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Abstract

A theoretical and practical investigation was performed by the EPECentre into the causes of previously unexplained excessive corona on ElectraNet's new 275kV line at Bungama, South Australia. The corona audible noise occasionally exceeds Australian Environment Protection (Industrial noise) Policy maximum acceptable levels.

Surface voltage gradients and corona inception voltages were calculated for the conductor spacing and arrangement. Three pieces of conductor, being used Bungama conductor, new Bungama conductor and new conductor from another manufacturer, were high voltage tested under a range of conditions in the HV laboratory at the Electrical and Computer Engineering Department, University of Canterbury. Corona discharge magnitudes and counts were recorded for original, cleaned and washed conductor situations. Rain was also simulated. A further test involving polished spheres was performed to determine the surface effect of both clean and dirty conductor grease on the electrical breakdown of air. A site visit to Bungama provided further evidence for the causes of the excessive corona.

The investigation revealed that a combination of dirty surface grease and high surface voltage gradients generates the high levels of corona. Several recommendations to prevent such a situation in the future are provided.

1 Introduction

ElectraNet own and operate the high voltage (HV) network in South Australia. The main transmission system consists of a 275 kV backbone. The predominant conductor used on the network is fully greased olive ACSR, configured in a single or duplex arrangement. According to ElectraNet, the performance of the network, in terms of corona, has been satisfactory.

The established Davenport-Para line (300km length) is PI construction with a flat conductor configuration using single olive conductor, shown in Figure 1(a). In 2006, the 275kV network was extended to Bungama substation near Port Pirie. A 7km double circuit transmission line was constructed to connect the existing Davenport-Para circuit to Bungama substation, using DT2/6 (strain) and DS2/10 (suspension or tangent) towers with 3 phase single conductors arranged vertically on each side, shown in Figure 1(b). Initially, one span was energised and excessive corona activity was observed from the new conductor, twice the level of the existing line, and other 275kV lines of the same construction elsewhere. Audible noise tests, conducted in March and April 2006, showed excessive noise levels of up to 51-52 dB(A) whereas the existing line noise levels were 43 dB(A).

Sections of strung conductors were hand washed to remove black, greasy surface material. No visible defects, edges, indents were noted nor any change in conductor diameter due to

tensioning. Corona dropped significantly where washed. Unwashed sections still had the same high levels of corona. A single span of the corona affected conductor was taken out for testing.



Figure 1 – (a) Davenport-Para line, (b) new Bungama line connecting to Bungama substation.

2 Overview of investigations

Three conductors (sizes are all - 54/7 x 3.50 mm) were supplied by ElectraNet for testing:

'**New Olex**' – Unused conductor of the same dimensions as the Bungama Midal conductor, but manufactured by another supplier.

'**Used Midal Bungama**' – A section of recovered conductor taken from the Bungama line after it was noted that excessive corona was present.

'**New Midal other project**' – Unused Midal conductor from another manufactured batch earmarked by ElectraNet for another transmission line project.

Investigations undertaken by EPECentre included the following items:

- A review of the surface voltage gradient (SVG) experienced by conductors on the Bungama line and Davenport-Para line, based on the designed line voltage (275 kV), the voltage level often used (290 kV), and maximum rated voltage level (302.5 kV).
- Visual inspections of the exterior of the conductors.
- Testing of each conductor to equivalent surface voltage gradients, under uncleaned, cleaned and wet conditions.
- Sphere gap testing with both clean and dirty grease to determine the effect on corona inception.
- A site visit to Bungama was conducted by EPECentre staff.

3 Surface voltage gradient and critical voltage calculations

The SVG on the conductors was calculated for the existing Davenport-Para line and for the new Bungama line, to replicate the electrical stress conditions in the HV lab at the EPECentre. An assumption that all conductors are a perfect cylinder was used.

For the Davenport-Para line three phase horizontal configuration, the conductor spacing is 7.86 m, and conductor diameter is 31.5 mm. Table 1 shows the SVG for the conductors. Air breakdown is at 21.2 kV_{rms}/cm.

Table 1 – Conductor SVG on the Davenport/Para line

Line to line voltage	Middle conductor SVG	Outer conductor SVG
275 kV _{rms}	16.8 kV _{rms} /cm	15.2 kV _{rms} /cm
290 kV _{rms}	17.7 kV _{rms} /cm	16.0 kV _{rms} /cm
302.5 kV _{rms}	18.5 kV _{rms} /cm	16.7 kV _{rms} /cm

For the new Bungama line with three phase vertical configuration on each side of the towers (one side is return line with rotated phase transposition), the conductor spacing on the smaller DT2/6 towers is 6.4 m (vertical) and 10.05 m (horizontal), and the conductor diameter is 31.5 mm. Table 2 shows the SVG for the Bungama conductors.

Table 2 – Conductor SVG on the Bungama line

Line to line voltage	Middle conductor SVG	Outer conductor SVG
275 kV _{rms}	17.3 kV _{rms} /cm	16.5 kV _{rms} /cm
290 kV _{rms}	18.2 kV _{rms} /cm	17.4 kV _{rms} /cm
302.5 kV _{rms}	19.0 kV _{rms} /cm	18.1 kV _{rms} /cm

The second calculation is for the disruptive critical voltage and visible critical voltage which are useful 'real-world' threshold indicators of when corona will occur. It accounts for conductor surface irregularity such as a stranded conductor. When a gradually increasing voltage is applied across two conductors, initially nothing will be seen or heard. As the voltage is increased, the air surrounding the conductors is ionised, and at a certain voltage a hissing noise is heard caused by the formation of corona. This voltage is known as the disruptive critical voltage. A further increase in the voltage would cause a visible violet glow around the conductors. This voltage is the visible critical voltage.

Disruptive critical voltage to neutral: $V_d = 21.1 a m_d r \ln(d/r)$ (kV_{rms})

Visible critical voltage to neutral: $V_v = 21.1 a m_v r (1+0.3/\sqrt{a r}) \ln(d/r)$ (kV_{rms})

where $a = 3.9211 p / (273 + t)$

p = atmospheric pressure (cmHg)

t = temperature (°C)

m_d = surface irregularity factor for disruptive critical voltage ($0 < m_d < 1$)

= 1 for smooth, polished, solid, cylindrical conductors

= 0.93-0.98 for weathered, solid, cylindrical conductors

= 0.87-0.9 for weathered conductors with more than seven strands

= 0.8-0.87 for weathered conductors with up to seven strands

m_v = surface irregularity factor for visible critical voltage ($0 < m_v < 1$)

= 1 for smooth, polished, solid, cylindrical conductors

= 0.93-0.98 for local and general visual corona on weathered, solid, cylindrical conductors

= 0.7-0.75 for local visual corona on weathered stranded conductors

= 0.8-0.85 for general visual corona on weathered stranded conductors

r = radius of conductor (cm)

d = spacing between two conductors (cm)

For three phase horizontal or vertical configurations, the factors 0.96 and 1.06 multiply the calculated voltages for the middle and outer conductors respectively [1]. These results are for fair weather. Stormy weather voltages are generally about 80% of the fair weather voltages [1].

The Davenport-Para and Bungama conductors have 61 strands, and both looked to have a few scratches, so surface irregularity factors $m_d = 0.87$ and $m_v = 0.8$ were used. Tables 3 and 4 show the critical voltages. V_{ds} is the disruptive critical voltage with stormy weather. Atmospheric pressure was taken as 76 cmHg (1013.25 hPa) and temperature as 25 °C.

Table 3 – Conductor disruptive and visible critical voltages on the Davenport/Para line

		Actual Davenport-Para voltages			
		275 kV _{rms} line to line	290 kV _{rms} line to line	302.5 kV _{rms} line to line	
	Inner conductor	Outer conductors			
V_d	172.4 kV _{rms} to neutral	190.3 kV _{rms} to neutral	158.8 kV _{rms} to neutral	167.4 kV _{rms} to neutral	174.6 kV _{rms} to neutral
V_v	196.5 kV _{rms} to neutral	217.0 kV _{rms} to neutral			

Table 4 – Conductor disruptive and visible critical voltages on the Bungama line

		Actual Bungama voltages			
		275 kV _{rms} line to line	290 kV _{rms} line to line	302.5 kV _{rms} line to line	
	Inner conductor	Outer conductors			
V_d	166.8 kV _{rms} to neutral	184.1 kV _{rms} to neutral	158.8 kV _{rms} to neutral	167.4 kV _{rms} to neutral	174.6 kV _{rms} to neutral
V_{ds}	133.4 kV _{rms} to neutral	147.3 kV _{rms} to neutral			
V_v	190.0 kV _{rms} to neutral	209.8 kV _{rms} to neutral			

The disruptive critical voltage strongly depends on the surface irregularity factor and can wildly vary below $m_d = 0.8$ with damaged or dirty conductor parts that present protrusions from the conductor surface. Water, sleet and snow lower the corona voltage. Conductor surface oil has very little effect. Humidity has no effect on the starting point of corona. Current in the wire has no effect except that due to heating of the conductor and air [2].

For the Davenport-Para line, its observed cleanliness indicated the surface irregularity factor $m_d = 0.87$ and resulting disruptive critical voltage is fair for this calculation. At the commonly used 167.4 kV_{rms} to neutral (290 kV_{rms} line to line), the working voltage is 97% of the disruptive critical voltage. For the Bungama line, the voltage is just over 100% of the disruptive critical voltage, meaning corona is likely to be present. However, it was observed that the Bungama conductors had significant dark patches of dirty material. It was anticipated that this would significantly change the surface irregularity factor m_d . The Bungama line was designed to be close to the limits for corona inception. Relatively minor surface features on the conductors could lead to significant corona discharge.

4 Visual inspections

A visual inspection of the exterior of the conductors was done to note the condition of the conductors as related to the HV tests, and to look for any cause of excessive corona.

The diameter of the conductors, measured using digital calipers, were as follows. These values were all close enough to each other and the manufacturers' specifications of 31.5mm.

'New Olex' = 31.56 mm

'Used Midal Bungama' = 31.52 mm

'New Midal other project' = 31.54 mm

The 'New Olex' surface had an oily feel. One side of the conductor had patches of black, dirty grease between the strands. The strands were otherwise clean, smooth and shiny. There were a few minor scratches and nicks on the outer strands. Internally, clean grease appears to be present on all conductors except the outer layer. This conductor is shown in Figure 2(a).

The 'Used Midal Bungama' had an oily feel, but dryer than the 'New Olex' conductor. There were a lot of dirty greasy patches that generally felt dry, and were mostly between the outer strands, but also right around the strands in places. There were a reasonable number of minor scratches on the outside of the outer strands, removing the shiny look. There were no lumps present, as seen on the live conductor at Bungama by EPECentre staff (described later in this paper). Unfortunately, it also appeared handling and packaging had removed some of the dirt and grease from the outside of the conductor. Internally, clean grease appeared to be present on all conductors except the outer layer. This conductor is shown in Figure 2(b).

The 'New Midal other project' conductor was generally clean, non-greasy and shiny all around. There was no dirty grease seen between strands. There were some minor scratches and nicks. Internally, clean grease appeared to be present on all conductors except the outer layer. This conductor is shown in Figure 2(c).

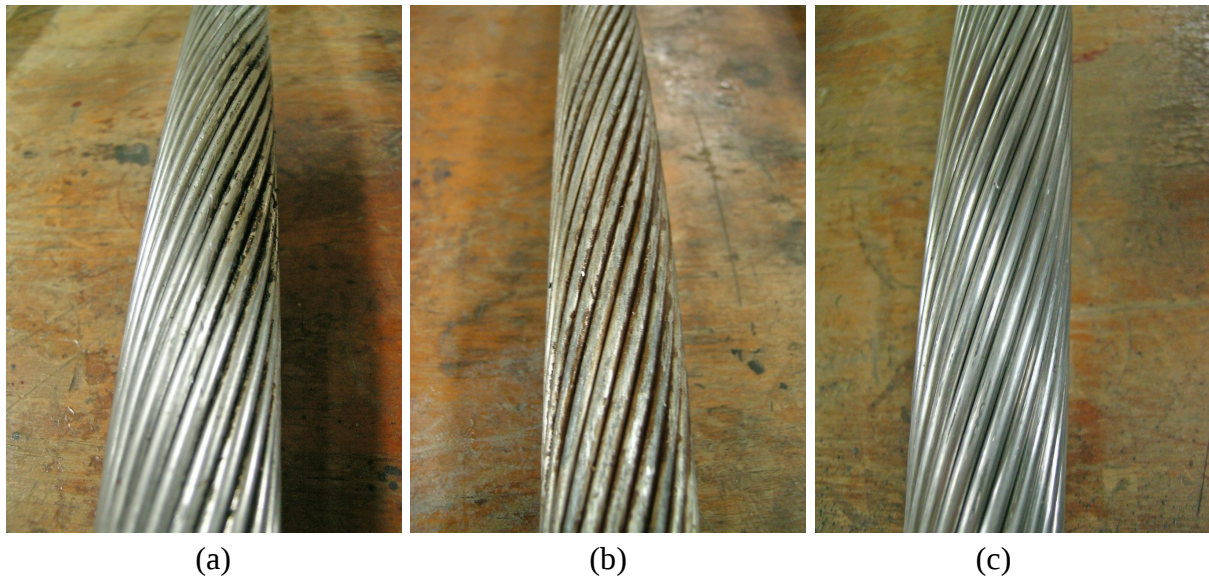


Figure 2 – (a) 'New Olex', (b) 'Used Midal Bungama' and (c) 'New Midal other project'.

5 Conductor high voltage tests

To determine the differences in terms of corona generation between the supplied conductors and also their cleanliness, a 4 m length of each conductor was energised by a HV transformer so that its SVG was similar to the situation experienced by the conductors on the Bungama transmission line. The following tests were made to the 'New Olex', 'Used Midal Bungama' and 'New Midal other project' conductors:

- | | |
|------------------------------------|---------------------------------|
| 1 Uncleaned cable | 4 Wiped cable with water spray |
| 2 Uncleaned cable with water spray | 5 Washed cable (after drying) |
| 3 Wiped cable (after drying) | 6 Washed cable with water spray |

For each test, three voltage levels were applied, equivalent to the SVG experienced by the Bungama transmission line conductors when the working voltage is 275 kV_{rms}, 290 kV_{rms} and 302.5 kV_{rms} (line to line). At each voltage, six power cycles were digitised at 25 Msa/s. Corona measurements noted included the number of corona pulses per power cycle, the

median charge of the recorded pulses and the maximum pulse charge recorded (units are pico-Coulombs). The analysis was performed using a custom Matlab function to analyse the pulses.

Each conductor was, in turn, suspended across the HV lab above a ground plane made up of aluminium sheets, as shown in Figure 3. Copper spheres were mounted at the ends of the conductor. The curvature of the transformer connection wire, the conductor under test and a 3 m end wire formed an approximate half circle, so as to minimise charge distribution variation along the length of the conductor under test.

A current transformer (CT) in the form of a Rogowski coil was attached around the earth connection of the transformer HV winding. The output of the CT passed through a 5 MHz low-pass RC filter. The capacitor here also provided signal integration so that the peak voltage of pulses represented the charge of the pulse. A Biddle Instruments calibrated pulse generator provided 1000 pC and 100 pC pulses to determine response. The oscilloscope response was linear to charge value to within 2-3%.

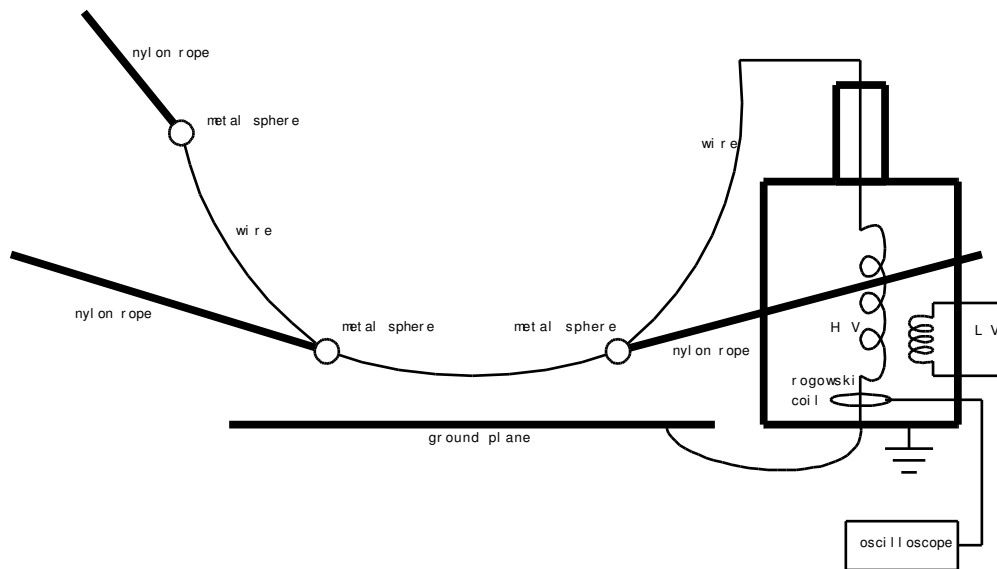


Figure 3 – Test setup for measuring corona from samples of the conductors.

For the tests with the wiped conductor, a clean cloth damped with turpentine was rubbed firmly along the length of the conductor to remove external deposits of grease and dirt. For the washed conductor, a soft bristled brush and turpentine was used to clean all visible grease and dirt.

The minimum height of the conductor for each test was approximately 40 cm, with each conductors' height being precisely measured with calipers. The energising voltage required to create the necessary SVG is:

$$V = SVG (r \ln(2h / r)) \text{ (Volts)}$$

where SVG is electric field gradient on the surface of the conductor, r is the radius of conductor, and h is height of centre of conductor above ground plane.

The tests were performed when the temperature was approximately 23 °C and humidity 55%.

Table 5 shows the results of the HV tests on the three conductors. In addition, corona flares were particularly apparent from scratches such as the one in Figure 4.

Table 5 – Corona measurements from HV conductor tests

Test	SVG equivalent to 275kV at Bungama			SVG equivalent to 290kV at Bungama			SVG equivalent to 302.5kV at Bungama		
	Pulse count per cycle	Pulse median (pC)	Pulse max (pC)	Pulse count per cycle	Pulse median (pC)	Pulse max (pC)	Pulse count per cycle	Pulse median (pC)	Pulse max (pC)
'New Olex'	2.5	99	178	5.7	75	218	9.5	95	306
'New Olex' wiped	0.3	69	77	0.2	137	137	0.7	127	168
'New Olex' washed	0	0	0	0	0	0	0	0	0
'New Olex' with water	7.2	72	109	10	74	149	16.8	75	158
'New Olex' wiped with water	4.7	81	178	13.1	80	229	14.5	81	298
'New Olex' washed with water	4.2	73	150	6.8	85	277	9.3	75	310
'Used Midal Bungama'	3.3	88	133	5.5	94	197	9.2	93	332
'Used Midal Bungama' wiped	0.3	88	113	0	0	0	1	153	263
'Used Midal Bungama' washed	0.8	115	229	0.8	136	154	1.5	175	269
'Used Midal Bungama' with water	5.2	71	134	12.2	77	147	17	84	218
'Used Midal Bungama' wiped with water	8.7	89	212	12.8	92	222	14.7	91	218
'Used Midal Bungama' washed with water	7.8	80	127	12	78	171	14	82	213
'New Midal other project'	0.8	85	107	0.7	120	176	3.3	101	218
'New Midal other project' wiped	0.5	101	114	0.5	72	104	0.3	145	185
'New Midal other project' washed	1.2	93	135	0.5	95	140	1	100	142
'New Midal other project' with water	5.7	76	174	6.3	86	151	10	81	179
'New Midal other project' wiped with water	7.8	73	127	10.5	80	121	14.1	81	150
'New Midal other project' washed with water	5.5	76	127	9.5	80	169	11.2	83	207

In general, any test where the pulse count was below 1 pulse per cycle, the pulse count was considered to be inexact and possibly non-existent. In these cases, corona pulses could be sporadic with periods of no corona.



Figure 4 - 'Used Midal Bungama' conductor with a jagged scratch which corona flared from.

The 'Used Midal Bungama', in its original uncleaned condition, had similar corona levels to the uncleaned 'New Olex'. Both conductors had some corona at 275 kV_{rms} with rapidly increasing corona levels with the slightly higher voltage levels at 290 kV_{rms} and 302.5 kV_{rms}.

The corona performance of the 'New Midal other project' conductor was significantly better than either of the others. It is suggested that this is because the 'New Midal other project' conductor was much cleaner in its original condition.

When the conductors were wiped, corona levels dropped to practically zero. Corona generated after wiping or washing the conductors appeared to be generated from scratches and other damage to the metal. This implied that while dirt and grease buried between outer strands does not create significant corona, when the dirt and grease extends around the outer strands, high levels of corona is generated.

For all conductors, the addition of water droplets on the conductor significantly increased the number of corona pulses, but most of these additional pulses tended to be lower in magnitude as shown by lower median pulse levels compared to the dry conductors. This was expected, as many small water droplets now provide a high SVG around them for corona to form.

6 Sphere gap tests

Two tests were made with a sphere gap arrangement. The first test was to analyse the effect on atmosphere breakdown that different conductor greases have when present on the surface of a conductor. The second was to note differences in atmospheric breakdown conditions between sites at the HV lab in Christchurch and that at Bungama near the transmission line. The test setup was designed to be portable to enable easy transport to Bungama.

A 12 V battery was connected to a Powertech MI-5085 inverter that fed to a small variac, so as to provide an AC waveform whose magnitude could be increased, as shown in Figure 5. The variac output connected to a 240V-15kV neon transformer. A Tektronix P6015A HV probe placed on the sphere gap was connected to a Fluke 41B Power Analyser. The sphere gap and HV probe rested on blocks of polystyrene. The spheres are 2 cm diameter.

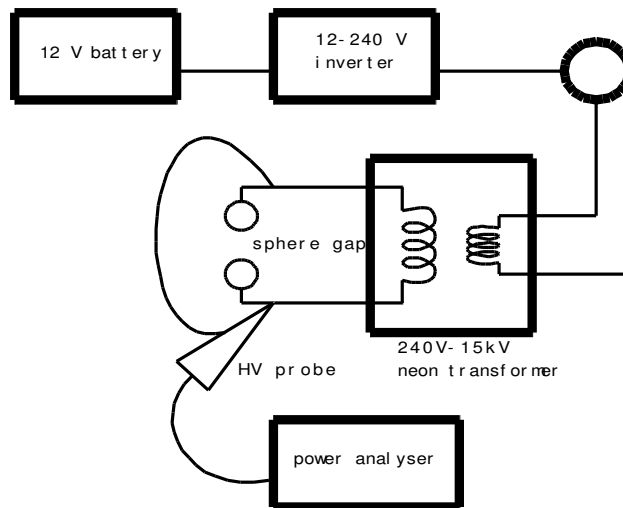


Figure 5 – Test setup for measuring atmospheric breakdown between two spheres.

For the first test, samples of clean grease from the 'New Olex', 'Used Midal Bungama' and 'New Midal other project' conductors were taken from the centre of each conductor. This grease appeared to be uncontaminated with dirt. Samples of dirty grease were also taken from the external surfaces of the 'New Olex' and 'Used Midal Bungama' conductors. The 'New Midal other project' conductor did not have any significant external dirty grease to sample.

The sphere gap was 5.54 mm, as measured with digital calipers. A sample of each grease was smeared into a thin layer onto one sphere. The test involved increasing the voltage steadily until breakdown occurred. The peak voltage just before breakdown was recorded. This was repeated ten times. The results are shown in Figure 6.

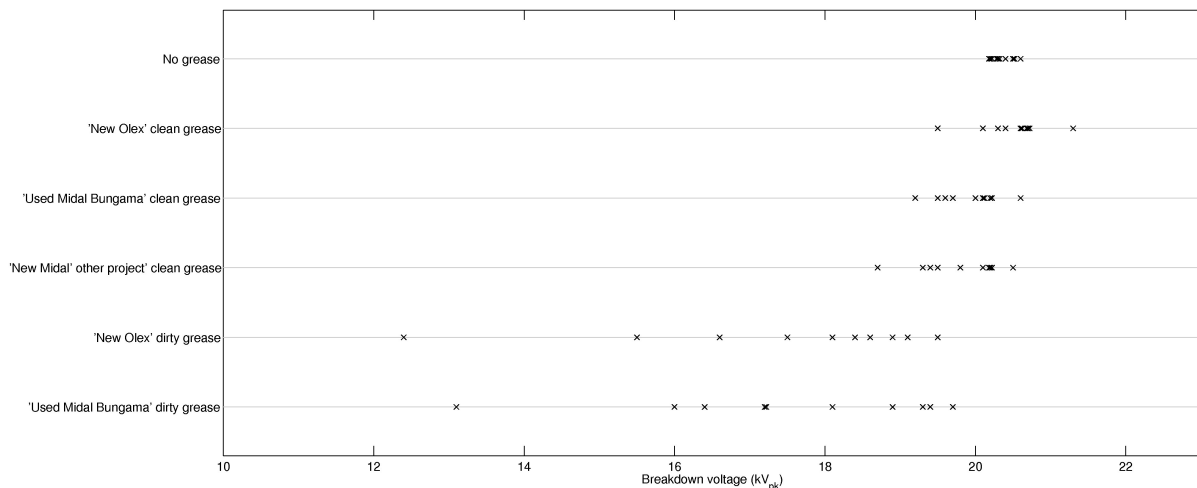


Figure 6 – Breakdown voltages across sphere gaps with various conductor greases applied to one sphere.

Mean breakdown voltages:

- No grease = 20.4 kV_{pk}
- 'New Olex' clean grease = 20.5 kV_{pk}
- 'Used Midal Bungama' clean grease = 19.9 kV_{pk}
- 'New Midal other project' clean grease = 19.8 kV_{pk}
- 'New Olex' dirty grease = 17.5 kV_{pk}
- 'Used Midal Bungama' dirty grease = 17.5 kV_{pk}

Applied dirty greases significantly lowered breakdown voltages, including some very low voltage values. There appeared to be little difference between the dirty grease sampled from the 'Used Midal Bungama' conductor and the 'New Olex' conductor.

The primary conclusion is that clean conductor grease that is present on the exterior of a conductor is unlikely to cause a significant corona problem. Unfortunately, when clean grease is initially present on the conductor exterior, it is highly likely to become contaminated with dirt or other similar material, either during conductor installation on the transmission line or later when wind blown dust is deposited on the conductor. Then, when grease is contaminated, the chances of corona will significantly increase.

For the second test to note any differences in the breakdown strength of air between the HV lab in Christchurch and Bungama, the same test setup was used with clean spheres. The equipment was also transported to Bungama. The sphere gap was set to $4 \text{ mm} \pm 0.03 \text{ mm}$ as measured with digital callipers. The temperature at both locations was 20-25 °C and atmospheric pressure approximately 1013 hPa. The test involved increasing the voltage steadily at approximately $0.2 \text{ kV}_{pk}/\text{sec}$ until breakdown occurred. The peak voltage just before breakdown was recorded. The results are shown in Figure 7.

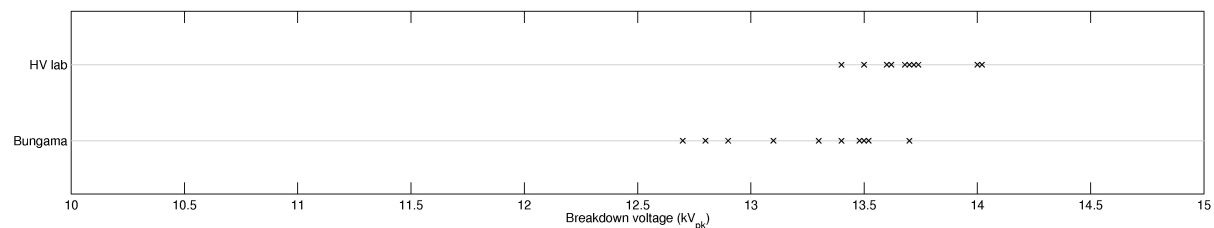


Figure 7 – Breakdown voltages across sphere gaps at Christchurch and at Bungama.

Mean breakdown voltages:

HV lab = 13.7 kV_{pk}

Bungama = 13.2 kV_{pk}

It is unknown why the atmospheric breakdown conditions are slightly lower at Bungama. However, this result means that corona is more likely to start at lower voltages at Bungama.

7 Site visit to Bungama

EPECentre staff, Stewart Hardie and Alan Wood, conducted a site visit to Bungama in March 2007. The weather conditions were sunny and very dry with temperatures in the high twenties. There was little to no wind.

Two points where the existing Davenport-Para line crosses the main highway south of Bungama were observed. Using binoculars, the conductor appeared to be clean, although weathered. This weathering was to be expected considering that this transmission line has been in service for several decades. No sound of corona could be heard coming from the conductor. A small coronal buzzing noise could be heard coming from one of the nearby towers.

Standing under the HV lines of the new Bungama line, a loud coronal buzzing noise could be heard coming from the transmission line. It was far higher than any level of coronal audible noise that the authors have heard from any HV power line, especially considering the dry, warm conditions. A black surface layer appeared to cover up to 50% of the conductor, in a patchy fashion. The coronal noise appeared to come from all sections of the transmission line. Figure 8 shows the black substance diagonally aligned with the strands of the conductor, suggesting that it has been sourced from within the conductor rather than being applied from an external source.



Figure 8 – Bungama transmission line conductor with a black substance apparently being emitted between strands.

Black lumps were also observed with binoculars along all sections of the Bungama conductors, as shown in Figure 9. The lumps ranged in size up to approximately 3 mm, with dozens to hundreds of lumps per metre of conductor. They appeared to be present on all of the conductors. The nature of the lumps could not be determined, but had the same colour as the substance covering the conductor. Considering the size of the black lumps and how much they protruded from the conductor surface, it is highly likely that they are a major contributing factor towards corona generation. It is possible the substance is grease leaking from the conductor, and allowing small objects such as dirt or flies to stick to the conductor. The surrounding countryside is dry and dusty. Also, a small wind twister was observed sucking dust up to heights above the Bungama transmission towers.

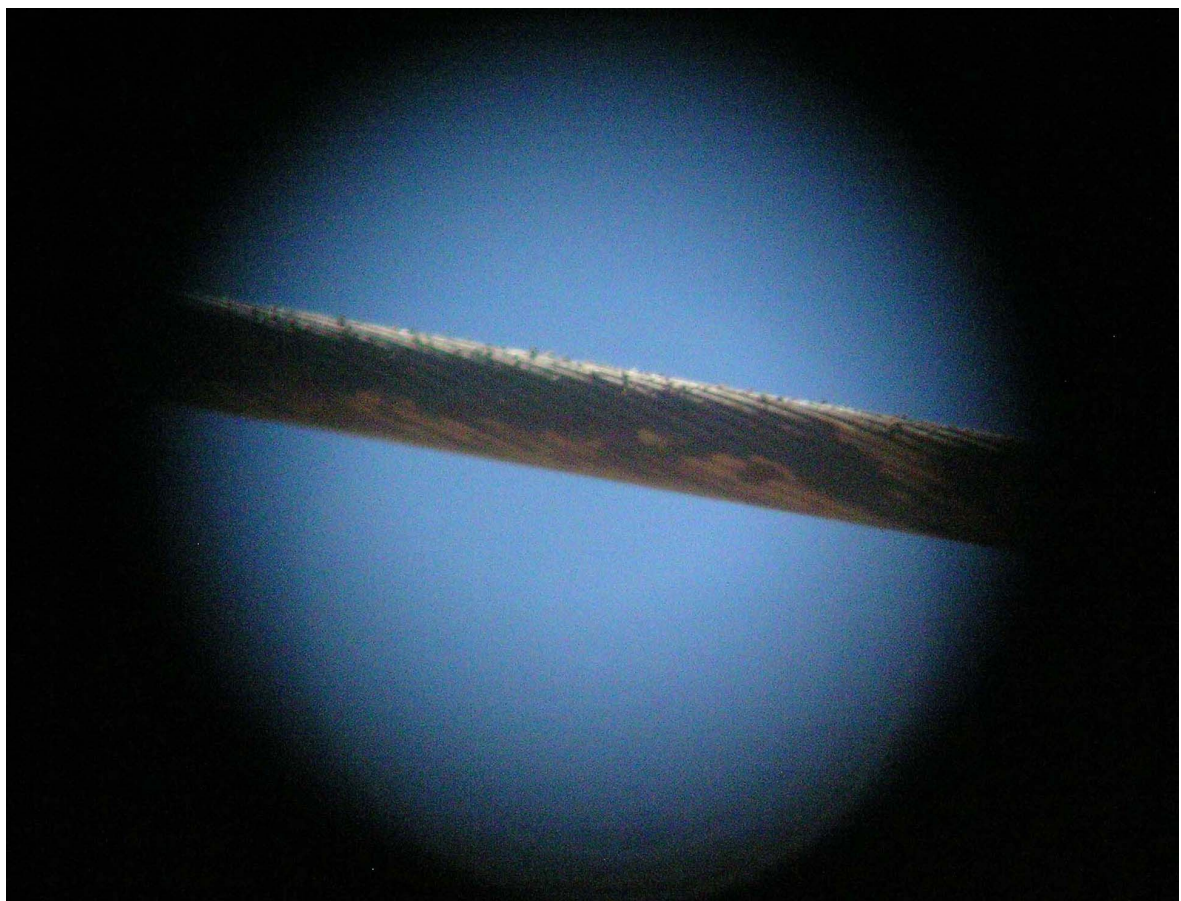


Figure 9 – Unknown black lumps present on the surface of one of the conductors on the Bungama transmission line.

8 Conclusions

The investigation indicated that the main cause of the Bungama line corona is dirt on the

external surfaces of the conductors.

Tests on the supplied Midal and Olex conductors showed a significant lowering of corona levels when the conductors were cleaned, regardless of the manufacturer.

As cleaning removes both grease and dirt, a sphere gap test was performed to separate the effects of clean grease and dirty grease. The tests demonstrated that clean grease has a negligible effect on electric breakdown, while dirty grease has a very strong effect.

The dirt on the conductors may have been from conductor handling during line construction, or from electrostatic attraction of contamination during line operation. As excessive corona was reported during line commissioning, the former may be the dominant source. Either way, the presence of surface grease had allowed the dirt to stick to the conductors. Both the Midal and Olex cable samples supplied to the EPECentre had surface grease. Observation of the Bungama line while in service indicated excessive levels of surface dirt, with lumps up to 3 mm diameter being clearly visible.

It was not within the scope of the investigation how grease came to be present on the conductor surface, or how sources of contaminating material came to be mixed into grease. However, it was noted that conductor manufacturers grease their conductors according to standards, and that excessive greasing during manufacture can lead to unwanted grease being present on ungreased outer strand layers after a period of time.

In addition, the SVG calculations showed that the designed working voltage of 275 kV is high for single conductors with the spacings set on the Bungama transmission line. According to ElectraNet, the line is often operated at 290 kV or higher, which increases the voltage gradient stress to a level where corona is likely in dry weather, even when the conductor is in good condition. The high SVG for the line design can be considered the secondary cause of the corona problem. More conservative design approaches, such as greater conductor spacing or the use of bundled conductors, would significantly lower the SVG on the conductors.

The used conductor supplied showed evidence of rough handling, with significant surface scratches. It is unknown if this was a result of the line stringing process, or from the decommissioning of a span for sample testing. However, scratches and scrapes on the conductor surface are a very significant source of corona, and should be minimised when the line design results in high surface voltage gradients.

9 References

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