2 LITERATURE REVIEW

The literature review commenced with a search for past work on gap etching analysis, followed by a search for topics relating directly to the gapped SiC surge arrester (utilised in pre-payment meters) and its immediate operating (lightning surge) environment:

- Gap etching analysis
- Surge arrester specifications and characteristics
- Lightning parameters – field and laboratory
- LV surge environment

2.1 Gap Etching Analysis

The earliest reference found is work by Bellaschi (1935) in reviewing the effects of lightning strikes on conductors (fusion, crushing, surface burning etc.) as experienced in the field and simulated in the laboratory environment. In particular "surface burning" on the face of de-ionising gap plugs, due to currents of 25, 50 and 100 kA, is briefly described but the technique is not explained.

Brown and Thunander (1976) make scant reference to gap etching analysis in their work on surge currents through Distribution class arresters. In determining the effective arrester current due to a direct stroke, they show that reflections effectively result in longer duration currents depending on arrester location, and speculate that longer duration surges produce larger gap etchings than short duration surges through the arresters. In a discussion of this paper, Westrom suggests the need for field studies at reasonable cost by inspecting the gap parts of suitable arrester designs, as subsequently done by Gaibrois, Mashikian and Johnson (1979).

The primary reference to gap etching analysis is that of Gaibrois, Mashikian and Johnson (1979) on behalf of the Electric Power Research Institute (EPRI), and subsequently published in a paper by Gaibrois (1981). A total of 2800 surge arresters – with 9, 10 or 18 kV rated gaps and an average 12 years of service - were examined and compared to a standard set of gap etchings produced by discharging currents of known waveforms and magnitudes through virgin gaps.

For the standard set of gap etchings, the standard 8/20 μs waveform was used with current magnitude I from 5 to 100 kA, translating into a Coulomb-charge Q range of 0.09 to 1.81 C. The size of the resultant gap etching reflects I (or Q) conducted by the gap. However, examination of the field gaps indicated that whilst any two etchings may have the same size, their appearances may be different i.e. matte effect vs. melted (displaced) metal - the latter indicating a surge of duration longer than 8/20 μs i.e. higher Q content for the same I.

Hence a supplementary standard set of gap etchings was produced using square pulses with selected combinations of current magnitudes (1 to 30 kA) and duration's (50 to 400 μs), translating into a Q range of 0.43 to 4.19 C. Table 2.1 shows the peak-current/waveform combinations comprising the standard and supplementary standard sets used in the EPRI study.

Table 2.1: Q matrix: peak-current vs. waveform

Q (C)		WAVEFORM						
		8/20 μs	SQUARE PULSE					
			50 μs	100 μs	125 μs	200 μs	250 μs	400 μs
I (kA)	1							0.45
	2					0.43		0.99
	4			0.43		0.99		
	5	0.09						
	6						1.31	2.85
	10	0.18				2.08		4.19
	20	0.36						
	30		1.28		2.97			
	40	0.72						
	65	1.17						
	100	1.81						

Therefore gap etching size and appearance reflect the current magnitude and the waveform (8/20 μs vs. long duration) of the surge passed through the gap.

In evaluating the 2800 surge arresters, the approach was to compare each etching per field gap to the 8/20 μs test gaps and assign a current and Coulomb value. The largest etching per gap was also compared to the longer duration test gaps by examining both the size and the amount of melted metal, and assigned a current and Coulomb value - the latter being considered a measure of the energy content of the surge.

In his discussion of Gaibrois' paper, Sakshaug supports the modified approach that the gap electrode markings represent a current-time product rather than current alone, and that estimates of current assuming an 8/20 μs waveform are far too high. In their discussion of Gaibrois' paper, Stringfellow and Eriksson express their reservations that gap etchings may be analysed to reliably obtain measures of current magnitude or duration, and suggest that power-frequency follow current may seriously affect the results.

Gaibrois responds that laboratory surges of various current magnitudes represent certain etching sizes and that the duration is represented by various amounts of melted gap plate material. Furthermore, he indicates that power-frequency follow current accounts for less than 1 C per instance – a 10 kA, 400 μs square wave surge equals 4.19 C. In their EPRI report Gaibrois, Mashikian and Johnson (1979) note that in some cases the gap plate is peppered by numerous marks no greater than a pinhead, which they believe to be due to power-frequency follow current and/or small current surges due to lightning induced voltages or switching-related overvoltages.

Related work by Fisher *et al.* (1990) considers the effect of direct lightning strikes to metal aircraft using a continuing (or square pulse) current of varying duration yielding 10 to 200 C. The volume of metal melted away (to form a hole through the metal skin) at a lightning attachment point is closely related to the Coulomb-charge carried into the point and to the type of metal and its thickness. Of course the volume of metal and the cross-sectional area of the hole are related by the thickness of the metal, hence supporting the current-time product dependency of gap etching area as per Gaibrois, Mashikian and Johnson (1979).

In summary, the EPRI approach was to use Coulomb-charge Q as a measure of the energy E released at the arc attachment point on the electrode surface, and relate this to the gap etching area A_e. This energy is the product of the arc current and the constant[1] arc root (anode or cathode) volt drop at the electrode (Fisher *et al*., 1990):

$$E = \int_0^T v(t)i(t)dt = V\int_0^T i(t)dt = V\,Q \qquad (2.1)$$

i.e. energy E released at each electrode surface is proportional to the total charge contained in the incident surge, where T is the duration of the surge.

Without an exact understanding of the physical process leading to etching of the electrodes, it nevertheless seems obvious that total charge movement (and not the net charge) applies in the case of a bipolar surge. Hence for completeness:

$$Q = \int_0^T \left|i(t)\right| dt \qquad (2.2)$$

2.2 Surge Arrester Specifications and Characteristics

International standards IEC 99-1:1991 and IEC99-5:1996, and course notes by van Coller (1995) contain useful definitions and related terminology pertaining to surge arresters and their application.

The required characteristics of surge arresters (gapped SiC and MOV) utilised in pre-payment meters were originally specified in Eskom specification NWS 1108:1991, subsequently revised as TRMSCAAP2:1994, rev. 1 and TRMSCAAP2:1994, rev. 2. In the first revision, the motivation for the changes was the new pre-payment meter withstand of 400 Vac (previously 280 Vac), whilst the second revision primarily served to clear up some confusion between the gapped and MOV arrester with respect to criteria and the operating duty test.

Whilst the gapped SiC arrester part of the specification is based on IEC 99-1:1991,

[1] Beyond the anode and cathode volt-drops, the voltage across the arc is not constant and is a strong function of a low arc current (van Coller, 2000).

there are three pertinent deviations:

- Nominal discharge current (8/20 μs) is 5 kA, as opposed to 1.5 kA or 2.5 kA that would typically be appropriate at LV level. This reflects the harsh LV lightning surge environment in parts of South Africa;
- High-current impulse test (4/10 μs) utilises 30 kA, as opposed to 65 kA that would be appropriate for 5 kA nominal discharge current;
- Operating-duty test also includes the application of the high-current impulse test above.

Thunander (1985), St-Jean and Latour (1984), van der Merwe (1993), and Woodworth and Fletcher (1991) provide comparisons between the gapped SiC and MOV technologies. The latter reference comments on the degradation of both the gap and the block material of SiC arrester technology due to repetitive surge duty and specifically degradation of the gap due to power-frequency follow current.

2.3 Power-frequency Follow Current

In Section 2.1 the concern was raised that power-frequency follow current may affect the gap etching analysis results.

However, according to Geldenhuys (1999), manufacturing spread results in a typical power-frequency follow current range of 5 to 40 A for the pre-payment meter gapped SiC surge arresters – depending on the manufacturer of the SiC blocks, each is marked with its particular power-frequency follow current as tested during manufacture. Therefore the SiC block to a large extent determines the amount of erosion in the gap due to power-frequency follow current. Furthermore, observed etchings in gaps, where 5 kA impulses were superimposed on 280 V, were dominated by the impulses and not the power-frequency follow current – the observed effects also tend be different.

As described in the "Operating-duty test" in IEC 99-1:1991, the passage of power-frequency follow current must be achieved through the application (superimposition) of an 8/20 μs current impulse with peak value equal to the nominal discharge current of the arrester i.e. 5 kA for the pre-payment meter surge arrester. Such tests are notoriously difficult and tedious because timing of the lightning impulse is important (Geldenhuys, 2000).

2.4 Lightning Parameters – Field and Laboratory

Anderson and Eriksson (1979) present a detailed discussion of parameters of lightning incidence, peak current amplitudes and impulse shape parameters, based on globally collated lightning data. Ground flash density figures for many towns and cities in South Africa are reproduced (courtesy of the CSIR) in Eskom's MV standard SCSASABE7:1998.

Various accepted standard test lightning impulse waveforms (voltage and current) are in use world-wide as reported by van Coller (1994), Eriksson and Geldenhuys (1985), Fisher and Martzloff (1976), and Fenimore and Martzloff (1992). The 1.2/50 μs (voltage) and 8/20 μs (current) waveforms are most commonly used. IEC 60-1:1989 defines the T_{front} / T_{tail} μs current impulse in terms of the 0.1, 0.9 and 0.5 criteria, as illustrated in Figure 2.1.

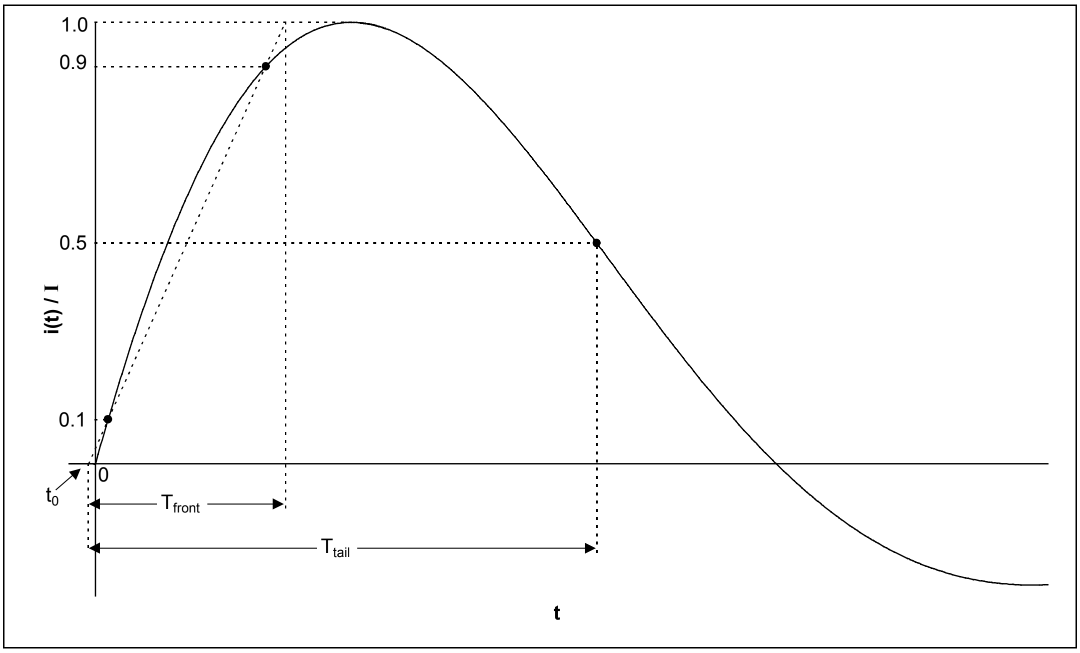

Figure 2.1: Current impulse definition as per IEC 60-1:1989

Notes:

1) t_0 is defined as the "virtual zero".
2) Up to 30% negative overshoot is permitted.
3) The voltage impulse is defined in terms of the 0.3, 0.9 and 0.5 criteria (van Coller, 1995).

2.5 LV Surge Environment

As illustrated in Figure 1.1, lightning surges impinging on pre-payment meter surge arresters are the result of various coupling mechanisms (direct strokes to MV and LV systems, induced voltages on MV and LV systems, surge transfer from MV to LV through distribution transformer).

The various mechanisms are covered in the Electrical Transmission and Distribution Reference book (1964), and by Anderson and Eriksson (1979), Sabot (1995), Gaunt, Britten and Geldenhuys (*circa* 1989), van Coller (1995), Rusck (1957), Chowdhuri (1991), Nucci (1995a, 1995b) and Kelly (1996). Ultimately it is necessary to know the quantitative nature of lightning surges impinging on the surge arresters without delving into complex calculations or simulations in this work. Therefore computer simulations and the collective knowledge and experience of various researchers should suffice as follows:

2.5.1 Computer simulations

Stringfellow (1990) performed a computer simulation to calculate the current and voltage waveforms of surges propagating onto associated low-voltage ac power systems when lightning (100 kA) strikes a nearby overhead distribution line. The work is based on long-duration current waveforms (8/80 μs) purportedly shown by other research to be more representative than the commonly used 8/20 μs waveform. The resulting current peak in the service-entrance surge arresters rarely exceeds 20 kA, however the longer waveform results in considerable duty.

Daguillon *et al*. (1996) used a Monte Carlo type simulation method in conjunction with EMTP to simulate direct and induced voltages on the LV line, thereby computing an over-voltage statistical distribution for phase-neutral and phase-ground at the service entrance. Pertinent lightning parameters such as ground flash density and the statistical distribution of stroke currents are inputs to the simulation. The phase-neutral distribution is in the range 400 V to 3 kV. Field monitoring over a period of three years at a single site shows reasonable correlation over part of this range. The phase-ground distribution is in the range

400 V to 20 kV, but no comparison with field monitoring is provided. Further work will see the inclusion of surges propagating through the Distribution transformer. Whilst this approach is comprehensive, the method detail is scant e.g. coupling models are not mentioned.

Van Coller and Kelly (1997) performed EMTP simulations to assess lightning surge transfer through Distribution transformers as a function of earthing practices pertaining to South Africa – multiple-earthed neutral (MEN) and single-point earth (SPE). The simulation utilised a wide-band transformer model developed by Kelly (1996) and typical LV topology (ABC and service cables). A chopped 300 kV, 1.2/50 μs voltage surge was applied in various configurations (common-mode and differential-mode) to the primary (surge protected to 95 kV) side of the transformer. It is shown that, in the absence of surge protection installed in the pre-payment meter, a maximum L-N surge voltage of up to 15 kV may appear at the service-entrance for MEN, when a common-mode MV lightning surge is applied.

As part of the aforementioned work, van Coller and Kelly modelled the influence of LV reticulation (ABC, bare conductor horizontal geometry and bare conductor vertical geometry) and earthing (MEN and SPE) practices on induced lightning surges. A lightning strike approximately 1 km from the mid-point of a typical length of LV line was modelled, using the Agrawal transmission line coupling model. Due to assumed Agrawal voltage sources, the results (line mid-point phase-neutral voltage) do not give absolute values but provide a relative comparison. Earthing practice has negligible effect, whilst the lowest induced voltage occurs for ABC and the highest for the bare conductor vertical geometry (i.e. 1.73 times higher than ABC).

The above simulations generally obtain high prospective lightning-related surge voltages, most likely due to flashovers on the MV and/or LV lines being ignored; flashover depends on the intrinsic BIL of the respective lines and/or the weakest points on the system, as follows:

- MV reticulation: Typically one overhead reticulation system is used in Eskom i.e. wood-pole, open-wire (various configurations) as per SCSASABE7:1998, because the use of concrete poles has been discontinued due to expense, and MV ABC is only used by exception (Whyte, 1999). As per SCSASABE7:1998, the BIL is required to be 300 kV for high lightning areas (> 2 ground flashes/km^2/year) versus 1.2 MV for low lightning areas (< 2 ground flashes/km^2/year). The lower BIL for high lightning areas allows the line to withstand expected induced surge voltages up to 250 kV, whilst flashovers are allowed for direct flashes because shielding wires are not used. Wherever ABC is utilised, its BIL is required to be at least 150 kV (Whyte, 1999).

- LV reticulation: The current Eskom standard is SCSASAAM2:1998 covering both open-wire (horizontal or vertical) and ABC. The standard does not mention a BIL, but this is considered unnecessary because possible flashover on LV systems would occur at transformer bushings and in pole-top boxes that intrinsically have lower BIL's than LV open-wire or ABC conductors (Whyte, 1999).

Furthermore, the emphasis in the simulations is on surge voltage rather than surge current. Skibinski, Thunes and Mehlhorn (1986) present an analytical determination of source impedance on the basis that it is critical in calculating the current-energy requirements of an energy absorbing surge protection device to a transient source. Their model uses a Thevenin-equivalent approach and a surge protective device model to calculate the surge current through the surge protective device for various test waveform transients. Of course the aforementioned simulations by Daguillon *et al*. (1996) and van Coller and Kelly (1997) could be extended to include the display of surge currents as the models inherently contain source impedance information (lumped parameters or surge impedance).

2.5.2 IEC 62066:1998

IEC 62066:1998 presents the collective knowledge and experience of various researchers/workers in the field of over-voltages (lightning, switching and temporary) on low-voltage systems. In this literature review, lightning-related over-voltages are of interest.

The document presents information on significant lightning parameters, various coupling mechanisms, MV/LV surge transfer and surge propagation/dispersion. Whilst the prospective over-voltages may be very high, these attenuate quickly due to line losses and flashovers on MV lines, and flashovers and multiple-branch surge current dispersion on LV lines.

It is stated that simulations have shown that surge currents through a surge protective device at the service entrance are in general less than 1 kA for induced voltages. Similarly a direct flash to the MV line at 250 m from the MV/LV transformer results in a surge current of only 200 A. The assumed service entrance earthing resistance was 50 Ω.

It is pointed out in this reference that caution must be exercised against unwarranted generalisations from illustrative examples because differing reticulation/earthing practices can yield broad results, but that large surges do not occur as frequently as limited available data might suggest. According to Geldenhuys (1999) this does not reflect the South African experience at all - it would appear that IEC 62066:1998 tends to reflect European experience, which is generally not associated with severe and frequent lightning.

2.6 Discussion

As per Section 1.3, the creation of a benchmark sample for pre-payment meter surge arresters requires the selection of two discharge current parameters:

- Applicable waveforms
- Peak-current range

2.6.1 Applicable waveforms

According to Miller and Westrom (1976), and Mambuca in his discussion of a paper by Sakshaug (1979), the standard 8/20 μs test wave used in past gap etching analysis work should not be considered an average wave.

A unipolar waveform is usually associated with natural lightning (Fisher, *et al.*, 1990) although this would typically apply to the current injected at the strike point. According to Stringfellow (1990) and Geldenhuys (2000), the distributed parameters of MV and LV reticulation result in longer rise- and tail-times, typically resulting in bipolar waveforms.

Stringfellow (1990) cites field studies showing that lightning current waveforms on power systems are much longer in duration than the standard 8/20 μs waveform, with an 8/80 μs waveform being more representative. For the South African MV/LV reticulation scenario, Geldenhuys (2000) suggests waveforms ranging between 4/40 μs and 4/70 μs (depending on typical lightning waveform distribution and MV/LV reticulation propagation effects).

2.6.2 Peak-current range

Opinions vary as to the prospective lightning-related surge voltages that may appear on LV lines - some of the literature indicates that surge currents discharged by arresters on LV reticulation are generally low in amplitude. However these tend to reflect European experiences (i.e. IEC 62066:1998) – less severe and less frequent lightning occurrence than in South Africa.

Further, it is recognised that the surge levels are a strong function of reticulation/earthing practices and characteristics, and specific local conditions such as soil resistivity, earthing impedance values, and the length and number of LV branches. This is best evaluated through simulations that include the modelling of line insulation parameters to account for flashovers on both MV and LV lines – such simulation is beyond the scope of this work.

Geldenhuys (2000) suggests the concept of a test space framework showing peak impulse current vs. waveform, where its extent should be such that it incorporates both the proposed waveform range and the type test parameters contained in the specifications (TRMSCAAP2:1994, Rev. 2 and IEC 99-1:1991). The test space framework is shown (not necessarily to scale) in Figure 2.2, where the triangles represent the existing type tests i.e. high-current impulse test (30 and 65 kA) and lightning impulse residual voltage tests (1, 5 and 10 kA).

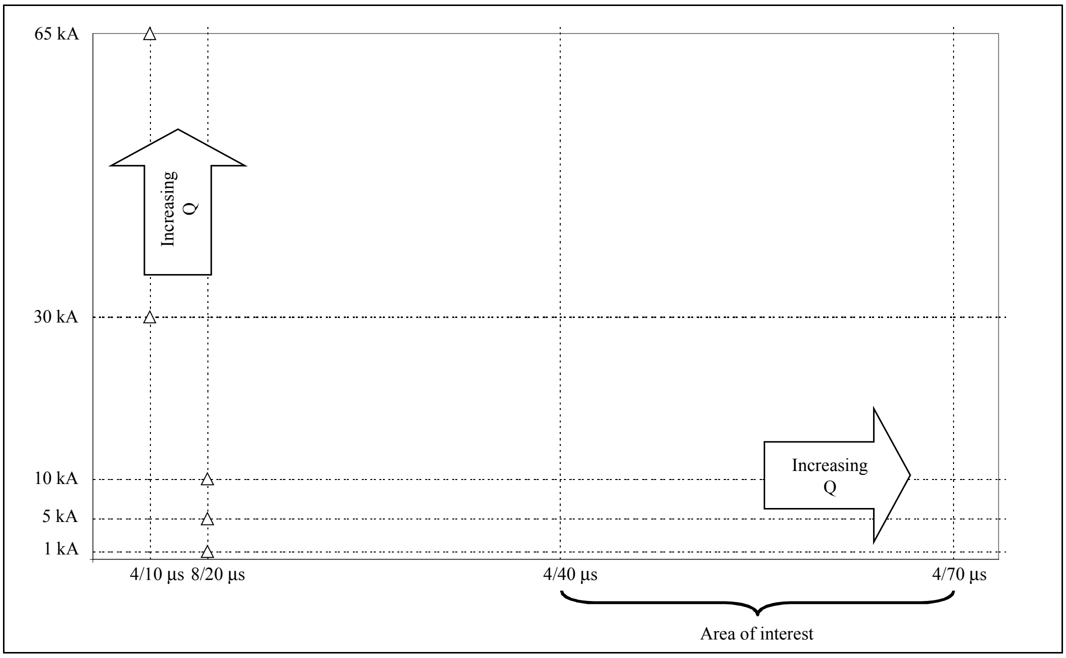

Figure 2.2: Test space framework (not necessarily to scale)

The test space framework may be further enhanced through linear axis scales (i.e. linear increase in Coulomb-charge Q) by considering that the total charge movement associated with a bounded, time-varying waveform, as per equation (2.2), may be further defined as follows:

$$Q = \int_0^T |i(t)|\,dt = I\int_0^T \left|\frac{i(t)}{I}\right| dt = I\ T_W \qquad (2.3)$$

where Q is charge (C), I is peak current (A), T is the duration (s) and T_W is defined as the area under the normalised (absolute) current waveform in units of time (s) i.e. an equivalent square-pulse duration that is unique for a particular waveform[2].

The various lightning waveform/peak-current combinations are simply selected within the “Area of interest”; practically this depends on the generator’s capability.

2.7 Conclusion

Few independent references exist on gap etching analysis - work conducted in this area is mostly related to Distribution system level. The EPRI study is the only

[2] For square-pulse waveforms, $T_W = T$ in each case.

comprehensive reference directly related to the objective of this work (refer to Section 1.3).

In attempting to compare the gap etchings of surge arresters removed from the field to a standard set of pre-conditioned, laboratory-created gaps (benchmark sample), there is the real concern that power-frequency follow current may seriously affect the results.

For the lightning waveform/peak-current combinations, a single waveform cannot represent that which occurs in the field, whilst the prospective surge levels will vary, because these depend on the lightning waveform distribution and MV/LV reticulation propagation effects due to reticulation/earthing practices and characteristics, and specific local conditions. Hence a test space framework, incorporating both the proposed waveform range and the type test parameters as per the relevant surge arrester specifications, is useful for the selection of various waveform/peak-current combinations between the 4/40 μs and 4/70 μs waveforms. Many combinations are possible, limited only by the impulse generator's capability and gap etching resolution.

Therefore the following research questions characterise the creation of the benchmark sample:

- Are the etchings repeatable for a given waveform/peak-current combination? How many samples are required to prove repeatability?
- Do equipment limitations (tolerances) affect the "repeatability" in the above?
- What minimum resolution is obtainable i.e. what is the smallest increment in Coulomb-charge that will allow differentiation?
- What is the minimum detectable Coulomb-charge?
- What is the impact of power-frequency follow current (50 Hz, 5 to 40 A) on the gap etchings?

The remaining chapters in this work address and/or take cognisance of these research questions.