# Development of Prototype Low-cost and High-strength Fault Current Interrupting Arcing Horns for 77 kV Overhead Transmission Lines

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Fault Current Interrupting Arcing Horns (FCIAH) are newly designed arcing horns installed on transmission line towers as a countermeasure against lightning damage that greatly contribute to reducing power interruption by interrupting fault current independently within an AC cycle. This paper describes the development of two new prototype FCIAH for further cost reduction and strength enhancement, using computational fluid dynamics and short-circuit tests.

**Keywords:** Fault Current Interrupting Arcing Horns, lightning, arc, computational fluid dynamics

## 1 INTRODUCTION

Most short-circuit faults in overhead transmission systems are attributable to lightning strikes, and thus an economical and effective countermeasure against lightning damage is required to secure a more reliable power supply.

Accordingly, Fault Current Interrupting Arcing Horns (FCIAH) for 77 kV overhead transmission lines, which are newly designed arcing horns installed on transmission line towers as a countermeasure against lightning damage, were developed in 2004 [1]. FCIAH contain cylindrical interruption cores made of polyamide resin on the tips of normal arcing horns, and greatly contribute to reducing power interruption by interrupting the fault current independently within an AC cycle. This paper describes the development of two new prototype FCIAH based on the recent need for further cost reduction and strength enhancement [2]. It also outlines the development approach for the prototypes, using computational fluid dynamics (CFD) and short-circuit tests.

## 2 EXISTING FCIAH

The appearance and structure of existing FCIAH for 77 kV overhead transmission lines are shown in Figs. 1 and 2 respectively, and their specifications are also shown in Table 1. FCIAH are installed on both the line and ground sides of bilateral insulator assemblies. When a flashover occurs between the interruption cores due to a lightning strike, their inner wall made of polyamide resin is vaporized by the heat from the fault arc. Then a high-velocity, high-temperature, high-pressure arc jet including the vapor of the polyamide resin is ejected from the tips of the interruption cores, thus interrupting the fault current [3]. Consequently, line protection relays seldom detect a fault within an AC cycle, and power interruption due to the opening of a circuit breaker in substations hardly ever occurs.

The inside of the interruption core is com-

*Fig. 1: Appearance of existing FCIAH*

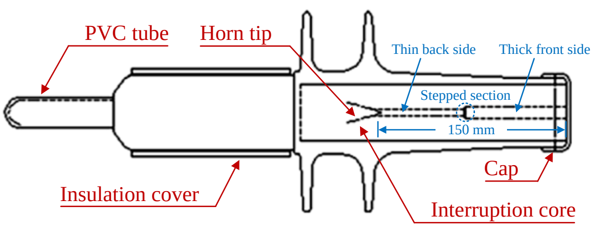


*Fig. 2: Structure of existing FCIAH*

*Table 1: Specifications of existing FCIAH*

| | |
|---|---|
| Rated voltage | 77 kV |
| Breaking current | Up to 10 kA |
| Explosion-proof current | Up to 10 kA |
| Current breaking time | Within an AC cycle |
| Iterative current breaking | Up to 5 times |

posed of a thin back side and thick front side across a stepped section that is 150 mm in total length.

## 3 PROTOTYPE DESIGNED FOR COST REDUCTION

To reduce the cost of FCIAH, we have improved the performance of the interruption core by clarifying the optimum internal structure of the interruption core for arc extinguishing and have reduced the number of interruption cores by replacing the line side of FCIAH with a normal arcing horn. We aim to achieve the same performance for the breaking current, current breaking time and iterative current breaking as for existing FCIAH.

### 3.1 DEVELOPMENT APPROACH

First, we doubled the length of the interruption core to 300 mm without changing the ratio of the back side to front side lengths, on the assumption that a longer interruption core is required to prevent the deterioration of current interruption performance due to the decrease in the number of installations.

Next, we clarified the internal diameter of the interruption core favorable for arc extinguishing by CFD simulation and adopting a convergent-divergent (con-di) nozzle design. The con-di nozzle produces a supersonic flow by the expansion of a high-pressure gas and is also employed in rocket engines. The high-velocity arc jet increases the arc power loss due to the convective effect, and operates in favor of the current interruption. Therefore, it is effective to discover the internal structure of the interruption core which produces the high-velocity arc jet by applying the con-di nozzle design. The con-di nozzle has an hourglass shape, whereas the inside of the interruption core has a stepped shape. The internal structure of the interruption core is designed to resemble a con-di nozzle as shown in Fig. 3.

The nozzle-expansion ratio $\varepsilon$[4] is given by

$$\varepsilon = \frac{A_e}{A_t} = \frac{\left(\dfrac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}}}{\left(\dfrac{p_e}{p_0}\right)^{\frac{1}{\kappa}}\sqrt{\dfrac{\kappa+1}{\kappa-1}\left\{1-\left(\dfrac{p_e}{p_0}\right)^{\frac{\kappa-1}{\kappa}}\right\}}} \cdots\cdots\cdots (1)$$

where $A_t$ is the cross-sectional area of the throat section, $A_e$ is the cross-sectional area of the nozzle outlet, $p_0$ is the stagnation pressure at the nozzle inlet, and $p_e$ is the static pressure at the nozzle outlet. The specific heat ratio $\kappa$ of polyamide resin is calculated by

$$\kappa = \frac{C_p}{C_p - \dfrac{P}{\rho T}} \cdots\cdots\cdots (2)$$

where $C_p$ is the constant-pressure specific heat, $\rho$ is the density, $T$ is the temperature, and $P$ is the static pressure. When $A_t$, $p_0$, and $p_e$ are given, $A_e$ can be obtained from Eqs. (1) and (2). Consequently, considering the relationship between the con-di nozzle and the interruption core shown in Fig. 1, the internal diameter on the front side can be calculated from the internal diameter on the back side and the pressures at the stepped and exit sections obtained by CFD-ACE+ software [5].

As shown in Fig. 4, the calculation domain is divided into finite volumes, and the flow field of the entire calculation domain is obtained by solving the conservation laws at each finite volume step by step. The mesh shown in Fig. 4 is only an illustration, not an actual representation. The mesh actually used in simulations is fine enough to deal with a supersonic phenomenon. 2D transient simulations were performed on the assumption that the inside of the interruption core is regarded as rotational

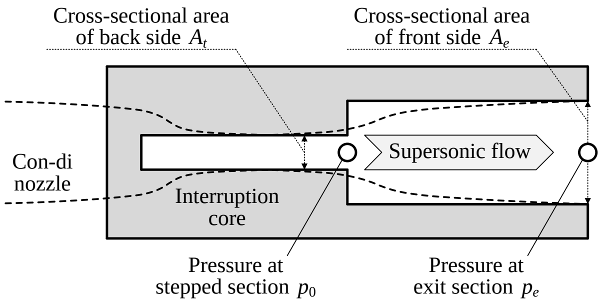


*Fig. 3: Comparison between con-di nozzle and interruption core*

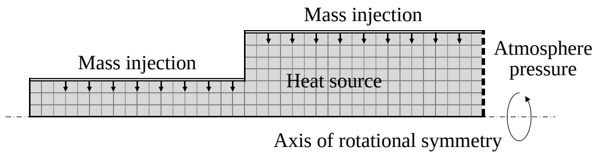


*Fig. 4: CFD simulation method*

axisymmetric and that FCIAH breaks the arc current through half an AC cycle. The arc power was evenly distributed into each finite volume as a heat source. The evaporation of the inner wall of the interruption core was expressed by the mass injection. The waveforms of the arc power and the evaporation mass were a half wave of 50 Hz as with the arc current, and their peak values were estimated from the results of short-circuit tests. The exit section of the interruption core was set to atmosphere pressure.

As an example in the case of an arc power of 8.23 $MW_{peak}$ equivalent to an arc current of 10 $kA_{rms}$, the pressure, velocity and Mach number distributions at the time of 5 ms, when the arc power and arc current become the maximum, are shown in Figs. 5, 6 and 7 respectively. From Fig. 7, it was found that the Mach number reaches 1.39 around the exit of the interruption core, and that the supersonic arc jet is ejected from the tip of the interruption core.

The appearance of the prototype designed for cost reduction developed by the above approach is shown in Fig. 8.

### 3.2 SHORT-CIRCUIT TESTS

Table 2 shows the test conditions. The test voltage was 69.7 kV, which was calculated by multiplying the rated voltage to ground of 77/√3 kV by the operation voltage factor of 11.5/11 [6] and the first-pole-to-clear factor of 1.5 [7]. The test current was 10 kA. The DC component of the test current was minimized in the current breaking test and maximized in the fracture resistance test. The transient recovery voltage was determined on the basis of JEC-2300-1998 [7]. In some cases, iterative current breaking was also confirmed by using the same test piece repeatedly.

Table 3 shows the test results. In the current breaking test, the prototype interrupted the current within an AC cycle in the first test. However, it interrupted the current after one and a half AC cycles in the second test in

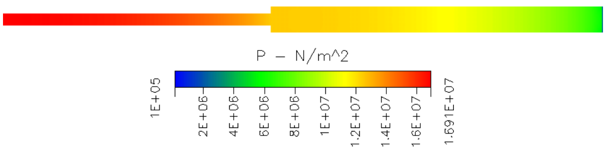


*Fig. 5: Pressure distribution*

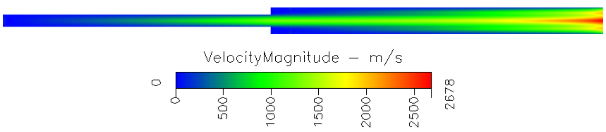


*Fig. 6: Velocity distribution*

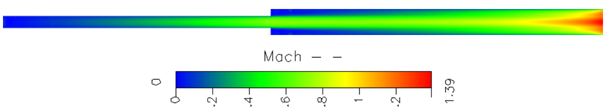


*Fig. 7: Mach number distribution*

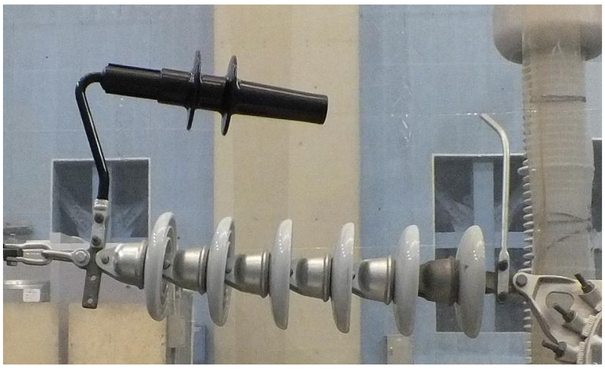

*Fig. 8: Prototype low-cost FCIAH*

*Table 2: Test conditions to verify characteristics of low-cost prototype*

| Verification item | | Current breaking | Fracture resistance |
|---|---|---|---|
| Frequency | | 50 Hz | |
| Voltage | | 69.7 kV | |
| Current | RMS value | 10 kA | |
| | DC component | Minimized | Maximized |
| Voltage supply duration | | 4 cycle | |
| Transient recovery voltage | $u_c$ | 138 kV | |
| | $t_3$ | 184 μs | |
| | $u_c / t_3$ | 0.75 kV/μs | |
| Arc ignition | | Copper wire of 0.2 mm$\phi$ | |

*Table 3: Test results for low-cost prototype*

| Current | | Verification item | | | | | |
|---|---|---|---|---|---|---|---|
| RMS value | DC comp. | Current breaking time in each test [cycle] | | | | | Bending of horn leg |
| | | 1st | 2nd | 3rd | 4th | 5th | |
| 10 kA | Min. | 0.5 | - | - | - | - | None |
| | | 0.5 | 1.5 | - | - | - | Aft. 2nd breaking |
| | | 1 | 1.5 | - | - | - | Aft. 1st breaking |
| | | 1 | 1 | 0.5 | 1 | 1 | Aft. 1st breaking |
| | Max. | 1 | - | - | - | - | Aft. 1st breaking |

some cases. Hence, the breaking current is comparable with that for the existing FCIAH, whereas the iterative current breaking is inferior to that for the existing FCIAH. In the fracture resistance test, the prototype horn leg was bent when the current breaking time was more than an AC cycle. In the future, we intend to improve the iterative current breaking by reviewing the interruption core and to enhance the fracture resistance by reinforcing the material used for attachment.

As described above, we succeeded in reducing the cost of FCIAH by replacing the line side of FCIAH with a normal arcing horn, although some issues remain.

## 4 PROTOTYPE DESIGNED FOR STRENGTH ENHANCEMENT

To enhance the strength of FCIAH, we have appended pressure relief holes and an arc-inviting horn to the prototype designed for cost reduction. We compromise on the deterioration of the current interruption performance to prioritize the enhancement of the strength.

### 4.1 DEVELOPMENT APPROACH

First, we added two pressure relief holes in the interruption core designed for cost reduction as shown in Fig. 9. The pressure relief holes formed a single straight line and were introduced to suppress the pressure rise in the interruption core due to the arc heat.

Next, we set an arc-inviting horn at the base of the arcing horn to reduce the damage to the interruption core by moving an arc generated by an excessive fault from the inside of the interruption core to the outside.

The appearance of the prototype designed for strength enhancement developed by the above approach is shown in Fig. 10.

### 4.2 SHORT-CIRCUIT TESTS

Table 4 shows the test conditions. In the fracture resistance test, the test voltage was reduced to 24 kV because of the capacity limitation of the test facilities. In the current breaking test, iterative current breaking was also confirmed by using the same test piece repeatedly.

Table 5 shows the test results. In the current breaking test, the prototype succeeded in breaking a current of 7 kA three times repeatedly. However, it failed to break a current of 8 kA in the second test. In the fracture resistance test, the interruption core retained its original form for a current of 15 kA but collapsed as a result of the arc heat for a current of 20 kA. Hence, compared with the existing FCIAH

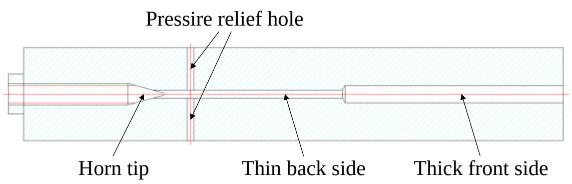


*Fig. 9: Cross section of interruption core*

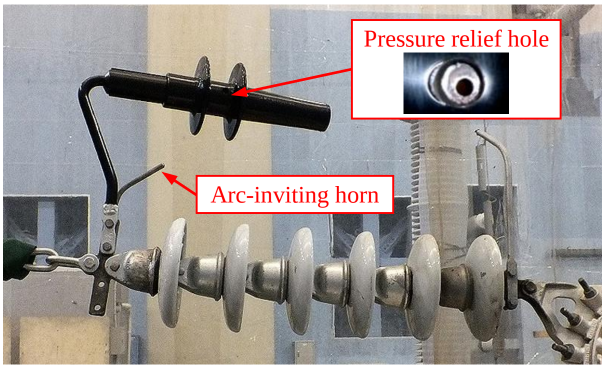


*Fig. 10: Prototype high-strength FCIAH*

*Table 4: Test conditions to verify characteristics of high-strength prototype*

| Verification item | | Current breaking | Fracture resistance |
|---|---|---|---|
| Frequency | | 50 Hz | |
| Voltage | | 69.7 kV | 24 kV |
| Current | RMS value | 8, 7 kA | 20, 15 kA |
| | DC component | Minimized | Maximized |
| Voltage supply duration | | 4 cycle | 8.5 cycle |
| Transient recovery voltage | $u_c$ | 138 kV | N/A |
| | $t_3$ | 184 μs | |
| | $u_c/t_3$ | 0.75 kV/μs | |
| Arc ignition | | Copper wire of 0.2 mm$\phi$ | Copper wire of 0.5 mm$\phi$ |

*Table 5: Test results for high-strength prototype*

| Current | | Verification item | | | |
|---|---|---|---|---|---|
| RMS value | DC comp. | Current breaking time in each test [cycle] | | | Part destroyed |
| | | 1st | 2nd | 3rd | |
| 8 kA | Min. | 0.5 | Failure | - | None |
| 7 kA | | 0.5 | 0.5 | 0.5 | None |
| 20 kA | Max. | N/A | | | Interruption core |
| 15 kA | | | | | None |

shown in Table 1, the explosion-proof current was increased from 10 kA to 15 kA, although the breaking current decreased from 10 kA to 7 kA. In the future, we intend to enhance the fracture resistance so that a current of 31.5 kA can be withstood, which is the maximum short-circuit current in Japanese 77 kV transmission systems.

As described above, we succeeded in enhancing the strength of FCIAH by appending pressure relief holes and an arc-inviting horn to the prototype designed for cost reduction, although some issues remain.

## 5 CONCLUSION

As reported in this paper, we have developed two new prototype FCIAH designed for cost reduction and strength enhancement. In the future, we will complete the development of the FCIAH and apply them in pilot studies in actual transmission systems.

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