Condition Monitoring of Metal-oxide Surge Arresters using Leakage Current Signature Analysis

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***Abstract*—Online condition assessment of surge arresters is necessary for early detection of problems and subsequent replacement of the device to avoid unplanned downtime and/or damage to the equipment being protected. The most common technique of monitoring and assessing the condition of the arrester is extraction of the resistive component of the leakage current. There are many drawbacks to this method arising from inaccuracies in the model-based approach and deficiencies in the understanding of the leakage current signal. This paper presents leakage current signature analysis (LCSA) as a method of assessing the condition of the surge arrester where the harmonics components of the current signal, extracted using Bayesian spectrum estimation, are used as indicators of degradation. An experimental methodology comprising measurement of the leakage current of arresters undergoing constant-stress accelerated degradation testing is employed. Results indicate that a consistent increase in the DC component of the leakage current signature in the case of degrading samples is the most likely indicator of condition.**

***Index Terms*—Metal-oxide surge arrestors, online condition monitoring, leakage current signature, Bayesian spectrum estimation.**

I. INTRODUCTION

Metal-oxide varistors (MOV) are the most commonly used type of surge arresters for protecting equipment and systems against direct or indirect effects of lightning surges and switching transients [1], [2]. The need to ensure these equipment and systems are effectively protected implores condition monitoring of the deployed surge arresters. Moreover, online condition monitoring of metal-oxide surge arresters (MOVs) is desirable because it is more conducive of a preventive maintenance strategy for protection applications. Recent advancements in assessing MOV degradation affords the possibility of detecting problems early [3], [4]. Leakage current monitoring is the most popular method as it can be used online, is non-invasive and is perhaps best suited for recent progress in understanding of MOV degradation mechanisms [5]. However, in spite of the numerous advantages of leakage current monitoring, there are still deficiencies and drawbacks with its application which are discussed here.

This paper proposes overcoming some of these deficiencies and drawbacks through a new approach of analysing the measured leakage current. The approach is based on extraction and analysis of the harmonic components of the leakage current using Bayesian spectrum estimation.

II. SURGE ARRESTER DEGRADATION AND CONDITION ASSESSMENT

The basic parallel resistance-capacitance (RC) circuit used to model insulators is also the most widely accepted characterisation of MOVs [6]. This is because MOVs have been found to behave similarly to insulating materials under nominal voltage and standard operating temperature [7]. The microstructural composition of a typical MOV unit comprises zinc-oxide grains and intergranular regions that constitute the resistive and capacitive elements of the basic model. This model forms the basis of leakage current monitoring on MOVs as most techniques involve extraction and analysis of the model's resistive component (i_R). Essentially, a progressive increase in this resistive component is an indication of MOV degradation. A number of variations of the resistive-current extraction method and basic model have been presented *inter alia* phase-shift estimation [8], variable compensation [9], and computational methods [10]. The reliance of bus voltage measurement is one of the major deficiencies common to all of the aforementioned techniques. Practical implementation for purposes of online monitoring is therefore challenging as continuous measurement of operating voltage at each MOV installation point is required. Besides the inaccuracies of the various equivalent models presented over the years, selection thereof still depends on the availability of system data, system complexity and the designers judgment [11]. Model-based leakage current monitoring inherits these complexities and inaccuracies. A more reliable, inexpensive and uncomplicated method of assessing the leakage current of the MOV is therefore needed. The proposed LCSA method overcomes these challenges as it only uses direct measurement of the leakage current to determine MOV condition without any equivalent model or assumptions about the protected system.

III. METHODOLOGY

A. Leakage Current Signature Analysis (LCSA)

A key driver in recent progress of signal processing is the general application areas of process and condition monitoring. Different forms of time- and frequency-domain analyses are employed in various condition monitoring applications. Popular techniques include Wavelet Transforms, Short-Time Fourier Transforms and spectral analysis [12], [13].

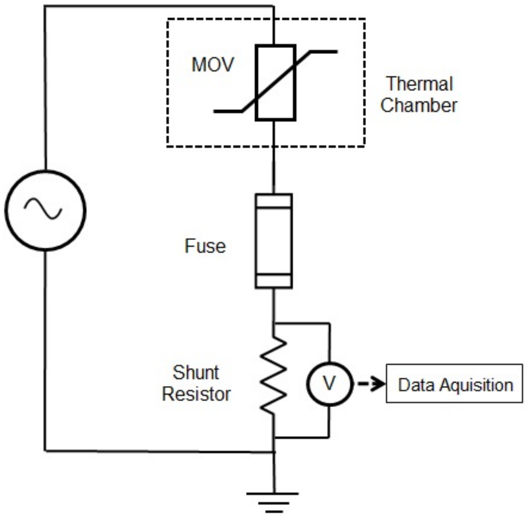

Figure 1: Experimental layout for conducting accelerated degradation of MOV and testing leakage current based signature analysis

This work proposes spectral analysis of the MOV's leakage current as means of assessing its condition. Techniques for spectrum estimation are categorised as parametric or nonparametric [14]. Bayesian spectrum estimation is a nonparametric method that does not make any assumptions about the sampled signal. The technique determines the expected value of the signal spectrum over the joint posterior probability distribution of both signal and noise parameters [15]. It has been shown to yield more accurate spectrum estimates for condition monitoring application relative to other well-known techniques such as the standard periodogram, Welsh and multiple signal classification (MUSIC), particularly for low signal-to-noise ratios [16]. Additionally, the Bayesian technique offers better resolution making it suitable for condition monitoring applications where the change in a particular harmonic order indicates the presence of a problem.

B. Experiment Design

In order to investigate the viability of the proposed method, the leakage current of the MOV must be analysed at different levels of degradation. The experimental setup shown in Fig. 2 was conceived for this purpose. The setup is used to conduct standard IEEE accelerated degradation testing of MOVs [17]. The thermal chamber enables controlled application of elevated temperatures. During the degradation testing, the leakage currents of the MOVs are recorded periodically using a shunt resistance and data acquisition system. A fuse is used for protection of the measurement equipment in the event of a short-circuit created when the MOV fails. Samples of low-voltage ZnO varistors sized 20 mm are used for the experiment.

1) Accelerated thermal degradation: Standard laboratory degradation tests for insulators are typically used for life modelling and failure process investigation [17]. These tests consists of accelerated thermal degradation of the insulator to simulate life degradation. Additional progressive or constant stresses may also be applied to simulate conditional failure process. Thermal degradation is modelled using the Arrhenius life model - given by (1) - through extrapolating life degradation times using the constant elevated temperature and the period over which the tested device is subjected to that temperature [18], [19].

Figure 2: Experimental setup for conducting accelerated degradation of MOV and testing leakage current based signature analysis

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

where:

t_t : extrapolated time,
t_{test} : accelerated degradation test time,
T_{test} : accelerated degradation test temperature,and
T_{std} : standard temperature (40^oC).

For the presented investigation, each MOV sample is subjected to a constant elevated temperature of 135^oC and external voltage supply equal to 85 % of its reference voltage i.e. 0.85 V_{1mA}. The test is conducted for a maximum period of 45 min or until the MOV fails. For example, the full duration of the test (45 min) simulates continuous operation of the MOV for 4523.67 $hours$ (approximately 27 weeks) under 85 % of its reference voltage.

2) V-I testing: The V-I characteristic of an MOV is the main measure of its performance, and a direct indication of its condition. This characteristic can be determined by progressive application of dc voltages to the MOV and measurement of the resulting current.

Degradation of an MOV causes a decrease in its ability to clamp a surge voltage. This is reflected by a decreases in the MOV's reference voltage V_{1mA}. Typically, a decrease of an MOVs' reference voltage in the range of 5 % to 10 % constitutes complete failure. Here, a 5 % drop in the V_{1mA} of the arrester is considered as an indication of its failure. The V-I characteristics of 5 MOV samples were determined before and after the degradation tests. Figure 3 compares the healthy and degraded (to failure) V-I characteristics of an MOV where the V_{1mA} decreased by 5.09 %.

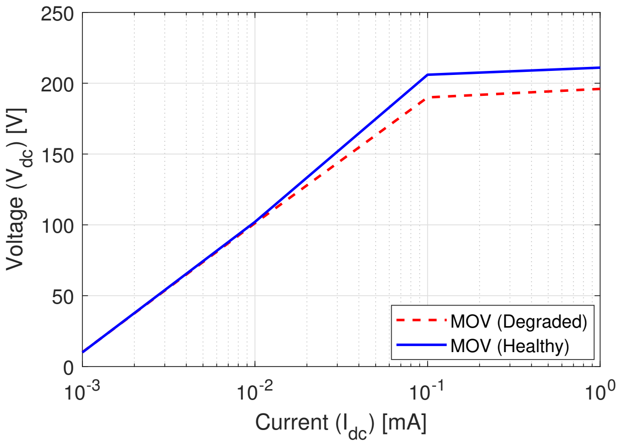

Figure 3: Experimental V-I characteristics of MOV obtained before and after degradation

IV. RESULTS AND DISCUSSION

The Bayesian spectrum estimates of the 5 MOV units' leakage currents, recorded at selected times, were computed. The current was sampled at a frequency of approximately 650 Hz. The posterior probability of four different harmonic components of the leakage current were determined - i.e. dc component, fundamental (50 Hz), second order (100 Hz), and third order (150 Hz). Estimates for MOVs 1 and 2 are shown in figures 4 and 5, respectively. These specific MOVs remained operational for the full duration of the accelerated degradation test. The V-I test conducted on these units after the degradation test indicated a negligible decrease in the V_{1mA} value confirming non-failure. The dc component of these recorded signatures are significantly higher than the other components. The only observable trend is that the dc components first rise before fluctuating for the remainder of the test. Figures 6, 7 and 8 show the spectrum estimates for MOVs 3, 4 and 5, respectively. These MOVs failed during the test at different times. Failure of these units was confirmed through the V-I test. Unlike with MOVs 1 and 2, the dc components of the leakage current signatures of the failed units exhibit a progressive increase with degradation. The initial rise in the leakage current dc component of the units that did not fail is an indication of degradation. The subsequent decrease in the leakage current dc component follows the physical degradation property exhibited by insulators called 'self-healing' [20], [21]. This essentially means that in some cases the surge arresters may undergo microstructural changes during normal life degradation so as to become more resilient instead of failing.

V. CONCLUSION

MOVs perform a key function in protecting power system equipment at various voltage levels. Monitoring the health of the MOV units is vital in ensuring that these equipment are well protected. Online monitoring methods are most desirable because it affords the opportunity for preventative

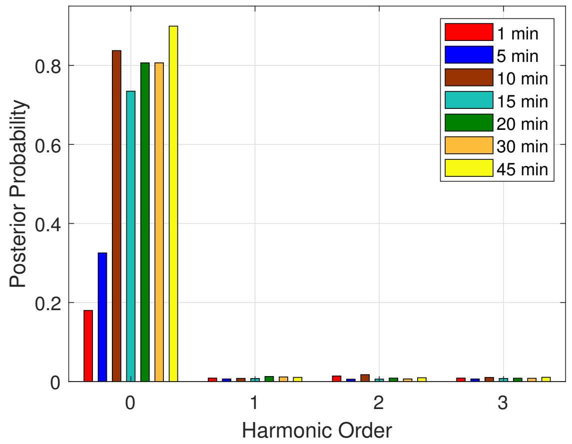

Figure 4: Spectrum estimates of MOV 1 leakage current after selected intervals during accelerated degradation testing

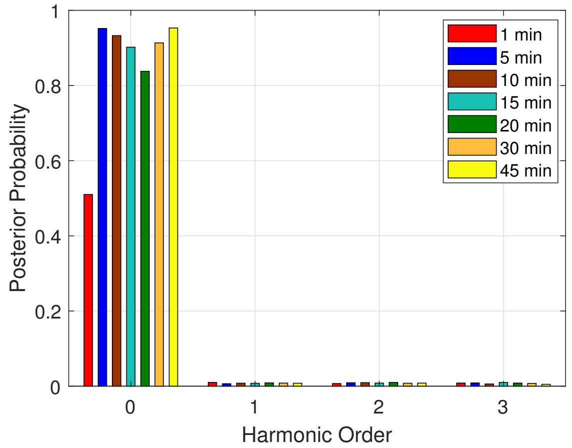

Figure 5: Spectrum estimates of MOV 2 leakage current after selected intervals during accelerated degradation testing

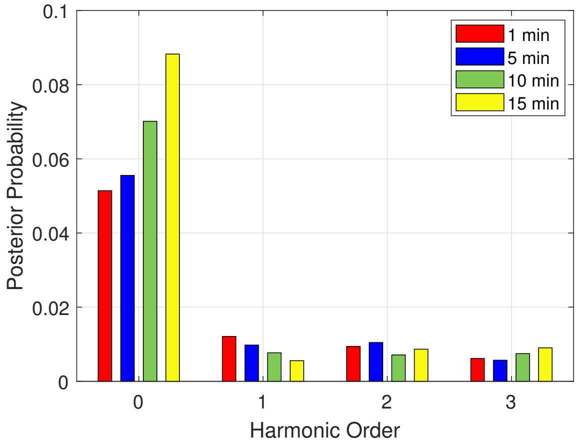

Figure 6: Spectrum estimates of MOV 3 leakage current after selected intervals during accelerated degradation testing

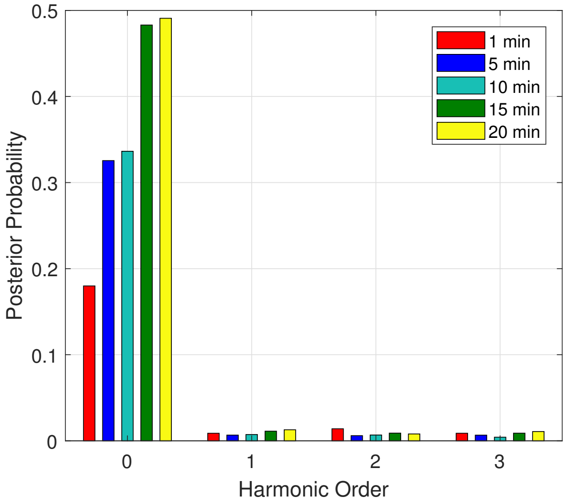

Figure 7: Spectrum estimates of MOV 4 leakage current after selected intervals during accelerated degradation testing

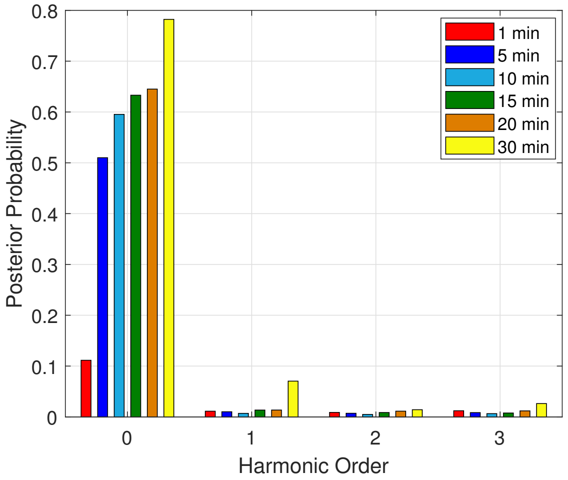

Figure 8: Spectrum estimates of MOV 5 leakage current after selected intervals during accelerated degradation testing

maintenance. Leakage current monitoring does provide such an opportunity, however all available variations of the method are based on uncertain equivalent models and have practical deficiencies. In this paper, an LCSA method was proposed that uses Bayesian spectrum analysis to determine the condition of the arrester. The method is not based on any equivalent model or assumptions about the protected system. An experimental setup comprising accelerated degradation testing was used to investigate the viability of the proposed method. Results indicate that the dc component of the leakage current spectrum estimates progressively increase as the arrester degrades towards failure. The leakage current signature of the healthy arresters did no exhibit the same progressive increase. LCSA is a potential alternative to currently available methods as this definitive trend could perhaps be used as an assessment technique in practice.

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