A NOVEL APPROACH FOR DETERMINING THE SURFACE ROUGHNESS FACTOR OF STRANDED CONDUCTORS

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ABSTRACT

This paper defines a new approach for determining the surface roughness factor of stranded conductors. Basic conductor corona theory is presented. Laboratory work and test results are also given. The concept of determining the conductor surface gradient based on the stranding and diameter of a conductor is described and is based on the laboratory test results.

I. INTRODUCTION

Corona performance is one of the parameters used in designing high voltage transmission lines. With the advent of compact transmission lines and the need to optimize power transmission, corona performance has become more important.

If a line is incorrectly designed with regards to its corona performance, it can lead to poor corona performance, which is manifested by one or all of the following:

- Radio interference, including power line carrier noise.
- Audible noise,
- Corona losses.

In general, line compaction will lead to a decrease in conductor spacing and clearances, which in turn leads to an increase in corona activity. Compact lines are designed to operate at or very close to corona inception.

The need for more realistic values of conductor surface roughness factors arises from a design requirement in which the ratio of the operating conductor surface gradient to the corona inception gradient is assessed, as a means of identifying possible conductors for a final design. Thus more reliable values of the surface roughness factor will allow this process to be refined.

It is imperative that the line designer has an accurate knowledge of the corona performance of a particular conductor that will be used, before the transmission line is constructed. In fact, more savings can be made above the savings of building a compact transmission line, if the corona performance of the line is optimized.

The aim of this work was to determine a preliminary estimate of the corona performance of a conductor.

II. CONDUCTOR CORONA PERFORMANCE

A. Corona inception gradient

Every conductor has an indicative value associated with it, which defines its corona performance; this value is called its corona inception gradient. Corona inception is defined by the initiation of positive streamer discharges near the conductor. This occurs when the conductor surface voltage gradient reaches a critical value.

On a transmission line, various other factors influence the magnitude of the surface gradient experienced by the conductor/s. These factors do not, however, increase or decrease the corona inception gradient.
Empirical formulas have been developed to determine the corona onset gradient for cylindrical conductors under both AC and DC voltage [2].

This inception gradient is dependent on several factors, which are: [1]

- Conductor diameter
- Conductor surface condition
- Ambient pressure and
- Ambient temperature.

The general formula, known as Peek's formula, which takes into account all these variables, is as follows.

$$E_c = mE_0\delta\left[1+\frac{K}{\sqrt{\delta r_c}}\right] \quad (1)$$

E_0 and K are empirical constants, which are dependent on the nature of the applied voltage.

Table 1. Corona inception constants

Constant	AC	Positive DC	Negative DC
E_0	21	33.7	31
K	0.308	0.24	0.308

m is the roughness factor, r_c is the conductor diameter in cm.

The variable δ in equation (1) is known as the Relative Air Density (RAD) and is defined by the following formula:

$$\delta = \frac{273+t_0}{273+t}\cdot\frac{p}{p_0} \quad (2)$$

Where: t = ambient temperature in °C.
p = ambient pressure
t_0 and p_0 are reference values. Usually t_0 = 25°C and p_0 = 760 torr or 1000 kPa.

B. Surface roughness factor

The factor m, in equation (1) is called the surface roughness factor of the conductor. This factor, defines the surface condition of a conductor. It is defined that the surface roughness factor of a conductor is equal to 1, for an ideally smooth and clean conductor. Even microscopic imperfections on the conductor surface, tends to reduce this value. Experimental studies have shown that practical stranded conductors that have surface irregularities such as scratches and nicks, may have a surface roughness factor of between 0.6 and 0.8. Under extreme conditions the roughness factor of certain conductors may be in the order of 0.2 [1].

The surface roughness factor is one of the more important preliminary factors in determining the corona inception of a transmission line. It is assumed that new, stranded conductors will have a surface roughness factor of 0.8. However this assumption is not very accurate and needs to be modified. With this in mind, tests were conducted on several conductors in order to determine a more scientific approach in the estimation of the value of m.

III. LABORATORY TESTS AND RESULTS

A. Laboratory Tests

The HVDC laboratory at the University of Durban Westville (UDW) has DC capabilities up to ± 500 kV. However for the purposes of the roughness factor testing, the laboratory's AC capabilities would be utilised. (It has an AC capability of up to 100 kV.) However it was foreseen that the roughness factor testing would require voltages up to 165 kV. In order to deliver this voltage level a second 100 kV transformer was cascaded with the first and they were thus able to supply a maximum of 200 kV.

The transformers were connected in cascade under the supervision of Professor Nelson Ijumba of the University of Durban - Westville.

Figure 1: Photograph of the cascaded AC transformers

All connections were made according to the manual supplied and were thoroughly checked for continuity before proceeding.

As the empirical formulas for corona onset gradients are generally based on visual detection of the light emitted by corona discharges in air, in the ultra-violet range, it was decided to use the COROCAM 1 in order to be able to detect when corona inception occurred.

It is known that a corona cage test configuration is best suited for determining the corona onset gradient of either single or bundled conductors' [1], since conductor surface gradients can be calculated using simple analytical methods. It was therefore decided to make use of the corona cage [3], which is housed, in the HVDC laboratory at UDW.

The tests were conducted as follows: after initial calculations, a conductor was strung up in the cage and the applied voltage was then increased. This continued, until corona was observed with the COROCAM 1. The voltage at which this occurred was noted. Once this voltage was obtained it was quite simple to calculate the corresponding surface gradient of the conductor tested. This was done 15 times in order to obtain an average value of the inception readings. For the cylindrical corona cage configuration the conductor surface gradient is given by the following formula: [3]

$$E_c = \frac{V}{r_c \cdot \ln\left(\frac{R}{r_c}\right)} \quad (3)$$

Where: E_c = conductor surface gradient

V = applied voltage

r_c = conductor radius

R = cage radius

The conductors tested were:

1) Pelican (21mm)
2) Tern (27mm)
3) King Bird (24mm)
4) Mink (10.98mm)
5) Wolf (18mm)

Once these conductors had been tested, they were removed from the cage and sand papered to make their surfaces smoother. They were then strung up again and re-tested. This was done in order to determine what effect the changing surface condition would have on the value of the roughness factor.

B. Test Results

Table 2 shows the test results for the un-sanded conductors.

The atmospheric conditions were as follows:

- air temperature 20°C,
- air pressure 1020 kPa,
- humidity 97%.

As can be seen from the results in table 2, the conductor surface roughness factors for all the conductors tested were relatively low.

The highest average roughness factor measured was 0.67 for the Wolf conductor. The low average surface roughness factors measured could be attributed to the fact that the conductors were stored outside for an extended period of time as and a result have become weathered with many little nicks and scratches on them.

Certain conductors had larger inter-strand distances than others did, and this could also lead to lower inception gradients and therefore lower surface roughness factors. The Tern conductor had the smallest inter-strand distance yet it had the lowest surface roughness factor, this was due to the fact that this particular conductor had the most nicks and tiny scratches out of all the conductors tested. This would have the effect of reducing the inception gradient for this conductor.

Table 2: Un-Sanded co nductor surface roughness factor.

Test	**Mink**	**Wolf**	**Pelican**	**King Bird**	**Tern**
1	0.58	0.68	0.56	0.57	0.558
2	0.61	0.65	0.57	0.60	0.50
3	0.59	0.65	0.55	0.57	0.48
4	0.61	0.68	0.61	0.53	0.54
5	0.53	0.69	0.57	0.53	0.46
6	0.57	0.65	0.59	0.53	0.48
7	0.61	0.67	0.55	0.60	0.56
8	0.61	0.69	0.55	0.57	0.53
9	0.59	0.69	0.55	0.60	0.51
10	0.59	0.67	0.57	0.61	0.51
11	0.60	0.65	0.56	0.58	0.48
12	0.59	0.68	0.53	0.60	0.52
13	0.60	0.64	0.53	0.59	0.50
14	0.57	0.69	0.54	0.58	0.55
15	0.62	0.68	0.55	0.58	0.57
Std Dev	3.39%	2.99%	3.57%	5.17%	5.88%
Ave	0.59	0.67	0.56	0.58	0.52

The Mink conductor had the largest distances between strands, yet it displayed the second highest roughness factor this is ascribed to the fact that this conductor was stored indoors and was relatively smooth when testing took place.

The conductors were then sand papered in order to remove any surface nicks and scratches, and the tests repeated. It should be noted that it was not possible to remove all the surface irregularities on each conductor. The results of which are shown in the next table.

As can be seen in table 3, all the conductors tested with the exception of the Mink conductor experienced an increase in the surface roughness factor after they, had been sand papered. The roughness factor measured on the sand papered Mink conductor was 0.002 lower than what was measured on the original Mink conductor. This cannot be taken as an indication that the roughness factor has decreased after being sand papered.

Table3: Sanded conductor surface roughness factors.

Test	Mink	Wolf	Pelican	King Bird	Tern
1	0.58	0.71	0.68	0.58	0.77
2	0.59	0.71	0.63	0.61	0.72
3	0.61	0.72	0.60	0.64	0.76
4	0.59	0.71	0.62	0.65	0.76
5	0.59	0.73	0.60	0.64	0.75
6	0.56	0.75	0.64	0.65	0.76
7	0.59	0.74	0.65	0.65	0.76
8	0.60	0.75	0.64	0.63	0.75
9	0.57	0.74	0.66	0.64	0.75
10	0.58	0.73	0.66	0.63	0.75
11	0.59	0.71	0.67	0.64	0.75
12	0.59	0.71	0.69	0.65	0.77
13	0.60	0.71	0.67	0.66	0.77
14	0.60	0.74	0.67	0.66	0.76
15	0.57	0.73	0.67	0.67	0.75
Std Dev	1.69%	1.37 %	4.62%	3.13%	1.32%
Ave	0.59	0.73	0.65	0.64	0.76

The roughness factor of the Mink conductor has stayed almost the same due to the fact that it was quite smooth when initial tests took place and as a result of this, sand papering did not have much of an effect on it. The roughness factor measured on the Mink conductor is low for both conditions (sand papered and not sand papered) and as mentioned earlier, this could be ascribed to the stranding of the conductor. Normally a conductor with fewer strands and a smaller diameter has larger spaces between the strands. This means that the conductor is not as “smooth” as one where the strands are more tightly wound. So even though the strands were relatively smooth, this conductor still had a relatively low surface roughness factor. It is therefore hypothesised that for smooth clean conductors the number and diameter of the strands plays the dominant role in defining the roughness factor as opposed to the popular belief that if the conductor is new and smooth then it must have a high roughness factor.

IV. ANALYSIS OF TEST RESULTS

For the purposes of analysis, we define a new variable $\mathbf{s_f}$ that we will call the stranding factor of a conductor. This stranding factor is defined as follows: It is the ratio of the outer strand diameter divided by the overall conductor diameter. I.e., $s_f = a/b$, where a = outer strand diameter, b = overall diameter. The stranding, strand diameter and diameter of the conductors tested are as follows:

Table 4: Stranding factors for various conductors.

Conductor	Num. of Outer Strands	Strand Diam. mm (a)	Cond. Diam. mm (b)	Str. Factor (Ratio of a/b)
Mink	6	4	10.98	0.36
Wolf	18	2.5	18	0.14
Pelican	12	4	21	0.19
King Bird	12	5	24	0.21
Tern	21	3.5	27	0.13

Table 4 above shows that although some conductors have a large strand diameter they may also have a large overall diameter. Therefore in order to get a better idea of what the roughness factor of this conductor could be; it is more informative to look at the Stranding Factor.

Table 5 below shows us the stranding factors of the various sanded conductors, together with their roughness factors.

Table 5: Stranding factors and roughness factors

Conductor	Stranding Factor	Roughness Factor
Tern	0.13	0.76
Wolf	0.14	0.73
Pelican	0.19	0.65
King Bird	0.21	0.64
Mink	0.36	0.59

Figure 2 is a graphical display of the roughness factors of the various conductors as a function of their stranding factors. It shows that there is a definite relationship between the stranding factor and the roughness factor of a clean, 'smooth', stranded conductor. It is felt that this result is fairly accurate, as the lower the stranding factor, the smoother the conductor is by definition. For an ideal un-stranded conductor the stranding factor is zero. The roughness factor for a conductor such as this is taken to be 1, if figure 5 were to be extrapolated it can be shown that a stranding factor of zero would correspond to a roughness factor with a value very near to or equal to 1. These results are however only representative of a few conductors, it is foreseen, that in order to get a more rigorous relationship, further testing is required.

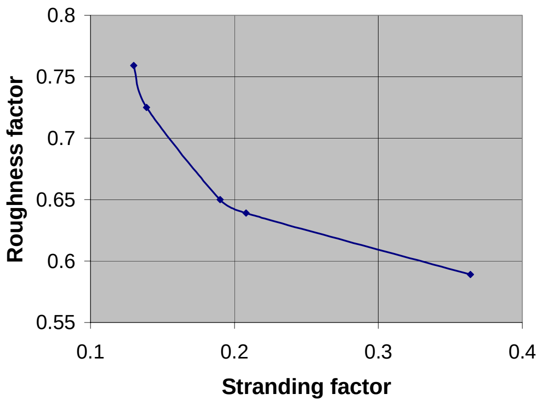

Figure 2: Roughness factor as a Function of Stranding factor.

It has thus been shown that although the conductors were clean and smooth, a roughness factor of 0.8 cannot be arbitralily assumed. Instead a more refined estimate can be made by taking the stranding factor into consideration.

V. CONCLUSION

An accurate estimate of the surface roughness factor is essential in line design and can bring about significant savings in costs. The work described in this paper has proposed a refinement in the estimation of this factor. The relationship between the stranding factor and the roughness factor has been shown.

Further laboratory testing should be undertaken with a range of different conductors with different diameters being tested. The effect of ageing on the surface roughness factor needs to be determined during these tests. These tests will verify and complement the work done thus far. It is foreseen that once exhaustive testing has been completed, that the conductor surface gradient and therefore the corona inception gradient of any new or aged stranded conductor may be accurately estimated, based on its stranding factor.

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