Validation of a High-Voltage Relay Modified for Deep-Sea Applications Using COMSOL Multiphysics®

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Abstract

This paper validates a high-voltage relay modified to suit the extreme deep-sea conditions using the COMSOL Multi-Physics® simulation method. For this purpose, a numerical simulation model is developed to carry out qualitative considerations with respect to optimizations. Initially, a three-dimensional geometrical CAD model of the high-voltage relay is created using the software *Inventor Professional Version 2021*. Later, the created CAD model is imported into the *COMSOL Multiphysics® 5.5* software to develop a numerical model which is simulated using the modules of AC/DC, electrostatic and stationary case. The model is developed by capturing the geometry and material properties of the high-voltage relay. Subsequently, the developed numerical model is simulated under three different operating environments: silicone oil, pure water and sea water. The pertinent field enhancements at the crucial locations are studied. Furthermore, specific points of interest are defined to identify and show the electric displacement field enhancements in critical areas of the relay. Once this is identified, the chosen relay is compared with the experimental findings to validate the design modification.

1. Introduction

High-voltage relays currently used for deep-sea applications must be designed for extreme underwater conditions. The materials used for development and the design procedures adopted to neutralize pressure conditions, corrosion problems and the other intricacies are novel, innovative, but expensive. Alternatively, the existing high-voltage electric switches, relays and pertinent components developed for outdoor applications can be suitably modified to meet high-voltage and high-pressure requirements for deep-sea applications [1]. Such an attempt would emerge as a reliable and cost-effective solution. In any case, a detailed investigation on understanding the electric displacement field distribution, localized field enhancements and other relevant design parameters are essential.

The crucial parameters that define the efficiency, lifetime and reliability of such modified components in an extremely challenging environment must be identified prior to their deep-sea commissioning [2]. A suitable way to achieve this is to perform a simulation study on such modified components to identify and /or estimate the expected numerical values, i.e. electric displacement field, of those crucial parameters that define their operating condition and reliability. In this regard, a generic 5 kV high-voltage relay that is commonly used for outdoor switching in air is selected and immersed in insulating liquid to increase its operating voltage from 5 kV to 20 kV respectively [1]. Subsequently, a numerical model of the chosen high-voltage relay, is simulated using COMSOL Multi-Physics® software.

2. Background

The purpose of using high-voltage relays in underwater or deep-sea applications is to establish and interrupt an electrical connection with minimum manual intervention. Naturally, the high-voltage relays are forming an integral part of an electrical system in onshore and offshore application. The relays contain two terminals or contacts that literally establish or interrupt the electrical connection. These contacts are adequately designed to operate under normal operating voltage (5 kV AC) and load currents and equipped to withstand the adverse transient conditions initiated by natural and/or switching phenomena. It is needless to mention that their usage in outdoor application with air as a medium is well established, however, extending the same for underwater or deep-sea applications requires additional care and attention. This implies encapsulating the relay assembly to withstand the higher water pressure and filling the same with incompressible liquid to handle mechanical loads. In case, if the liquid filled is an insulator, then there exists a possibility to increase the operating voltage of the relay. In this context, an experimental study of a high-voltage relay has already been investigated and the crucial points, which decides the operating condition and reliability has been identified. As a next step, a simulation study that validates the design modification made to adopt the chosen high-voltage relay is initiated, which forms the subject matter of this paper.

During underwater or deep-sea application, in addition to the normal load voltage and current, the high-voltage relays must have the potential to withstand transient power signals, fault currents and switching surges, respectively [3]. So, obviously breaking an electrical connection under a transient condition would require higher electrical power involving larger surge voltage and surge currents. During its operation, one of the terminal / contacts of the high-voltage relay is usually at higher potential, while the other may be at the same level or at ground. The former case may not pose a serious issue while the latter might be, as the potential between the switching terminals are larger causing field enhancements. The presence of water or another insulating medium may produce a space-charge distribution at the high-voltage terminals thereby helping to evade higher electric fields.

Nevertheless, the transient switching conditions introduce momentary or persisting field enhancements causing surge voltage and / or currents to flow which eventually causes malfunction, unexpected circuit interruption and / or premature failure. In addition, the application AC field and its dynamic change in the magnitude and polarity causes the charge to replenish every cycle causing more adverse conditions. So, if proper care is not exercised, there is an easy chance for electrical discharges and / or arcing to occur at the weak points resulting in premature failure. In this regard, the chosen high-voltage relay is subjected to slightly modification to suit its deep-sea application. The modification implies providing a better insulating medium at the relay terminals. Following this, performing electrostatic field studies might help in understanding the actual situation and initiate preventive measures and design improvements.

3. Procedure

The high-voltage relay chosen for simulation purposes is designed and optimized to operate under 5 kV AC in outdoor conditions (air as surrounding medium). Further increase in operating voltage would result in malfunction of the switch and in some cases a premature failure. The reasons for premature failure are attributed to the field enhancements at the switching terminals / contacts causing spurious discharges and sometimes arcing. In some cases, the field coils may be damaged due to overheating. A possible way to avoid this is by immersing the chosen relay in an insulating medium that would apparently enhance its breakdown strength and reduce spurious discharges. In this context, an experimental study on a low-power high-voltage relay has already been investigated [1].

In this study, it was identified through experiments that the switching terminals or contacts and its structural asymmetries limit further increase of its operating voltage. Simple modification made by immersing the high-voltage relay resulted in further increase of the operating voltage from 5 kV to 20 kV [1]. The reason is attributed to the reduction of electric filed enhancements at the switching terminals of the relay thereby enabling the possibilities of increasing the operating voltage. Following this, a FEM-based simulation study is initiated to validate the experimental findings reported in [1] and to identify if discharge locations are predefined or appear randomly. In this process, first, the geometrical parameters and the medium in which the relay will be operated is identified. Next, these parameters are captured and developed into a 3D model using a CAD software. It can be assumed that the actual problem arises at the switching terminals and not in the field coil or housing body. So, the numerical model is further simplified, and the switching terminals are focused and simulated. Subsequently, the developed CAD model is imported into *COMSOL Multi-Physics simulation software* and simulated using the electrostatic module. The medium under which the numerical model representing the switching terminals are set to silicone oil. In addition to this, being an underwater application, the response of the switching terminals under pure water and sea water medium is also investigated.

4. High-Voltage Relay Switch

A standard 5 kV high-voltage relay switch is selected for validating the experimental findings reported in [1]. Figure 1a and 1b show the picture and its 3D CAD model representation of the high-voltage relay chosen for this study. The chosen high-voltage relay (RL-42, rated 5 kV AC) is an electromechanical type, popularly used for switchboard manufacturing. The chosen high-voltage relay is low cost, robust and practically applied in electrical systems and switchboard manufacturing. Further it incorporates widely proven technology and offers a virtually unlimited service life. The basic body of the relay switch is made of PBT GF 30, designed with maximum switching volt-ampere of 5 kVA of ohmic load and can be used for AC and DC applications. The relay is placed in a container and simulated under silicone oil, pure and sea water medium.

(a) (b)

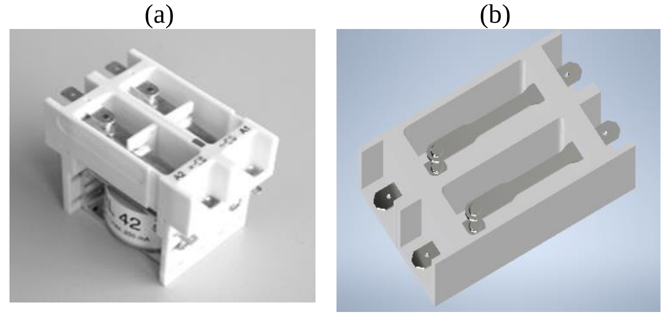

Figure 1. Picture of high-voltage relay involved in the present simulation study (a) Actual (b) 3D representation.

4.1 Numerical Simulation Model

The relay body consists of *Polybutylene Terephthalate* and *Glass Fiber Filler* while the switching terminals are made of *Copper*. The relay is immersed and operated in silicone oil to mitigate field enhancements and spurious discharges. Table 1 shows crucial parameters for materials included in the simulation that emulates real-time conditions. As an initial step, the geometrical and material details and their properties of the chosen / modified high-voltage relay is noted down. Subsequently, the CAD software (Inventor Professional / Version 2021) is used to capture and reproduce the structure and geometry of the chosen high-voltage relay.

Table 1 Parameters used during simulation of numerical model representing the switching terminals of high-voltage relay [4-6]

Material	Parameters used for simulation
	Relative permittivity (ε_r)
	–
Silicone oil	1.403
Pure water	80
Sea water	70

During the development of numerical simulation model, in addition to the geometrical and materials details, the data and inferences obtained from literature [1] are incorporated.

This implies, the properties of the materials used, crucial locations of field enhancements and the medium in which the relay would be operating, are incorporated in the model. It becomes clear from literature [1] and table 1 that the relay is equipped with better materials for housing the field coils and switching terminals. However, the switching terminals are optimized for operation under ambient air and designed to handle up to 5 kV, 10 A respectively. Obviously, it is natural that the intricacies would arise from the switching terminals. The same has been experimentally identified and reported in [1]. Considering this, the switching terminals and the crucial locations from where the electric field enhancements may occur are identified and included. Figure 2a shows the crucial locations in the chosen high-voltage relay and figure 2b shows its equivalent 3D-model representation. Once the necessary precautions are exercised, the CAD model is imported into *COMSOL Multi-Physics® 5.5* and subjected to FEM based electrostatic simulation.

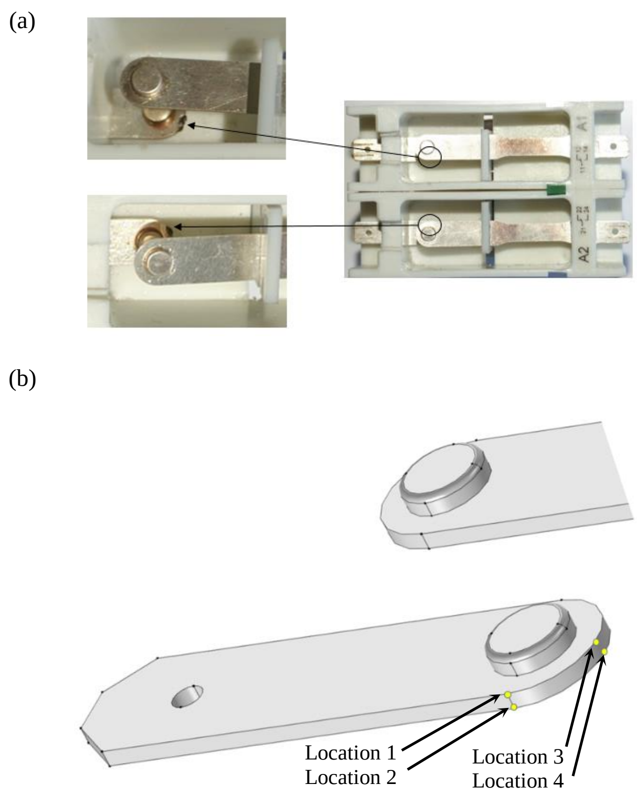

Figure 2. Pictorial description of the chosen relay (rated 5 kV) and crucial locations of field enhancements identified from literature [1] (a) Locations 1 to 4 identified (b) Equivalent 3D model developed using *Inventor* software.

4.2 Using COMSOL Multi-Physics Simulation

The simulation model approach is adopted as the material properties, field enhancements etc., are assumed to be linear. Such an assumption is valid as the field is expected to be time invariant or stationary. So, naturally, the governing equations are solved by selecting the stationary case. The magnitude of simulation voltage is set from 5 kV to 20 kV in discrete steps (i.e., 5 kV, 8 kV, 10 kV, 15 kV, 20 kV) and the electric displacement field, or simply identified as **D**, is observed. Hence, in case of any field enhancements, the respective flux density would be larger and would increase with respect to the simulated voltage. Furthermore, the different calculating points are defined according to figure 2 to show the electric displacement field conditions in critical areas using point evaluation. For this reason, a numerical simulation model is prepared to be able to carry out qualitative considerations with respect to optimizations. In this context, finite element method (FEM) based numerical electric field simulation have been initiated.

4. Simulation Results

The numerical model representing the switching terminals of the chosen high-voltage relay is simulated under silicone oil, pure water, and sea water, respectively. In all, the silicone oil and pure water are insulators with high dielectric constants and breakdown strength while the sea water has free ions that makes it conductive. The usage of silicone oil is to understand the maximum voltage until which the relay can be operated. At the same time, the simulation under pure and sea water is to emulate underwater conditions in which the relays may be operated. At first, the crucial locations that disturb the field distribution and causes localized electric field enhancement, is identified. Figure 2b shows the 3D numerical model of the switching terminals, indicating possible locations of field enhancements. Figure 3 shows the electric displacement field simulated using the numerical model of the switching relay. It becomes clear from the figure 3 that the switching terminals has two spots of field enhancement which matched with the findings reported in [1]. These spots are ear-marked as '*location 1*' to '*location 4*' and further monitored. Pertinent results are in consonance with expectation and match with the findings reported in [1]. Following this, the potential of silicone oil and usage of pure water for mitigating the field enhancements are investigated.

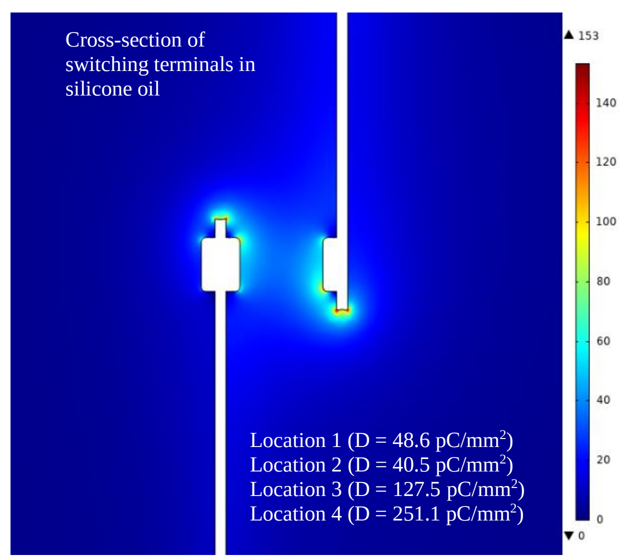

Figure 3. Electric displacement field (norm) simulated from the numerical model representing the switching terminals of the relay.

Figure 4 shows the electric displacement field (norm) at the switching terminals of the high-voltage relay simulated at 20 kV, in different mediums. Figure 4a shows the typical dimension of the switching terminals simulated under silicone oil, where further application of voltage induced stronger electric field intensity at the crucial locations. Nevertheless, the presence of silicone oil (figure 4b) as a medium have mitigated these effects thereby providing an opportunity to increase the operating voltage from 5 to 20 kV. The same can be verified by observing the electric displacement field (shown in figure 4b) at the crucial locations marked as 'location 1' to 'location 4' respectively in tables 2 and 3. At the same time, using pure water as an operating medium, although being a good insulator (relative permittivity (ε_r) = 80), emerged with interesting results. Theoretically, the pure water doesn't have free ions that aids the conductivity. Also, the dielectric strength of water is around 70 kV/cm which is higher than it is in air. Nevertheless, the applied electric field is quite stronger which in turn produces a strong electric displacement field.

Pure water may be used as a dielectric provided its level of purity is maintained at all times [6]. Even pure water has ions since the H2O dissociates into H+ and OH- ions making it a weak electrolyte. The ratio of concentration of H+ in H2O is given as 2.8x10-9 (at 37 deg C) [6]. Hence, it doesn't take larger fields to accelerate protons to dissociate OH- ions thereby rendering it conductive [6]. So, thereby maintaining its level purity by de-ionizers, the dielectric constant and its breakdown strength can be maintained close to 65 kV/mm to 70 kV/mm [6]. Nevertheless, it is not an economical solution as such de-ionizers and other pumping mechanisms are expensive. Considering sea water which is still higher in conductivity reduces the breakdown strength to an extremely low value.

Figure 4c and 4d shows the respective electric displacement field (norm) of the switching terminals simulated under pure water and sea water mediums respectively. At first glance, it appears from these figures that a stronger electric displacement field may be expected between the switching terminals. The reason might be due to the random movement of water molecules which doesn't allow the after-effects of polarization. The application of electric field would cause a mild dissociation of H^+ and OH^- resulting in smaller degree of conduction. The pure water induced stronger electric fields at the crucial locations ('*location 1*' to '*location 4*') respectively. Such stronger electric fields would induce discharges causing malfunctions and premature failures. On the contrary, operating the relay in sea water emerged slightly better. The apparent electric displacement field seems to be slightly reduced due to the ionic conductivity. At the same time, it is important to mention here that the present simulation study involves static electric field and not in relation to the critical breakdown strength. Tables 2 and 3 show the numerical values of the electric displacement field that would help to identify and quantify the actual intensity of fields at these locations. It becomes clear from tables 2 and 3 that the silicone oil has mitigated the adverse effects of field enhancement at the crucial location of switching terminals. The relative intensity of the electric field remains reduced which might help evading spurious discharges and arcing phenomena.

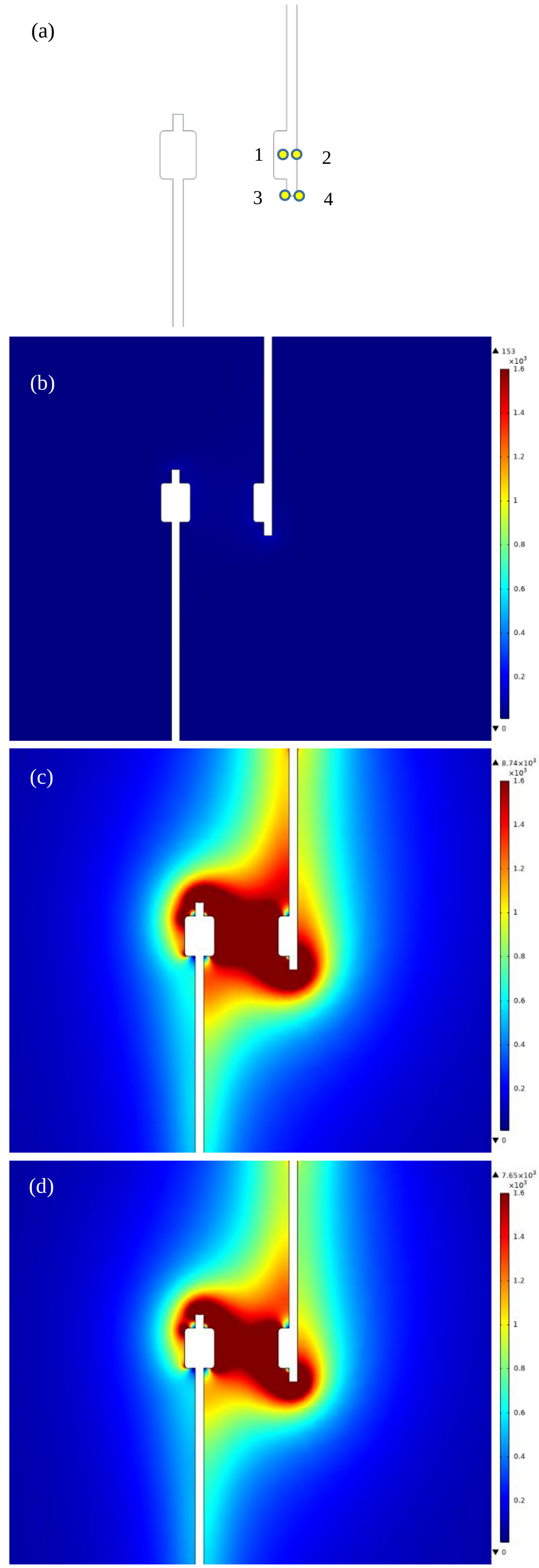

Figure 4. Simulation of electric displacement field (norm) [pC / mm²] at the switching terminals in different medium (a) Crucial location (b) Silicone oil at 20 kV (c) Pure water at 20 kV (d) Sea water at 20 kV.

Table 2 Electric displacement field at the crucial points 1 and 2

Medium	Simulation Voltage	Electric Displacement Field (norm)	
		Crucial point 1	Crucial point 2
	kV	pC/mm²	pC/mm²
Silicone oil	5	12.2	10.1
	8	19.5	16.2
	10	24.3	20.2
	15	36.5	30.4
	20	48.6	40.5
Pure water	5	693.2	577.1
	8	1109.1	923.3
	10	1386.4	1154.2
	15	2079.7	1731.3
	20	2772.9	2308.4
Sea water	5	606.57	504.95
	8	970.5	807.93
	10	1213.1	1009.9
	15	1819.7	1514.9
	20	2426.3	2019.8

Table 3 Electric displacement field at the crucial points 3 and 4

Medium	Simulation Voltage	Electric Displacement Field (norm)	
		Crucial point 3	Crucial point 4
	kV	pC/mm²	pC/mm²
Silicone oil	5	31.9	62.8
	8	51	100.4
	10	63.7	125.5
	15	95.6	188.3
	20	127.5	251.1
Pure water	5	1817.3	3578.8
	8	2907.7	5726.1
	10	3634.6	7157.6
	15	5451.9	10736
	20	7269.2	14315
Sea water	5	1590.1	3131.4
	8	2544.2	5010.3
	10	3180.3	6262.9
	15	4770.4	9394.3
	20	6360.5	12526

5. Inferences

The inferences gathered from this simulation study are given below:

1. It appears from this simulation study that the geometry of the switching terminals of the chosen relay has significant impact on the operating voltage.
2. Immersion of the relay in silicone oil has enabled further increase of the operating voltage from 5 kV to 20 kV (table 2 and 3). Nevertheless, the crucial locations at which the spurious discharges may occur remained the same indicating the requirements of physical modification to its structure.
3. Further operation of relay underwater may not be feasible, as the field enhancements at the crucial locations are larger. Considering pure water, despite better dielectric constant and breakdown strength, the loosely packed water molecules and their random movements may pose a problem.

Thus, it appears from this simulation study that the low-power high-voltage relays can be used for deep-sea applications with considerations of adjustments to avoid field enhancements. In this context, silicone oil may emerge as a better material. The silicone oil may also prevent the contacts and field coil from salt-water corrosion. The present study is limited to static electric field simulation, but not in relation to its critical breakdown strength.

6. Conclusions

This paper presents a FEM study of a 5 kV power relay that is modified to meet the requirements of higher voltages up to 20 kV. The COMSOL Multiphysics® software and the electrostatic module enable a comprehensive analysis of the various physical processes that affect the design. The presented procedure can be used as a qualitative technique to validate various implementation situations. In addition, the technical pre-requisites for the insulation materials, employed for high-pressure and underwater applications can be optimized. At the same time, it is important to mention that the simulation involving static electric field is alone considered, but not in relation to the critical breakdown strength. This approach is acceptable as the critical breakdown strength of the sea water weak as it is highly conductive in nature.

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