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Electric Field Analysis of High Voltage Submarine Cable with Insulation Defects- A FEM Based Simulation

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ABSTRACT

Demand for electricity and concern towards environment is increasing nowadays. Thus, green energy sources like wave, hydroelectric, off-shore wind power, etc, are the need of the hour. Green energy sources are located in offshore and to connect these to mainland submarine power cables are used, Submarine power cables are underwater cables used to transmit power across rivers or sea. The continuous increase in the electricity demand operation of the cable to be continuous, long term, safe and stable and it is very important to detect the insulation state of the cable. Failures of cable are due to human as well as environmental interference. Environmental interference include abrasion, geology, dredges, crushing, water pressure, temperature, salinity and nature of sea. Human interference includes anchors, fishing. The water pressure is hydrostatic pressure which increases for every ten meters depth of water and introduces mechanical stress on the cable. The temperature decreases as depth of water increases and this causes thermal stress on the cable. The salinity of sea also causes chemical stress on the cable. Thus, the power cable which is subjected to electrical, thermal and mechanical stresses leads to contraction and expansion of cable which may leads to formation of air gap (void) in the insulation of the cable during the operation. If the electric stress in air void is higher than air's breakdown strength, discharge occurs in the gap and insulation degrades gradually, releasing by-products like methane, hydrogen, carbon-monoxide, carbon-dioxide. Further, due to the liberation H2 and CO, water droplets are formed in the insulation leading to formation of water voids but it is rarely formed. Mechanical and chemical stresses, fishing and anchoring are leading to some small cracks in the cable. The ingression of water and other substances through cable cracks for long period may lead to damages. The initial detection of such defects in the cable can be done by partial discharge (PD) measurement and the distribution of electric field gives insight of PD. The proposed work has considered a 132kV HVDC single-core submarine power cable laid on sea-bed. The construction of HVDC submarine cable as well as its 2D model has been developed using ANSYS maxwell. Electric field distribution analysis of the cable has been carried out with and without defects in the insulation using FEM based ANSYS maxwell software. Special attention is given to the comparison of field for various insulation defects (void due to air, water and water or steel ingress). The results show that field at the defects are distorted.

KEYWORDS: HVDC submarine cable, FEM, ANSYS MAXWELL,sea environment, partial discharge, insulation defects, cable laid on sea-bed.

1. INTRODUCTION:

Submarine power cables are underwater cables to transmit power via both fresh and sea water bodies. In cases where huge sea needs to be crossed such cables are required for interconnecting countries, islands and continents electrically. Such electric link between countries reduces number of power plants by interconnecting different sub-international grids. Fewer power plants result in both environmental and economic benefits. Submarine power cables can be HVAC or HVDC. Mostly HVDC is preferred as it has many advantages like transmission with less losses, no compensation devices required, connection between multi frequency grids and more economical.

In this modernized world, both the demand for electricity and the concern towards environment is quite high. Hence, to adhere to this electricity generation with green energy sources is widespread. Green energy sources like wave, wind, hydroelectric, off-shore wind power etc. are away from demand site and are rarely found. To make efficient use of such energy sources transmission side is also expanding, by using water routes to transmit power where required. Installation of submarine cable depends on water depth, in shallow water, cables are dug into seabed to prevent damage from human activity. In deep water, they are laid on seabed. In places where high sea-currents are awaited they are bolted to the seabed. Sometimes are passed through pipe.

These cables now form a significant part of transmission system, and its failure is not acceptable. The failure of cable is mostly due to insulation breakdown. The insulation failure is mainly cause of formation of air gap, water gap, ingression of water or other substances. Such defects are caused due to both human and nature interference. Human interference include anchors, fishing and highest percent of failures are seen because of this in water depth up to 300m or less. Nature interference include dredges, abrasion, geology, water pressure andnature of sea [1]. The early detection of such faults improves its reliability.

The defects in the insulation like air gap, water gap and water or steel ingression causes insulation failure in the long period. And can be detected in initial stage by on-line PD measurement method and other on-line methods. where measurements are taken and analyzed. Based on measured data the cause and location can be accurately identified. As, field stress gives insight into partial dischargeand other activities in the defective region, by simulating electric field for defects, effect of each defect on the cable is investigated and analyzed to properly understand PD pattern and suggest other pattern that can be used for the detection of defect, and record it for future use. The main work carried out here is to analyze electric field dispersion in 132kV HVDC submarine cable due to defects like air, water gap and water, steel ingression from sea-bed and sea-water sides using FEM. FEM is used as it gives accurate, reliable results [2]. Effect of load, thermal variation on defect is not considered in this work.

2. SINGLE-CORE 2D MODEL OF HVDC SUBMARINE CABLE

HVDC submarine cable is designed for 132kV voltage with great care according to IS 7098-3 [3] standard. 66kV AC cable is used as 132kV DC cable. The cable structure has copper core, XLPE insulation, lead sheath, stainless steel amour with suitable dielectric permittivity and bulk conductivity and radius of these parts respectively are 6mm, 16.3mm, 18.2mm, 20.2mm. The submarine cable laid on sea bed is considered here. So, the region around the cable is modelled by splitting it into sea-bed and sea-water with relative permittivity of 25, 81 respectively and conductivity of 1.0, 0.25 respectively. The ANSYS model is as shown in Fig 1. [4]

Section following up discusses on the modelling of defects in this cable, so that field due to each defect is simulated separately, then analyzed how the field is different due to each defect.

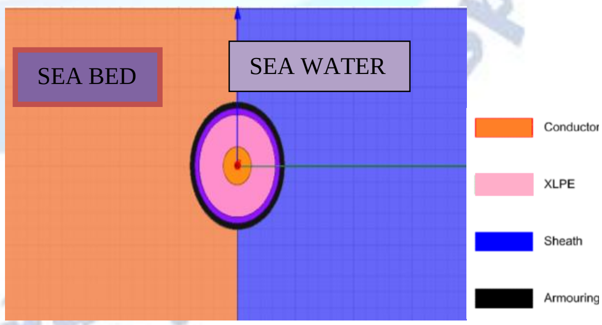

Fig 1: 2D model of single-core HVDC submarine cable

3. HVDC SUBMARINE CABLE WITH DEFECTS

This part deals with the design and modelling of 132kV HVDC submarine cable with air gap, water gap and also with water, steel ingression from both sea-water and sea-bed sides using ANSYS maxwell software of version 15.0. The details about the defect formation are mentioned here.

A. Defect- Air Gap

Submarine power cables are subjected to electrical, thermal, mechanical, chemical stresses. These stresses lead to contraction and expansion of cable which leads to formation of air gap in the insulation of the operating cable. The air gap formed in insulation will usually be spherical in shape. Diameter of air gap is very small than cable diameter, hence it can be approximated to circle [5].

The air gap of 3mm diameter is placed at distance of 10mm from the conductor. The circle of 3mm diameter is assigned with the following parameters to represent air gap, material- air, relative permittivity- 1.006, bulk conductivity- 0 siemens/m.

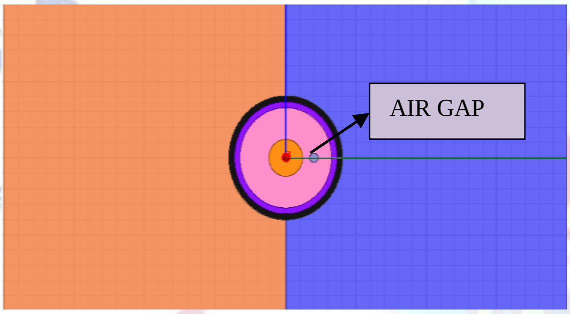

Fig 2: 2D model of HVDC submarine cable with defect- air Gap

B. Defect- Water Gap

If the electric stress in air is higher than air's breakdown stress, discharge occurs in the gap and slowly insulation degrades releasingby-products like methane, hydrogen, carbon-monoxide, carbon-dioxide. Due to hydrogen and CO water droplets is formed in the insulation. The formation of air gap leads to water gap formation, but are rarely formed. According to physics, liquids always try to reduce their surface area hence, its shape changes. To model, such water gap we would want to use different software like AUTOCAD or solid works. But in this ANSYS software, water drop is approximated to circle of radius r.

The above designed air gap is replaced with water gap of 3mm diameter at a distance of 10mm from the conductor, and it is assigned the fresh water as material with following factors, relative permittivity- 81, bulk conductivity- 0.01 siemens/m.

C. Defect- Water Ingression from Water Side

The submarine cable is subjected to external aggression like fishing, anchor, crushing which creates crack and leads to ingression of sea water into the cable.

The damage in the metallic sheath causes sea water to suddenly flow into the cable. The flow is such that it is sucked in the cable. Hence, the volume will be less towards the conductor core and high at the cable metallic shield. Adapting to this concept, the water ingress or penetration is modelled as in the Fig.3. Fan-shaped design with outer length of 1.2mm and inner length of 0.6mm, with a depth of 10mm is drawn and assigned sea-water as material with the below parameters, relative permittivity- 81, bulk conductivity- 1 siemens/m

Fig 4 shows cable with water ingress from water side.

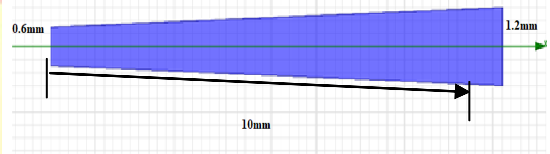

Fig 3: Dimension of water ingress

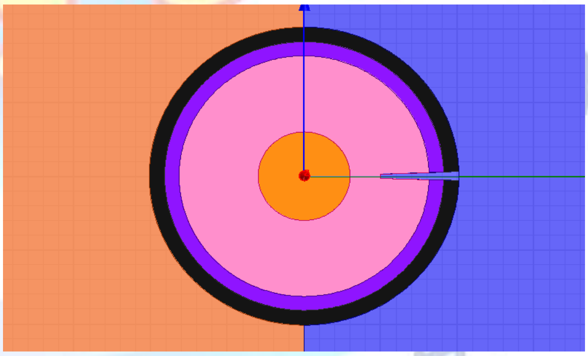

Fig 4: 2D model of HVDC submarine cable with water ingress from water-side

D. Defect- Steel Ingress from Water-Side

When the steel structure ingresses in the cable by accident due to human activity or any other activity. The cable is damaged. The variation in the electric field distribution is observed due to this steel ingression.

The steel structure is modelled with following random shape and dimensions, fan shaped with an inner length 0.2mm, outer length 1.2mm and depth of 10mm. It is as shown in Fig.5 The steel material is assigned to it with the following parameters

Relative permittivity- 1

Bulk conductivity- 2000000 siemens/m.

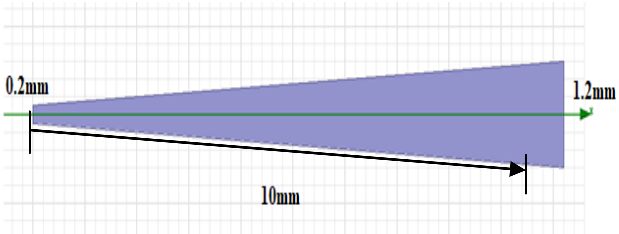

Fig 5: Dimension of steel ingression

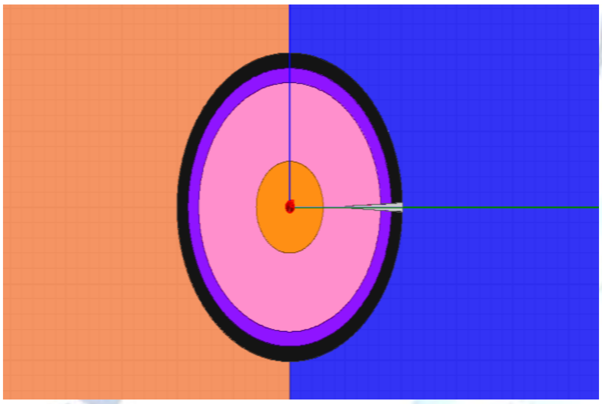

Fig 6: 2D model of HVDC submarine cable with steel ingress from water-side

E. Water, Steel Ingress from Sea-Bed Side

Submarine cable laid on sea-bed is considered. In order to analyze whether there would be any difference in the electric stress if the water, steel ingress occurs from sea-bed side. The same dimensions of water, steel ingress is modelled from sea-bed side. The Fig 7 shows the model.

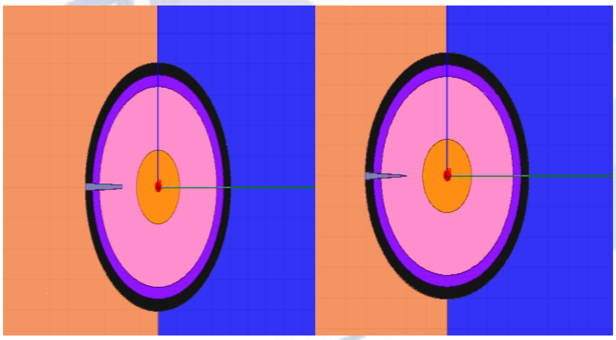

Fig 7: 2D model of HVDC submarine cable with water, steel ingress from sea-bed side

4. SIMULATION RESULTS AND ANALYSIS OF ELECTRIC FIELD

Simulated electric field pattern in submarine cable with and without defects are observed and analyzed in this section.

A. Electric Field Distribution in cable without defects

Simulation result of normal cable without defect is as noticed in Fig 8. The electric field across the insulation is such that it is higher near conductor and away from the conductor it decreases. The maximum electric field is 2.2025X10^7V/m. The field uniformly decreases from conductor up-to grounded lead sheath as shown in Fig.9. Next, the simulation is done to analyze the distribution of electric field due to defects.

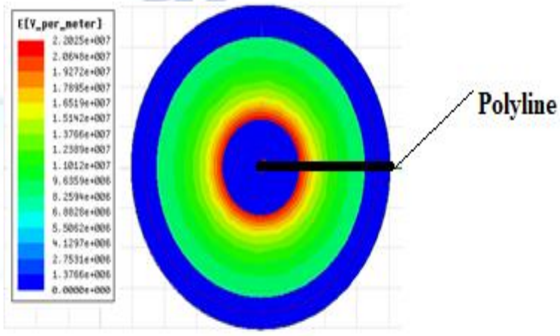

Fig.8:Electric field distribution in cable without defects

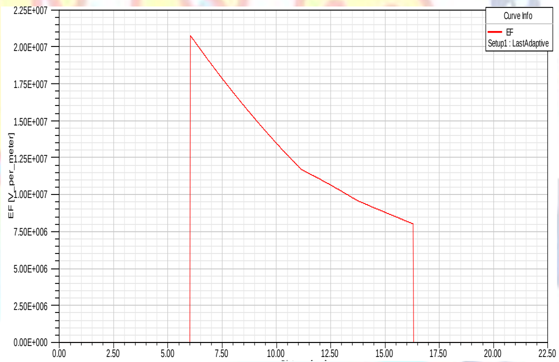

Fig 9: Electric field distribution in cable without defect

The graph is plotted by drawing polyline along radial direction of cable as shown in Fig.9 The graph shows the field distribution at points as we move away from the conductor core, insulation, lead sheath, armor.

B. Electric Field Distribution in Cable with Defects

The simulation results due to defects are observed.

Case 1: Defect- Air Gap

When the air gap defect is formed, electric field is distorted as shown in Fig.10. The field is decreasing as it moves away from the conductor core, but this pattern is interrupted in air-gap and the high field strength is reached up to 2.4646X10^7V/m at tip of air gap. The distortion in electric field distribution is as plotted in

Fig.11. The electric field stress is more than breakdown strength of air, hence partial discharge occurs.

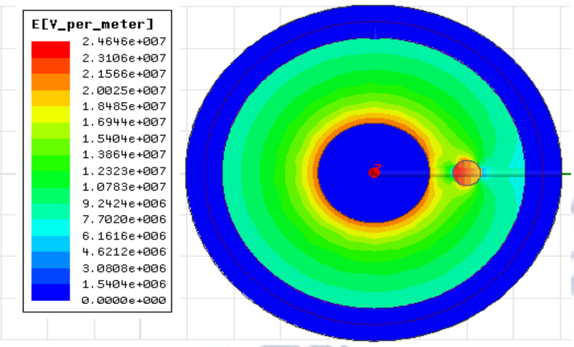

Fig 10: Electric field distributionin cable with defect- air gap

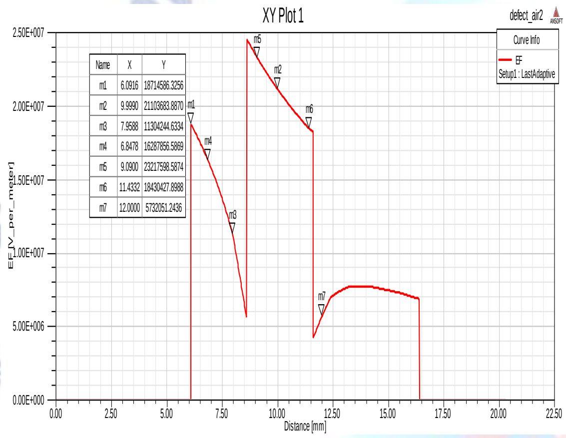

Fig 11: Electric field distribution in cable with defect-air-gap

Case 2: Defect- Water Gap

The electric field distortion due to water gap formation in cable is as shown in Fig.12 and Fig.13 The electric field strength is increased suddenly at the tip of the water gap close to the conductor core and inside the water gap there is no much electric field, as water is conductive in nature. The electric field near the tip of water gap is 3.0687X10^7V/m, which is high enough to erode the insulation and leads to formation of water tree which evolves into electrical tree leading to partial discharge after ling time. TDR technique is made use for detecting water trees in initial stage, before partial discharge occurrence [6].

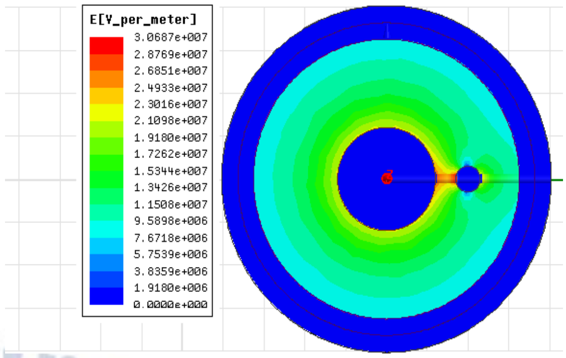

Fig 12: Electric field distributionin cable with defect-water gap

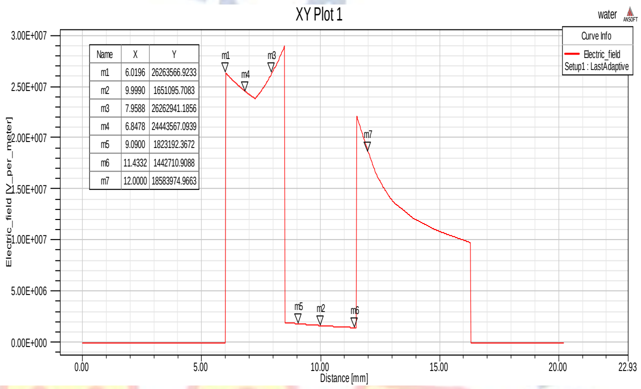

Fig 13: Electric field distribution in cable with defect-water-gap

Case 3: Defect- Water Ingress fromsea-water and sea-bed side

With ingression of water from outside towards the conductor, the electric field is distorted, field inside water is very less, but at the tip of water ingress it is quite high that is about 2.7299X10^7V/m, but the strength is less at the tip than at tip of water gap, but is high enough to breakdown the insulation. After, long-time it causes high frequency discharge [7]. The variation of field across the cable is as appeared in Fig.14 and Fig.15

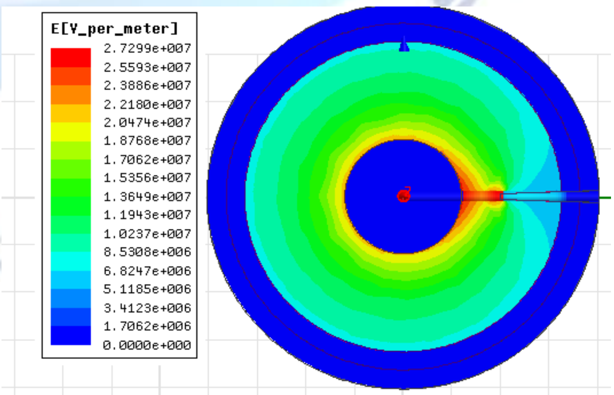

Fig 14: Electric Field distributionin cable with defect-water ingress from water side

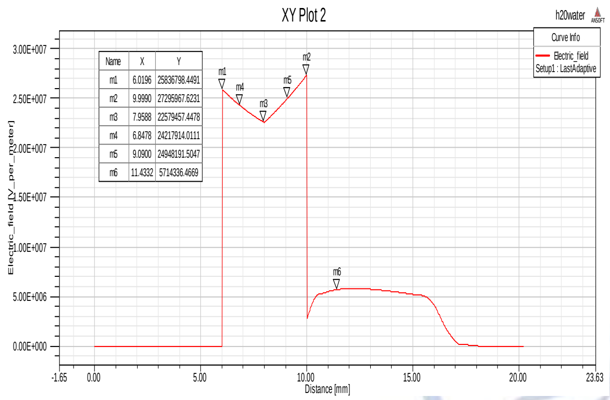

Fig 15: Electric field distribution in cable with defect-water ingress from water-side

Similar changes happen when water ingress occurs from sea bed side, but the maximum stress at the tip of the water ingress is 2.9989X10^7V/m which is slightly higher than from water-side ingression.

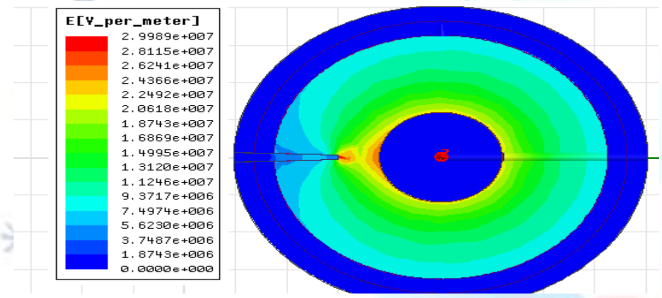

Fig 16: Electric Field distributionin cable with defect-water ingress from sea-bed side

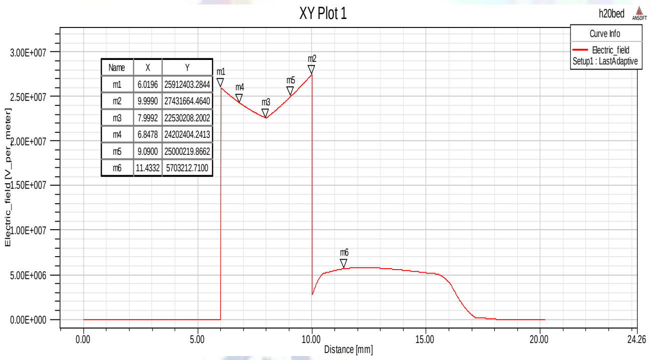

Fig 17: Electric field distribution in cable with defect-water ingress from sea-bed side

Case 4: Defect- Steel Ingress from water-side and sea-bed sides

Steel ingression into the cable causes complete distortion of electric field as shown in Fig.18. The field is highest at the tip of the ingression that is about 6.9894X10^7V/m, which is high enough to cause breakdown of the insulation, in the long run it causes high frequency discharge. The plot in Fig.19 shows how the field in the cable varies due to steel ingression. The field as in normal cable, is decreasing away from the conductor, but at point close to ingression it starts increasing and highest at the tip, but inside steel ingress field is zero.

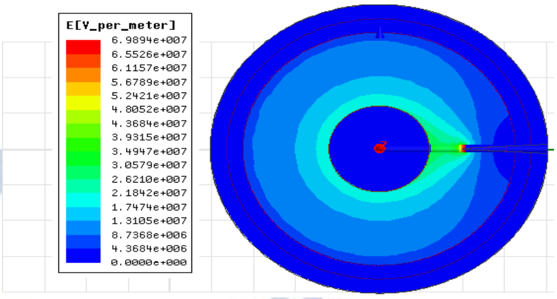

Fig 18: Electric Field distributionin cable with defect-steel ingress from water side

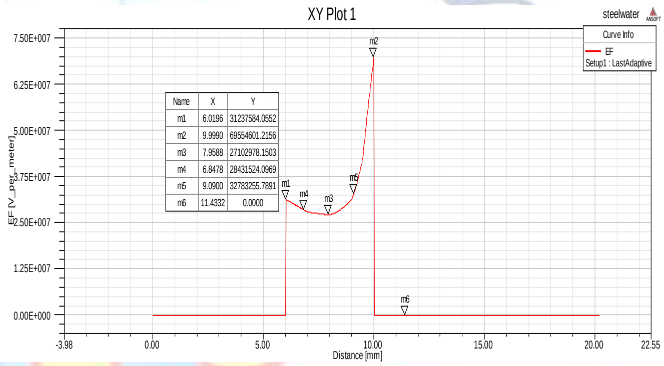

Fig 19: Electric field distribution in cable with defect-steel ingress from water side

When the steel ingress happens from the sea-bed side the field is distorted in a similar manner as in water-side ingression as shown in Fig.20, Fig.21. But, the highest field at the tip is 4.6455X10^7V/m which is very less than in the steel ingression from water-side.

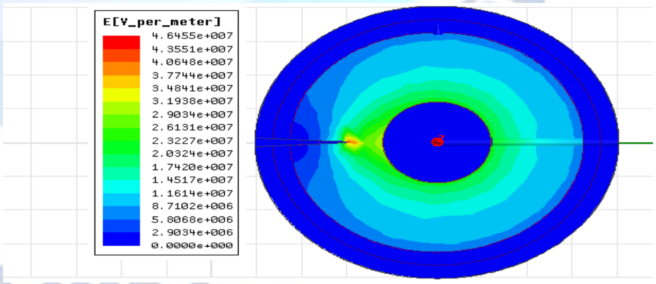

Fig 20:Electric Field distributionin cable with defect-steel ingress from sea-bed side

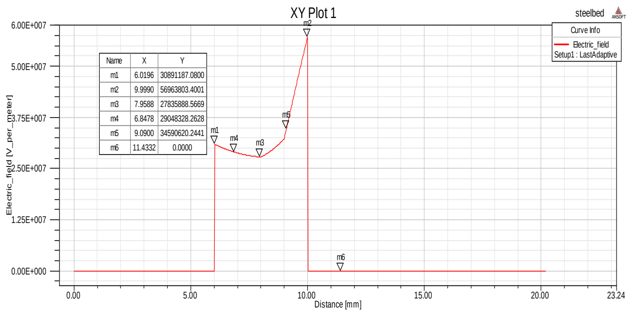

Fig 21:Electric field distribution in cable with defect-steel ingress from sea-bed side.

5 points within insulation i.e., at a point near conductor (A), at highest field point (B), at intermediate point between A, B (C), at point inside defect (D), field strength value is observed, recorded and analyzed as in Table 1.

Table1: Field strength at different points due to defects and discussion.

Defect	Field strength value (10^7 V/m)				Remarks
	Point A (6.0196)	Point B (tip of defect)	Point C (7,9588)	Point D (11.4332)	
Air gap	1.8714	2.4646	1.1304	1.843	Strength is high at the tip of air gap and inside also it's high, leading to breakdown of air, hence sudden partial discharge
Water gap	2.6263	3.0687	2.4443	0.14427	At the tip of water gap, strength is highest and high enough to erode the insulation, but there is no field inside gap, so no discharge, but water tree is formed. PD is formed after long time leading to insulation breakdown. PD formation takes long time and water tree detection is hard. To detect water tree at initial stage TDR technique can also be used as PD measurement cannot detect the defect at early stage
Water ingression from water-side	2.5836	2.7299	2.2579	0.5714	Highest at the tip and inside there is very less field and becomes zero as we move. Less field corresponds to conductor.It forms closed conductor hence, leads to leakage of current. Water tree is formed in this case as well. As, water tree is formed partial discharge formation takes long time.
Water ingression from sea-bed	2.5912	2.9989	2.2530	0.5703	Similar thing happens, but highest field value is slightly higher than in water-side ingress.
Steel ingression from water-side	3.1237	6.9894	2.7102	0	Highest at the tip and inside field is zero, as it is a very good conductor and also becauseits shape forms closed loop, leakage current will be high. PD activity is also present. Hence, PD or leakage current detection can be done to detect defect at early stages.
Steel ingression fromsea-bed side	3.0891	4.6455	2.7835	0	Similar thing happens, but highest field value is very small compared to water-side ingress.

5. Conclusion

Modelling of 2D model of 132kV HVDC single-core submarine cable laid on sea-bed was done with air gap, water gap and water, steel ingression from both sea-bed and sea-water side using ANSYS maxwell simulation software and investigating the effect of these different defects by analyzing the electric field distribution was done. The conclusion of this work is as follows.

- Air gap formation cab be detected by PD measurement
- Water gap formation can be detected by PD measurement, but for detection of defect at early stage, TDR can be used.

•Water, steel ingress is associated with both PD and leakage current, hence both PD and leakage current measurements can be used for their early detection.

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Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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