducted to verify any probability of similar ageing PDF, and consequently the reliability and the ageing rate functions.

III. Results and Discussion

The extrapolated ageing times as well as the cumulative probability of ageing obtained using equations (1) and (2) respectively, are used to plot the CDF graphs of MOSA operating under low and high THD voltage stress. The CDF graphs obtained under both conditions are demonstrated in figures 3 and 4, respectively.

Applying equation(3) leads to the following respective correlation factors: σ_1 = 0.969156 (For MOSA under low THD voltage stress) and σ_2 = 0.974395 (For MOSA under high THD voltage stress). It could be observed that the values obtained happen to be higher than the critical correlation value (for

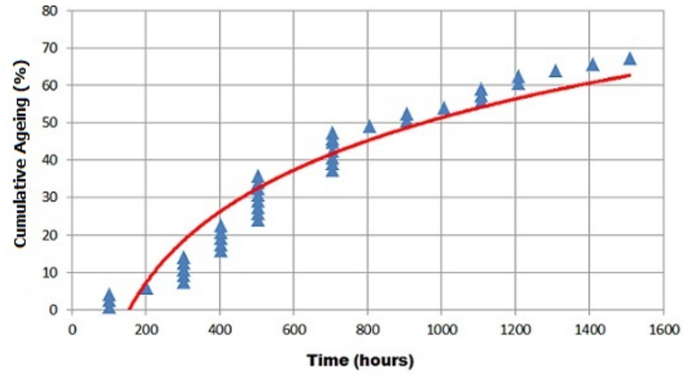

Fig. 3. CDF graph for MOSA under voltage stress with THD = 1.5%

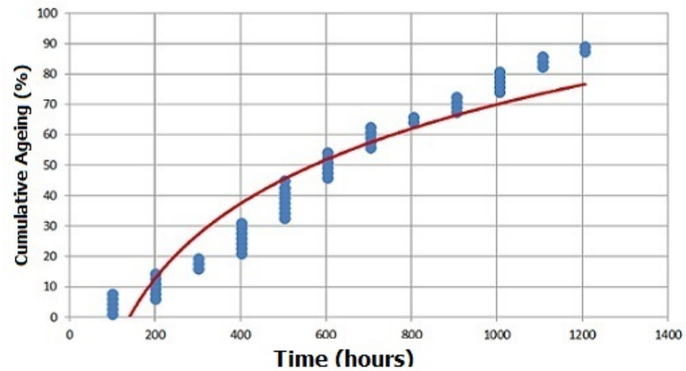

Fig. 4. CDF graph for MOSA under voltage stress with THD = 8.5%

r = 60 samples) such as indicated in figure 2. This therefore confirms that the ageing times distribution obtained show good fit to the Weibull distribution.

The results obtained from equations (4) and (5) respectively lead to the following values of the estimated parameters for the ageing time distribution for samples under low THD voltage stress: β_1 = 1.63; $\frac{1}{\lambda_1}$ = 1079.4 hours. For samples under high THD voltage stress, the following parameters are obtained: β_2 = 1.8 and $\frac{1}{\lambda_2}$ = 765.22 hours. From the CDF graphs, it could be observed that the location parameters are found to be as follows: γ_1 = γ_2 = 100.6 hours.

The likelihood ratio test such as described on the basis of equation (6) is worked out to be -1.2855 which is less than the value of 6.635 (the chi-square distribution value at 0.01 significance level at 1 df), such as indicated in [24]. This therefore validates the alternative hypothesis which implies no probability of similar PDF, such as expressed in equation (7), for MOSA operating under 1.5% and 8.5% of THD content in the voltage stress. Therefore, the reliability and the ageing rate curves could be plotted. This is given in figures 5 and 6, respectively. It could be observed that the reliability of MOSA subjected to voltage stress with high content of harmonics proves to be low, while the ageing rate function of such samples is shown to be high.

Using equation (8), leads to the mean life of MOSA operating under voltage stress with a THD content of 1.5% to be 770.852 hours as opposed to that of the samples subjected to the applied voltage with a THD content of 8.5%, which

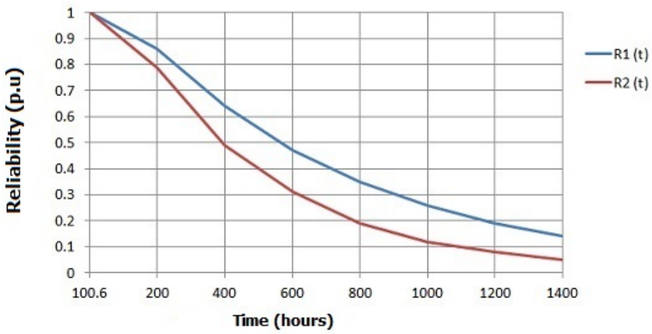

Fig. 5. Reliability curves

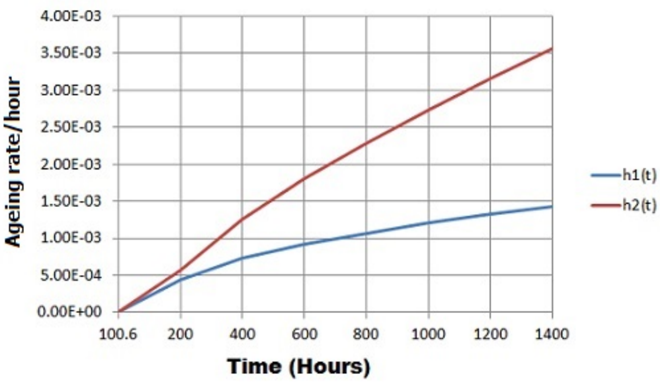

Fig. 6. Ageing rate curves

showed a reduced mean life of 538.622 hours. This therefore indicates a mean life reduction of 30.13% for MOSA samples operating under voltage stress with high THD content.

IV. Conclusion

The continuous conduction of MOSA under distorted AC voltage stress is simulated and subsequently analysed in this study. The extrapolated ageing times obtained show good fit to the Weibull statistical distribution which is therefore applied in order to estimate the mean lifetime of MOSA under distorted AC voltage stress, using the probability density function. The results obtained indicate the following:

1) MOSA devices continuously operating under AC distorted voltage stress with higher THD content will experience increased rate of ageing.
2) The higher the distortion in the AC voltage stress applied across MOSA components, the faster the ageing rate and therefore the lower the reliability.
3) The presence of higher distortion content in the voltage stress constantly applied across MOSA will have the effect of reducing the mean life of these surge protection devices.

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