This paper highlights the use of IR testing beyond that of insulation monitoring. Depending on the test setup, one can predict to a reasonable degree the presence and type of insulation fault. Through theory and experimentation, spot IR, time-resistance, and ramp testing methods are demonstrated to determine the root-cause failure of previously submerged and operational electrical cables in the offshore energy industry. In addition, the recovery of low IR by **V-LIFE**, a cabled 'healing' solution, is demonstrated on the failed electrical components.

Failure Investigation

Root-Cause Analysis of Failed Submerged Electrical Cables

Dr. A. R. Langley

VIPER INNOVATIONS

COMMON FAILURE MODES FOR SUBMERGED UMBILICALS & CABLES

The failure of submerged cables can occur due to a variety of reasons, typically involving open circuits, short circuits and electrical insulation failure. The latter is of interest in this article, where previously submerged electrical flying leads (EFL) are investigated to determine the possible cause of failure. This is attempted by performing a series of insulation resistance (IR) tests. IR testing has the capability of determining whether or not a weakness is present in the insulation and, even better, has the potential to elucidate the type of fault present such as water ingress or localised weaknesses. This article aims to highlight the breadth of information that can be obtained from performing a variety of IR tests.

INSULATION RESISTANCE (IR) TESTING

Insulation resistance (IR) testing conditions are generally dictated by the system under test and any time constraints the user may have. IR testing is based on a fairly simple concept – apply a voltage between the cable conductor and earth, measure the leakage current and subsequently calculate the IR. The IR is calculated based on one of the most fundamental equations in electronics, Ohm's Law. Depending on the parameters chosen and the system under test, much more detail can be gathered about the state of the insulation. This section discusses such testing methodologies and refers to the IR testing of a submerged cable.

IR Testing: How and What is Measured?

In routine testing DC voltage is normally used, as with a megohmmeter. However continuous monitoring with an IR tester, such as an insulation monitoring device (IMD), usually utilises some form of AC waveform. This is because DC measurements are susceptible to interference from noise or stray currents. The testing discussed herein predominantly concerns DC voltage testing.

When a voltage E (Volts, V) is applied, current flows through the cable insulation. This is known as leakage current I_{leak} which in turn, according to Ohm's law, provides the IR such that,

$$\mathrm{IR} = \frac{E}{I_{\mathrm{leak}}}$$

However, the current measured by an IR tester is the total current I_{total} which includes capacitive and absorption currents I_{cap} and I_{abs}, respectively, in addition to I_{leak} where,

$$I_{\mathrm{total}} = I_{\mathrm{leak}} + I_{\mathrm{cap}} + I_{\mathrm{abs}}$$

and,

$$\mathrm{IR} = \frac{E}{I_{\mathrm{total}}}$$

Capacitive and absorption currents are associated with the charging of a capacitor, which consists of two conductive mediums separated by a dielectric (insulating) material such as an insulated copper cable submerged in seawater illustrated in Fig 1. When a DC voltage is applied between the two conductors, charge carriers within the conductors move to/from the conductor surface, causing an equal and opposite charge at the facing conductor surfaces. The dielectric develops an electric field with which molecular dipoles align.

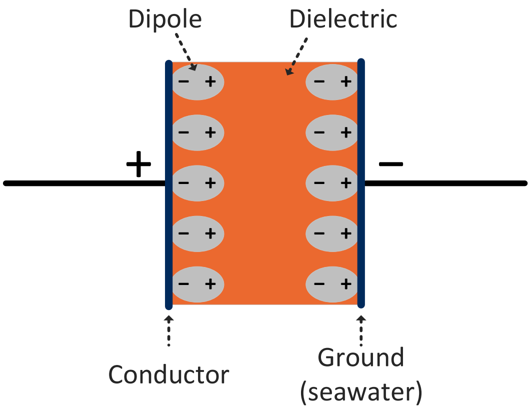


Fig 1. Illustration of a capacitor.

Capacitive current stems from the movement of charge carriers to/from the conductor surface, whereas absorption current stems from the movement of dipoles within the insulation.

So, how do capacitive and absorptive currents affect an IR test? At the start of a DC voltage IR test, capacitive, absorption and leakage currents are present. Capacitive current dominates at the start and is typically much larger than leakage and absorption currents. With time, capacitance and absorption currents will dissipate, dictated by the ability of a material to store charge (which insulators do more effectively). Capacitive current dissipates quickly compared to absorption current, shown graphically in Fig 2. The reduction in current therefore causes a continual increase in IR during an IR test. Most IR testing methods, however, take these effects into account.

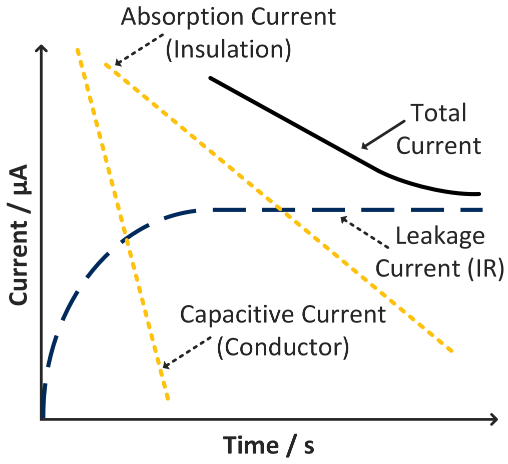


Fig 2. Capacitive, absorption, leakage and total current as a function of time during IR testing.

IR Testing Methods

IR testing serves as a useful troubleshooting tool to monitor and respond to known problems. IR testing can indicate whether an insulation fault is developing, and whether a system might need maintenance or, in some cases, replacing. It should be noted that **repeated IR testing on a single system should be performed under the same test conditions and test equipment if possible.**

The simplest form of IR test is a constant voltage test performed for a specified period and recording the IR at a set time. Choosing an ideal DC voltage and timescale depends on the system at hand, such as the cable length and withstand voltage, and time constraints the user may have.

The IR test time can be 60 s long, known as a 'Spot Test', or longer. A one-minute minimum is advised intending to avoid effects from capacitive current, illustrated in Fig 3 where the IR increases rapidly in the first instance. Indeed, absorption currents will also be present. Spot testing therefore only gives a rough idea of the insulation integrity. Increasing the test time, however, can improve accuracy, known as a 'time-resistance' test.

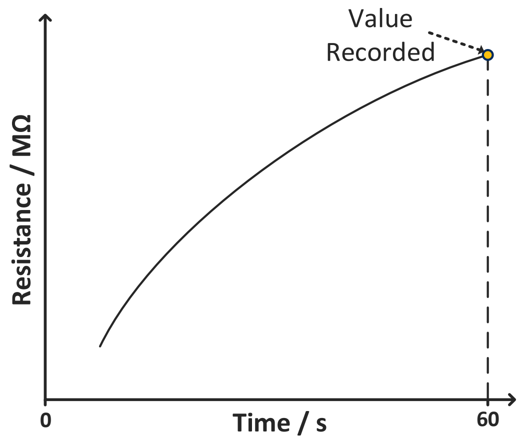


Fig 3. An 'ideal' insulation resistance (IR) value recorded at 60 s during a constant voltage IR test.

Fig 4 demonstrates a time-resistance test for 'good' insulation where the IR continues to increase due to the slow discharge of absorption current and low leakage current. For 'poor' insulation one might observe an IR decrease. For 'poor' insulation the initial absorption currents will be smaller and the leakage current higher or even increasing with time, leading to an IR decrease.

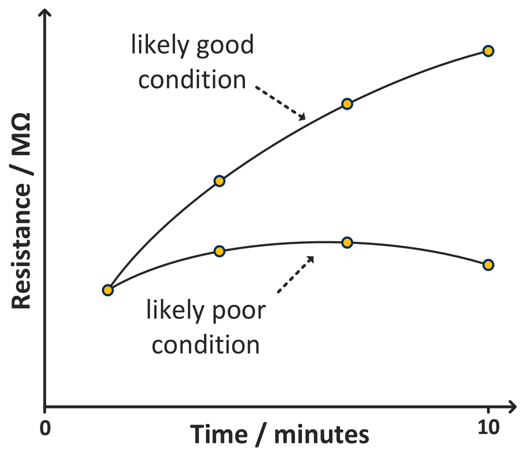


Fig 4. IR trends for 'good' and 'poor' insulation.

Further to observing IR trends, quantitative measures can be obtained to determine the possible condition of the insulation. The dielectric absorption ratio (DAR) is one of them, which describes the ratio of two time-resistance values,

$$\text{DAR} = \frac{\text{IR @ 1 minute}}{\text{IR @ 30 seconds}}$$

A DAR < 1 indicates that the IR at a larger timescale is smaller than that at a shorter timescale. This means that absorption current is masked by leakage current in turn indicating poor insulation. The higher the DAR the better the insulation integrity due to a high absorption current. Similar to Spot Tests, DAR values offer a rough indication of insulation integrity. Some would argue that retrieving a DAR at 10 mins:1 min would be more accurate, also known as the polarisation index (PI),

$$\text{PI} = \frac{\text{IR @ 10 minutes}}{\text{IR @ 1 minute}}$$

Typical PI values corresponding to certain degrees of insulation integrity are given in Table 1. Information gathered from DAR and PI tests depends on the system tested. A PI value between 1-2 could be ‘satisfactory’ for short sections of house wiring, but ‘questionable’ for long offshore cables. All the same, these are useful measures which help to determine whether to intervene or investigate problems further. In addition, more than one test type should be performed to ensure accuracy and consistent outcomes.

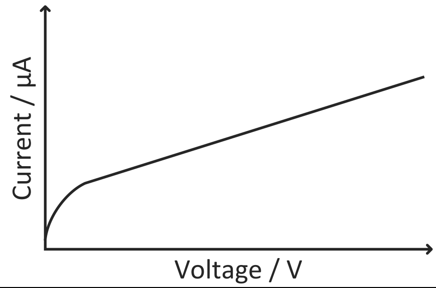
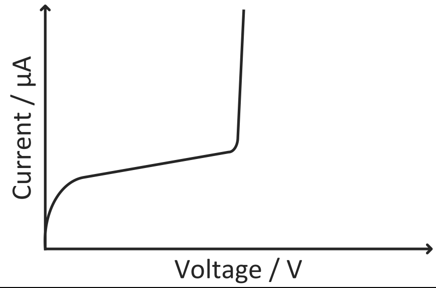
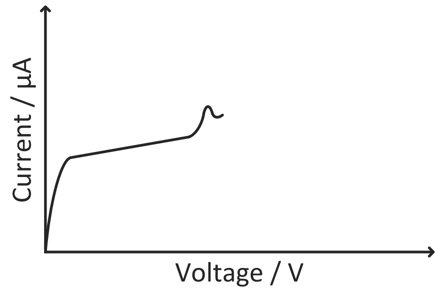
Table 1. PI values and insulation condition.

PI Value	Insulation Condition
< 1	Poor
1-2	Questionable
2-4	Okay
> 4	Good

Another useful IR testing method is ‘Ramp Testing’ where the voltage is continually increased at a constant rate to a specified voltage, e.g. a sweep rate of 100 V minute^{-1} up to 500 V. It is advised that spot and time-resistance testing is performed prior to ramp testing and should be taken into account when deciding on ramp testing conditions.

The response of insulation to a ramp test provides detail on the condition of the system and can allow the user to detect small defects in the insulation. For this test, the leakage current is plotted as a function of voltage. Certain voltage-current trends can indicate ingress and localised faults, with some common trends summarised in Table 2.

Table 2. Insulation condition and corresponding voltage-current relationship during a ramp test.

Condition	Voltage-Current relationship
Good	
Moisture Ingress	
Localised Weakness	

A smooth almost linear increase in current with voltage is expected for ‘good’ insulation condition. The increase comes from capacitive and absorption current which do not dissipate due to the continually changing voltage. When the behaviour deviates from this ‘ideal’ behaviour, this warns that the test is tending towards insulation breakdown. If a large spike in current is observed (see Table 2), this could indicate water/moisture ingress. If small ‘blips’ in current are observed, this could indicate local weaknesses in the insulation.

The testing methods described will be applied to perform a failure investigation involving two previously submerged electrical flying leads (EFL) which were in use on a subsea control system.

FAILURE INVESTIGATION

The root-cause failure of two electrical flying leads (EFL) is discussed here. Previously submerged in the North Sea, the EFLs under investigation were used in power channels. Following failure due to low IR, the EFLs were retrieved and sent to Viper for root-cause analysis. A brief history of the EFLs and planned testing follows.

EFL History

The two EFLs, part of power channels 1A and 1B of a subsea production control system, were installed in 2007 with production starting in 2008. After eight years, power channels 1A and 1B started to trip due to low IR in 2016 and intervention took place in 2017. The low IR faults were isolated to two EFLs. These EFLs were subsequently recovered and replaced.

Recovered EFL Components

The 1A and 1B EFLs were recovered complete with the cable, male receptacle (MR) and female plug (FP) connectors (see Fig 5). The 1A EFL (**A**) was acquired in-tact. The 1B EFL was in its constituent parts: cable (**B**) and both connectors (**C**). Each EFL consists of four lines 1, 2, 3, and 4 where 1&2 and 3&4 are twisted screened pairs (TSP) (see Fig 6). TSP 1&2 on both EFLs was in use during operation.

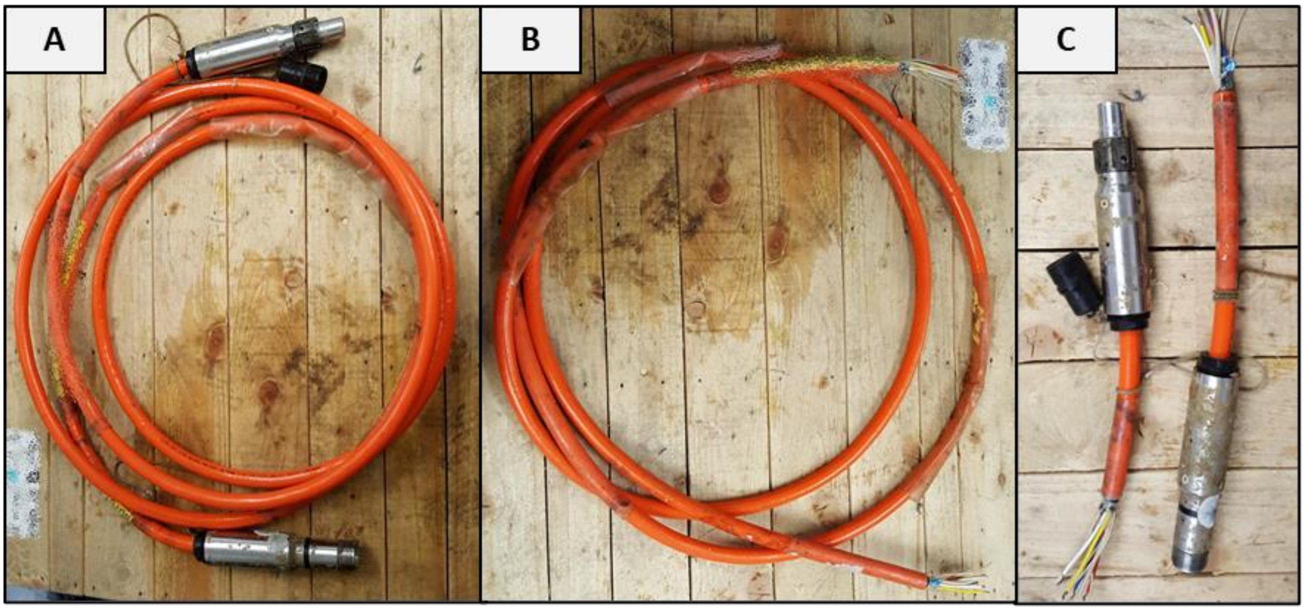


Fig 5. Photographs of EFL components denoted A) 1A EFL, B) 1B cable and C) 1B FP (left) and 1B MR (right).

Cable Cross-Section

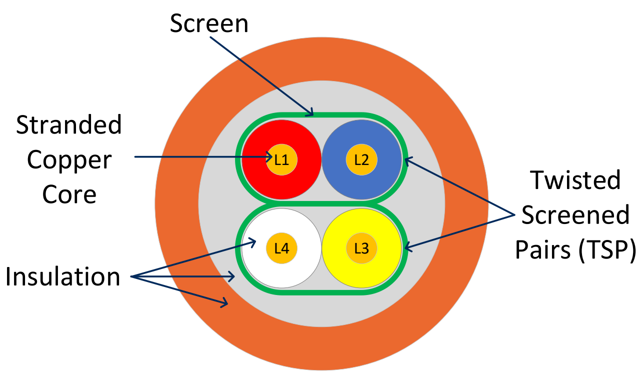


Fig 6. Cross-section of acquired EFL cables.

Test Procedure

The reported investigation consists of a series of IR tests in both ‘dry’ and ‘wet’ conditions. ‘Wet’ conditions refer to submersion in synthetic seawater. IR testing methods included spot IR tests at 250 V, the calculation of PI from time-resistance plots, and ramp testing to 500 V. These tests were performed on each line 1-4, or pairs 1&2 and 3&4 where possible, line-to-line, line-to-ground and pair-to-ground. IR tests were performed on different ‘assemblies’, e.g. connecting the 1B plug and/or receptacle to the 1A EFL.

ROOT-CAUSE ANALYSIS

Spot IR, PI and Ramp tests were performed in order to determine to a reasonable degree the cause of low IR in the given EFL components. Furthermore, the type of fault causing low IR is also predicted according to Ramp Test analysis. That said, it is important to remember that IR testing in general can only give an *indication* of the presence and type of fault in a given system. To truly confirm a fault, more conclusive measures should be taken to retrieve physical evidence of a fault to complement IR testing hypotheses. Such methods can include dismantling the cable and connectors and using costly analytical imaging tools (e.g. X-ray imaging and scanning electron microscopy (SEM). Here, only the use of IR testing methods are described.

Spot IR Testing

To start, different assemblies involving the 1A and 1B EFL components underwent spot tests in dry and wet conditions which were subsequently compared. Such assemblies are indicated in Table 3 where, for example, '1A EFL + both 1B connectors' refers to the 1A EFL being connected at both ends to both 1B connectors. In particular this configuration allowed or the full submersion of the 1A EFL. Testing different configurations allowed for conclusions to be made for each component.

Spot IR test results are given in Table 3 for line-to-ground at 250 V at 60 s. The ground for dry measurements was the connector shell or internal drain wire (connected to the screens) present in the cable. Table 3 shows for dry conditions that the IR was generally high, between 1 MΩ and 100 GΩ. Tests concerning Line 1, however, produced an under-range IR (< 500 kΩ) for assemblies including both the 1B connectors and the isolated 1B FP.

Highlighted in yellow in Table 3 is a significant reduction in IR compared to dry conditions. Clearly, line 1 and line 3 for most assemblies experienced a significant IR decrease in wet conditions. Most notable for line 1 was an IR < 500 kΩ recorded for the 1B FP and a decrease from 75 MΩ to 3 MΩ for the 1A EFL. Line 4 also exhibited an IR decrease (53 to 20 MΩ) for the 1A EFL + 1B MR. Therefore **faults may be present in line 1 and line 3 of the 1A EFL and 1B FP, and line 4 of the 1B MR.**

IR increases from dry to wet conditions were also observed and likely due to measurement repeatability errors. In practise, differences between dry and wet IR values are likely to be very small. The IR values for submerged assemblies are still relatively high, however, in the MΩ region. The insulation was therefore effective in wet conditions. It is important to stress that spot tests provide an *indication* of a fault. To investigate and confirm these findings, additional tests are needed.

Table 3. Dry and wet spot IR measurements (Ohms, Ω) for different test assemblies at 250 V at 60 s.

IR test 250 V 60 s	**Line to Ground**							
	Line 1		**Line 2**		**Line 3**		**Line 4**	
Assembly	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
1A EFL	75 MΩ	3 MΩ	74 MΩ	185 MΩ	71 GΩ	36 GΩ	> 500 GΩ	222 GΩ
1A EFL + 1B MR	7 MΩ	5 MΩ	13 MΩ	10 MΩ	17 MΩ	8 MΩ	53 MΩ	20 MΩ
1A EFL + 1B FP	6 MΩ	< 500 kΩ	12 MΩ	same	174 GΩ	11 GΩ	24 MΩ	61 MΩ
1A EFL + Both 1B Connectors	< 500 kΩ	< 500 kΩ	2 MΩ	1 MΩ	95 MΩ	4 MΩ	3 MΩ	9 MΩ
1B Female Plug (FP)	< 500 kΩ	-	252 GΩ	-	477 GΩ	-	9 MΩ	-
1B Male Receptacle (MR)	69 MΩ	-	13 MΩ	-	16 MΩ	-	32 MΩ	-
Both 1B Connectors	< 500 kΩ	-	4 MΩ	-	1 MΩ	-	2 MΩ	-
1B Cable	> 500 GΩ	same	> 500 GΩ	same	> 500 GΩ	same	> 500 GΩ	same

'-' not performed in wet conditions. Shaded yellow boxes indicate a significant reduction in IR from dry to wet conditions.

PI Testing

Following spot IR testing, time-resistance plots were gathered for each pair to ground in wet conditions for 1A EFL + 1B MR, 1A EFL + both 1B connectors and 1B cable assemblies. Time-resistance data was obtained at 250 V and 500 V for 10 minutes. 500 V was chosen to stress the cable insulation further, which may highlight weaknesses not observed at 250 V.

Starting with the 1A EFL connected to the 1B MR, the time-IR plot is given below in Fig 7. As expected, the IR increased with increasing DC voltage for both pairs 1&2 and 3&4. The plot shows that the IR was low for pair 1&2 in the single MΩ compared to 3&4 in the 10's MΩ, consistent with spot IR test readings for lines 1-4. A noisy IR for 3&4 at 250 and 500 V (yellow and grey, respectively) was observed reflecting erratic leakage current. This could indicate the presence of multiple weaknesses in the insulation or, in other words, multiple current leakage paths. In all cases, however, the IR generally increased with time and thus a PI value > 1 is expected – indicating 'questionable' or better insulation integrity.

Table 4. PI values for submerged assemblies.

Assembly	Pair	PI @ 250 V	PI @ 500 V
1A EFL + 1B MR	1&2	1.3	1.1
	3&4	3.29	1.2
1A EFL + both 1B connectors	1&2	1.4	1.0
	3&4	4.0	1.7
1B cable	1&2	1.0*	1.0*
	3&4	1.0*	1.0*

*IR over-range during measurement (> 500 GΩ).

PI values are given for the 1A EFL + 1B MR assembly in Table 4. All PI values were between 1-4, therefore indicating a 'questionable' to 'okay' insulation condition range. The drastic reduction from 3 to 1 for 3&4 at 500 V is a consequence of the noisy IR signal observed for 3&4. The noisy IR renders the PI value unreliable. This highlights the importance of observing the time-IR trends _and_ PI values when making conclusions. Overall, noisy IR and low PI values provide a cause for concern regarding the integrity of lines 1-4 of the 1A EFL + 1B MR assembly.

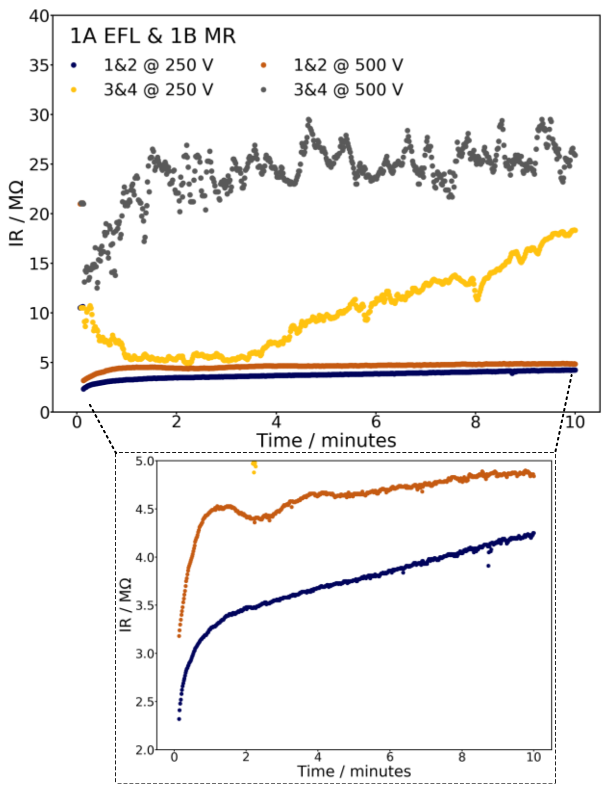


Fig 7. Time-resistance plot for 1A EFL + 1B MR.

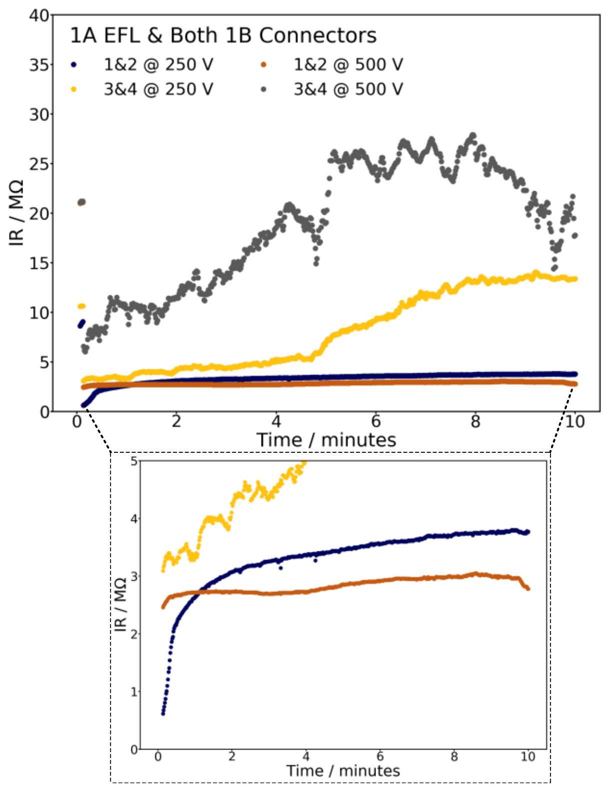


Fig 8. Time-resistance plot for 1A EFL + both 1B connectors.

Similar results, given in Fig 8, were observed for the 1A EFL with both 1B connectors. Noisy IR was observed for 3&4 and similar IR values observed for the pairs at 250 and 500 V. Again, noisy IR could indicate multiple faults in the insulation. For the pair 1&2, the IR was greater at 250 V than the IR at 500 V (the reverse is expected for healthy insulation). This could indicate the presence of a fault in the pair, where absorption current is smaller and leakage current is large due to the presence of contaminants/water ingress. PI values for this configuration (see Table 4) were similar compared to the absence of the 1B FP, with PI between 1 and 2, indicating 'questionable' insulation integrity. Again, the high PI value of 4.0 for 3&4 was deemed unreliable due to noisy IR observed for the pair. Overall, no major changes are evident from the addition of the FP and the lines remained in a 'questionable 'state.

The time-resistance plot for the 1B cable is given in Fig 9. The plot depicts over-range readings for each pair at each voltage (> 500 GΩ at 250 V, and > 1000 GΩ at 500 V). The 1B cable insulation was therefore deemed to be in excellent condition. The over-range values yield the PI values of 1 meaningless.

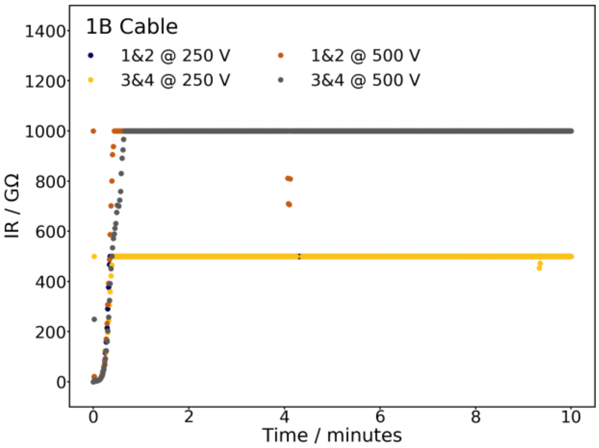


Fig 9. Time-resistance plot for 1B cable.

Lastly, the high IR for cable 1B showed that the low IR of the 1B EFL experienced during operation must stem from faults in the 1B FP and 1B MR. For the 1A EFL, faults are suspected on all lines but of differing degrees. Distinguishing the extent and type of damage requires another technique to provide more detail. Such a technique used here is ramp testing.

Ramp Testing

To further investigate and confirm likely faults exposed by IR testing and PI measurements, ramp tests were performed on each line 1-4 for a wider range of assemblies in wet conditions. The results are presented as voltage-current plots, sweeping at a rate of 100 V minute^{-1} to 500 V. Here the same voltage for PI tests was used which yielded enough information without repeating at higher voltages.

Two notable observations were made for current-voltage curves given in Fig 10 for the 1A EFL: **1)** high currents up to 2.5 mA were exhibited by line 1 and **2)** line 1 was unable to achieve 500 V. Most IR testers limit the voltage when a high current is detected (associated with a short circuit), serving as a protective measure avoiding further insulation degradation. Line 2 also exhibited a momentary current spike to 2 mA. It is possible this is an effect of line 1 since lines 1 and 2 are not screened from each other. Lines 3-4, which reach 500 V, exhibit currents in the nA range. It was deduced that line 1 of the 1A EFL likely suffered from water ingress, and lines 2-4 were in 'good' condition.

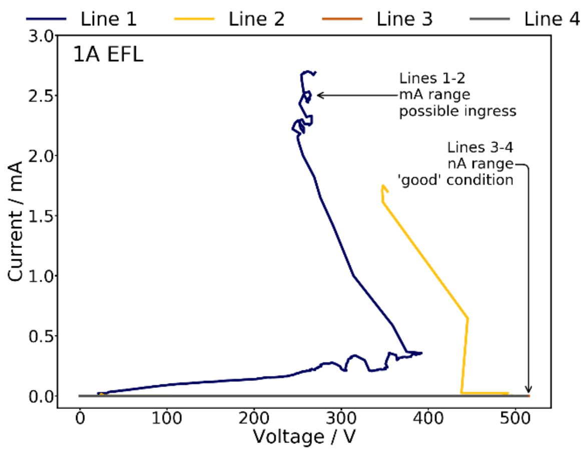


Fig 10. 1A EFL ramp test results for lines 1-4.

Ramp test results for the 1B FP connected to the 1A EFL, given in Fig 11, were similar to the 1A EFL. High currents were observed for line 1 up to 2.5 mA, and low currents for lines 2-4. For lines 2-4 the current had increased compared to the 1A EFL entering into the low µA range, therefore deemed 'okay'. Overall, line 1 was proposed to suffer from water ingress in this assembly and lines 2-4 in 'okay' condition.

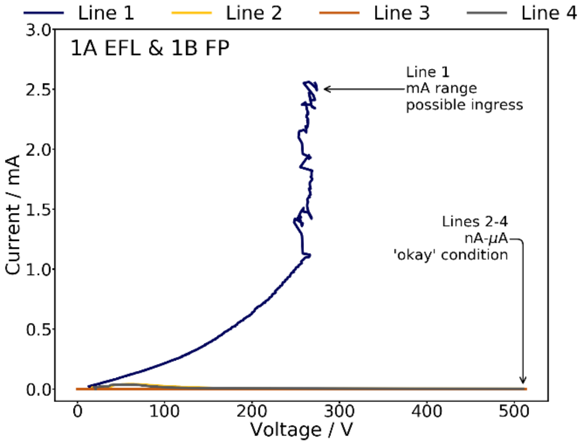


Fig 11. Ramp test results for lines 1-4 for the 1A EFL connected to the 1B FP.

When the 1B MR was connected to the 1A EFL, the ramp test results for line 1 differed compared to other results with the 1A EFL. Fig 12 shows that for all lines 1-4, currents in the µA range were obtained. Current in the mid-µA range is indicative of a 'questionable' condition, applying also to lines 2-4. Noisy current, or 'blips', indicate the possibility of local insulation faults.

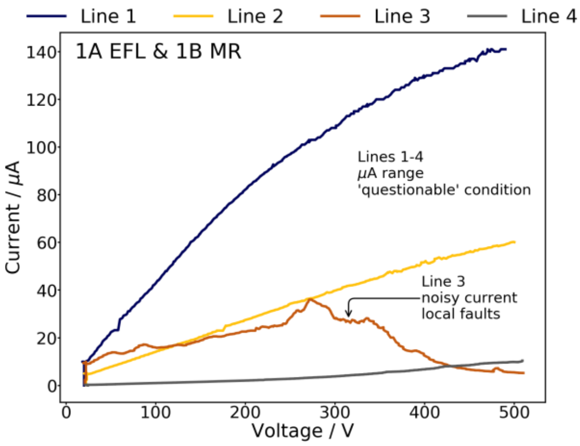


Fig 12. Ramp test results for lines 1-4 for 1A EFL connected to the 1B MR.

Worth noting is the fact that the 1A EFL + 1B MR assembly was first to undergo a ramp test. This could explain the lower currents generated during the ramp test compared to previous observations. The DC voltage could have damaged the insulation further so when the 1A EFL underwent more ramp tests, higher currents were observed.

When both 1B connectors were connected to the 1A EFL the current responses, given in Fig 13, were similar to those observed for the 1A EFL and 1A EFL + 1B FP assemblies. Line 1 provided currents in the mA range, once again indicating water ingress. The results were consistent with those for line 1 of the isolated 1A EFL. Lines 2-4 exhibited currents in the µA range, with a relatively linear increase in current. Therefore the insulation for lines 2-4 was 'questionable' with no fault types suspected.

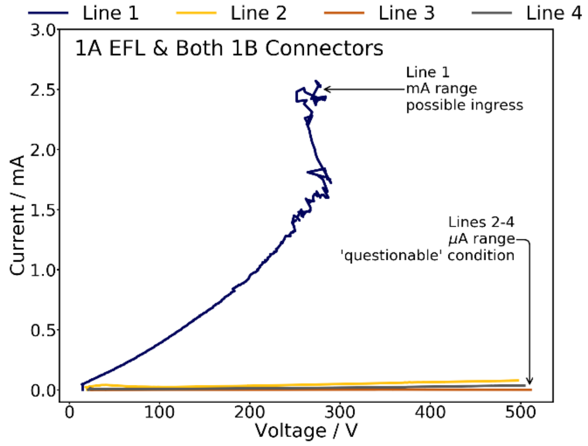


Fig 13. Ramp test results for lines 1-4 for 1A EFL connected to both 1B connectors (MR and FP).

Finally, currents given by the 1B cable (see Fig 14) were extremely low during ramp testing, in the single nA region. Low currents were indicative of excellent insulation integrity for all four lines in the 1B cable. The current traces appear noisy, but this low current noise represents electrical noise from the test setup.

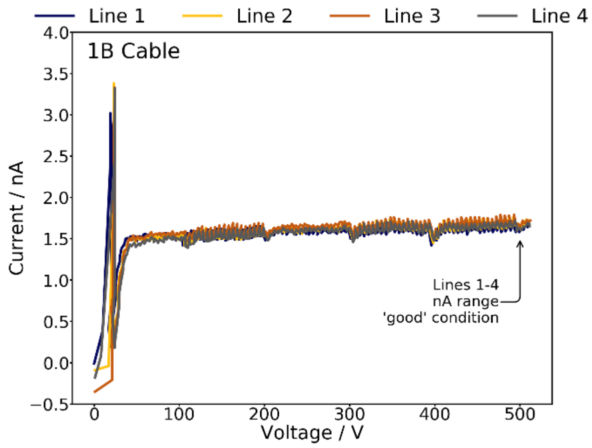


Fig 14. 1B cable ramp test results for lines 1-4.

In summary, the likely fault types determined for the assemblies under investigation were:

- Water ingress for line 1 in 1A EFL and 1B FP,
- Local faults for line 3 in the 1B MR.

V-LIFE: Recovering a low IR Fault

It is all very well determining the fault present in submerged cables, but how does one rectify an IR fault such as seawater ingress? In general, if the IR fault renders the system non-functional, the equipment will be replaced. Replacement of submerged equipment is a costly effort. An alternative, however, does exist for submerged cables. That being an innovative cable healing solution, **V-LIFE**.

V-LIFE, a software-activated function of Viper's topside-located **V-LIM**, provides an active 'healing' solution and prolongs the lifetime of submerged cables – an obvious choice considering the costs and downtime associated with replacing submerged equipment. When insulation is damaged to the extent that seawater reaches the conductor (typically copper), the conductor corrodes (translating to copper loss). The continual corrosion of the conductor will eventually lead to failure. To avoid this, **V-LIFE** can be enabled. **V-LIFE** initiates an electrochemical process at the conductor which blocks the insulation fault with an insulating precipitate. This leads to reduced leakage current and thus increased IR. To demonstrate the effective recovery of IR on submerged cables, the 1A EFL and 1B connectors studied in the failure investigation described in this paper were put under the influence of **V-LIFE**.

The final stage for the EFLs investigated in this paper was to 'heal' and improve the IR with **V-LIFE**. The 1A EFL was connected to both 1B connectors and submerged in saltwater. The pair 1&2 was connected to a **V-LIFE** enabled **V-LIM**. This pair was chosen since these were the operational lines during subsea production and showed significant signs of water ingress according to ramp testing.

Fig 15 provides the **V-LIFE** IR for the EFL assembly. Starting at an IR of approximately 650 kΩ, the system IR increased markedly to approximately 260 MΩ in just one week. After two weeks, the system was at a staggering 440 MΩ. This was a considerable improvement in IR, showing that **V-LIFE** successfully recovered the IR of a submerged EFL with suspected seawater ingress. **V-LIFE** therefore had a positive impact on the insulation integrity of the faulty lines.

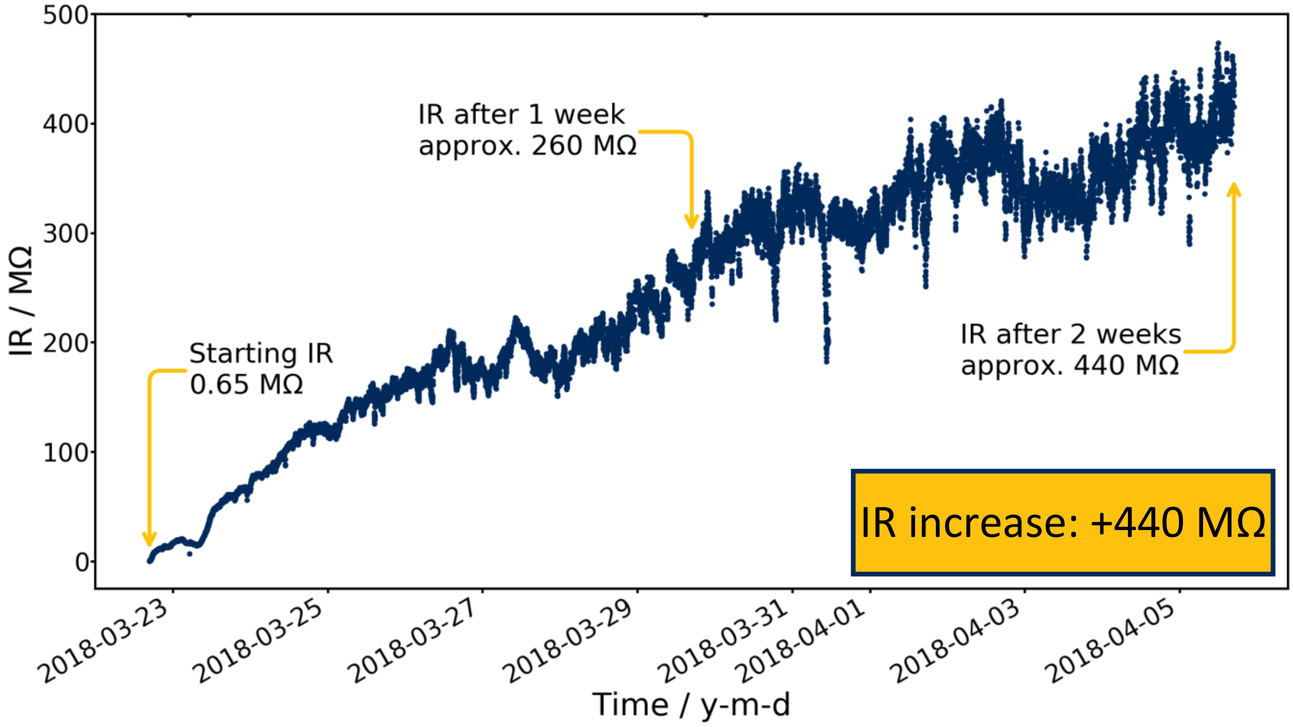


Fig 15. **V-LIFE** IR for 1A EFL & both 1B Connectors.

CONCLUSIONS

The testing outlined in this article shows that it is possible to hypothesise, to a reasonable degree, the cause of failure of retrieved EFLs. This was done by combining multiple IR testing methods, highlighting the importance of using multiple techniques when preforming failure investigations. A strong advantage to this method of failure investigation is the non-invasive nature of the testing (i.e. not having to disassemble the components).

Through product of elimination, three IR testing methods ‘spot’ testing, time-resistance and ramp testing performed on acquired EFL components deduced the presence of insulation faults, or lack of, and in some cases the type of fault in the 1A EFL and 1B EFL components. Such deductions are summarised in the illustration below. It is hypothesised that channel 1A and 1B EFLs failed due to water ingress in line 1. More specifically, **water ingress in line 1 of the 1B female plug and 1A electrical flying lead.** Furthermore, ramp testing, with support from time-resistance plots, warned of the presence of **local insulation weaknesses for line 3 of the 1B MR.** The remaining lines were in ‘okay’ to ‘good’ conditions other than for the 1B MR, which were ‘questionable’ across the board.

In light of the rather severe faults associated with line 1, **V-LIFE** drastically improved the IR of the pair 1&2. Suspected water ingress can be mitigated by the ‘healing’ effect of **V-LIFE**, where an IR increase > 400 MΩ was observed in two weeks.

To confirm the proposed faults, one could pinpoint the fault location and type of fault by breaking down the EFLs into their constituents, i.e. stripping the cable and dismantling the connectors. A less invasive approach would be to adopt the costly use of X-ray imaging.