International Journal of Systems Signal Control and Engineering Application 10 (1-6): 16-23, 2017
ISSN: 1997-5422

Modeling of Field Emission Current to Diagnosis Internal Pressure of Vacuum Circuit Breakers

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Abstract: Condition monitoring of vacuum circuit breaker is one of the important factor to determine its life time. Internal pressure of vacuum interrupter is the main parameter of vacuum circuit breaker conditioning. Rise of internal pressure exceeding a certain threshold value cause's loss of current switching capability and electric insulating properties. In recent decades many internal pressure determining methods have been researched to evaluate the influences of different parameters. Although most of them are based on experimental tests but none of them was a satisfying and reliable method to give enough information about residual vacuum pressure. Thus, the field emission current is modelled and simulated in this paper using plasma modelling by Particle in Cell (PIC) method in order to determine the relation of current and vacuum pressure. The simulation results demonstrate that pulsed current with field emission current used for diagnosis vacuum pressure of vacuum interrupter.

Key words: Field emission current, vacuum interrupter, vacuum circuit breaker, Particle in Cell (PIC), ionization current, residual

INTRODUCTION

Vacuum Circuit Breakers (VCBs) which operate in medium voltage distribution system are reliable, maintenance-free and have a high life expectancy (Koochack-Zadeh and Hinrichsen, 2008). However, it has been noticed that now a days, network owners are beginning to concern about the vacuum conditions and subsequently, the switching capabilities of these vacuum circuit breakers (Merck *et al*., 1999). Conducting condition monitoring on the vacuum pressure to expand VCBs application reliability in networks is a challenge considering the functionality of these breakers critically depends on the vacuum pressure inside their tubes. To determine the internal pressure of vacuum interrupter which is in service, most manufacturers use the Penning or Magnetron method (Schellekens, 2014; Merck *et al*., 1998; Mao and Wang, 2005; Kumar and Shrinivasa, 2014; Niayesh, 2015). In the case of an abnormal increase of the internal pressure, the vacuum interrupter will no longer be able to fulfill its main functions. Rise of the internal pressure above 0-1 Millitorr causes at first, the loss of high current switching capability. At a pressure which is one or two orders higher, the vacuum interrupter also loses its insulating properties (Xu *et al*., 2014; Frontzek and Konig, 1993). The task of re-examining the internal pressure of vacuum interrupters after several years of service requires simpler procedures capable of being applied at site to find out mainly, if the above mentioned pressure level is still maintained. The method should be as simple as possible, and based on the measurement of only one or two electrical parameters with minimum expense in apparatus and time (Frontzek *et al*., 1993).

In recent decades, many different practical methods are studied to measure the internal pressure of vacuum circuit breakers. These include the measurement of the breakdown voltage, current switching capability, arc voltage, partial discharge, X-Ray signals and electromagnetic waves (Nakaoka *et al*., 2014; Xin *et al*., 2012; Xing-ming *et al*., 2012; Ziyu *et al*., 2000, 2006).

Another method that has recently been used is pressure estimation through field emission current. A few researches were done to investigate the correlation between the current for field emission and the vacuum breakdown in vacuum circuit breaker (Zadeh *et al*., 2011; Donen *et al*., 2012; Zadeh *et al*., 2010; Makabe *et al*., 1997; Popov *et al*., 2001). It was discovered that the difference of field emission current has influence on the electrical breakdown voltage when the value of the field emission current is close to the occurrence of the electrical breakdown. The method based on the analysis of field emission currents after arc polishing of contacts is introduced by Frontzek and Konig (1993). It shows that the absolute value of a field emission current depends on

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the gas layer that always exists on solid surfaces even in vacuum interrupter and the duration of the adsorption of this gas layer on a metal surface is lower for the higher internal pressure. According to Frontzek and Konig (1993) and Raad *et al.* (2016), the gas layer could be removed from parts of the contact surface with the help of arc polishing. Afterward, the re-adsorption of the gas layer can be observed by measuring the field emission currents, the re-adsorption of the gas layer can be observed.

While the published research showed the correlation between field emission current, electrical breakdown voltage and vacuum pressure, the affectivity percentage of vacuum pressure and field emission current on each others are still not investigated properly. In this study, Particle in Cell (PIC) method of plasma modeling (Verboncoeur, 2005) is used to simulate the current of field emission to determine the relation of field emission current and vacuum pressure. The simulation results are presented in three different modes, i.e., by using arc polishing method as presented by Frontzek and Konig, (1993) and Kunchur *et al.* (2013), simulation of field emission current and applying magnetic field and impulse current concurrently. The simulation results demonstrated the advantage of applying impulse current together with field emission current to determine the vacuum gas pressure inside the vacuum interrupter.

MATERIALS AND METHODS

Vacuum insulation

Field emission: Field Emission (FE) refers to the process of extracting electrons from the surface of a material under the influence of an externally applied electric field. In order to be emitted, electrons need to overcome a potential barrier given by the difference in height between the Fermi and vacuum levels, also known as work function of the material (Φ) (Hudson, 1998). In the absence of an electric field, the potential barrier has infinite width and its height is given by the work function (Φ). In this case for the emission of electrons to occur, electrons are required to jump over the top of the potential barrier. This mechanism is denominated thermionic emission and is the dominant mechanism for the emission of electrons from surfaces at high temperatures.

On the other hand, if a strong electric field is applied, the potential barrier is deformed (Schottky effect) so that it becomes finite in width. These conditions allow electrons to quantum mechanically tunnel through the distorted potential barrier instead of having to jump over it. This mechanism for the emission of electrons is denominated field emission (Hudson, 1998; Smith and Silva, 2008; Fowler and Nordheim, 1928; Castano, 2006; Tahmassebpour, 2017). The Field Emission (FE) mechanism was first explained by Fowler and Nordheim (1928), Castano (2006), Tahmassebpour (2017), Mori *et al.* (2005), Seyedhosseini *et al.* (2016) and Kunchur *et al.* (2015). It was established by Fowler and Nordheim that at low temperatures, the emission current of electrons from a material surface is a function of the work function (Φ) of the material, the applied Electric field (E) and a field enhancement factor (β) due to special geometric configurations of the emitting material. The general form of the Fowler-Nordheim (F-N) equation is to:

$$J_{FN} = (A_{FN}\ (\beta_{FN}E)^2 / \Phi_w) \times \exp\ (B_{FN}\upsilon\ (y)\Phi_w^{3/2} / \beta_{FN}E) \quad (1)$$

With:

$$A_{FN} = e^3 8\pi / h_p = 1.5415\times10^{-6}\ [\mathrm{AeVV^{-2}}] \quad (2)$$

And:

$$B_{FN} = -4/3((2m_e)^{1/2} / e(h_p / 2\pi)) = 6.8309\times10^9\ [\mathrm{eV^{-3/2}Vm^{-1}}] \quad (3)$$

In this equation, JFN is the emitted current density [mA/mm^2], E is the effective electric field acting over the emitting surface [V/m], βFN is a field enhancement factor, Φw corresponds to the characteristic work function of the emitting material [eV], e and me are the charge and mass of the electron respectively and hp is the Planck's constant. The other correction parameters can be found using the functional forms:

$$y = \frac{C_y E^{1/2}}{\Phi_w} \quad (4)$$

And:

$$\upsilon\ (y) = 1 - C_v Y^2 \quad (5)$$

where, C_y and C_v are correction factors discussed somewhere else.

Simulation of field emission current: According to Fowler-Nordheim equation, the current of field emission does not depend on vacuum pressure. It will ionize the atmosphere and creates plasmaconsisting of electrons, positive ions and neutral gas.

There are few software to simulate the plasma. In this study in order to investigate the effect of vacuum pressure on the field emission current, MAGIC Tool Suit software is used. MAGIC is electromagnetic Particle-in-Cell Finite-Difference, Time-Domain (EM PIC FDTD) software for simulating plasma physics processes, i.e., those processes that involve interactions

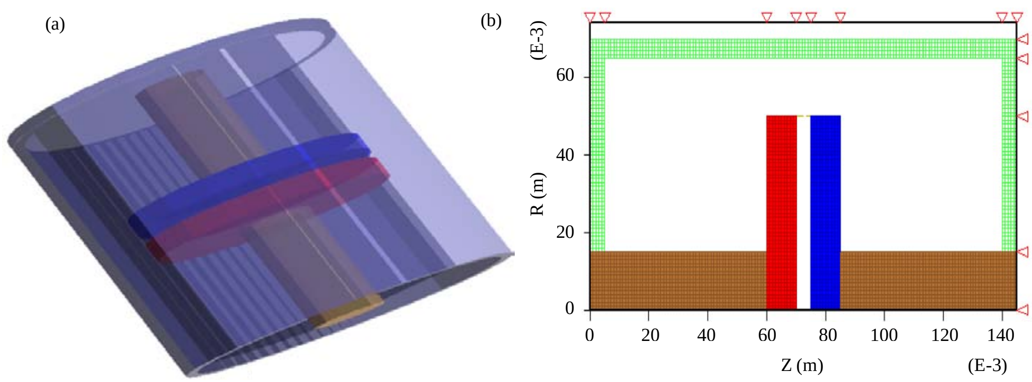

Fig. 1: Three-dimensional: a) and two-dimensional; b) Structure for the simulated vacuum interrupter

between space charge, electromagnetic fields and background gaseous media (Seyedhosseini *et al*., 2016; Kunchur *et al*., 2015, 2013; Rahmani *et al*., 2011). Beginning from a specified initial state, the MAGIC simulates a physical process as it evolves in time. The full set of Maxwell's time-dependent equations is solved to obtain electromagnetic fields. Similarly, the complete Lorentz force equation is solved to obtain relativistic particle trajectories and the continuity equation is solved to provide current and charge densities for Maxwell's equations. The other advantage of utilizing MAGIC is the code has been provided with powerful algorithms to represent structural geometries, material properties, incoming and outgoing waves, particle emission processes and ionization of background gaseous media. As a result, the code is widely applicable to broad classes of plasma physics problems.

A structure as shown in Fig. 1 is defined in MAGIC Tool Suit Software. In this structure, the contacts are considered as cobalt-copper contacts with the work function = 4.5 φ and the 0.5 cm distance from each other. Contactor's radial is defined as 5 cm. While the amplitude and frequency of the applied voltage are maintained as constant, the changing patterns in the current of field emission versus the changes in vacuum pressure will be obtained. The Fowler-Nordheim equation in MAGIC Software is simulated using emission high-field function. However, in order to study the effect of changes in the vacuum pressure of VCB on field emission current, another function called "Ionization" should be used. Using this function, the vacuum pressure inside the VCB can be adjusted to the desirable value. The current created from ionization of natural gas inside the vacuum interrupter can be driven using Ionization function. It should be noted that both the ionization and emission high-field functions will deliver the output current

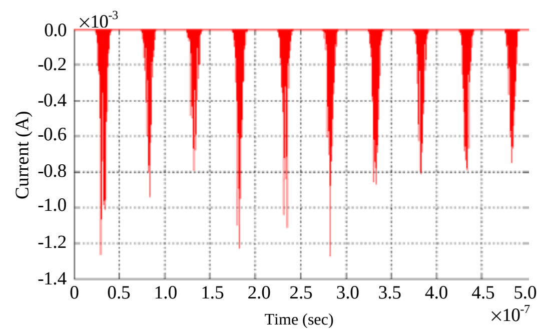

Fig. 2: Ionization current for the 1 Millitorr pressure

separately which means in order to drive the final current, all of the outputted current from these two functions should be added. Figure 2 shows the ionization current for the Millitorr 1 pressure.

The simulation of the field emission current is done between pressure ranges from 1 Millitorr to 10^{-4} Millitorr as the threshold pressure in the real vacuum interrupter is 10^{-1} Millitorr. Furthermore, the increase of pressure of more than this threshold leads to the loss of dielectric properties of the vacuum circuit breaker. The current changes for this pressure range are shown in this simulation. Based on Eq. 1, the field emission current is exponentially proportional to the applied electrical field and since in the real VCB, the electrical field is not uniformed, so in order to increase the similarity of the simulated model with the real vacuum circuit breaker, a coefficient factor called β is used.

Figure 3a shows the electrical field changing curve between the two contacts in the simulation software. As can be seen, the electrical field between the two contacts is uniformed in the software's output. However, in the real case, this electrical field is not uniformed. The non-uniformity of the electrical field in actual structure will be compensated using coefficient β.

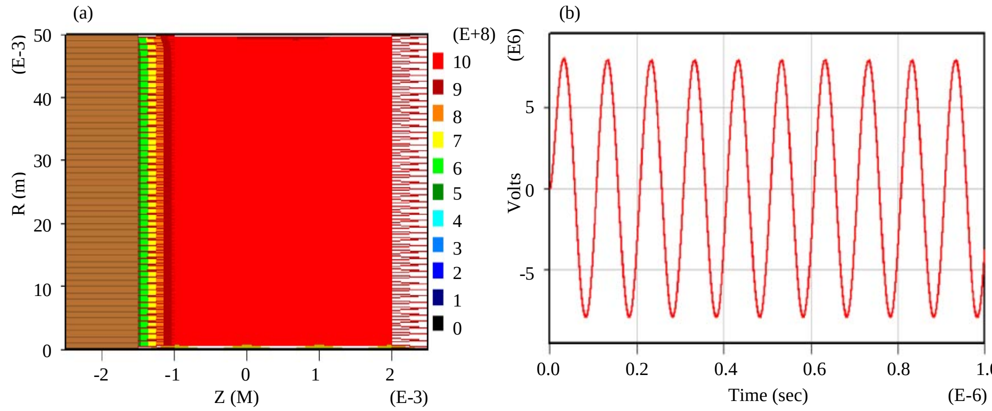

Fig. 3: a) Applied electrical field curve between the two contacts; b) The applied voltage curve

Since, the software doesn't have a factor like β, an amount of β will be applied to the amplitude of the applied voltage. To do so, 20 KV applied voltage between two contacts multiplied by the field enhancement coefficient (β = 225) and the applied voltage as shown in Fig. 3 is obtained. The time step for the simulation which is set by the software is 1.68 picoseconds. So, in order to analyze the result of the simulation for a few periods of sinusoidal wave and considering the independency of the field emission current with the frequency (Eq. 1), the frequency of the applied sinusoidal voltage has been selected as 10 MHz. Using the selected frequency, the simulation run time for each set pressure is varied between 115-190 min.

The current will be emitted from one of each contact during each half-cycle of the applied sinusoidal voltage due to the inter-changing of locations between the cathode and anode in each half-cycle. The simulation software has the capability of considering the emission current for both contacts. Therefore, the final measured current should be the sum of the measured currents in both cathode and anode. As mentioned before with the changing of vacuum pressure in the software and the use of Ionization, the current based on this function will be determined. The final field emission current is the sum of currents from ionization as well as from anode and cathode. The amount of this current for different pressures will be shown in the next section.

RESULTS AND DISCUSSION

The current of field emission is flown by applying voltage (Fig. 3) between two contacts and varies for different vacuum pressure. For instance, the field emission current for 1 and 10^{-4} Millitorr are shown in Fig. 4. Figure 5 shows the different field emission current for different vacuum pressure in a given curve. The maximum

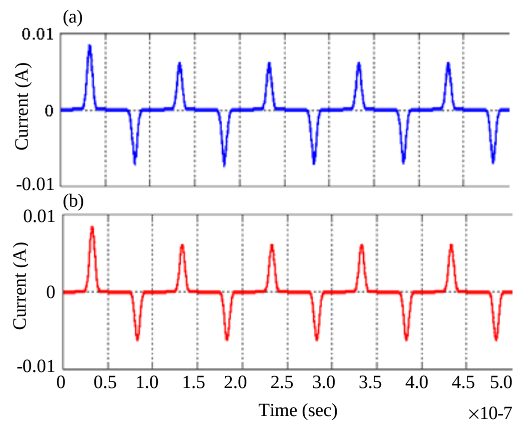

Fig. 4: The field emission current for the vacuum pressure: a) 1 Millitorr (blue); b) 10^{-4} Millitorr (red)

range of the field emission current for the mentioned vacuum pressure range is shown in Fig. 5. As can be observed in Fig. 5, the changing range for the field emission current for the given pressure range is not excessive and the current variation are unnoticeable.

It has been shown that the field emission current alone doesn't have a noticeable change for different vacuum pressure and as the aim is to propose a method to determine the vacuum pressure by measuring the field emission current, another method for measuring the vacuum pressure changes will be introduced in this study inspired (Frontzek and Konig, 1993). In this method, the field current emission will firstly be flown by applying the sinusoidal voltage. Then, after a few cycles of voltage, an impulse current will be applied between the contacts. Frontzek and Konig (1993) this impulse current is called as "Arc Polishing". The field emission current with the impulse current for 1 and 10^{-4} Millitorr is shown in Fig. 6. Different current for different vacuum pressure is presented in Fig. 7a. As can be seen, the maximum amplitude for the impulse current is proportional with the

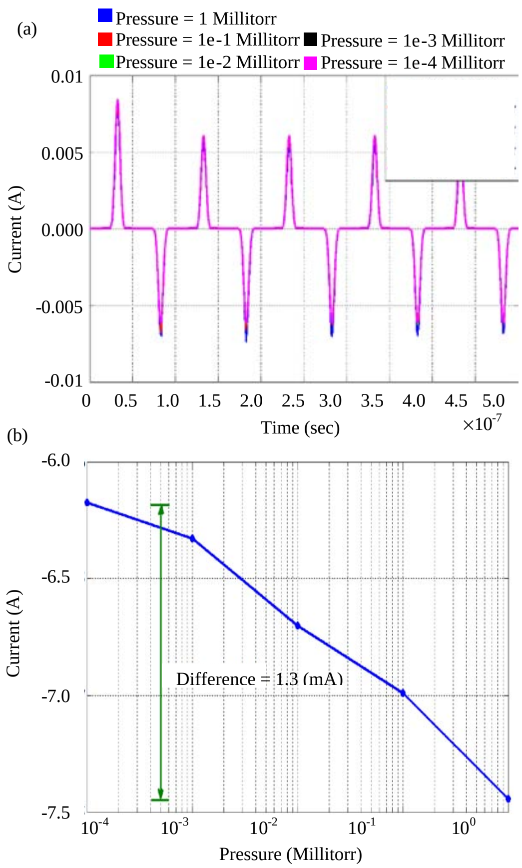

Fig. 5: a) Different current emissions for different vacuum pressures; b) The maximum amplitude of the field emission current for different vacuum pressures

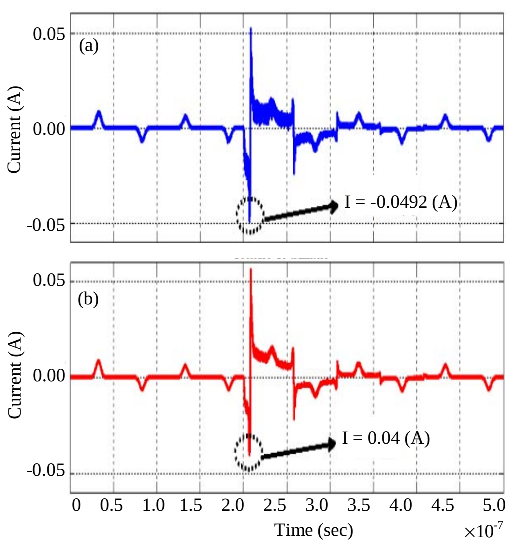

Fig. 6: The field emission plus impulse current for 1 Millitorr (blue) and 10^{-4} Millitorr (red)

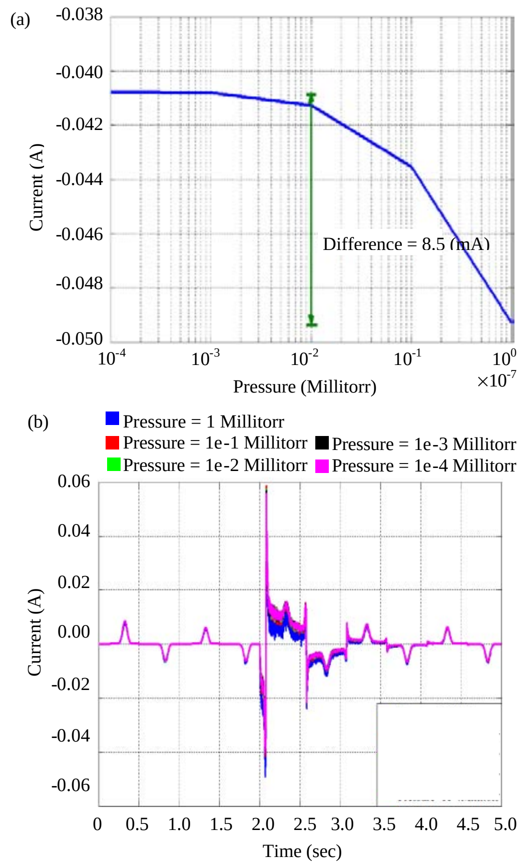

Fig. 7: a) Dfferent currents versus different pressure; b) Mximum amplitude for impulse current plus field emission current versus different vacuum pressure

vacuum pressure and the current's amplitude increases with the increase in vacuum pressure. Figure 7b shows the range of variation in the maximum amplitude for the impulse current plus the field emission current versus different vacuum pressure. By fitting a curve on Fig. 7b, the relation between the current and the pressure will be obtained as Eq. 6.

Figure 8 shows the applied voltage curve and measured field emission current. As can be seen, the current exists in each half-cycle of sinusoidal voltage due to the inter-changing of location between anode and cathode.

Comparing Fig. 5 and 7, it can be seen that the percentage of changes in the field emission current versus the changes in the vacuum pressure is higher when the impulse current is considered. This variation for field emission current is only 14.05% while the value increases to 17.91% when the impulse current is added with field emission current. This increase is the result of gas

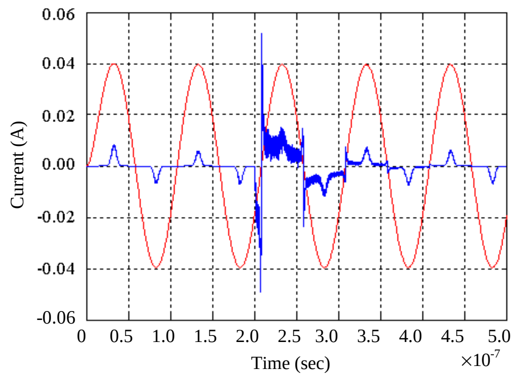

Fig. 8: The field emission current and applied voltage

Table 1: Driven coefficients for proposed pressure-current fitness function for different simulation methods

Method of simulation	a	b	c
Only field emission current	-0.001756	0.1419	-0.005714
Field emission and arc polishing current	-0.014360	0.7058	-0.040720

ionization in spaces between the two contacts when the impulse current is applied. The amount of this ionization highly depends on the vacuum pressure inside the vacuum chamber.

As can be seen, applying magnetic field yields the maximum variation of field emission current to be increased which consequently yields to a design of simpler circuits for any future field emission current measurement and therefore a better and cost effective detection of vacuum pressure level. Based on the exponential curve on each of the shown graphs in Fig. 8, the relationship between the pressure and the current would be as the following:

$$I = a \times P^{b} + c \tag{6}$$

In other words, by performing simulations presented in this study, the model of the relationship between the vacuum pressure and field emission current is obtained as Table 1.

CONCLUSION

Two different methods to measure and simulate field emission current wereproposed in this study. By analyzing the various current curves for each proposed method, it has been determined that the variation in the field current emission is highly correlated to the ionization current. Based on the presented results, it was shown that for various vacuum pressures, the percentage of changes in the field emission current for the second method of which arc polishing current was also applied was higher.

Therefore, field emission current measurement while the arc polishing current is appliedis easier and more accurate. This was due to the high dependency of ionization current to the pressure changes. This ionization current tends to be zero for very low pressures.

The simulation results proved that by designing a suitable measuring circuit to measure the field emission current due to concurrent application of sinusoidal voltage, impulse current and the vacuum pressure inside the vacuum interrupter can be determined.

Nomenclature

FE = Field Emission
FNE = Fowler-Nordheim Equation
PIC = Particle in Cell
VCB = Vacuum Circuit Breaker
VI = Vacuum Interrupter

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