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Characterizations of solid-liquid interface in a wet-mate subsea HVDC connector

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ABSTRACT

Wet-mate connectors represent essential and technically challenging components in a subsea HVDC system. In this paper, systematic characterizations of solid-liquid insulation system implemented in a Wet-Mate subsea connector are presented with special focus on the interfaces. First, conduction in the liquid gap was studied using the current-voltage characterization and the Kerr electro-optic field mapping to establish the correlation between conduction and DC field grading for various electrode gap configurations and oil types. Secondly, Kerr electro-optic field sensing was extended to solid-liquid interfaces for model Wet-Mate connectors. Studies suggest that DC field grading in solid-liquid insulation particularly along the interface is influenced by regimes of conduction depending on the electrode configuration, gap separation, polarity, oil type, moisture and contaminants, and such dependences are further affected by the DC properties of hybrid solid-liquid insulations. Exemplar modelling studies conducted on representative design configurations indicate that this comprehensive basic study could provide insight into the tailoring of solid-liquid interfaces with low field distortion under quasi steady-state and polarity reversal operations for safe design and optimization of DC Wet-Mate connectors.

1. Introduction

Oil and gas (O&G) industries are undergoing a transformation from reservoirs in existing brownfield sites to offshore drilling activities located in deeper water. For technical and economic reasons, processing of hydrocarbons is preferred on the seabed in Ultra Deep-Water (UDW) sites instead of doing it on a host platform at the surface. As a result, O&G industries are continuously seeking new technologies for accessing deep sea petroleum resources. Subsea DC transmission and distribution system is a promising technology for electrifying subsea O&G production with high power, long distance and UDW depth [1,2].

For subsea DC power system such as the Modular Stacked Direct Current (MSDC) system, Dry-Mate (DM) and Wet-Mate (WM) connectors are essential components for system field deployment, faulty component isolation and repairing. Currently, there are commercially available DM and WM AC connectors, such as GE Vetco Gray MECON™ with a rating of 36 kV/500 A for operation in a depth of 3048 m [3]. Technical challenges of DC WM connectors include those related to DC systems as well as subsea installation and operation [1,2,4,5]. Comparing to existing subsea AC connectors, a subsea DC connector would require different electrical insulation system due to significant difference between AC and DC electric field grading. In AC system, the electric field is capacitive graded, i.e., determined by dielectric permittivity, which is nearly independent of the field and temperature. On the other hand, for DC system, the field is resistively graded, i.e., determined by electrical conductivity, which has strong nonlinear field- and temperature-dependence. In addition, the effect of space charge poses another challenge for DC insulation. Under DC voltage, with the presence of an interface between different materials, electrical charges migrate and accumulate therein to form space charges that can significantly alter the field distribution. Furthermore, during fault transients and polarity reversal events, superimpose of AC and DC field components results in an exceedingly high electric field. Therefore, DC connectors must also be designed to operate reliably for ont only capacitive grading, but also resistive grading, and a combination of resistive and capacitove grading [4,5].

WM connectors will be installed remotely at the rated water depth, with the interior of the WM chamber exposed to seawater during the mating process. Their electrical insulation must be reliably established after the mating is finished. Under these remote and harsh environment conditions, servicing of equipment is restricted, and reliability is of utmost importance. However, the dielectric strength of the insulating

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material is highly sensitive to contaminations. For DC insulation in particular, the contaminants can affect the conductivity and charge distribution of the material, which in turn affect the DC field distribution. Special insulation designs and material formulation have been developed specifically for cables and cable accessories in HVDC transmission and distribution system and have undergone significant progress in recent years. However, due to the requirement of subsea installation, certain contamination may be unavoidable. For example, in a WM connector, the interior of WM chamber must be exposed to seawater during the mating process, and afterward, the electrical insulation performance is re-established. Even with specially developed rinsing, flushing techniques, remnant contaminants could still present in the insulation after wet-mating. To achieve high reliability of DC WM connectors, it is important to understand the impact of seawater-related contamination on DC insulation [5].

Solid-liquid insulation systems employed for converter transformers have been extensively studied [6]. Certain common features are shared by converter transformer and WM connector hybrid insulation systems. For instance, the conductivity of oil is typically one to two orders of magnitude higher than solids, and hence under DC steady state the electrical stress almost completely lies in the solid insulation. However, the insulation system of a converter transformer is different from that in a WM connector. First, the insulation materials used in a converter transformer are different from those in a WM connector. Pressboard-transformer oil insulation system is most commonly used in converter transformers while WM connectors under study rely on epoxy/rubber and synthetic ester oils insulation. Secondly, during the operation of a WM connector, there are inevitable moisture and seawater contaminants in the mating chamber while converter transformers are manufactured with well-established vacuum drying and baking processes.

For WM DC connectors, oil is an integrated part of the insulation system and provides one of the two barriers in the hybrid insulation structure (Fig. 1). The reliability of oil insulation is highly important. In a proper WM DC connector design, most of the field stress is distributed in solid insulation. However, under transients due to high voltage fault, the stress in oil and along the oil-solid interface can be very high. Therefore, in order to design reliable insulation systems for WM DC connectors, it is important that the behaviours of the DC stressed liquid, solid-liquid interface as well as the effects of marine environment are fully characterized.

In this paper, a comprehensive study was conducted to determine the materials and interface properties that are critical for WM DC operation. The type of materials and interfaces under investigation include: oil insulation, solid-liquid interface, with the consideration for the effects of moisture and salt contaminations. The characterizations include current-voltage measurement and Kerr electro-optical field mapping for oil gaps and along oil-solid interfaces, with barrier layers.

2. Experimental investigation

2.1. Current-voltage characteristics

The investigation of the influence of electrode gap and purity of the oil on the conduction current was carried out by monitoring the quasi steady-state conduction current with a Keithley picoAmp meter for samples subjected to DC bias provided by a Spellman high voltage DC supply. The test cell containing two circular brass electrodes was filled with ~500 mL of oil and kept in dry and clean laboratory conditions. All measurements were conducted at room temperature and atmospheric pressure.

2.2. Kerr electro-optics set up

The Kerr electro-optic measurement system was developed to probe the electric field distribution in liquid insulator as shown schematically in Fig. 2. This oil field sensing method is based on transverse spatial electro-optic modulation, where a phase retardation is developed between lights polarized in parallel and perpendicular to the applied field as the result of Kerr quadratic electro-optic effect [7,8]. In considering the ultra-small Kerr constant of synthetic ester oil used in this study ($7.56 \times 10^{-16}\, m/V^2$), a small AC voltage (200 V, 1 kHz) is superimposed

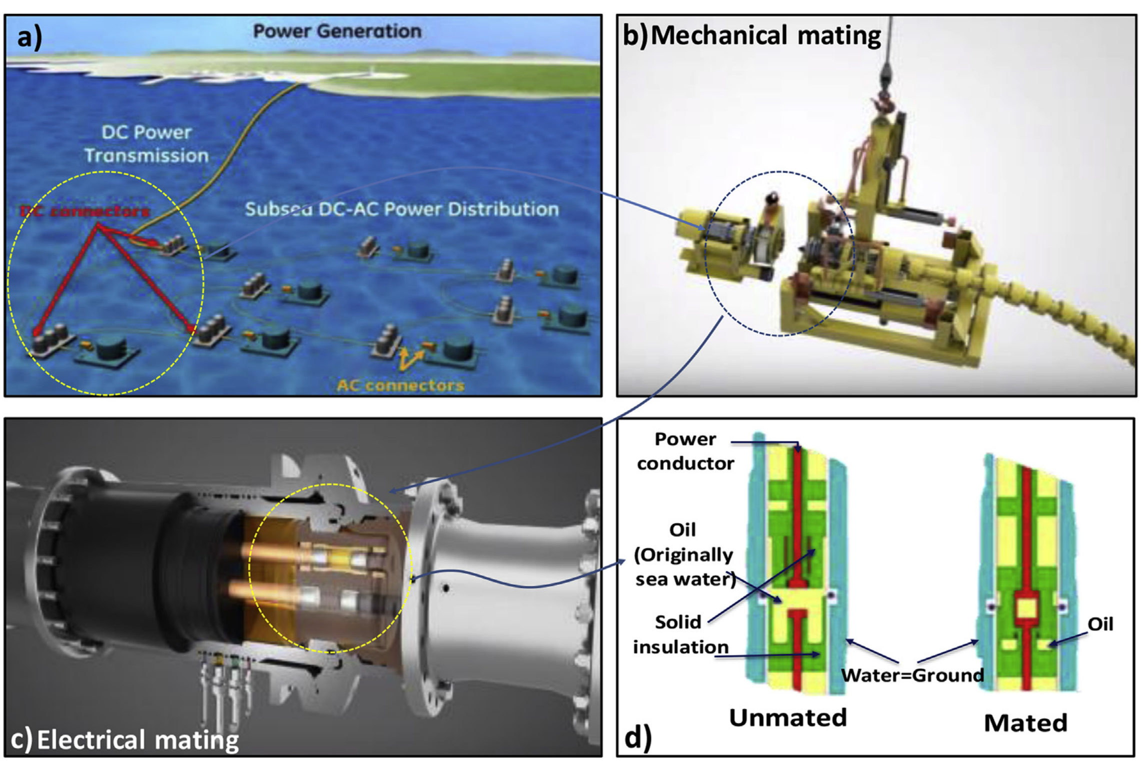

Fig. 1. DC WM connectors used in subsea O&G processing.