6 CONCLUSIONS AND RECOMMENDATIONS

The specific objective of the work documented in this research report is the creation of a benchmark sample to facilitate gap etching analysis of pre-payment meter surge arresters removed from the field. Gap etching analysis of these field gaps is required to ascertain whether the surge arrester specification for prepayment meters adequately represents the LV lightning surge environment.

6.1 Summary and Conclusions

The following sub-sections provide a summary and conclusions reached for each of the central chapters.

6.1.1 Literature review

The primary reference to gap etching analysis is the EPRI study relating to Distribution system gapped SiC surge arresters, where field-gap etchings were categorised in terms of Coulomb-charge content through visual comparison to a benchmark sample created using various waveform/peak-current combinations. In this modified approach, the gap etchings represent a current-time product rather than current alone, and the appearance of an etching yields an indication of the surge duration i.e. 8/20 µs vs. long-duration. One criticism of the study - emphasised in a discussion of an EPRI paper - is the largely ignored potential effect of power-frequency follow current on field-gap etchings; whilst raised as a research question, its resolution is beyond the scope of this work.

Other literature review topics covered surge arrester specifications and characteristics, lightning parameters – field and laboratory, and the LV surge environment. This led to the concept of a test space framework - peak current vs. waveform - containing the waveform range: 4/40 µs to 4/70 µs, as the specific “Area of interest” towards the creation of a benchmark sample, and peak current range: 0 to 65 kA. Various research questions were raised relating to etching repeatability, minimum obtainable etching resolution, and minimum detectable Coulomb-charge.

6.1.2 Defining the test space

Three waveforms were selected: 4/40 μs, 4/55 μs (typical average) and 4/70 μs; additionally the 8/20 μs waveform was selected because it is an industry standard.

The available lightning impulse generator at the University of the Witwatersrand has a 2^{nd}-order RLC discharge circuit, where the capacitor comprises four individual capacitors. These may be connected into three main configurations: series, series-parallel and parallel, thereby allowing three overlapping peak current ranges. The minimum per range is determined by the minimum charging voltage that ensures that the surge arrester gap sparks over, whilst the maximum per range is determined by the maximum allowable charging voltage for the particular capacitor configuration.

An analytical approach was used to calculate the required resistance and inductance values in the 2^{nd}-order RLC discharge circuit per capacitor configuration and waveform, thereby requiring 12 resistive inductor components.

Overall the available lightning impulse generator placed limitations upon the extent of the test space that could be populated i.e. less than 50% of the "Area of interest". The need for spark-over of up to four series-connected surge arrester gaps (etching repeatability requirement) resulted in typically non-overlapping peak-current ranges per waveform.

6.1.3 Design and construction of resistive inductors

To ensure that the desired waveforms were consistent over the current ranges, a thorough quantification of the stray resistance and stray inductance of the discharge circuit for each of the capacitor configurations was undertaken to ascertain the actual resistance and inductance values required for each resistive inductor component.

Whilst the values are easily achieved using Nichrome wire and winding techniques such as loosely packed solenoid or loosely packed bifilar, the thermal capability of the components demands sufficient thermal mass to avoid significant changes in resistance value or at worst destruction of the components. Hence the design and construction of the low inductance components was challenging – during this process a novel inductance-reducing winding technique comprising anti-parallel strand loops was devised.

Due to time constraints, six components out of the required 12 were constructed representing the 8/20 μs and 4/70 μs waveforms, pending creation and analysis of a reduced benchmark sample using these components. However, due to the stray inductance limitation – particularly demanding for the third capacitor configuration – two components yielded a 16/36 μs and a 5/72 μs waveform. Whilst the latter is a reasonable approximation of a 4/70 μs waveform, the former is unsuitable for further use.

The anti-parallel strand loop components produced the smoothest waveforms, whilst the loosely packed solenoid components produced severe ringing at the origin, most probably due to inter-turn (parasitic) capacitance and/or magnetic flux linkage between the horizontally mounted spark gap assembly (generator) and the horizontal turns of the component.

6.1.4 Creating and analysing the benchmark sample

The peak-current range for each of the remaining five constructed components was defined by quantifying I vs. V_s under short-circuit conditions. Furthermore, this quantification allowed the desired I to be achieved almost precisely due to negligible loading by the test-piece, even for four series-connected gaps, thereby ensuring repeatability.

Preliminary visual inspection of the resulting reduced benchmark sample showed that the etchings are mostly ellipsoid and that, apart from the size of a given etching pair, the difference in appearances i.e. dull vs. shiny indicates the polarity for unipolar surges, whilst for bipolar surges the appearances are dull. Furthermore the largest etchings are not confined to the central hub area.

An empirical linear relationship between gap etching area and peak current emerged per waveform, once all gap etching areas - constrained to the central hub area of the gap plate - had been measured. The physical extent of the central hub provides a limit beyond which these relationships are no longer linear because the gap size increases. The major and minor axis diameters were measured using a profile projector with 20x- and 50x-magnification and with a measurement system allowing x-y measurements to an accuracy of 1 micron. The etchings are not always clearly defined with the possibility of measurement error due to the nature of operation of the profile projector; this prompted the compilation of a visual gap etching measurement guideline, where each etching is first inspected using a 10x-magnification loupe. Overall, the standard deviation of the gap etching areas for most of the waveform/peak-current combinations is less than 10% indicating that ellipsoid approximation and human measurement error are acceptable.

The A_e vs. I empirical expressions for the 8/20 and 4/70 μs waveforms enable the calculation of peak currents for a measured field-gap etching area, provided the etching does not extend beyond the central hub, which subsequent work has shown to be unlikely in practice. The estimated A_e vs. I expressions for the 4/40 μs and 4/55 μs waveforms must be treated with circumspection, as they are computed from the available data for the 8/20 μs and 4/70 μs waveforms.

6.2 Recommendations for Future Work

The following sub-sections provide recommendations for future work.

6.2.1 Lightning impulse generator

For the lightning impulse combination generator in the HV laboratory of the Electrical Engineering Department at the University of the Witwatersrand, the spark gap assembly should be vertically mounted and/or magnetically screened to avoid coupling into the solenoid or even bifilar resistive inductors (refer to Chapter 4).

6.2.2 Resistive inductor components

Given that the thermal mass requirement results in bulky resistive inductor components for which a low inductance may be required, a further consideration is a shunt having low thermal mass immersed in a fluid having high heat capacity but low electrical conductivity (refer to Appendix D). This concept needs to be explored further.

6.2.3 Potential effect of power-frequency follow current

It is assumed that the power-frequency follow current (if initiated) will most likely utilise the low-impedance arc of the lightning surge discharge current to produce an etching for the composite waveform discharge current through the arrester.

To ascertain the potential effect of power-frequency follow current requires a set of complete gapped SiC surge arresters to be subjected to a range of lightning impulse currents superimposed upon 230 V, and compared to the benchmark sample. It should be noted that such laboratory work is notoriously difficult and tedious because timing of the lightning impulse is important (refer to Chapter 2).