RELATIONSHIP BETWEEN CORONA POWER LOSS AND AUDIBLE NOISE

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ABSTRACT

Results are reported on an initial investigation into corona power loss and its relationship to corona initiated audible noise. The work has the goal of being able to accurately predict the corona power loss, from a transmission line, from knowledge of the audible noise on the line. Corona power loss and its relationship to corona current, applied voltage and electric field is also examined.

Experiments were performed using two single phase, different diameter, corona cages. Although the corona cage test results showed no correlation between corona initiated broad band audible noise and corona power loss, a linear empirical relationship, with excellent correlation, was found to exist between corona power loss and 100Hz Hum (dBA above 20μPa).

Results showed that, at the same magnitude of electric field, within the two different diameter corona cages, the corona current is the same magnitude and the corona power loss is proportional to the applied voltage.

DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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19th day of NOVEMBER 1997

STRUCTURE OF DISSERTATION

This dissertation has been written in the form of a concise paper with a large collection of Appendices. The detailed literature survey; corona cage drawings; source code for computed calculations; graphical illustrations of all corona power loss measurements; and statistics used have been placed in these Appendices.

ACKNOWLEDGEMENTS

The author would like to thank the following people for their valuable contributions towards this project :

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Finally a special word of thanks to Prof Jan Reynders for his guidance, words of wisdom and the opportunity afforded me to complete this project.

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1) INTRODUCTION

The breakdown of air near a transmission line, due to corona, generates heat, light, audible noise and radio interference - all manifestations of the release of energy that must be supplied by the utilities. This energy loss is termed corona power loss and has, in general, been found to be negligible in fair weather, as compared to its occurrence in foul weather.

Corona power loss is of concern to the utilities as its generation can contribute considerably to the cost of supplying electricity (7). It is therefore important that the supply utility not only designs overhead lines to operate below the corona threshold but also that they have an accurate method of measuring or predicting corona power loss on existing lines in service, in the interests of curbing corona activity.

Numerous studies into corona power loss measurement and its prediction have been undertaken and, arguably, the most significant of these has been the work carried out at Project UHV. This research facility, sponsored by the Electric Research Council of the United States, investigated the effects of transmission line corona in order to provide industry with basic data for the design of conductors for both EHV and UHV transmission. Tests were performed in single phase corona test cages and results were scaled by means of generation quantities (Appendix 1) to give meaningful results for three phase transmission lines.

Measurements, undertaken at Project UHV (7), included investigating the relationship between corona power loss and corona initiated audible noise. However, this work was not taken further and the possibility of predicting the transmission line corona power loss, from a knowledge of the audible noise on the line, was not explored.

The following project investigates not only the measurement of corona power loss but also its relationship to corona initiated audible noise.

The work forms the initial stage of work to determine the corona power loss from a transmission line, from a knowledge of the audible noise on the line. It is envisaged that an empirical relationship exists between corona power loss and audible noise and this is analyzed. Determination of an empirical relationship between the two entities would allow for accurate prediction of corona power loss from transmission lines which are in service.

Experimental work was carried out in the High Voltage Laboratory at the University of the Witwatersrand using two different diameter, single phase corona cages (Appendix 2). Point sources were used to enhance the electric field on the conductor surface and provide sources of corona activity.

The use of the two cages allowed for an investigation into how cage diameter affects corona power loss from a conductor. Electric fields, of the same magnitude, were setup in each cage and valuable information on the proportionality of voltage to corona power loss was obtained. This is especially important in the design of power transmission lines, using single phase corona cage test facilities, with respect to designing below the corona threshold.

In order to obtain electric fields of the same magnitude, in the respective cages, a 3-dimensional finite element analysis package (20) was used for theoretical prediction of the fields.

2) BACKGROUND

2.1) CORONA POWER LOSS

Corona power loss occurs on transmission line conductors when the voltage gradient in the immediate vicinity of the conductor surface exceeds the breakdown strength of air (8). The resulting discharge releases energy in various forms and this represents an amount of energy that cannot be recovered by the supply utility.

It has been shown (8) that maximum calculated corona power loss can be of the same order of magnitude or even higher than resistance losses. Bartnikas and McMahon (1) list, as an example of appreciable corona power loss , the following : A three phase overhead transmission line with a 10m flat spacing and a conductor diameter of 42mm may lose up to 2.5kW per kilometre at 350kV in dry weather. In wet weather the corona loss can be as high as 44kW per kilometre. At 400kV, the same line loses 6kW per kilometre, in dry weather, and 114kW per kilometre when wet.

From the above figures it is evident that corona power loss in fair weather is negligible as compared to the loss in foul weather. Indeed few fair weather corona loss results from Project UHV are available and most conductors tested were mainly checked for foul weather performance. Continuing in this vein, Gary and Clade (3) investigated the predetermination of corona losses under rain and devised loss curves as a function of the conductor surface gradient. This work showed good correlation between measured and predicted transmission line power loss.

Aside from theoretical prediction it is evident, from the literature, that corona power loss can accurately be measured with the use of single phase test cages (3,5,8). Values obtained in this manner need to be scaled, by means of generation quantities (Appendix 1), in order to obtain meaningful results for three phase conditions.

2.2) AUDIBLE NOISE

Audible noise from transmission lines occurs primarily in foul weather (7). In dry conditions, the conductors usually operate below the corona inception level, and very few corona sources are present. In wet conditions, however, water drops collecting on the conductors produce a number of corona discharges, each creating a burst of noise.

Corona initiated audible noise consists of two components, namely, a broad band component and secondly, a low frequency pure tone. The low frequency pure tone occurs at twice the power frequency i.e. 100Hz, and is due to the motion of positive and negative ions around conductors carrying alternating current (7). This pure tone is clearly illustrated by Comber et al (4) in sound measurements taken using an A-weighted sound level.

A-weighting is a measurement technique used to take into account the fact that the human ear is more sensitive in the mid-range of frequencies. Although other weighting functions exist, the A-weighted sound level, expressed in dBA, is by far the most commonly used (19).

The range of pressure variations that the human ear can detect is extremely wide i.e. a very loud sound can have as much as 1,000,000 times the rms sound pressure of a very quiet sound. Therefore, for convenience, a compressed scale has been devised on the basis of the logarithm of the sound pressure (Appendix 1). Unless otherwise explicitly stated it is understood that the sound pressure is the rms sound pressure and that the reference pressure is 20μPa.

As for corona initiated power loss, prediction of audible noise has also been investigated (14). Results obtained for the theoretical model showed good agreement with measured values.

Measurements regarding the prediction of corona power loss from a knowledge of the audible noise on the line were not encountered in any of the literature. A relationship between corona power loss and 120Hz Hum (dBA above 20μPa) was however plotted for a UHV test line (7) and this forms the basis for further investigation into possible prediction of corona power loss from knowledge of the audible noise.

3) EXPERIMENTAL PROCEDURE

The average corona power loss, for experimental purposes, was calculated using the integral of the instantaneous voltage multiplied by the instantaneous corona current i.e.

$$P = \frac{1}{T}\int_0^T v.i.dt$$

where : P = average power

T = period over which measurements were taken

v = instantaneous voltage

i = instantaneous corona current

A digitising oscilloscope was used for the multiplication of the current and voltage waveforms and to perform the necessary integration.

Corona current comprises a capacitive component and a 50Hz component. The 50Hz component of the corona current is the only component which contributes to the real corona power loss. In previously conducted experiments (16,17) this component of the current was filtered out from the capacitive component and utilised in required calculations.

In this experiment the integration of the instantaneous current and voltage ignores components which do not contribute to the real power loss i.e.

$$P = \frac{1}{T}\int_0^T v.i.dt = VI\cos\theta$$

where : P = average power

T = period over which measurements were taken

V = rms voltage

I = rms current

θ = difference in phase angle between voltage and current

From the above theory it is clear that any capacitive current flowing in the circuit will not contribute to the real power loss i.e. the difference in phase angle between the voltage and capacitive current component is 90° and the equation sums to zero in this case.

Harmonics, if present, contribute to the instantaneous value of both the current and voltage. The above method of power measurement, therefore, automatically inc udeds the influence of harmonics.

3.1) EXPERIMENTAL SET-UP

Measurements were taken using two solid aluminium cages, one of 300mm diameter and the other of 480mm diameter, through which a copper conductor of 15mm diameter was strung. Points were soldered to the surface of the conductor and used as sources of corona activity. A schematic of a length of the conductor is given below :

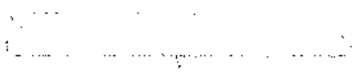
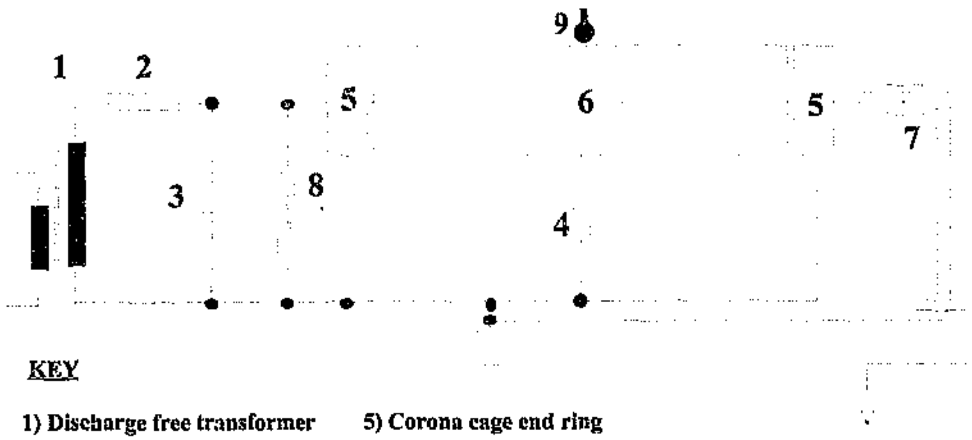


Figure 1 : Section of Copper Conductor Indicating Corona Point Source on Surface

The solid aluminium corona cages were erected in the high voltage laboratory such that the circuit arrangement was that shown below :



KEY

1) Discharge free transformer
2) Current limiting resistor
3) 1000pF Capacitor
4) 50 ohm resistor
5) Corona cage end ring
6) Corona cage
7) Support Insulator
8) Resistive divider
9) Microphone

Figure 2 : Corona Cage Circuit Diagram

- point sources were essentially cones of 4.5mm in length with a base diameter of 3.3mm and a tip diameter of 0.55mm.
- the high voltage source consisted of an AC supply voltage controlled via a variable auto-transformer which fed into the transformer.
- the 1000pF discharge free coupling capacitor facilitates the passage of high frequency current impulses.
- the cages were constructed of solid aluminium and connected via the 50Ω resistor to earth
- the microphone was suspended above a ten centimetre, wire gauze covered hole which was machined into the top of both cages. The solid nature of the cage eliminated transmission outside the cage and no external reflections needed to be considered..

- a free field 1" microphone in conjunction with a sound level meter was used as the acoustic transducer and fed into the digitising oscilloscope.
- a discharge free transformer, with maximum output voltage of 50kV (rms), was used as HV source for the 300mm diameter cage.
- a 140kV (rms) transformer was used as input for the 480mm diameter cage.

The voltage waveform applied to the set-up was measured using a 1000:1 resistive voltage divider which was input to a Tektronix TDS 544A Digitising Oscilloscope. The corona current was measured across the 50Ω resistor. The divider was calibrated using a precision resistance measurement and the oscilloscope was calibrated using an internal calibrator.

3.2) METHOD

Measurements followed the same procedure for both cages. Starting with a single point on the surface of the conductor, ten readings of the corona loss were taken at escalating voltages. A measurement of the audible noise was made at the highest value of voltage applied to the conductor, for each number of corona point sources i.e. corresponding to the tenth reading of corona power loss.

The audible noise was measured by means of a microphone suspended above the corona cage. This microphone was input to a sound level meter and the resulting waveform was input to the oscilloscope and saved to disk, for further manipulation. These readings were repeated for up to ten points on the surface of the conductor. Prior to each measurement, the microphone and sound level meter were calibrated using the calibrator supplied with the meter.

In order to obtain the corona power loss the input voltage waveform was multiplied by the output voltage, as picked up across the 50Ω resistor, and the resulting waveform integrated - all functions performed by the oscilloscope. The resulting waveform had to

be further manipulated in order to obtain the corona power loss, and was saved to disk and then down loaded to MATLAB™ (Appendix 3). The waveform was divided by 50, in order to obtain the correct value of corona current and then multiplied by 1000 to compensate for the resistive voltage divider. Division of the waveform by the period over which the measurements were taken yielded a single value of corona power loss.
The audible noise waveform was also down loaded to MATLAB™ (Appendix 3). A Fast Fourier Transform was performed on the waveform in order to obtain the frequency components of the measured signal. The resultar[illegible]veform was used to determine the 100 Hz Hum of the signal and this value was usec[illegible] representative of the audible noise on the line i.e. the broad band noise was ignored for the purposes of the experiment.

It is important to note that all waveforms, obtained from the oscilloscope, were sampled at 250kHz and consisted of a record length of 15000 points.

4) EXPERIMENTAL RESULTS

Although the focus of the project was placed primarily on the relationship between corona power loss and audible noise, the relationship between applied voltage and electric field was also investigated. Measurements, within the two different diameter cages, were required to be taken at the same electric field magnitudes. In order to achieve this, theoretical prediction of the electric field, at the corona point source tip, was performed using a 3-dimensional finite element package (20).

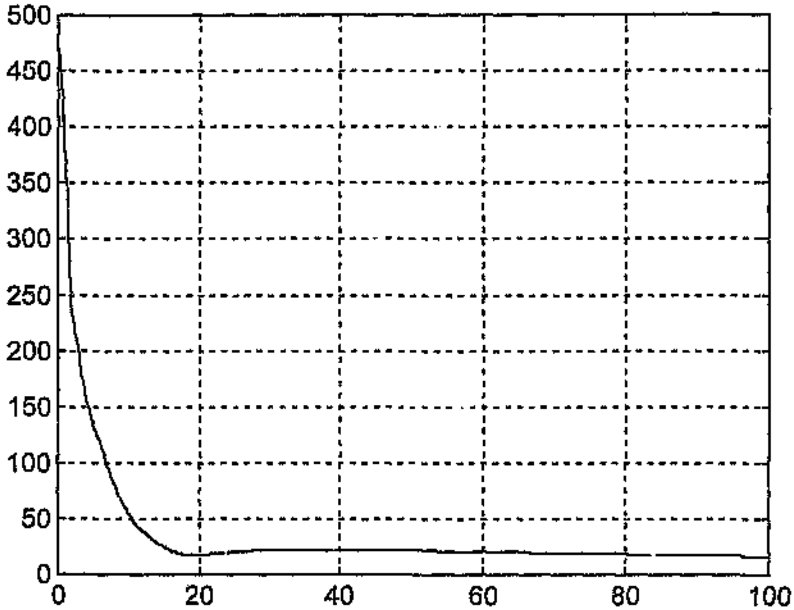


Figure 3 : Simulated E-field Magnitude at a Single Corona Site - 300mm Cage (Normalised to 1V)

Figure 3 indicates the theoretical prediction of the electric field magnitude, obtained for a single corona point source located on an energised conductor, within the 300mm diameter earthed corona cage.

The results obtained are for a conductor carrying a potential of 1V. The electric field at any potential applied to the conductor can be found by scaling the indicated plot. The peak value of the curve for the 300mm diameter cage is located at 481V/m.

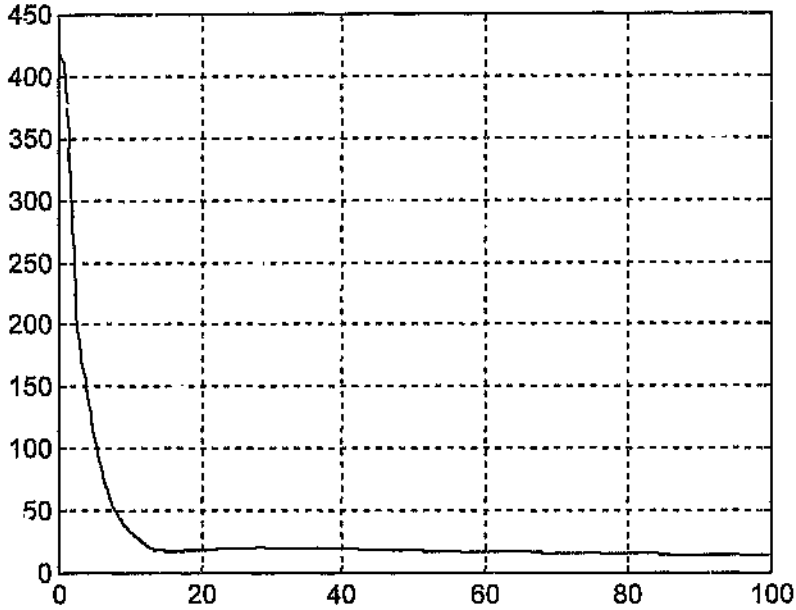


Figure 4 : Simulated E-field Magnitude at a Single Corona Site - 480mm Cage (Normalised to 1V)

Figure 4 indicates the electric field magnitude plot obtained for the 480mm diameter cage. The curve peaks at 427V/m in the case of the larger cage. Only a single point on the conductor surface was used for simulation purposes as, during experimentation, points were spaced such that the electric fields at the respective points could not influence one another. Points were spaced either side of the conductor not less than 100mm from one another.

Significant corona initiated audible noise was observed in the 300mm diameter cage at 27.9kV(rms) and this was chosen as a maximum voltage measurement value for this cage. Similarly, a value of 35.7kV(rms) was chosen for the 480mm diameter cage.

These chosen values of voltage give rise to electric field magnitudes of 19.0kV/mm and 21.6kV/mm in the respective cages, using the theoretically calculated curves above. This results in a 12% difference in theoretical field magnitudes between the two cages. Measurements, as indicated in Figure 7, show that the magnitudes of the corona current, at 27.9kV(rms) and 35.7kV(rms) in the respective cages, are within 5% of one another.

Therefore it is assumed that if corona current magnitudes are equivalent, the electric field magnitudes must be equivalent. Also, simulation results cannot be considered to be completely accurate as small variations in the conductor alignment within the cages can lead to differences in electric field magnitudes. A 12% difference could thus be accepted for simulation results and the electric fields were considered to have the same magnitude in the two cages, based on the knowledge of the equivalent corona current magnitudes.

Total corona current was measured at the maximum voltages for the respective cages i.e. 27.9kV(rms) in the 300mm cage and 35.7kV(rms) in the 480mm cage. Figure 5 and 6 indicate the measured current for both cages.

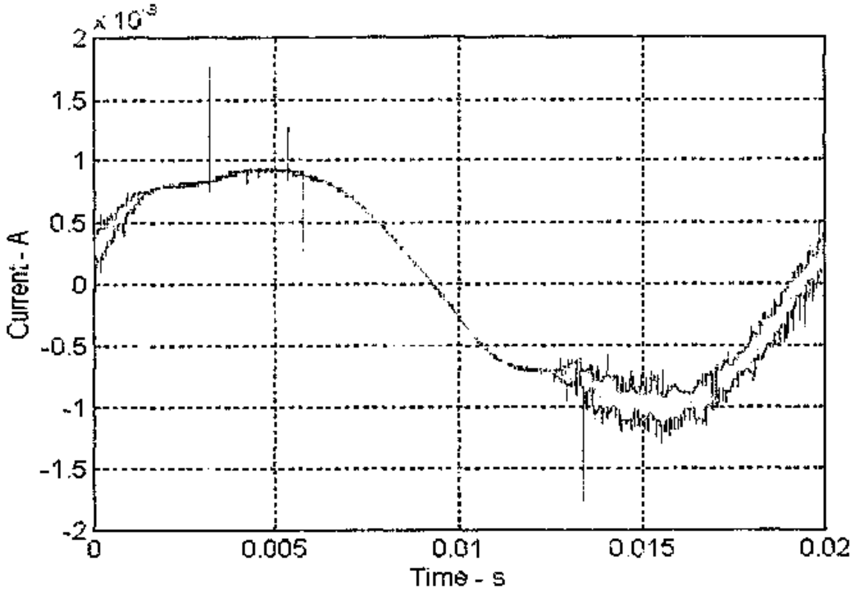


Figure 5 : Current Measured Across 50Ω Resistor at 27.9kV(rms) - 300mm Cage

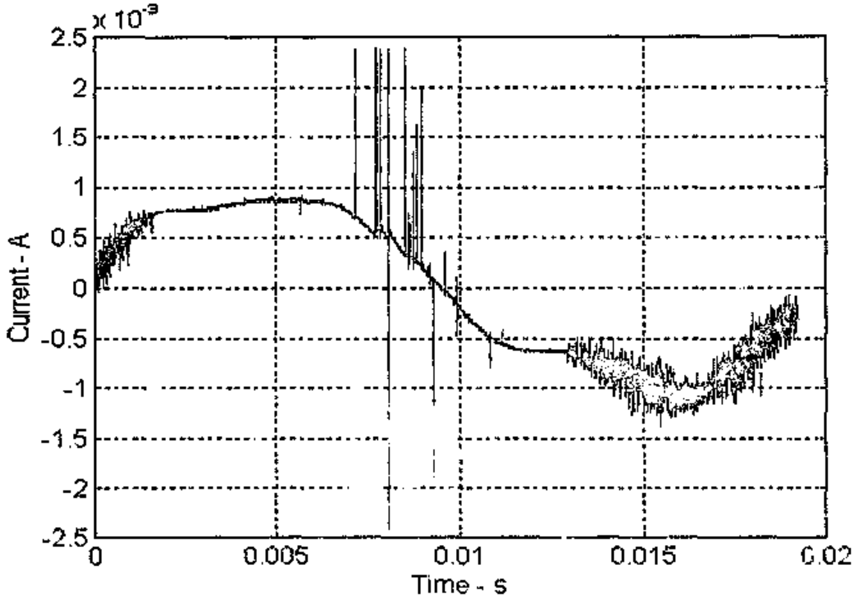


Figure 6 : Current Measured Across 50Ω Resistor at 35,7kV(rms) - 480mm Cage

A single period of the total current waveform, measured across the 50Ω resistor, is indicated in the waveforms above. In order to obtain the 50Hz component, of the corona current the waveform was downloaded to MATLAB™ (Appendix 3), the Fast Fourier Transform calculated and the 50Hz component filtered out.

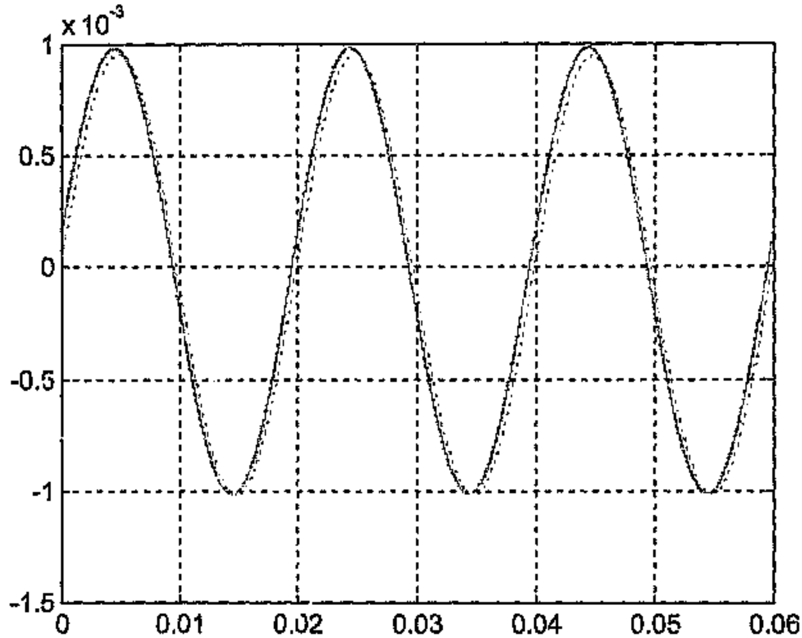


Figure 7 : 50Hz Component of Corona Current as Measured at Peak Voltages and Equivalent Electric Fields, in Both Corona Cages

Figure 7 shows the filtered 50Hz component of the corona current, for both cages, for the full period of measurement i.e. 3 cycles of the 50Hz waveform. The larger current magnitude was obtained in the 480mm diameter corona cage.

Corona power loss results were taken in the range of 15.7kV(rms) to 27.9kV(rms) for the 300mm cage. For the 480mm cage the range was 21.9kV(rms) to 35.7kV(rms). These values were chosen so as to be above the corona threshold but below breakdown, within the corona cages.

Readings were taken for up to ten corona point sources on the conductor surface. Figure 8 indicates the results obtained for the corona power loss as a function of the number of corona point sources. Results for both cages are shown.

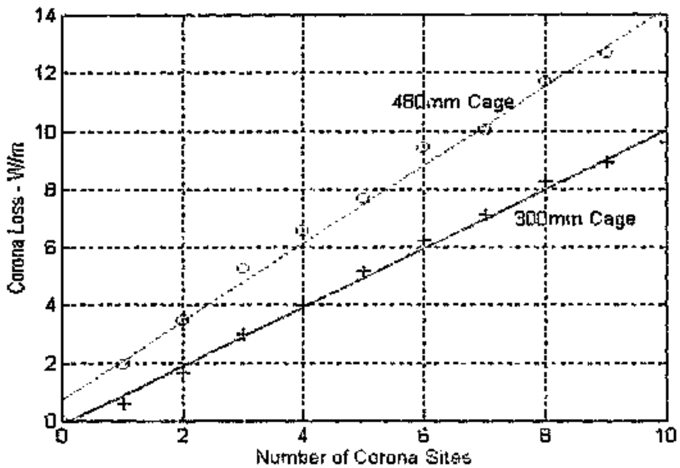


Figure 8 : Corona Loss as a Function of Number of Corona Sources

Figure 8 shows the readings obtained for the maximum voltages within the two cages i.e. 27.9kV(rms) and 35.7kV(rms) respectively. Comprehensive results, across the respective voltage ranges - indicating corona loss curves obtained for 1 to 10 sites in both cages - are contained in Appendix 4 and Appendix 5.

Maximum corona power loss, obtained for the 300mm diameter cage at 27.9kV(rms) was 9.63W, with ten corona point sources on the conductor surface. The corresponding maximum loss; in the 480mm diameter cage was 13.65W at 35.7kV(rms).

As can be seen, when the electric field magnitude is the same, in different diameter corona cages. the corona power loss is significantly higher in the larger diameter cage (Appendix 4 and 5).

A single measurement of audible noise was made per number of sites on the conductor surface, for each cage. Measurements were made at the maximum voltages used for the different cages i.e. each noise measurement was made at 27.9kV(rms) in the 300mm cage and each one at 35.7kV(rms) in the 480mm cage.

As indicated previously, the audible noise consists of a broad band component and low frequency pure tones. The pure tone, at 100Hz, is distinctly higher in magnitude than other frequencies (Appendix 6). Because the 100Hz Hum value is so distinct it was decided to use only the magnitude of the sound wave (dBA above 20μPa) at this point as representative of the audible noise from the corona point sources.

Audible noise measurements were taken using an A-weighted network and results reflect the noise above a reference pressure of 20μPa. Figure 9 shows 100Hz Hum (dBA above 20μPa) plotted against the number of corona point sources, for both cages.

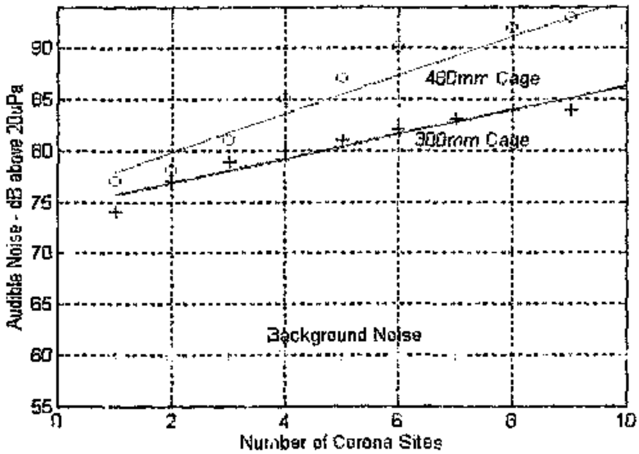


Figure 9 : 100Hz Hum (dBA above 20μPa) as a Function of Number of Corona Sources

Figure 9 indicates the trend that the 100Hz Hum follows as the number of sites on the conductor are increased.

The maximum 100Hz Hum obtained in the 300mm diameter cage was 86dBA - corresponding to ten corona sites on the conductor surface. A maximum of 93dBA was found in the 480mm diameter cage with nine corona point sources on the conductor surface.

The background 100Hz Hum is also indicated on the plot. This value was obtained by taking a noise measurement without the conductor, in the corona cage, energised. As can be noted, the noise due to the corona is considerably louder than the background value. Figure 10 and 11 show the 100Hz Hum (dBA above 20μPa) plotted against the corona power loss.

Measurements of 100Hz Hum (dBA above 20μPa) and corona power loss were taken at voltages of 27.9kV(rms) in the 300mm diameter cage and at 35.7kV(rms) in the 480mm diameter cage.

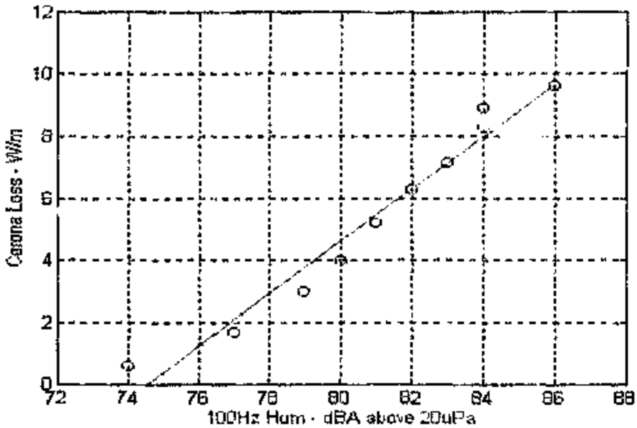


Figure 10 : Least Squares Trend of Corona Loss as a Function of 100Hz Hum (dBA above 20μPa) - 300mm Corona Cage

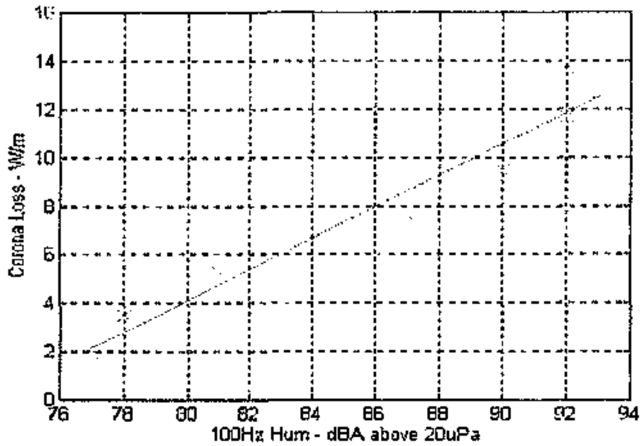


Figure 11 : Least Squares Trend of Corona Loss as a Function of 100Hz Hum (dBA above 20μPa) - 480mm Corona Cage

The above plots indicate the trend followed by the two curves with a clearly linear relationship evident between the two entities. Indeed, the correlation (Appendix 7) for the 300mm cage is **r = 0.98** and for the 480mm cage is **r = 0.95**. There is thus a strong positive relationship between the corona power loss and the 100Hz Hum.

The standard deviation, (Appendix 7) for the data, was also calculated and is given by **S = 2.9W/m** for the 300mm and **S = 4.1W/m** for the 480mm diameter corona cage.

Sound pressure due to the corona varies inversely with the square root of distance away from the line, i.e. for every doubling of distance the sound pressure decreases by 3dB (7). Applying this theory to the results obtained yields the following :

Distance from line = 300mm (Microphone location for 300mm Cage)

$$\therefore \text{ Normalised distance for 480mm Cage } = \frac{480}{300} = 1.6$$

∴ As the pressure varies with the inverse of the square root of distance away from the line we have :

$$20\log_{10}\left[\frac{\text{sound pressure}}{\text{reference presssure } \times \sqrt{1.6}}\right] = 20\log_{10}\left[\frac{\text{sound pressure}}{\text{reference pressure}}\right] - 2 \ \text{(dB)}$$

Therefore, by decreasing the sound pressure level, as measured for the 480mm cage, by 2dB, it is possible to compare the values so obtained with those from the 300mm cage. Figure 12 below shows the curves obtained by normalising the sound pressure levels to the 300mm corona cage.

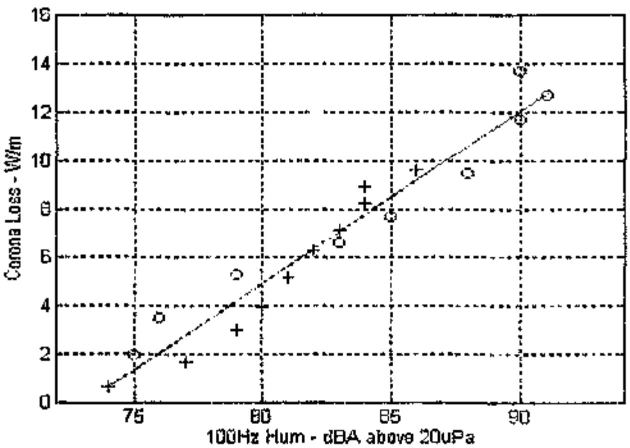


Figure 12 : Power Loss as a Function of 100Hz Hum (dBA above 20μPa) - Normalised to the 300mm Corona Cage

The correlation for the above data is **r = 0.97** and the standard deviation is **S = 5 1.**

5) DISCUSSION OF RESULTS

Results obtained show clearly that the effects of corona increase with increasing corona intensity. Corona power loss as a function of the number of corona point sources (Figure 8) follows this expected trend i.e. as the number of sources increases so too does the corona power loss. The power loss trend curves obtained (Appendix 4 and 5), compare favourably with results obtained in experiments of the same nature (8,9,17).

Similarly, the audible noise increases with an increase in the number of corona point sources. The audible noise has been shown to consist of a high frequency component which results in a crackling, frying or hissing noise (Appendix 6) (7). The second component of the noise is a low frequency pure tone or 100Hz Hum (Appenuix 6). The 100Hz Hum was chosen as a representative value of audible noise due to the distinctness of the noise at this frequency (Appendix 6).

Results are consistent with those found at Project UHV (7), at which tests were performed in UHV corona cages. These data confirm that corona power loss and hum are both caused by the cylindrical movement of ions in the electric field of the conductors. The larger the number of ions, the larger will be both the power dissipated by their movement and the variation in air pressure caused by their movement (7).

An excellent correlation was found between the corona power loss and 100Hz Hum. From the calculation of the standard deviati[illegible] it is evident that the corona loss data is not spread over a wide range of values. Inste[illegible] corona power loss increases in an orderly, linear fashion as the audible noise increases.

From the curve showing values normalised to the 300mm cage (Figure 12) it is evident that from knowledge of the audible noise on the line a reasonably accurate prediction of the corona power loss can be determined.

Thus the experimental data, obtained using a corona test cage facility, can be used to predict the corona power loss from a transmission line from a knowledge of the audible noise, produced by the corona.

Although good results have been obtained under laboratory conditions, the tests need to be further extended to include transmission lines. It is envisaged that, in the field, a measure of the 100Hz Hum can be obtained by placing a microphone underneath a line in service and then, by use of an appropriate correction factor, as deduced from corona cage testing, an accurate prediction of the corona power loss can be made.

Results investigating the applied voltage and corona power loss relationship were based on the use of the two different size corona cages. However, in practice, a single corona test cage facility is usually used to test various conductor configurations (2,5,19). In the case of the single cage test facility all test lines are energised to a single value of electric field, which is chosen to be below the fair weather corona inception field. Lines are then artificially sprayed with water, simulating rain, and corona related measurements are taken.

A fixed electric field value is therefore chosen and all conductors are designed to operate below this field strength. However, when testing dissimilar geometries in the same corona cage, possibly also operating at different service voltages, it would be possible to energise the different test lines with the same voltage, in order to obtain the pre-chosen electric field.

Results obtained from this project have clearly shown that for the same electric field, and consequently the same corona current, the corona power loss is proportional to the applied voltage i.e. at the same electric field, in different diameter corona cages, the power loss is greater in the cage of larger diameter.
Corona power loss results for single test cage facilities, using different conductor configurations, could thus yield the same corona power loss at the same electric field, provided the same voltage is used to energize the line.

It is of importance to realize that similar test results can therefore be obtained for totally different conductor configurations, even for lines operating at different service voltages. This illustrates the importance of the use of conversion factors such as generation quantities (6) for single corona cage test facilities, in order to obtain values which approximate practical conditions.

6) CONCLUSIONS

Results have indicated that corona power loss, at equivalent electric field magnitudes in different diameter corona cages, is proportional to the voltage applied to the conductor. This indicates that loss can be scaled with voltage, for similar geometries, provided the conductor surface fields remain the same. At equivalent electric fields, in different diameter corona cages, the corona current is comparable in magnitude and was measured to within 5%.

Single corona cage test facilities, testing dissimilar geometries which possibly also operate at different service voltages, must ensure the use of conversion factors such as generation quantities in order to produce meaningful results.

Corona power loss and 100Hz Hum (dBA above 20μPa) both increase with increasing corona intensity i.e. as the voltage applied to the conductor increases so too does the corona activity. Also, both entities increase as the number of corona point sources on the conductor surface is increased.

It has been shown that, for a single phase corona cage, a linear empirical relationship exists between corona power loss and 100Hz Hum. The statistical correlation between corona power loss and 100Hz Hum (dBA above 20μPa) was found to be **r = 0.98** and **r = 0.95** for the respective test cages, and **r = 0.97** for results normalized to a single test cage. Therefore, with suitable calibration, 100Hz - twice power frequency - Hum (dBA above 20μPa) can be used to estimate corona power loss.

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