



# A novel approach for basic insulation-level (BIL) enhancement of vacuum interrupters

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## Abstract

This article introduces a newly developed design method that may be utilized in modern high-voltage vacuum interrupter (VI) design. At first, a typical 24 kV vacuum chamber is modeled using finite-element method. Potential and electric field profiles are derived and analyzed in detail. To continue, the proposed approach which consists of twin metallic rings placed in the porcelain tubular insulator is added to the previous model and the new model is analyzed in three steps: short-, medium- and long-course scenarios. The achieved patterns illustrate the severe reduction in electric field value of the contacts' surface especially for long-course prototype (up to 74.2%). This phenomenon is discussed in detail. Considering the Fowler–Nordheim quantum tunneling equation; a reduction in electric field intensity brings to lower field emission current value which is the most important factor of breakdown during BIL tests. It is important to note that any reduction in electric field value results in decrease in micro-discharge value and microparticle movement, which are the additional reasons for vacuum insulator failure during high-voltage pulse insertion. This means that the inception voltage of the proposed VI can be increased so that higher BILs like 63 kV insulation high voltage requirements are achieved. The reduction rate of field emission current density is reduced to 4.9% of its initial value for or 120-mm course which expresses the effectiveness of this new approach.

**Keywords** Vacuum interrupter · Basic insulation level (BIL) · Finite element · Electric field · High voltage

## 1 Introduction

Vacuum interrupters are the most utilized medium-voltage, ( $V < 36$  kV), electrical apparatus for interrupting current application in a distribution electrical networks since 1965; the main reason is their heavy-duty, maintenance-free and environment-friendly properties comparing with SF<sub>6</sub> circuit breaker. The current will be quenched at the first zero crossing [1–9].

Dielectric behavior of vacuum circuit breaker (VCB) seems to be more critical compared to SF<sub>6</sub> apparatus. Low BIL endurance is the main reason that this favorable circuit breaker could not be erected in higher standard voltage levels like 63 kV nominal voltage systems. BIL of a VI depends on the pressure, the distance between electrodes and the materials used for electrode alloy for distances of about 1 cm and pressures of about  $10^{-7}$  torr; the dielectric strength ranges

from 150 to 300 kV/cm. Change in contacts' alloy and conditioning the protrusions located on the contacts' surface using high voltage pulses are investigated in detail in previous tasks [10–15].

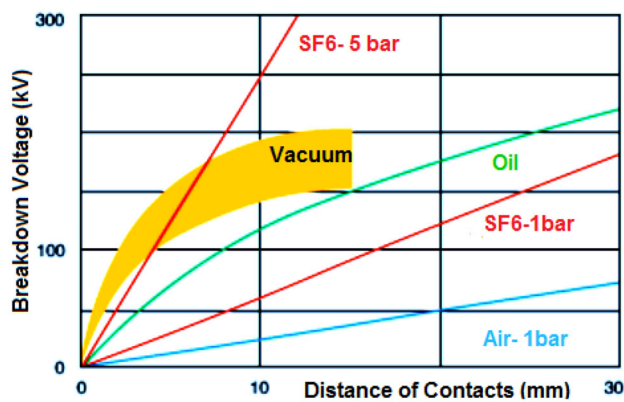
Investigating breakdown mechanisms in vacuum illustrates that the main reason for ignition is electric field intensity. Any effort which reduces, especially the microscopic electric field of energized contacts, presents a new way for higher BIL accessibility. The main goal of this article is to demonstrate the new optimized design of modern vacuum chambers with enhanced microscopic electric field value that leads to higher BIL circuit breaker design [3, 8, 16–19].

## 2 Breakdown in vacuum

Breakdown phenomenon in vacuum has a very different mechanism comparing with other insulating materials like air and SF<sub>6</sub>. Breakdown phenomenon in vacuum relates to pressure, distance and electrode types.

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**Fig. 1** Dielectric strength of some insulators comparing with vacuum [8]

A wide variety of circuit breakers (CB) are produced and erected. But one of the most utilized switches especially after the early 1980s is vacuum type CB. Nowadays, more than 80% of medium-voltage interrupters consist of a vacuum chamber (rest are SF6 type). The main reason is the maintenance-free superiority, heavy-duty operation and especially environmental-friendly properties of this reliable equipment [7]. During the separation of two contacts in a vacuum chamber, the produced metallic inter-electrode plasma is dispersed and the metallic arc is extinguished at the first current waveform zero crossing. Moreover, after quenching of current there is a dynamic interval which lasts for about 15  $\mu$ s, during this interval which is also named “*post arc interval*”, the conductive hot plasma with temperature about 2–2.5 eV disappears and the current is interrupted. It is important to note that dielectric recovery process between the VI contacts relates to the diffusion of metallic plasma medium. If transient recovery voltage (TRV) originated from inductive external current outstrips the dielectric recovery process, the switch reignites and instantaneous vacuum breakdown occurs resulting in unsuccessful operation of the switch.

Many investigations are performed to study the dynamics of arc quenching process and inter-electrode plasma diffusion process to modify the risk of failure and present better understanding of the quenching arc mechanism [2–5]. One of the most important terms in plasma modeling equations is induced electric field intensity in the chamber. Furthermore, in the state of the open contact without inter-electrode plasma, for 63 kV (72.5) level the dielectric strength of the VI corresponding to IEC 62271-100 should withstand 345 kV. But in the experimental tests for a typical a VI, the obtained BIL result is illustrated in Fig. 1. Concerning curves in Fig. 1, it is clear that BIL of a typical VI is less than 220 kV (regarding to vacuum value inserted in the chamber). So this CB type is not applicable at 63 kV voltage level [7].

For this reason, these types of interrupters are utilized only at 36 kV nominal voltage level and below (specially 20 kV).

The investigations for achievement higher BIL are based on utilization of two or more chambers in series with (or without) parallel dividing voltage capacitors or utilization of contacts with different alloys or nanotechnology structure.

In an open contact state, the breakdown occurs as a result of one of the main reasons listed below [3]:

- *Field emission* which is described by Fowler–Nordheim equation and demonstrates current emitted from cathode contact originated from inter-electrode electric field.
- *Anode phenomena* it result from absorbed gases on the contact surface or metallic vapor originated from anode contact as a result of electron beam strike to the anode.
- *Microparticles* this factor indexes 20–80- $\mu$ m metallic surface-placed particles that accelerate regarding their electric charge and inter-electrode-produced electric field.
- *Micro-discharges* it demonstrates 0.05–100 ms current pulses discharging charge of contacts capacitance resulted from inserted high voltage and inter-electrode electric field.

## 2.1 Electric field impression

Excepting anode phenomena which affects the breakdown phenomena relate to absorbed gases’ value on the contact surface; all other breakdown factors are depending to electric field value strongly. Particularly, field emission current value as a main factor relates to the field as described in Eq. 1:

$$J_{F.N.} = \frac{A}{\varphi_B} E^2 e^{-\left(\frac{B\varphi_B^{3/2}}{E}\right)} \quad (1)$$

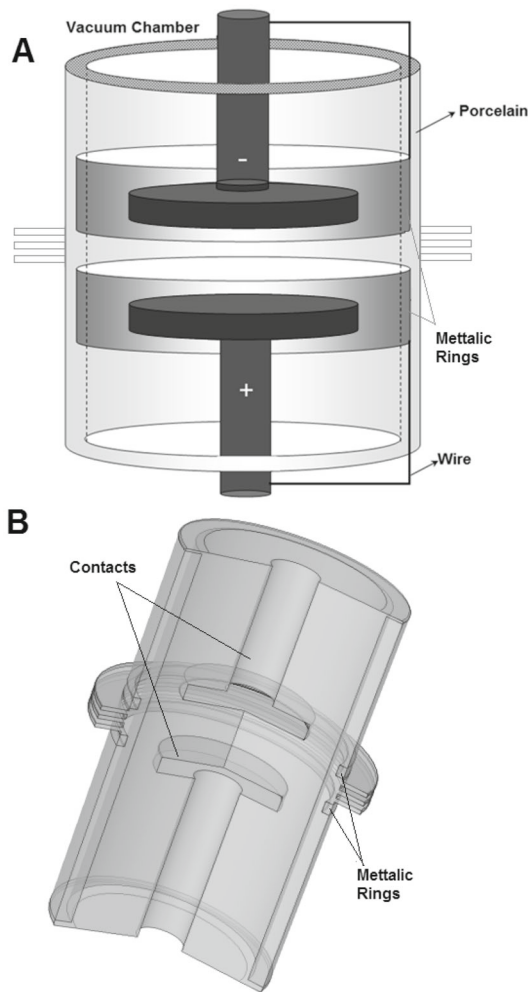
$J_{FN}$  is the electronic current density in  $A/m^2$ ;  $A = 1.54 \times 10^{-6} \text{ AJ/V}^2$ ;  $E$  is the electric field in  $V/m$ ;  $\varphi_B$  is the work function of material in eV;  $B = 6.83 \times 10^9 \text{ V/mJ}^{1.5}$ .

In this equation,  $A$  and  $B$  are constants (in simplified cold metals and alloys),  $\varphi_B$  demonstrates work function potential of material (4.5 eV for copper) and is the other constant of Eq. 1; finally  $E$  is the value of inserted external electric field intensity on contact surface. Electric field value is the most important factor which affects the field emission current significantly.

The main goal of this article is to introduce a new approach to reduce electric field value so that the output value of Fowler–Nordheim equation reduces significantly.

## 3 Proposed procedure

As discussed before, a new proposed structural design is discussed in this section. The procedure is based on mounting



**Fig. 2** Schematic diagram of the proposed new VI design. Rings mounted inside the porcelain (a), 3D schematic of the proposed arrangement (b)

two metallic rings inside the porcelain housing of the vacuum bottle as illustrated in Fig. 2.

Figure 2 shows two metallic rings are installed symmetrically and surrounded by two internal contacts; as is illustrated three sheds are also considered to increase creepage distance in the stress region of the porcelain housing.

Two metallic rings which are desired to connect related contact potential will affect and interact with internal electric field so that decreases resultant electric field value on the contact surface. Then, using finite-element software the proposed structure is simulated and the obtained electric field values are discussed in details. It is important to note that we aim to decrease electric field value in open contact status to overcome the restrictions of low basic insulation level (BIL) of a VI prototype regarding to IEC 62271-100.

**Table 1** Boundary, domain conditions and material properties

Boundary domain	Boundary condition
Cathode and its ring	$V = 0$
Anode and its ring	$V = 24 \text{ kV}$
All boundaries of porcelain with domain specification	Zero charge, $ND = 0, \epsilon_r = 7$
Internal domain (vacuum)	Charge conservation $E = -\nabla V, \nabla \cdot (\epsilon_0 \epsilon_r E) = \rho_v$
Contacts' domain	Copper specification

## 4 Simulation and results

With utilization of proper FEM software (COMSOL), also considering boundary conditions as listed in Table 1 and electrostatic computational package, using 21 150 mesh elements, modeling process is performed to solve the problem.

The differential equation which should be considered is Laplace equation (Eq. 2). It is important to note that the magnetic field analysis is ignored in this simulation because in FN equation, only electric field factor is considered. Furthermore, BIL tests are performed only in open contact status of a high-voltage circuit breaker that no current crosses from the chamber. Also we ignore earth effect and other surrounding equipment during this simulation.

$$\nabla^2 V = 0 \tag{2}$$

In this article, three scenarios related to three different contact distances are considered.

### 4.1 Long contact distance

The simulation results are presented in Fig. 3. It is illustrated that the derived electric field value decreases in the proposed design comparing to the basic structure. Particularly, near the contact surface electric field value decreases intensively. It is important to note that electric field stress is relocated from contacts to the peripheral region which easily is tolerable and can be controlled.

### 4.2 Medium contact distance

The obtained results for medium distance (30 mm) are presented in Fig. 4. As one gets electric field value also decreases in the proposed design but the reduction value is smaller comparing to the previous arrangement. Maximum value of electric field in this arrangement is equal to 756,412 (V/m).

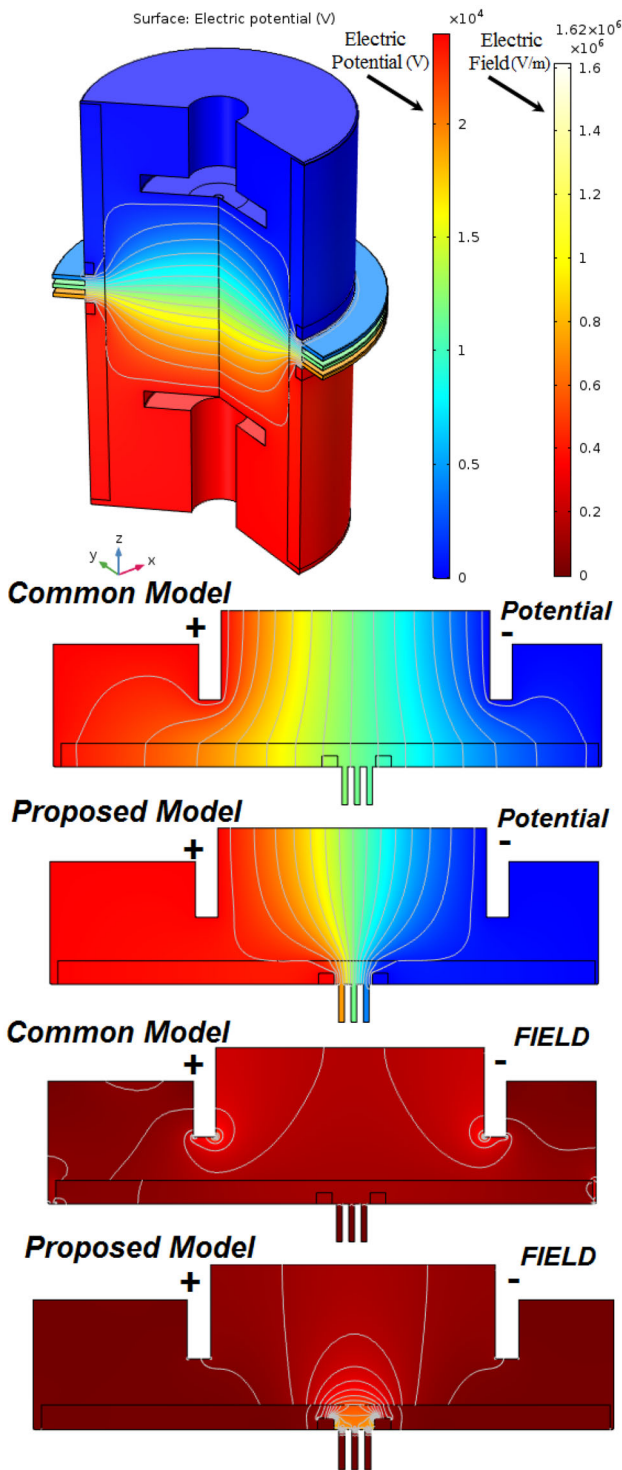


Fig. 3 Derived patterns for potential and electric field values for common and proposed models (long contact distance, 120 mm)

### 4.3 Small contact distance

The simulation results for small course of contacts are presented in Fig. 5. For this arrangement, we obtain that the

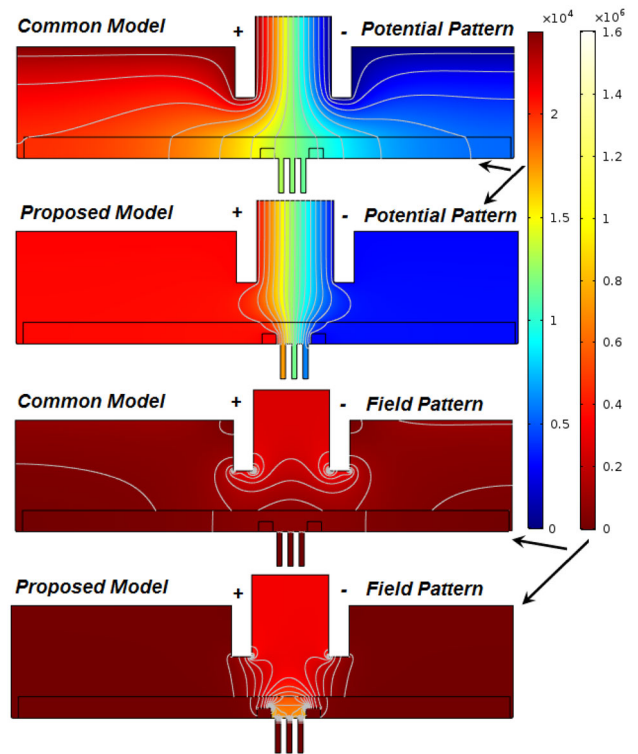


Fig. 4 Derived patterns for potential and electric field value for common and proposed models (medium contact distance, 30 mm)

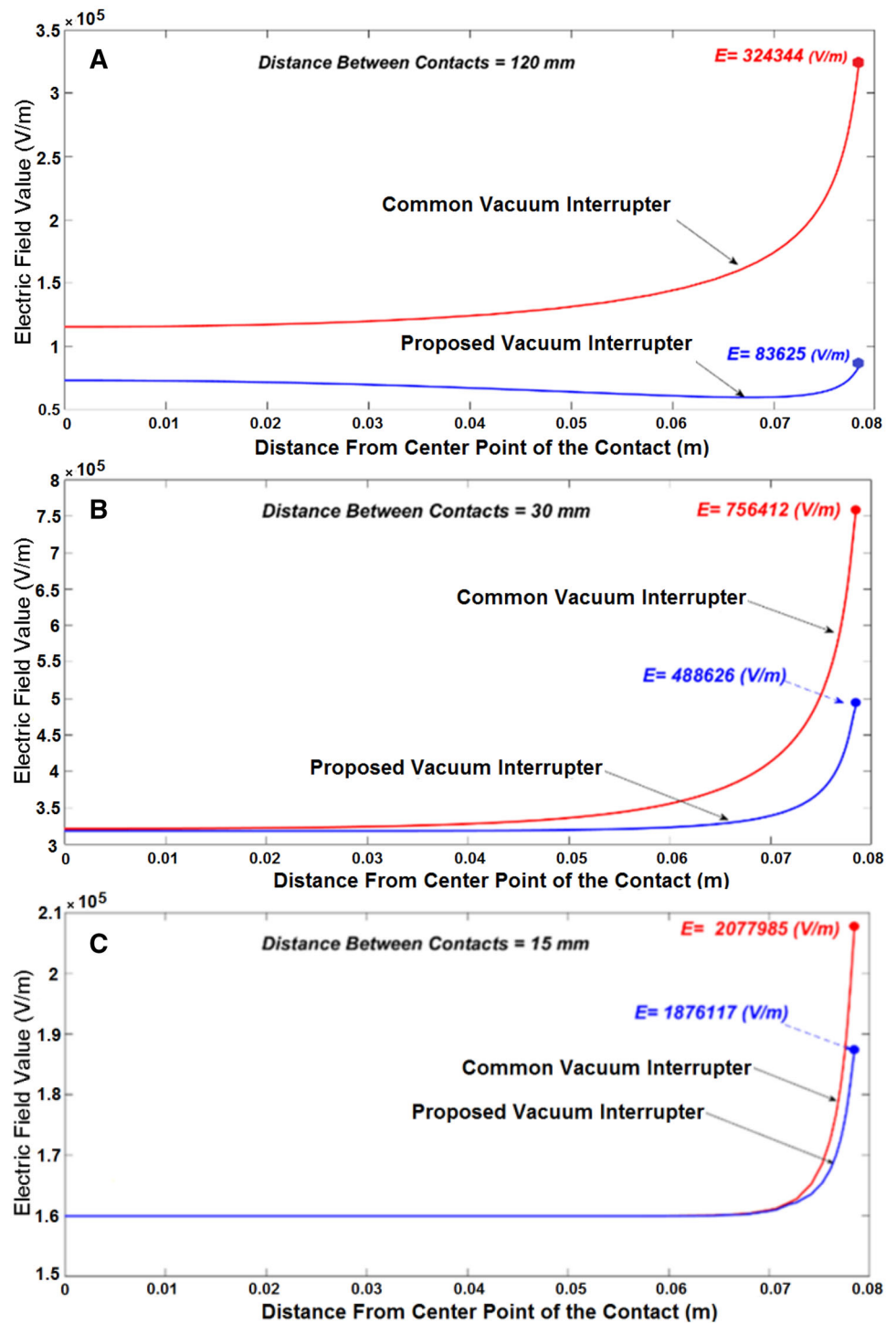
electric field decrement only occurs in the peripheral region of the contacts. In this simulation, the full course length is considered 15 mm and the inter-contact electric field value is doubled comparing to previous contact distances [2,077,985 (V/m)].

## 5 Discussion

From Figs. 3, 4, 5 and 6, we observe that the idea of mounting two metallic rings in the peripheral area of a vacuum chamber results in significant reduction in electric field value on the contact surface. The results of reduction percentage for three different contact courses are illustrated in Table 2. Regarding the results of this table, it is clear that the proposed design is effective especially for long distance between open contacts (74.2% reduction rate for 120 mm distance between contacts).

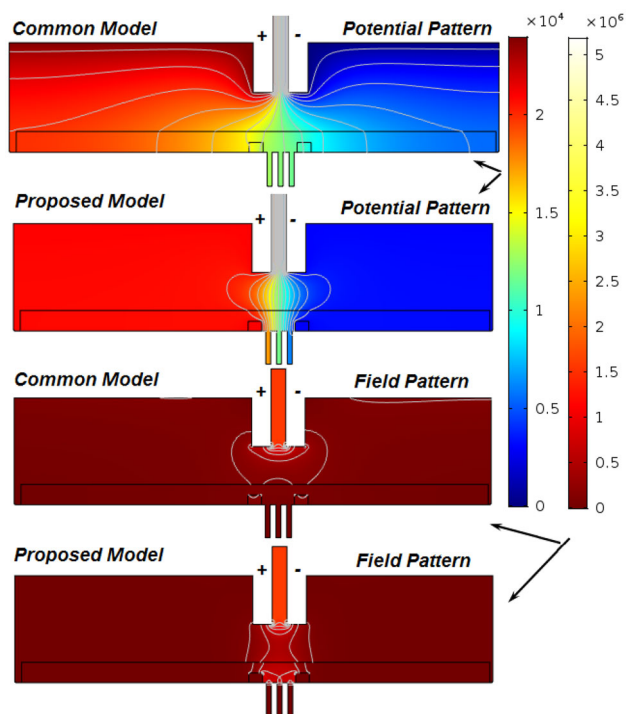
It is important to investigate the field emission current density change as the most important factor of cold breakdown in vacuum chamber. Successful reduction in electric field in the order of 74% results in the significant reduction in the field emission current density on the order of 95.1%. Furthermore, micro-discharge currents and microparticles which are other breakdown reasons (as discussed in Sect. 2) relate also significantly to the electric field value as shown in to Table 2 which

**Fig. 5** Reduction of electric field value for common and proposed models for various inter-contact distance (a 120 mm, b 30 mm, c 15 mm)



also reduces significantly. Where all of the reasons of the breakdown process in a vacuum interrupter, especially field electron emission, reduce as discussed before, the inception voltage which is checked by inserting an impulse waveform to the vacuum chamber will increase regarding field emission current density reduction percentage; for example, for 30 mm inter-contact distance the increment of BIL voltage

rate theoretically is about 61.3%. The result is that the new proposed arrangement design is very efficient especially for long distance contact.



**Fig. 6** Derived patterns for potential and electric field values for common and proposed models (small contact distance, 30 mm)

**Table 2** Electric field and field emission current density reduction percentage for proposed model comparing with a common prototype

Open contact distance (mm)	Electric field reduction (%)	Field emission current reduction (%)
120	74.2	95.1
30	35.4	61.3
15	9.7	21.6

## 6 Conclusions

This paper presents a new approach to enhance and develop a modern design method for a vacuum interrupter regarding reduction in the inter-electrode-induced electric field value, aimed to significantly decrease field emission current density. This current is the main reason of vacuum insulation failure. So the proposed procedure results in higher inception voltage level (increment of BIL value). The idea is to equip the proposed prototype with two metallic rings placed at the peripheral zone of the housing chamber (porcelain) and connect them to the inserted potential of the related contacts of the VI. Then, this concept was investigated in detail for three various inter-electrode alternative courses.

At first, the geometry of a typical prototype and proposed model was drawn using SolidWorks software and imported to finite-element software in 3D format to solve the related Laplace equation, with utilization of electrostatic module of the FEM software considering proper boundary condition. The simulation results for electric field value and potential patterns were derived at three various contact distances (120, 30 and 15 mm); the results demonstrate very interesting result especially for electric field value. Especially for long courses like 120 mm, electric field reduces to 74.2% of its initial value (comparing with the common prototype). As was discussed regarding to Fowler–Nordheim field emission equation, the electric field reduction rate can affect and significantly reduce field emission current density to 4.9% of its initial value for 120 mm inter-electrode course (38.7% for 30 mm and 78.4% for 15 mm). Field emission current is the main reason of breakdown in cold contact vacuum interrupters. The main reason that a VI is not applicable for 63 kV and above is this factor which causes vacuum dielectric failure under 63 kV BIL test. The result of this new proposed design is that the inception voltage value increases significantly to the levels that produced inter-contact electric field returns to its inception value in the common VI prototype. The results are also discussed for three different contact courses which endorse this new approach as a new effective design for modern vacuum interrupters.

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