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Simulation and analysis of surface discharge development in oil immersed paper insulation

***Abstract**. Surface discharge is a discharge phenomenon over a solid insulation in a gas or liquid insulation. However, the theory about discharges in liquid and multiple dielectrics is less comprehensive than that in gases. This paper proposes a theoretical and simulation analysis of surface discharges for rod-plane electrodes with oil immersed paper insulation under ac voltage. Based on liquid streamer theory and surface discharge process in gases, a hypothesis is presented first. In highly purified oil, the electron emission from local high electric field strength region is responsible for the surface discharge initiation. Also, the electric field distortion caused by gas bubbles is considered to stimulate a surface discharge evolution process. A flashover might occur along the oil immersed paper insulation when the gas bubbles bridge a channel between the electrodes. Then by establishing the physical model and employing software "COMSOL Multiphysics" as a numerical modeling tool, the electric field distribution can be computed and influencing factors can be analyzed. Simulation results show that the electric field strength concentration at the triple junction region of the high voltage electrode and the oil immersed paper insulation would result in the field emission of initial electrons. Also, in this insulation system, gas bubbles might be a dominant contributor to the development of surface discharges.*

***Streszczenie.** Analizowano powierzchniowe rozładowanie i ładowanie w atmosferze gazowej i ciekłej. W artykule zaproponowano nową uściśloną teorię zjawiska popartą symulacjami. Badana jest izolacja papierowa nasączona olejem. Uwzględniono zakłócenia pola elektrycznego powodowane pęcherzykami gazowymi. (**Symulacja i analiza teoretyczna wyładowania powierzchniowego w izolacji papierowej olejowej**)*

Keywords: surface discharge, oil immersed paper insulation, physical model, finite element analysis.
Słowa kluczowe: wyładowania powierzchniowe, izolacja papierowa olejowa.

Introduction

The reliability of any electrical apparatus is largely determined by the condition of its insulation. Therefore, as a major insulation method, the degradation of oil immersed paper insulation system can threaten the operation safety of high voltage equipment, for instance, power transformers. Among the failures of power transformers, partial discharges (PD) are primarily responsible for the accelerated degradation of the insulation system. However, it is hard to prevent those local defects in a transformer which might be generated occasionally during the manufacturing, transporting and operating processes. Common types of PDs involve needle-plane discharges caused by oil contaminated with metal particles, cavity discharges caused by cavities embedded in pressboards, and surface discharges on pressboards [1,2]. Currently, the investigations of PDs have been concentrated on the measurement, data processing and classification of PD signals [3-7]. However, there is less agreement on the physical mechanism of PDs in liquid dielectrics and multiple dielectric materials. The reasons responsible for this have two main aspects. On one hand, the nature of breakdown in dielectric liquids is still disputed, while electron avalanche ionization and streamer mechanisms were accepted in the course of a few decades to explain the breakdown in gases. On the other hand, existing studies were limited to the cavity discharge model [8-11]. Few investigations have been taken on the interpretation of physical mechanisms of surface discharges and needle-plane discharges in liquid and multiple dielectrics. Therefore, the main goal of this paper is to present a theoretical and simulation analysis of surface discharges in the oil immersed paper insulation.

In the theoretical analysis part of this paper, classical theories describing the surface discharge process in gases are reviewed first [12-17]. According to [12], the surface discharge evolution process in gases may be divided into three stages: the initiation stage, the development (or growth) stage, and the final stage. However, the interpretations of the surface discharge development process are varied from different environmental conditions [13-17]. In liquid dielectrics, this physical process becomes more complicated. Streamer theory in liquids has been developed recently [18, 20]. It indicates that many factors are to be considered other than those in gases, such as electrode geometry, physical properties of liquids, temperature, and hydrostatic pressure [18-21].

Based on the actual experimental model, a simulation study of surface discharges for rod-plane electrodes with oil immersed paper insulation is undertaken in this work; software "COMSOL Multiphysics" is employed as a numerical modeling tool. Then, the electric field distribution of this model is determined. Results show that the highest electric field strength occurs at the triple junction region of the high voltage electrode and the oil immersed paper insulation interface, which is almost three times the average stress value at the center of the pressboard. Therefore, electrons are more likely to be emitted from this area. In turn, surface discharges are initiated. By investigating the impact of electric field distortion by gas bubbles developing, simulation findings suggest that the existence of micro-bubbles and nano-bubbles can significantly enhance the maximum electric field strength. Also, the electric field strength is higher when the radius of the bubble is smaller. Therefore, gas bubbles might be a dominant contributor to the development of surface discharges in oil immersed paper insulation.

This paper has the following highlights:

In the theoretical part, the focus is on the surface discharge model of the rod-plane electrodes with oil immersed paper insulation. Also, a discussion about the discharge development process is presented based on the classical surface discharge theory and liquid streamer theory. Subsequently, a hypothetical explanation is proposed to describe the physical evolution process of this model. This explanation might not be complete but aims to provide a novel and reasonable vision on this subject according to the existed references.

In order to verify this hypothesis, a series of exploratory simulation work is described in this paper. A simplified simulation model is introduced. The FEM software "COMSOL Multiphysics" is employed to calculate the electric field distribution under a certain ac voltage. More importantly, the electric field distribution distortion by gas bubbles is also examined quantitatively. The examination indicates that the size and number of dissolved gas bubbles would reveal the severity of surface discharges in oil immersed paper insulation systems.

Theoretical analysis

Initiating electrons in liquids

While the theory of the gas discharge inception is well understood, the interpretation of the discharge initiation in liquid remains less clear. Two of the existing theories are generally accepted. The first one is based on the presence of gas bubbles. Since the permittivity of gas is much smaller than that of liquid, the regions inside the gas bubbles will have higher electric field strength values than those outside the bubbles [18, 19]. Electron emission at the bubble–liquid interface would serve as the primary source of electronic emission, followed by the Auger processes initiated by these primary electrons after traversing and gaining energy within bubbles. On the other hand, another hypothesis is analogous to gaseous breakdown. High field electron emission might occur in the local high electric field strength region due to the geometrical asymmetry of the insulation system [20, 21]. When it comes to the highly purified dielectric liquid, the second hypothesis is more reasonable. It will be illustrated in detail in Section 3.

Surface discharges in gases

There are three explanations described by the classical theories of the propagation of free electrodes [12]: 1) secondary electron emission avalanche (SEEA); 2) cascade propagation along the surface of the insulator; and 3) electrons elastically strike the insulation surface without an avalanche, shown in Figure 1, respectively. According to SEEA, accelerated initiating electrons impact the insulation surface under the applied electric stress. During this process, more and more electrons are produced and the collision process is enhanced. Finally, a surface flashover is triggered. As a result, the propagation of surface discharges strongly depends on the properties of the insulation material. Hence, a complete breakdown is not supposed to be accomplished instantly. It is always in the order of microseconds rather than nanoseconds.

Anderson and Brainard stressed the important influence of absorbed gas bubbles in the solid layer [13]. Considering SEEA, accelerated electrons bombard the solid insulation to release the gas which was absorbed by the solid layer. Under the electric stress, the released gases are expected to gather together in the form of polarized gas clouds, which would result in increasing electron emission from the triple junction region and thus leading to a complete breakdown. Cross emphasized that the induced field would accelerate the process of electron emission [14].

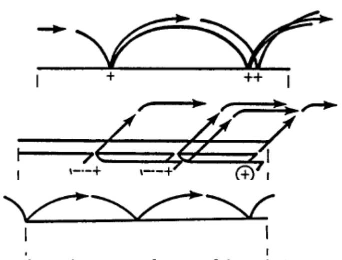

Fig. 1. Electron paths along surface of insulator according to gas discharge theories [12]

A different viewpoint was postulated by Avdienko and Malev. They suggested that the joule heat effect was a critical factor leading to surface discharges instead of SEEA [16]. They also argued that the joule heat under electric stress would lower the overall resistivity in terms of partial thermal breakdown（$\rho < 10^{12}$ ohm.cm） [17].

Discussion on surface discharges in oil immersed paper insulation

As discussed in the previous section, it is generally accepted that the SEEA and the release process of absorbed gases in solid insulation are the two main contributors leading to the development of surface discharge. However, considering the extension of these theories into the oil immersed paper insulation, two major difficulties are raised: on one hand, what is the composition of the absorbed gases in oil? On the other hand, as the oil density is much larger than that in gas (10^6 times or more), the scattering rates are high and the mean free paths are low. As a result, an avalanche might not be formed since the scattering energy is too low [18].

Three possible explanations of these problems are: 1) internal vaporization; 2) molecular decomposition; and 3) mechanical movements [20, 21].

Charge inception could contribute to localize Joule heating due to high electric field strength, subsequently leading to a partial vaporization. Besides, McCluskey and Kao argued that mechanical movements and cracks would accelerate formation of tiny bubbles, whose diameters might be in the order of micrometers, even nanometers [22, 23]. Hence, localized low density regions become formed. Conceptually, when those regions local density decreases, scattering rates would drop somewhat, leading to larger mean-free paths. As a result, free electrons would gain more energy under the electric stress. Furthermore, lower liquid densities would decrease the dielectric constant effectively by lowering the screening ability. As is known, those areas of lower permittivity tend to have higher electric field strength under the same electric stress. Accordingly, a positive dynamic feedback effect takes place.

Similar to the hypothesis in gases, Atrazhev proposed that a continuous heating process could cause the liquid temperature rise beyond the boiling temperature under a long duration impulse [24]. In such a metastable liquid, the explosive boiling process of liquid evaporation would be critical to the breakdown in liquids. However, the thermal process of joule heating strongly depends on the impulse duration. When considering the significance of all the influencing factors, the impulse duration may be neither too long nor too short. If the impulse is too long, direct thermal breakdown might occur. If it is too short, on the contrary, the thermal effect might be too weak to cause liquid evaporation [24, 25].

Therefore, a hypothesis is proposed. In highly purified oil, electron emission from local high electric field region initiates surface discharges. Then, micro-bubbles may be formed by one of the following ways: 1) respiration of liquid dielectrics, especially transformer oil in the open type transformer; 2) liquid molecular evaporation by overheating in local high electric field strength region; 3) chemical bond breakage by mechanical stress and thermal effect resulted from partial discharges. Then, the electric field distortion caused by these gas bubbles becomes the major factor leading to a surface discharge evolution process. A flashover would occur along the oil immersed paper insulation when the gas bubbles bridge a channel between the electrodes.

Modelling and FEM Analysis on Surface Discharge in Oil Immersed Paper Insulation

Mineral oil

Since the mineral oil has good properties of arc extinction, thermal transmission and oxidation stability, it has been widely used as an insulating material in power transformers. Therefore, it is also referred to as transformer oil. The major components of transformer oil are alkane, naphthene, and arene [26].

Worthy of mentioning, moisture and dissolved gas content are the key factors indicating the aging condition and insulating performance. The test specimen used for the modeling and experiments described in this paper is purified transformer oil without water, dust or other impurities. However, air is unavoidable in transformer oil in service. Therefore, after the analysis on the mechanism of surface discharges in pure oil, this paper will discuss the impact of micro-bubbles on the development of surface discharges in oil.

Insulating pressboard

Electrical insulation papers are paper types that are used as electrical insulation in many applications due to pure cellulose having outstanding electrical properties [27]. The transformer pressboard is a type of electrical insulation paper, whose major components are cellulose, hemicellulose and lignin. Cellulose is a good insulator and is also polar, having a dielectric constant about 6.5. In transformer oil immersed paper insulation, the permittivity of insulating paper depends on the oil absorbency. Besides, permittivity is closely related to temperature, humidity and frequency of applied voltage. The specimen of this study is well oil immersed Kraft paper under 50 Hz, 60 deg C, having a relative permittivity 3.0 and conductivity about 10^{-14} S•m-1.

Surface discharge defect model

The typical defect model is designed in the laboratory according to the model of CIGRE Method II [28-30], shown in Figure 2. The electrodes were 20 mm (diameter) × 45 mm (thickness), and 60 mm (diameter) × 10 mm (thickness) copper plates, which ensure good conductivity. A piece of 80 mm (diameter) × 1 mm (thickness) Kraft pressboard was placed between the electrodes. Furthermore, the insulation pressboards should be fully dried and polished smoothly before oil impregnation. The oil index satisfied the IEC 296-82 and ASTM D 3487-1993 standards.

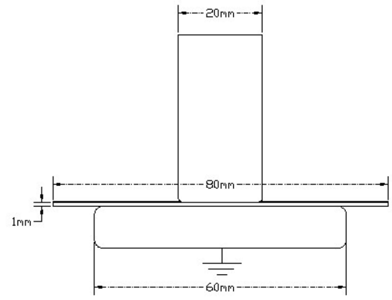

Fig. 2. Simulation model of surface discharge in oil-paper insulation

Electric field analysis using FEM software

When modeling actual devices, there is not only an intrinsic time scale of charge relaxation time but also an external time scale at which a device is energized. The observation time is also important. It is the relationship between the external time scale and the charge relaxation time that determines what physics interface and study type to use. The charge relaxation time is shown in equation (1).

$$\tau = \frac{\varepsilon}{\sigma} \tag{1}$$

Where ε is the permittivity of dielectric, σ is the relative conductivity, and τ is the relaxation time constant. By calculation, the magnitude of τ is in the order of 10^{12}~10^{14} s. When the frequency of applied voltage is 50 Hz, the external time scale is short compared to the charge relaxation time, the charges will not have time to redistribute to any significant degree. Thus the charge distribution can be considered as an electrostatic formulation.

Under static conditions, the electric field is conservative. Equations (2) and equation (3) describe the electrostatic field in dielectric materials.

$$\nabla \times E = 0 \tag{2}$$

$$\nabla \cdot D = \rho \tag{3}$$

Where E represents the electric field strength; D is the electric displacement; and ρ is the space charge density.

By combining the definition of the potential with Gauss' law, Poisson's equation can be derived, shown in equation (4).

$$\nabla^2 \varphi = -\rho / \varepsilon \tag{4}$$

In this equation, φ represents the potential. When there is no space charge distribution, Laplace's equation is deduced in equation (5).

$$\nabla^2 \varphi = 0 \tag{5}$$

The electrical energy function is shown by equation (6)：

$$W_e = \int_V (\int_0^T E \cdot \frac{\partial D}{\partial t} dt) dV \tag{6}$$

Since Poisson's equation is a secondary nonlinear differential equation, the second order solution interval should be necessarily continuous. Under the influence of boundary conditions and meshing, the coefficient matrix created might be ill-conditioned due to the discontinuity at several singularities. Then, the convergence rate might be low, and even misconvergence may occur. Therefore, by functional theorem, the problem due to differential equations could be converted to solve the extreme values of equivalent integral equations. Besides, using the integration by parts method, the order of continuity could be lowered to first order. The convergence rate is highly improved. Furthermore, weak form modeling is employed as a part of the solution technique.

Software "COMSOL Multiphysics" is employed as a numerical modeling tool. The boundary condition of this model is shown in equation (7).

$$\begin{aligned} n_2 \times (E_1 - E_2) &= 0 \\ n_2 \cdot (D_1 - D_2) &= \rho_s \end{aligned} \tag{7}$$

Where n_2 is the outward normal from medium 2; E_1, D_1, E_2, and D_2 are the electric field strength and electric flux density of medium 1 and 2, respectively; and ρ_s is the space charge density.

Simulation result and discussion

Electric field distribution under AC voltage

As there was no uniform function to estimate the initial surface discharge, most of the inception voltage data were obtained by experiments. The surface inception voltages are given in the interval of 13-18 kV [8, 31]. A 50 Hz, 18 kV ac sinusoidal voltage was applied at the high voltage electrode, while the lower electrode was grounded. Figure 3 shows the equipotential lines of this surface discharge model. Since the configuration of this model is symmetrical, only half of the physical model is shown in this figure.

In Figure 3, it can be observed that the most intense electric field appears in the triple junction region of the high voltage electrode and the oil immersed paper insulation interface. Furthermore, a specific calculation was performed in this region, shown in Figure 4. Along the insulation pressboard, the electric stresses are distributed symmetrically. The maximum electric field strength on this pressboard is depicted in Figure 5, when the phase is 90 deg. In the central part of the pressboard embedded in electrodes, the electric field stress can be considered uniform. However, the triple junction region has the highest electric field strength up to 24 kV/mm, almost three times that at the center of the pressboard. As a result, it is more likely to emit electrons in this triple junction region. This result shows good consistency with that of experiments given by [32].

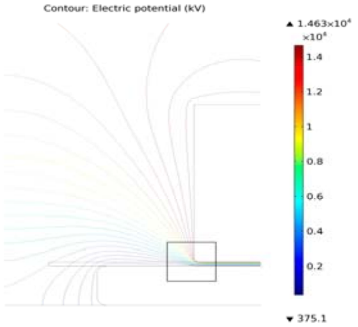

Fig. 3. Equipotential lines of the surface discharge model (at the phase of 90 deg)

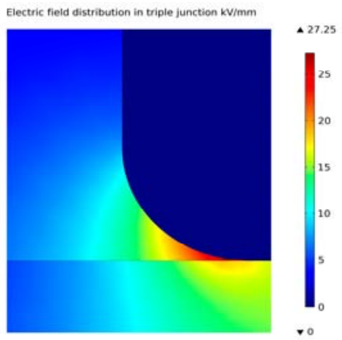

Fig. 4. Electric field distribution in triple junction region

Besides, when the condition is ideal, the maximal electric field strength, E_{max}, of this model is linear with the external voltage $V_{applied}$, plotted in Figure 6.

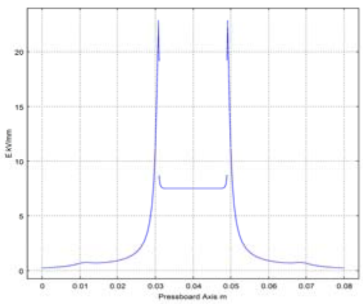

Fig. 5. Electric stress distribution along the insulation pressboard

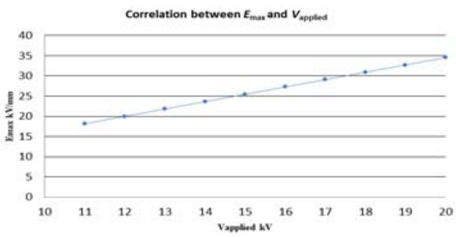

Fig. 6. Correlation between Emax and Vapplied

As discussed in Section 2, due to the lack of a comprehensive liquid state theory, very few publications describe the process of molecular ionization in dielectric liquids [33]. Generally, the electric field dependent molecular ionization and the electric field enhanced ionic dissociation are the two basic forms leading to avalanches. However, the positive ions and negative ions caused by ionic dissociation are both immobile. Then, it is more reasonable to interpret the avalanche formation process as molecular ionization, which could produce free electrons with high mobility. The models that do exist in the literature are based on Zener's theory of electron tunneling in solids [34], shown in equation (8):

$$G_I(|\vec{E}|) = \frac{e^2 n_0 a |\vec{E}|}{h} \exp\left(-\frac{\pi^2 m^* a \Delta^2}{e h^2 |\vec{E}|}\right) \qquad (8)$$

Where G_I is the complete molecular ionization charge density rate; a is the electronic charge; is the molecular separation; $|\vec{E}|$ is the magnitude of the electric field strength vector; h is Planck's constant; m^* is the effective electron mass in the liquid; n_0 is the number density of ionizable species; and Δ is the molecular ionization energy.

Since these constants of the transformer oil are seldom defined, it is still difficult to estimate value of emitted electrons by certain high electric field strength precisely.

Influence of micro-bubbles on the electric field distribution

As discussed in Section 2, the existence of micro-bubbles have a significant influence on the development of surface discharges, even flashovers, no matter whether they are in liquid or solid dielectrics.

The origin of micro-bubbles has three possible explanations: 1) respiration of liquid dielectrics, especially transformer oil in the open type transformer. The major component is air; 2) liquid molecular evaporation by overheating in local high electric field strength region; and 3) chemical bond breakage by mechanical stress and thermal effect resulted from partial discharges. The major components are methane, ethane, ethylene and acetylene.

Figure 7 presents the electric field distortion caused by micro-air bubbles. Because of the conservation of electric flux and lower permittivity of air, the electric field strength is higher in the bubble than that in the surrounding transformer oil. The maximum electric field strength area exists in the inner surface of bubbles. The magnitude is up to 36.95 kV/mm, which is much higher than 3 kV/mm, the critical breakdown value of air. Therefore, the high electric field strength would lead to self-sustained discharge in the bubbles. Free electrons are released during this process and accelerated to impact the liquid molecular nearby. Besides, to determine the impact of the micro-bubbles, it is necessary to examine the influence of the radii of bubbles. Results indicate that the maximum electric field strength is higher while the bubble is smaller, depicted in Figure 8.

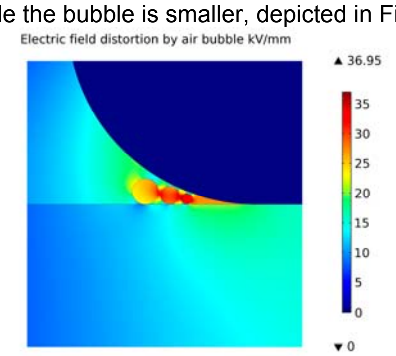

Fig. 7. Electric field distortion by air bubbles

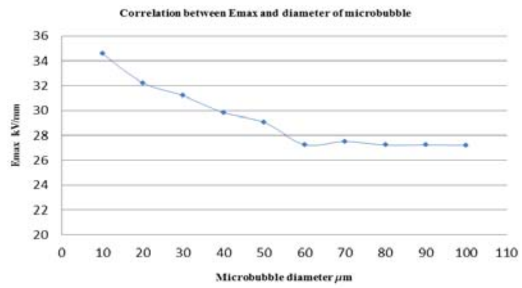

Fig. 8. Correlation between Emax and diameters of microbubbles

Other influential factors

1) Hydrostatic pressure

It is illustrated in Section 4.2 that the existence of air bubbles would result in significant distortion of electric field strength distribution. Analogous to Paschen's law in air, the hydrostatic pressure has a similar effect on breakdown voltage in liquids. When the hydrostatic pressure grows, the radius of the bubble is limited. As discussed in the last section, breakdown is more likely to occur as the endured field increases. However, when the hydrostatic pressure increases to a critical value, scattering rates are high and the mean-free paths are low. Hence, the scattering energies are not enough to create an avalanche. It is validated in [35].

2) Impurities

In actual operation cases, solid impurities might exist in transformer oil, such as iron filings and wood ashes. Furthermore, these dispersive impurities might accumulate to form a bridge which provides the discharge channel. As the applied voltage grows, a surface flashover might be triggered.

3) Other factors

During the streamer propagation process, it has been suggested that net space charge might be formed due to asymmetry in the generated carriers' mobility [33]. The distortion of electric field by a space discharge can be calculated using equation (9):

$$E_m = E_{applied} - \sum_{1}^{m} E_{induced}^{i} \qquad (9)$$

Where $E_{induced}^{i}$ represents the induction field strength by the i*th* net space discharge; $E_{applied}$ is the external applied electric field strength; and E_m is the electric field strength of the outer margin by the mth net space discharge.

In addition, the temperature rise would not only change the electrical properties but accelerate the formation of micro bubbles. Protrusion in the pressboard would also cause localized field concentration.

Conclusions

The classical theory about surface discharges in gases and liquid streamer mechanism has been revisited. Since the physical mechanism of surface discharges in liquid and multiple dielectrics remains not completely known, this paper presents a theoretical and simulation analysis of surface discharges in the oil immersed paper insulation based on the theory of surface discharges in gases and liquid streamers. Several conclusions can be drawn as follows:

- A hypothesis about the physical evolution process of the surface discharges in the oil immersed paper insulation is presented after a theoretical discussion.
- A simplified simulation model has been introduced and the electric field distribution under a certain ac voltage has been determined: in highly purified transformer oil, initial electrons would be emitted in the triple junction region at the high voltage electrode and the oil immersed paper insulation interface, which has the highest electric field strength due to the geometrical features of the region;
- The electric field distortion by gas bubbles has also been examined quantitatively: analogous to the mechanism in gases, micro-bubbles even nano-bubbles can significantly enhance the maximum electric field strength, which might be the major factor leading to the discharge process. The maximum electric field strength of the simulation model configuration has an increasing tendency as the bubble size decreases;
- Simulation results show good consistency with the proposed hypothesis and some experimental results reported in papers.

Acknowledgment.

Project No.CDJXS12150002 is supported by the Fundamental Research Funds for the Central Universities. This work is also supported by the Funds for Innovative Research Groups of China (51021005). The authors sincerely express their thanks and regards to Prof. Emeritus Stephen A. Sebo and Professor Donald G. Kasten of The Ohio State University. Their suggestions and comments are invaluable on this work.

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