An experimental work on effect of bending down conductor with reinforced concrete

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Abstract: Down conductor is one of the pivotal parts of the Lightning Protection System (LPS) that diverting the lightning current captured by the air termination system to the earth termination system in each protected structure. A straight down conductor, is ideally suited for the best-case scenario regarding reliability and safety protection. One to aesthetical aspects, down conductor is undesirably bent in most current buildings. However, only the primary bare type of a down conductor is undergone such process, and bent at a certain degree which depending on the structure itself. Hence, this study is to investigate the bending degree effect on down conductors, by looking at breakdown voltage around the bent area with the presence of concrete wall and reinforcement bar. This experimental work conducted on a reduced scale of reinforced concrete which tested with high impulse voltage. It was determined that the bending down conductors has a significant effect on the bent (vertex) area with the interaction of concrete wall and reinforcement bar.

Keyword: bending down conductor, bent effect, reinforced concrete, breakdown voltage of reinforced concrete

1. Introduction

Practically, the installation of down conductor is undesirably bent due to aesthetic value of the structure in the LPS. According to the rules, there were no guidelines stated neither IEC 62305 series, nor other established standards for bending degree of down conductor and the permitted bending degree. Nevertheless, IEC 62305-3 suggested, that the common structure, it must be more than two down conductors with a safety distance in between to be cautioned and if practicable it is placed at the unprotected corner [1]. Moreover, it only states that a straight and vertical down conductor is advisable in order to provide the shortest distance to earth for lightning current to be dispersed into earth [1].

2. Scenario of bending down conductor

At the present time, there is limited scientific evidence in journals pertaining to this particular matter. Therefore, there is no bent degree limitation when installing the down conductor. Figure 1 shows some of the practical installation of down conductor which has been bent due to the structure of the building. Another significant reason is for the bent down conductor, in terms of safety to the protected structure and users. As based on the electric field, there are differences due to the mutual inductance effect on the bending part of down conductor. Thus, the higher electric field on the bent down conductor, there is a possibility of arcing into the reinforcement bars along the concrete. Furthermore, there is the possibility of arcing to the nearby external objects and humans from the bent down conductor besides the magnetic force and skin effect that will detach the down conductor from the wall.
According to the Department of Public Works, Malaysia, report; there was a case related to this bent conductor in which at Building of the Malaysian Parliament, it was found to have a distinct burn mark on a nearby wall [3]. This indicated a serious problem as this Malaysian Parliament building is an old building, which used an external down conductor system that might not be able to function properly by limiting the rise of potential at the point of strike, causing a burn mark and damaging some part of the wall being protected. Thus, this study is conducted to investigate this matter with a reduced scale of reinforced concrete that tested with the impulse generator.

3. An Experimental Work

The experimental work centred on the reinforcement of bar concrete with bent down conductor. Each specimen was injected with a high impulse voltage of 1.2/50 µs using the 'Up and Rising' method. This method was by applying the impulse voltage with the increment of 5 kV starting from the 30 kV (breakdown of air) until the breakdown occurred. The breakdown was determined by the first visible arcing occurring at the area between down conductor and reinforced concrete sample. The typical experimental setup is shown in Figure 2 and the experimental work was conducted on bent down conductor of 90º angle with L-shape reinforced concrete as in Figure 3.

**Specification of specimen sample**
A copper down conductor tape of 30 mm x 2.5 mm which is the minimum dimension recommended by IEC standard is chosen. The grading sample of the mixture of reinforced bar concrete, M25 was produced based on the standard criteria as per BS 8110 [4]. Table 1 indicates the classifications and specifications of the concrete used.
The designs considered for the reinforced concrete specimens used in the experiment was a scaled down specimen can be seen in Figure 4 and Figure 5, the L-shape of reinforced concrete with the dimensions according to the standard [4]. Only a concrete of 0.5% moisture content were applied in this study.

![Figure 4. Specimen of L-shape reinforced concrete.](image1)

![Figure 5. Dimension of L-shape reinforced concrete.](image2)

The sample of reinforced concrete, was left under sunny conditions for 1 to 3 weeks period. To identified the moisture content, the measurement is using Standard Test Method for Indicating Moisture in Concrete by the Plastic Sheet Method, ASTM D4263, which a humidity reading is taken under the plastic with a dew point hygrometer [5].

The reinforcing bar (rebar) or reinforcing steel, used for the experiment was of a standard size number 6 of a metric sized rebar, with 6 mm diameter and weighing 0.222 kg/m per unit length. The rebar of carbon steel, complied with the EN 10080 Standard specification. Although there were numerous sizes of rebar available, the small size of this rebar was selected for the worst-case scenario in this study.

4. Results and Discussion

The following sections describe the results based on the 'Up and Rising' method applied, with the voltage increased step by step, 5 kV uniformly to get the first breakdown or until the arcing occurred. Table 2 summarised the applied voltage that is injected into the samples that causes the breakdown in the sample of reinforced concrete. Most the results reflect a negative polarity due to the randomly generated positive and negative impulses applied, as 90% of lightning impulse are negative wave shapes [6-7]. To simplify conditions, only the magnitude of voltage was evaluated in each case.

| Total of testing | Average applied voltage, kV | Average voltage at breakdown, kV | Standard deviation |
|------------------|-----------------------------|---------------------------------|-------------------|
| 30 samples       | 59.90 (≈ 60)                | 31.30 (≈ 31)                    | 1.93              |

The reinforced concrete with the 90º down conductor was tested under the conditions noted earlier.
which, the bent copper down conductor was placed at the side of the reinforced concrete almost gapless. This resembled an actual situation where the placement of the bent down conductor is attached to the concrete wall. In this test, the reaction between the reinforced concrete and the down conductor was examined, given that the impulse was directly injected through the down conductor. The flashes occurred between the reinforced concrete and a bent down conductor is indicated in Figure 6(a). Figure 6(b) showing an area the arcing occurred between the reinforced concrete and the down conductor. From the observations, the flashes appeared only in the region between the bent down conductor and the concrete, this existed in the bending part of the down conductor.

![Image](image_url)

Figure 6(a). The occurrence of flashes for the 90º down conductor with a reinforced concrete.

Figure 6(b). The existence area of flashes from the top view of reinforced concrete.

Figure 7(with noise) shows the corresponding non-breakdown voltage waveform recorded before the arcing occurred and Figure 8 (with noise), is the breakdown characteristics of the reinforced concrete with the 90º down conductor respectively. There was significant difference in characteristic of voltage waveform, when the breakdown occurred at 60 kV input of impulse voltage was applied. After the noise smoothing, the voltage at breakdown was approximately 31 kV; the 50% breakdown value for the negative impulse is shown in Figure 9 (without noise).

![Image](image_url)

Figure 7. The non-breakdown voltage waveform.
Figure 8. The breakdown (negative) profile of 90° down conductor with reinforced concrete.

Figure 9. The breakdown feature at 31 kV (negative polarity) for the 90° down conductor with reinforced concrete.

The determination of the breakdown value of 31kV was for 50% of applied disruptive discharge voltage, for approximately 30 impulse attempts based on equations (1) and (2).

\[ A = \sum_{i=1}^{r} i k_i \]  \hspace{1cm} (1)

\[ V_{50\%} = V_{50\%} + \Delta V \left( \frac{A}{k} \mp \frac{1}{2} \right) \]  \hspace{1cm} (2)

Where \( A \) is equal to the number of attempts at \( i^{th} \) step \( (k_i) \), \( \Delta V \) is voltage step, \( k \) is breakdown attempts and \( V_0 \) is least breakdown voltage value for number of attempts. The value under the reference condition of the 50% breakdown voltage, for atmospheric conditions or \( V_{corrected} \), was obtained by applying equations (3) and (4) [8-10].

\[ V_{corrected} = \frac{V_{50}}{K_t} \]  \hspace{1cm} (3)

\[ g = \frac{V_{50}}{\frac{500}{500} L \delta k} \]  \hspace{1cm} (4)

Where, \( V_{50} \) is measured or estimated 50% breakdown voltage at actual atmospheric conditions, (kV), \( K_t \) is atmospheric correction factor, \( L \) is minimum discharge path (m), \( \delta \) is relative air density and \( k \) and \( g \) is dimension-less parameter with the air density and humidity correction components in relation to IEC 60060 - 1:2008 [8]. Prior to this, the standard reference atmosphere temperature was, \( T_0 \) is 20 °C, (273 K), the absolute air pressure, \( p_0 \) is 1.013 hPa (1.013 mbar) and the absolute humidity \( h_0 \) is 11
Next, the value of absolute humidity $h$ being calculated using equation (5) [8-10],

$$h = \frac{17.6 \times 6.11 e^{24337}}{0.4615 (273+t)}$$  \hspace{1cm} (5)

The estimated room pressure was assumed to be 1013 Pa, and the air density $\delta$ was calculated using equation (6).

$$\delta = \frac{P}{p_0} \frac{273+\theta}{273+t}$$  \hspace{1cm} (6)

Therefore, the parameter $k$, and exponent’s correction $m$, and $w$ are based on Table 3. From calculating, parameter $k$, is 1.0387, the determined value of $m = 1$, $w = 0$ and parameter $g > 2.0$.

| Type of Test | Parameter $k$ | Condition |
|--------------|---------------|-----------|
| DC           | $1 + 0.014 (h/\delta - 11) - 0.00022 (h/\delta - 11)^2$ | $1 \text{ g/m}^3 < h/\delta < 15 \text{ g/m}^3$ |
| AC           | $1 + 0.012 (h/\delta - 11)$ | $1 \text{ g/m}^3 < h/\delta < 15 \text{ g/m}^3$ |
| LI/ SI       | $1 + 0.010 (h/\delta - 11)$ | $1 \text{ g/m}^3 < h/\delta < 20 \text{ g/m}^3$ |

Therefore, the atmospheric correction factor $K_t$ is found by applying the density correction factor $k_1$ and humidity correction factor $k_2$. The calculation was determined by applying equations (7), (8) and (9).

$$k_1 = \delta^m$$  \hspace{1cm} (7)

$$k_2 = k^w$$  \hspace{1cm} (8)

$$K_t = k_1 k_2$$  \hspace{1cm} (9)

Hence, for 31 kV of voltage at the breakdown point for the reinforced concrete with 90° down conductor arrangement, the 50% breakdown voltage or the $V_{corrected}$ is 31.68kV under reference conditions. This value calculated based on the temperature around 25.9~26.4 °C, and humidity of 60~66% throughout the experiment. This corrected value is assumed the actual value for the voltage at the breakdown. The outlines shown in the graph are similar for breakdown characteristics, whereas the L-shaped concrete has a smaller value, near to the breakdown of air (30kV/m). The possible reason is that at the bent part of down conductor, the current density was higher and with the electromagnetic effect of steel rebar [11] and chloride transport in concrete [12], it increased the chances of breakdown occurring at lower levels. Moreover, at the area of breakdown of most of the samples there were visible small cracks which similar with the previous research [13].

5. Conclusion

As consequence, it was found that the bent down conductor has a significant influence on the reinforced concrete. This is indicated by the arcing existed precisely at the bent area, when the impulse voltage was injected to the bent down conductor. The voltage at breakdown was determined with atmospheric correction factor was considered during the experiment.
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