AC TO DC LINE CONVERSION: A COMPARISION OF EMPRICAL TESTS VERSUS THEORETICAL MODELS

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Abstract: Theoretical calculations have suggested that the power transfer capacity of an existing AC transmission line may be increased by converting the line to DC operation. Additionally, Eskom have experienced difficulties in obtaining new transmission line servitudes hence conversion to DC may result in increased capacity. Due to the infant nature of conversion of lines, reliance on simulation packages is not well understood. Thus tests were conducted at the EPRI HVDC test facility in Lenox Massachusetts to compare the data obtained from simulation packages to empirical data. These tests were conducted on a number of configurations i.e. quad conductor bipolar; twin conductor monopole; single conductor monopole as well as a single conductor and quad conductor bipolar setup. This paper presents the key results from the initial studies undertaken, and it is shown that at low conductor surface gradients, the levels measured are quite dispersed and not in good agreement with predictions; the reasons are duly explained.

1 INTRODUCTION

Theoretical calculations have suggested that the power transfer capacity of an existing AC transmission line may be increased by converting the line to DC operation. Also, the voltage withstand of insulation is better utilised by DC voltage, which is constant and not time-varying as is the case with AC voltage. DC corona effects at high voltages are also less severe, which may result in higher-than-expected DC voltages to be used [1].

With power transfer capability requirements for existing servitudes ever increasing, it would be beneficial to Eskom to understand the issues involved with AC to DC conversion of transmission lines and, more importantly, to gain insight into how such conversion can result in addition of significant value, and especially what other countries' experiences are in this regard [1].

Due to the infant nature of conversion of lines, reliance on simulation packages is not well understood. Thus tests were conducted at the EPRI HVDC test facility in Lenox Massachusetts to compare the data obtained from simulation packages to empirical data. These tests were conducted on a number of configurations:- quad conductor bipolar; twin conductor monopole; single conductor monopole as well as a single conductor, quad conductor bipolar setup.

The studies detail specifics to the electrical environment, included: Radiated Radio Interference (RI); Radio Influence Voltage (RIV); Radio frequency excitation functions; Propagation of modal noise currents; Audible noise (AN); Electric fields; Ionic currents to ground; Space charge and Anomalous coupling.

2 TEST SETUP AND METHODOLOGY

Tests were conducted at the EPRI HVDC test facility in Lenox Massachusetts from the 7th April 2008 until the 18th April 2008. The aim of the tests was to determine whether the audible noise, electric field strengths and RI (radiated and conducted) could be predicted by making use of the various simulation packages.

Tests were conducted on a quad conductor bipolar; twin conductor monopole; single conductor monopole as well as a single conductor, quad conductor bipolar setup.

Specific details are provided in the following sections.

2.1 Test Configurations

The four test setups mentioned above were used to achieve various conductor surface gradients in order to generate enough corona activity for measurable audible noise discharges.

The various test configuration setups are summarised in Table 1.

Table 1: Test Configuration

	Quad Bipolar	Twin Monopole	Single Monopole	Single / Quad Bipolar
Conductor diameter	3.52 cm	4.5 cm	2.82 cm	2.82 cm / 3.52 cm
Sub-conductor spacing	45.72 cm	41.9 cm	N/A	N/A / 45.72 cm
Phase spacing	15.24 m	N/A	N/A	7.62 m
Conductor attachment height	25.98 m	12.47 m	15.00 m	15.00 m, 25.98 m
Conductor sag	10.67 m	N/A	9.30 m	9.30 m, 10.67 m
Characteristic impedance	308.2 Ω	332.3 Ω	427.5 Ω	427.5 Ω / 308.2 Ω
Conductor surface gradient (kV/cm) @ 1. 320 kV, 2. 550 kV.	1: 12.71 2: 21.85	1:14.85 2: 25.52	1: 32.85 2: N/A	1: 37.61 / -11.69 2: N/A

2.2 Measurements undertaken

Measurements made under the various configurations were as follows (Table 2):

Table 2: Measurement matrix

	Quad Conductor - Bipolar	Twin Conductor – Monopolar	Single Conductor - Monopolar	Single / Quad Conductor - Bipolar
Conductor Diameter	3.52 cm	4.5 cm	2.82 cm	2.82 / 3.52 cm
AN Tests	X	X	X	X
Rad. RI Tests	X	X	O	O
Con. RI Tests	X	X	X	X
E-Fields	X	X	X	X
Ions	X	O	X	X

Key: X – Test done, O – Test not done

2.3 Measurement Equipment

The equipment used for the tests were as follows:

Audible noise measurements – NLS Sound level meter. The NL-32 sound level meter is capable of measuring A-weighted and 1/3 octave levels.

Sound level meters are used to measure sound pressure level according to specific standards. The current International standard for sound level meter performance is IEC 61672:2003 which mandates the inclusion of an A-frequency-weighting filter.

RI (conducted and radiated) – Rohde & Schwarz ESIB40/B16/B18 EMI Test. The Rohde & Schwarz receiver is capable of measuring, RMS, quasi-peak and CISPR Average simultaneously. Measurements were made from 100 kHz to 3 MHz.

Conducted Noise – Measurements were made by using a coupling capacitor and inductor combination which tuned the circuit to the desired frequency (500 kHz). The coupling circuit is shown in Figure 1.

Measurements were made for the following bipolar voltage levels, 320 kV, 350 kV, 400 kV, 450 kV, 500 kV and 550 kV. The frequencies considered for each voltage level tested were as follows, 150 kHz, 300 kHz, 500 kHz, 750 kHz, 1 MHz and 2 MHz.

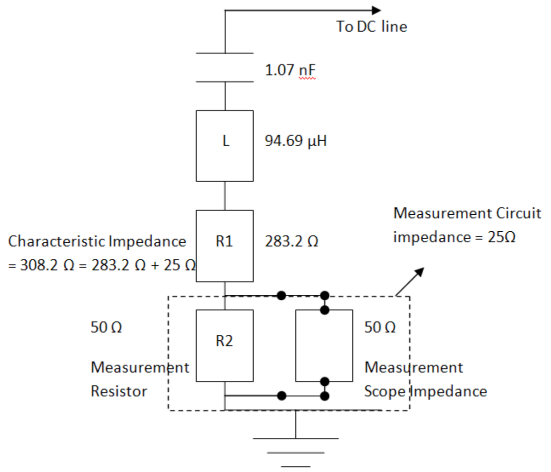

Figure 1: Conducted noise measurement circuit

Ionic Currents – A Wilson plate was used for these measurements. The principle of operation of the Wilson plate is as follows: The plate is placed at a specific location, relative to a DC line. The collecting plate is insulated from ground and connected to ground via an ammeter. Ionic currents generated due to corona activity on the DC conductor drift to ground, these currents are then collected by the surface of the collecting area of the Wilson plate. The collecting plate surface area is of a known size, typically 1 m^2. The ionic current density is then calculated by dividing the measured current by the surface area of the collecting plate. Typical currents are in the order of nA to µA. The Wilson plate is generally connected to ground via an ammeter, the ammeter used in the initial measurements was a Keithley unit.

Electric field measurements – The electric field meter used for these tests was the Monroe model 257D electrostatic field meter. It is a vibrating plate type field meter; this type of field meter is described in [2]. The sensitivity of the meter was 0.1 kV/m.

The guard plate used together with the Monroe electric field meter had dimensions of 1.21 m by 1.21 m. A circular cut out was made in the middle of this plate in order for the field mill to be slightly below the surface, without touching the guard plate, which was grounded.

The Monroe round field meter probe would fit into the round aperture cut into the plate. The probe was then connected to the meter by means of a data transfer cable, as specified in the operating manual.

3 RESULTS: TWIN CONDUCTOR – MONOPOLAR

This set of tests was conducted on the twin conductor test line The use of the twin conductor test line allowed for a 16.8% increase in conductor surface gradient compared to the quad conductor test line for the same applied voltage. Due to the location of the test line and its proximity to the DC source, it was only possible to energise one of the twin conductor bundles at a time. Therefore bipolar testing could not be carried out. Only positive polarity tests were carried out. The weather conditions were fair, cold with no rain.

The conductor surface gradients ranged from 14,9 kV/cm at +320 kV to 25,6 kV/cm at + 550 kV.

3.1 Electric Field Measurement Results

The results of the twin conductor monopole electric field measurements versus the 50% fair predictions given by the EPRI TL Workstation are shown in Figure 2.

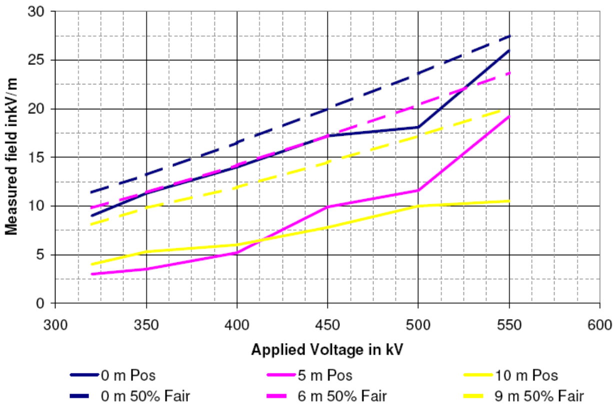

Figure 2: Twin conductor measured E-field versus 50% Fair Prediction

Figure 2 shows that the predicted E-field values are lower than the actual measured values from the monopolar test line. The slopes of the predicted values are also more similar to the slopes of the measured results when compared to the EPRI TL electrostatic prediction. From Figure 3 it can be seen that the measured results lie within the two predictions. This is a good result and in keeping with theoretical considerations. The conductor surface gradient which was 25.6 kV/cm is not particularly high, however the specific line used in the tests had not been used for many years and that it was quite possible that the surface condition of the conductor was quite rough due to a collection of debris and insects during the years of non-operation.

As corona activity was taking place on the conductor, the electric field measured should be higher than the predicted electrostatic case. However, the corona activity was not intense therefore the fact that the measured results were below the predicted 50% value for fair weather is reasonable.

3.2 Audible Noise Measurement Results

Audible noise measurements were made to determine whether the simulation results could be applied to an actual line. The main aim was to determine how closely the simulated values were to the actual measured values.

Figure 3 shows the results of the audible noise measurements at various measurement points for different applied voltages. It also gives the values predicted by the EPRI TL workstation as well as values predicted by Maruvada [3].

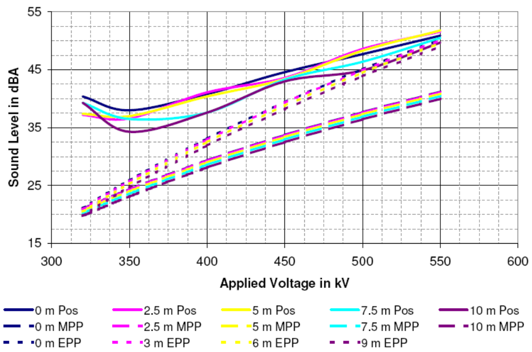

Figure 3: Twin conductor audible noise measurements as a function of positive applied voltage

To determine whether the measured audible noise results correlate to the predicted values as given by Maruvada [3], the following equation was analysed.

$$AN = AN_0 + 86\log(g) + k\log(n) + 40\log(d) - 11.4\log(R)$$

Where: AN_0 *= -100.62 for n>2 and -93.4 for n = 1,2*

k = 25.6 for n >2 and 0 for n = 1,2
g is the gradient at which the measurement is made.
n is the number of sub-conductors
d is the conductor diameter
R is radial distance from conductor

Figure 3 shows that the predicted values as given by the Maruvada prediction are much lower than the actual measurements, however the slope of the curves are fairly similar. The predictions given by EPRI seem to be closer to the actual measurements than the Maruvada predictions, but only at the higher conductor surface gradients. This was due to the presence of background noise in the region of 40 dBA which affected measurements at the lower voltage levels. The slopes of the EPRI predictions and the actual measurements are not similar, the EPRI prediction results in a steeper slope. So, although the measurement values are far higher at the lower applied voltages, the EPRI prediction values are more or less the same as the measurement values at the higher voltages (i.e. at the highest gradient of 25,6 kV/cm.).

Figure 4 shows the results of the audible noise measurements as a function of lateral distance away from the conductor. It indicates that the measured values are higher than the predicted values. Comparing the measurements to the Maruvada predictions, it can be said that the predictions are about 10 dB lower than the actual measurements.

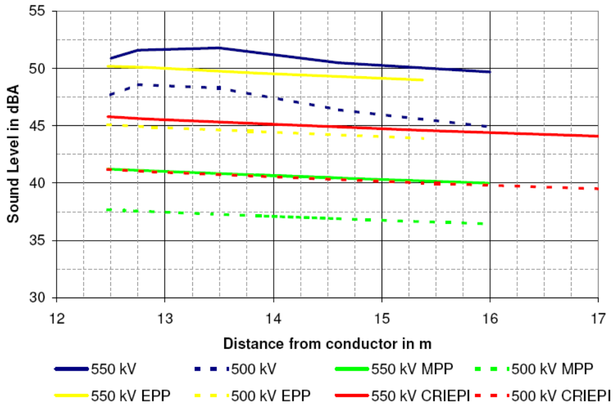

Figure 4: Audible noise measurements as a function of distance from the positive conductor

Comparing the measured values to the EPRI predicted HVTRC values we see that for the case of 550 kV applied to the pole conductor, the difference is approximately 2 dB, averaged across the graph. This is a very close agreement. Finally the CRIEPI predictions lie between the Maruvada predictions and the EPRI predictions. From the large spread in predicted values it indicates that the use of the predictions must be done cautiously.

3.3 Conducted Noise Measurement Results

The conducted noise measurements on the twin conductor monopole line were done using the coupling system depicted in figure 1. Two measurements were carried out with the twin conductor bundle, they were at 320 kV and 350 kV respectively. The 320kV result is shown in Figure 5.

Figure 5 shows the results of the noise level measured at 320 kV as a function of frequency. All three curves follow the same trend. There is a peak at 300 kHz, followed by a secondary peak at 750 kHz with a final peak at 2 MHz. From 2MHz to 4 MHz, the level drops with an increase in frequency as expected.

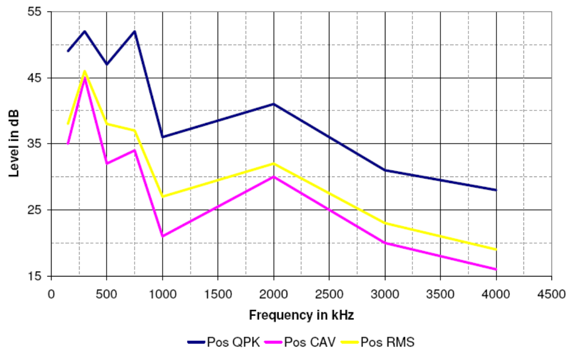

Figure 5: Twin conductor monopolar at 320 kV

Figure 6 shows the conducted noise results as a function of voltage (both positive and negative), measured at a frequency of 150 kHz. As expected, the general trend is an increase in noise measurements with an increase in voltage.

The positive noise levels are higher than the negative values, this too is expected. The Quasi Peak (QPK) values are the highest, followed by the RMS values with the CISPR Average (CAV) values being the lowest measured for both polarities.

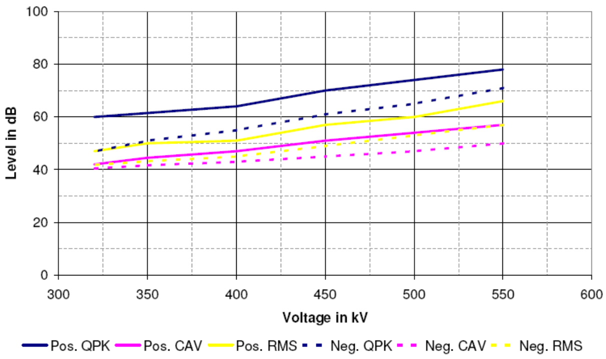

Figure 6: Twin conductor monopole as a function of applied voltage

3.4 Radiated Noise Measurement Results

Initial measurements were made directly under the positive pole at midspan, measurements were then made at 20 m intervals, under the line, away from the DC yard. Measurements up to 60 m away from the midspan position were made for an applied voltage of 320 kV and 350 kV. Measurements at applied voltages of 400 kV, 450 kV, 500 kV and 550 kV were only carried out at a distance of 60 m away from the midspan position.

Figure 7 shows the results of the measurements made at 320 kV directly under the pole conductor at midspan. From Figure 9 it can be seen that the RMS values measured has a peak value at 750 kHz whereas the QPK and CAV values peak at 1 MHz. Once attaining their peak values, all three curves decrease with an increase in frequency. There is no significant difference in levels measured for 320 kV or 350 kV applied to the pole conductor.

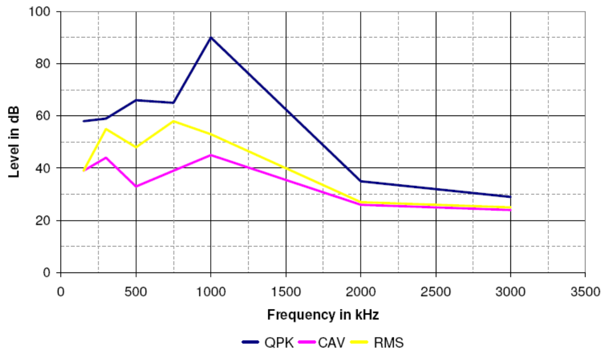

Figure 7: Radiated noise levels for 320 kV applied at midspan

Figure 8 shows the results for applied voltages of 500 kV and 550 kV at 60 m and the measured values all have a peak value of 1 MHz. The values then decrease as a function of frequency up to 2 MHz, after which the values tend to increase again. This is most notable in the QPK readings for both applied voltages. The measurements at 550 kV result in higher values being obtained when compared to the measurements done at 500 kV, once again this is expected.

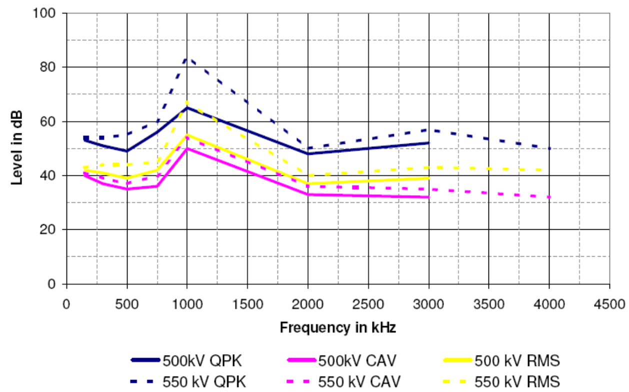

Figure 8: Radiated noise levels for 500 kV and 550 kV applied at 60 m away from mid span

3.5 Ionic Current Measurement Results

No ionic current measurements were made under this test line. Audible noise and electric field measurements were completed before the ionic currents could be measured. The line was deemed to be unsafe to work under as a defective insulator was spotted on the line. As a precautionary measure all work under the line was ceased.

4 SUMMARY OF RESULTS

The summary of the results are depicted in table 3.

Table 3: Summary of results

TEST	ELECTRIC FIELD	AUDIBLE NOISE	RADIO INTERFERENCE	ION GENERATION
Quad bundle	The results are not affected by the lower gradient to the extent that the audible noise levels are. This is because it is primarily the electrostatic field which is being measured.	Inconclusive, because background noise too high and conductor surface gradient too low.	Still being analysed	It should be noted that the predicted values do not take corona inception into account. When correcting for this fact the measurements results are more closely correlated to the predicted results
Twin bundle	On the whole, the results are consistent, and have been found to be most accurate for measurements under the live conductor An overall accuracy of 15 to 20% is attainable. It is not clear why the negative field is higher than the positive.	The results are inconsistent with the two single conductor cases. Here, the predictions are whole much lower than the measured levels. One reason appears to be that the Maruvada correction for 1 and 2 conductors is given as k=0	Still being analysed	No measurements were done
Single conductor, monopolar	The influence of space charge has not been clearly identified in the results.	EPRI, Maruvada predictions 6-8 dB above measured levels. Consistent results, otherwise	Still being analysed	The predicted levels are in general 2-3 times the measured values.
Single conductor, bipolar	The significance of the EPRI 50% level predictions, for which the agreement is quite good, needs to be explored further.	Measured curve about 7-8 dB above that for the single monopolar case. The Maruvada formula predicts a difference of 4,9 dB	Still being analysed	The measured levels are roughly correlated with conductor gradient, for about the same atmospheric conditions. On the whole, the results are "sensible", but they need to be assessed more deeply.

5 CONCLUSIONS

5.1 EPRI Lenox Laboratory Facilities

The main limitation in the tests was the maximum test voltage of ±550 kV; this meant that the highest conductor surface gradient attainable for the quad conductor bundle (21,85 kV/cm) was not realistic. This applied in particular to the audible noise tests.

5.2 Electric field measurements

The results of the electric field measurements indicate that the electric field under the line is most accurately represented by the BPA 50% fair weather prediction. However, as the measurement point moves away from the line, toward the servitude boundary the electric field is more accurately represented by the electrostatic case.

5.3 Audible noise measurements

The results of the audible noise measurements indicate that for most configurations tested, the predicted levels were much higher than the actual measured values.

The EPRI HVTRC predictions were consistently 10 dB to 15 dB higher than the measured values, the BPA and Maruvada predictions were quite similar, the CRIEPI predictions were similar to the BPA predictions, except for one instance when it was almost identical to the measured values.

The fall off of audible noise with distance was very similar for the measured and predicted cases, i.e. the slopes of the curves were very similar as a function of distance away from the conductor. This tends to imply that there is a constant offset between the measured values and the predicted values.

5.4 Radiated noise measurements

The absolute levels of radiated noise are still being assessed. However, it has been found that the roll-off with frequency above 1 MHz is approximately 1/f where f is the frequency in MHz. This is what is expected.

The quasi-peak/RMS difference in noise levels, namely, about 14 -17 dB, is higher than the 8 dB difference found from AC corona studies. This is a most significant and useful finding, particularly as regards to the possible impact of HVDC lines on signal-to-noise ratios in any nearby sensitive radio receiving stations.

5.5 Conducted noise measurements

The levels of the conducted noise measured, indicate that this noise will not be a significant deterrent to the use of Power Line Carrier (PLC) on AC lines that have been converted to HVDC operation, however further evaluation of exact geometries are required in order to state this for each individual line configuration.

The levels measured decreased with an increase in frequency as expected. Wet weather conducted noise measurements were lower than the corresponding dry weather measurements, also as expected.

5.6 Ionic current measurements

From the limited measurements of ionic current under the test lines, it can be said that the levels measured are well below the predicted levels, under the line. As the measurement point moves toward the servitude boundary the measured values tend toward the predicted values (i.e. 0 nA).

6 ACKNOWLEDGMENTS

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7 REFERENCES

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